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OAKLAND BAY TRACON AND LOS ANGELES TRACON:
Case Studies of Upgraded Third Generation Terminal ATC Operational Impact

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16. Abstract This report documents the work performed by Stanford Research Institute (SRI) to assess the impact of Upgraded Third Generation (UG3RD) Terminal Air Traffic Control (ATC) System alternatives on control facility operations. The various UG3RD features would be added incrementally to the current Automated Radar Terminal (ARTS) III terminal ATC operation; the alternatives under evaluation are automatic data handling, basic metering and spacing (M&S), conflict probe, area navigation, Discrete Address Beacon System (DABS) data link (incorporating advanced M&S), and DABS-based intermittent positive control.

Using data collected at the Oakland Bay and Los Angeles Terminal Radar Approach Control (TRACON) ARTS III facilities, models were developed that relate the air traffic capacity of terminal area sector traffic controllers to their workload. The Relative Capacity Estimating Process (RECEP) is used for modeling controller work such as monitoring displays of radar-derived situation data; making decisions; voice communicating with pilots to transmit clearances, maneuver instructions, proximate traffic and navigational advisories; communicating with other controllers to coordinate their control actions; and maintaining computerized and hard-copy data records describing aircraft flights. The workload models differentiate the work activity of various ATC sectors and quantify sector traffic capacity (aircraft/hour) according to visual and instrument approach operations and to the number of men assigned to a sector control team. Sector capacity estimates made for ARTS III and UG3RD system alternatives enable comparison of multisector manning requirements at increments in traffic projections for the two TRACON study sites.

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This work was performed at SRI's Transportation Center under the direction of Dr. George J. Couluris and the supervision of the Center's director, Dr. Robert S. Ratner. Mr. Jerome M. Johnson developed the descriptions of sector traffic operations and applied the potential conflict processing models. Ms. Marika Garskis and Ms. Rilla Reynolds contributed significantly to data collection, reduction, and interpretation.

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EXECUTIVE SUMMARY

This report documents work that Stanford Research Institute (SRI) has performed for the Office of Aviation Policy, Federal Aviation Administration (FAA), Department of Transportation, to assess the impact that certain proposed Upgraded Third Generation (UG3RD) Terminal Air Traffic Control (ATC) System alternatives would have upon terminal ATC operations at the Oakland Bay and Los Angeles Terminal Radar Approach Control (TRACON) facilities. To compare the operational effects of the alternative UG3RD, we estimate controller manning requirements associated with each alternative system, based on models of controller workload and on traffic forecasts provided by the FAA. The basic modeling formulation was developed in previous contract work addressing enroute ATC operations for the Office of Aviation Policy and the Systems Research and Development Service, FAA; this modeling scheme has been adjusted to represent terminal ATC operations, based on field observations made at the two TRACON study sites.

Method of Approach

We collected data at the Oakland Bay TRACON and the Los Angeles TRACON describing the task activities of the terminal sector control team which are required under the current Automated Radar Terminal System (ARTS) III operation. Data was collected from the six sectors (out of ten) at the Oakland Bay TRACON which handle arrival and departure traffic for San Francisco International Airport and from all four sectors (supported by two parallel monitoring positions) of the Los Angeles TRACON, which serves the Los Angeles International Airport. However, operations at each airport's Airport Traffic Control Tower, which are not collocated with the TRACONs, are not addressed in this report. Both TRACONs are designated as Group I Terminal Control Area (TCA) facilities.

For each sector, the data were used to construct workload models describing the sector team routine, surveillance, and conflict processing requirements observed at each TRACON. Routine work includes air/ground (A/G) voice communications, manual computer data entry or display operations, paper flight strip and scratch-pad data processing, intersector interphone voice communications, and face-to-face communications. Surveillance work involves the visual observation of radar-derived aircraft situation data on a plan view display (PVD). Conflict processing work includes potential conflict recognition, assessment, and resolution decision making and it involves A/G voice communications. The models were used to quantify the relationship between workload limits and traffic capacity for the selected sectors of the two TRACONs. Workload-capacity relationships were developed for various sector manning regimes under both visual and instrument approach operations. These workload models and capacity relationships describe the operational characteristics of the current ARTS III terminal ATC system, which is the base from which we have postulated the evolution of the UG3RD systems.

To analyze ATC evolution through successive automation levels, we adjusted parameters of the workload models to represent the effects of various UG3RD systems on the sector teams' capability for traffic handling. The parametric values encode assumptions we have made as to how each system would be implemented in an operational terminal environment, and how each system would affect the task activities and workload characteristics of individual sector teams. The modeling approach, which we call the Relative Capacity Estimating Process (RECEP), estimates the sector traffic capacity associated with an UG3RD system relative to the performance requirements of current ATC operations.

The capacities estimated for individual sectors were used to determine multisector manning requirements for increments in day-shift traffic projections. Peak-hour manning requirements for each sector were determined by matching sector capacities against traffic projections and estimating the resectorization and sector manning increases needed to handle the increments in traffic. We have not attempted to estimate delay effects because such effects would largely be determined by airport constraints, rather than constraints upon TRACON controllers. The individual sector manning requirements (for each sector's peak hour in the day shift) were combined to estimate multisector day-shift manning, which includes the number of sector radar and handoff positions--controllers, coordinators, parallel monitors, and flight data--needed to handle the projected traffic. This estimate does not include staffing allowances for administration, relief, annual and sick leave, excess shift capacity, training, or special assignments. For each sector, we used the 1975 statistics on busy day (90th percentile) eight-hour traffic as the base for projections. This procedure was applied to the current ARTS III and UG3RD systems to enable comparison of manning requirements at selected traffic levels.

Sector traffic capacities for the UG3RD systems were derived using the workload models, from which we determined multisector manning requirements. Therefore, the resulting manning estimates are sensitive to the subjective judgments we have made in structuring the workload models so that they describe an evolutionary implementation of UG3RD features. In the remainder of this Executive Summary, we briefly review the operational assumptions and present the manning estimates.

Assumptions

The systems are examined in sequence under the assumption that each UG3RD feature is added to the previous system. The UG3RD features, added consecutively to the ARTS III Base (System 1), are:

- Automated data handling (System 2)
- Basic metering and spacing (System 3)
- Sector conflict probe (System 4)
- Area navigation (RNAV) (System 5)
- Discrete Address Beacon System (DABS) data link (System 6)
- DABS-based intermittent positive control (IPC).

Automated Data Handling (System 2)--This first add-on to System 1 includes the implementation of an electronic tabular flight data display at sector positions. The tabular display is an electronic presentation of flight data, designated to replace paper flight strips and attendant manual activities. It would effectively automate some of the controller's manual and verbal tasks associated with control procedures and flight data distribution.

Basic Metering and Spacing (System 3)--This feature, which we assume is added on to System 2, is a terminal ATC device to maximize airport runway use through precise control of interarrival times at runway thresholds. Suggested control instructions regarding aircraft headings, speeds, and altitude would be issued to TRACON controllers by the computerized metering and sequencing operation. Some workload reductions would be realized because this system would reduce the decision time a controller needs to assess and determine aircraft sequence assignment and to detect potential conflicts along inbound flight paths. We do not envision a significant impact on minute-by-minute control activities.

A refined metering and spacing system would extend the basic service by including departures and multiple airports in complex terminal areas. A refined system would not fundamentally change the basic metering and spacing operations, and we have not explicitly modeled such a refinement.

Sector Conflict Probe (System 4)--This feature, which we assume is added on to System 3, alerts controllers to potential conflicts and recommends resolution actions. To provide an operationally realistic time prediction horizon with a low false-alarm rate, we assume this feature will be used when aircraft first enter a sector. Since A/G communications are required to transmit conflict resolution instructions, workload reductions affect only conflict detection and assessment tasks.

RNAV (System 5)--This feature, which we assume is added on to System 4, incorporates navigation avionics to achieve close-spaced multi-lane traffic routes. Processing of overtaking conflicts in departure sectors would be eliminated by placing successive aircraft on closely spaced parallel routes.

DABS Data Link (System 6)--This feature, which we assume is added on to System 5, transmits digital data to pilots, including routine clearances and conflict avoidance directives. It is not intended to transmit extensive nonstandard-format messages. The data link, integrated with extensive computerization, is the basis for the "control-by-exception" concept in which the controller would become a system manager who is not routinely engaged in making minute-by-minute tactical decisions. He would have to monitor the computerized sector control operation and intervene when necessary to adjust procedural rules, respond to pilot requests, or resolve nonstandard situations. We note that the advanced metering and spacing feature functions with the data link, and this feature is included in terminal ATC control-by-exception operations. In modeling the workload changes associated with this system, we have accounted for the automation of certain routine and conflict tasks while allowing for the controller work required to maintain operational cognizance.

DABS IPC--IPC provides traffic advisories and threat avoidance commands to pilots, as needed. Since this service could operate in the positive control environment on imminent conflict situations that might be missed by controllers, we have assumed IPC to be a safety enhancement device which would not directly affect routine staffing requirements. IPC may be necessary to provide fault tolerance in the event of failure in the operation of the other UG3RD enhancement systems. However, we have not explicitly modeled DABS IPC.

Results

Projecting 25 percent increments in traffic, we have determined busy-day, day-shift controller manning requirements for the six Oakland Bay TRACON sectors and the four Los Angeles TRACON sectors. Results of these analyses for the ATC system alternatives are partly summarized in Table S-1. The factors shown in this table measure the growth estimates for traffic and manning relative to the 1975 busy day.

According to Table S-1, manning requirements increase as the traffic approaches twice the 1975 level and gradually level off as traffic increases beyond this 2.0 factor (or thereafter, depending on the alternative UG3RD system). In developing these manning requirements, we recognized that the Oakland Bay and Los Angeles TRACONs currently have a well-developed sectorization structure, and major increases in the number of control sectors are not expected. Therefore, the manning increases shown in Table S-1 are largely due to within-sector manning adjustments (e.g., one-man versus two-man sectors), with some allowances for minor sectorization adjustments. This limit on the number of sectors and logical limits on sector team size cause our manning projections to level off.

Because of the manning limitations, we expect workload saturation to occur if traffic increases significantly beyond the 2.0 factor. If such an increase occurs, traffic disruptions would cause significant change to the operational assumptions we have made in modeling sector capacity and manning. Therefore, as far as the manning factor estimates in Table S-1 are concerned, comparisons between systems should be made only for those traffic factors at or below 2.0. But in any case, manning comparisons at higher traffic levels should not be relevant to the Oakland Bay and Los Angeles TRACON sectors since traffic forecasts for their primary airports do not approach the 2.0 level by the year 2000.

Figure S-1 contains a composite graphical representation of the relationships found in Table S-1 between traffic and day-shift manning requirements for traffic factors at or below 2.0. The graphical representations were structured by fitting curves to the paired data given in Table S-1 for both TRACONs. Figure S-1 enables comparison of the overall manning trends associated with each ATC system alternative; these graphs do not describe manning relationships developed for a specific TRACON.

Table S-1

TRACON CONTROLLER DAY-SHIFT MANNING FACTOR
ESTIMATES FOR STUDY SITES

Operational System	TRACON* \ Traffic Factor	Day-Shift Manning Factor by Traffic Factor (1975 Base)						
		1.0	1.25	1.5	1.75	2.0	2.5	3.0
1. Current ARTS III	OAK	1.00	1.13	1.25	1.63	2.00	2.13	2.13
	LAX	1.00	1.29	1.85	2.00	2.29	2.29	2.29
2. + Automated Data Handling	OAK	0.75	1.00	1.13	1.50	1.63	1.75	1.88
	LAX	0.86	1.14	1.57	1.71	1.86	2.00	2.00
3. + Basic Metering and Spacing	OAK	0.75	1.00	1.00	1.38	1.50	1.75	1.88
	LAX	0.86	1.14	1.29	1.71	1.86	2.00	2.00
4. + Sector Conflict Probe	OAK	0.75	1.00	1.00	1.25	1.38	1.75	1.88
	LAX	0.86	1.14	1.29	1.71	1.86	2.00	2.00
5. + RNAV (100% RNAV Aircraft)	OAK	0.75	0.88	1.00	1.25	1.38	1.75	1.88
	LAX	0.86	1.14	1.29	1.57	1.86	2.00	2.00
6. + Control-by-Exception (100% Data Link Aircraft)	OAK	0.50	0.50	0.88	0.88	1.00	1.38	1.38
	LAX	0.57	0.57	0.71	0.71	1.14	1.43	1.43

*Terminal sectors studied include six sectors (AR-1, AR-2, AR-9, AR-10, DR-1, DR-2) at the Oakland Bay TRACON (OAK) and four sectors (AR-1, AR-2, DR-1, DR-2) at the Los Angeles TRACON (LAX).

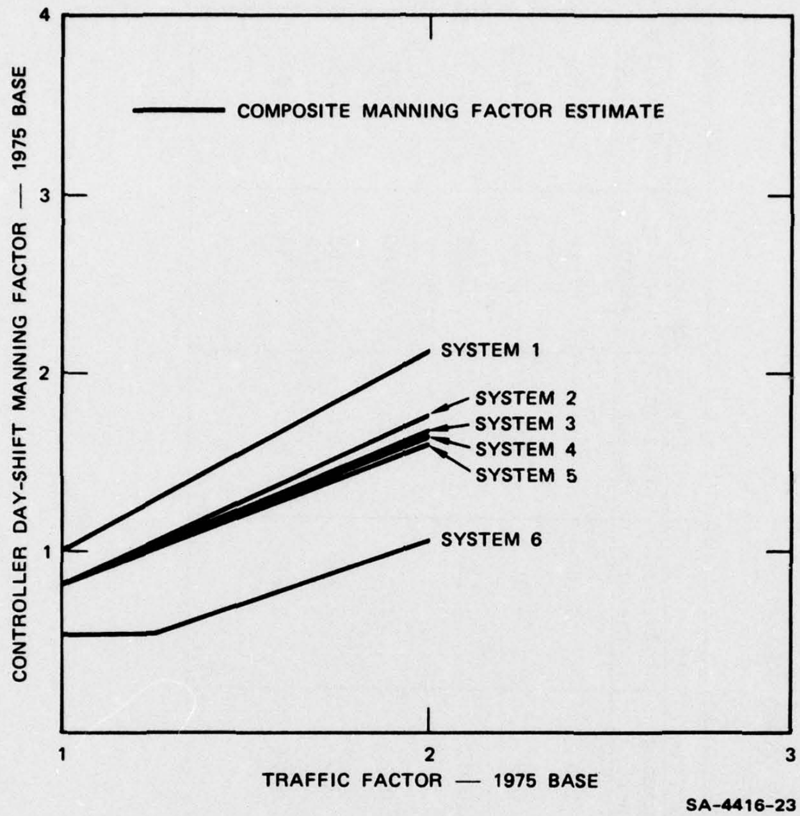

FIGURE S-1 TRACON CONTROLLER MANNING TREND

Observations

To provide some insight into the relative efficiencies of the systems, we examine the productivity trends of Figure S-1 at the current traffic factor (1.0) and then double this traffic level. As shown in Table S-2, a productivity factor is determined and used to measure the traffic handling capabilities of each system's control personnel, relative to the current ARTS III base (System 1). At the 1.0 traffic factor, System 2 (automated data handling) shows a 25 percent productivity gain relative to System 1, while System 6 (DABS data link) shows an 85 percent productivity gain over System 1; the intermediate systems show no productivity gains beyond those achieved by System 2. At the 2.0 traffic factor, System 2 shows a 14 percent productivity gain, and System 6 shows one of 87 percent; the intermediate systems show incremental gains of lower magnitude.

Table S-2

TRACON PRODUCTIVITY TREND COMPARISONS*

System	Current Traffic (1975)			Double the Current Traffic		
	Traffic Factor	Manning Factor	Productivity Factor*	Traffic Factor	Manning Factor	Productivity Factor*
1. Current ARTS III	1.0	1.0	1.0	2.0	2.13	0.94
2. + Automated data handling	1.0	0.8	1.25	2.0	1.75	1.14
3. + Basic metering and spacing	1.0	0.8	1.25	2.0	1.68	1.19
4. + Sector conflict probe	1.0	0.8	1.25	2.0	1.65	1.21
5. + RNAV (100% avionics)	1.0	0.8	1.25	2.0	1.62	1.23
6. + DABS data link (100% avionics)	1.0	0.54	1.85	2.0	1.06	1.87

$$^{*}\text{Productivity factor} = \frac{\text{traffic factor}}{\text{manning factor}}$$

We see that Systems 2 and 6 are shown to have the most significant impact on manning requirements, while Systems 3, 4, and 5 have limited effect. However, through evolutionary development the latter systems are assumed to be integrated into System 6, and their operation would be required to achieve the productivity gain of System 6.

Remarks

Manning estimates were made using controller workload models. These models are reasonably logical representations of ATC systems operation, but, being analytical in nature, they are merely abstractions from the real world. Therefore, the resulting staffing estimates should only be interpreted as first-order predictions of the relative effect of the various UG3RD automation features. These estimates should be useful guidelines for further experimental testing of the various systems in order to define their operational and technological design feasibility, and for developing detailed economic feasibility analyses.

Relative to operational and technological feasibility, we emphasize that many of our modeling assumptions are based on judgments concerning the implementation capabilities of the enhancement features. We assume, for example, that a conflict probe could indeed be used to predict and resolve conflicts within an air space sector; however, there is the question of whether a conflict probe of any type could be integrated with a controller's human cognitive capabilities. In fact, the basic issue of productively interfacing man and machine applies to each feature and requires considerable additional study, experimentation, and evaluation. This is especially true of the data-link-based control-by-exception operation in which the cognitive processes of the controller must be evolved into a system-interactive monitoring mode. Moreover, further research is needed to ascertain the degree to which a controller's cognitive capacity would constrain his ability to handle more traffic.

In regard to economic feasibility, our manning estimates provide insights into the relative effectiveness of each system in reducing FAA operating costs for manpower. Howevever, a full economic analysis would have to consider trade-offs between FAA costs for operations, engineering and development, and capital investment and user costs of delay and avionics. Furthermore, since the scope of this effort is restricted to estimating TRACON manning requirements, the various UG3RD systems are not assessed relative to safety, airport capacity, and other effects. Systems that do not have a significant effect upon TRACON manning, such as IPC or Wake Vortex Avoidance, should not be dismissed lightly; such features may contribute important qualities other than reduced terminal manpower needs.

I INTRODUCTION

A. Objectives and Scope

The work described here assesses the effect on terminal air traffic control (ATC) operations of various automation systems proposed as part of the Upgraded Third Generation (UG3RD) Terminal ATC program. The alternative UG3RD systems are examined in the light of currently observed control operations in order to judge how these automated advances might successfully be integrated with operational requirements and how controller activities might change. We evaluate the operational potentials of the various UG3RD alternatives by estimating and comparing their effects on manpower needs at two terminal facilities, the Oakland Bay and the Los Angeles Terminal Radar Approach Control (TRACON) facilities. The currently used Automated Radar Terminal System (ARTS) III was selected as a basis for comparing the manning requirements.

This study was performed for the Office of Aviation Policy, Federal Aviation Administration (FAA), under Contract DOT-FA75WA-3714.

B. Background

This work is based on ATC analysis capabilities developed by SRI during projects previously conducted for the FAA. The first project[1-4]* was a multiyear effort performed for the Systems Research and Development Service, FAA, during which we studied enroute ATC operations, developed various analytical models of ATC operations, and studied the operational realities of automation and its potential for implementation. The models included the Relative Capacity Estimating Process (RECEP), which relates controller workload requirements to sector traffic capacities, and the Air Traffic Flow (ATF) network simulation model, which assesses traffic capacity and delay in a multisector enroute environment.

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*A list of references is appended to this report.

The second project[5] was a case study of UG3RD ATC operational impact for the Los Angeles Center, which we performed for the Office of Aviation Policy, FAA. We used the RECEP and ATF models to estimate staffing needs under the various automation systems. A similar case study was performed for the Atlanta Center as part of the current overall contract effort, but it is documented[6] separately from this report.

The studies in this report of UG3RD operational impact at the Oakland Bay and Los Angeles TRACONs parallel those of the two initial centers. However, the TRACON case studies are based on applications of the RECEP model and do not use the ATF model (since we assume terminal area delays are largely determined by airport constraints rather than terminal controller limitations). In using RECEP to model UG3RD ATC system alternatives, we made a number of assumptions and judgments regarding the feasibility of implementing these alternatives in an operational environment. Our models of controller workload encoded such assumptions regarding possible system implementation. In some cases, these assumptions do not fully conform to the various designs suggested by FAA specialists and others,[7-9] but the staffing analyses we performed required operational descriptions that were both realistic and consistent with current ATC development programs. Where such descriptions were not available in sufficient detail, we postulated development of the necessary operational procedures.

C. Method of Approach

We are concerned with the impact of automation on ATC capacity. Based on our observations of ATC operations, we concluded that in almost all cases, the limits on capacity are associated with controller workload. Hence, we chose to focus on controllers, controller teams, and team organization. Because ATC services involve complex decision making by many people, we decided that our approach had to be based on measurements of present operations which are the best example of such complex decision makings; this provides a realistic base from which to develop operating descriptions of possible enhancement systems. Therefore, we used operations data collected at the Oakland Bay and Los Angeles TRACONs where Arts III was in full use.

Because capacity is so closely related to controller operations, we have expressed the effects of UG3RD system equipment and functions in terms of the changes these systems would effect upon present controller workload. Current controller operations were observed in the field at six sectors of the Oakland Bay TRACON and the four at the Los Angeles TRACON; these data were used in developing RECEP models that estimate sector capacity. The revised controller operations expected under each alternative UG3RD system were then fed into the RECEP model to determine sector capacity for each alternative. Sector capacities were estimated for both visual and instrument approach conditions and for alternative sector team manning regimes. For each ATC system, including the ARTS III base, the capacity data were then used to estimate the number of radar and handoff positions--controllers, coordinators, parallel monitors, and flight data positions--needed in each sector to handle increments in projected traffic. These estimates are made separately for the two TRACON sites, and they represent manning requirements in the selected multisector areas for the day shift of the busy day (90th percentile). These predicted manpower needs can be used to compare the potential operational impact of the UG3RD systems.

We emphasize that these manning estimates rely heavily on the validity of the RECEP models. The basic RECEP technique has been applied to 16 sectors in enroute and terminal facilities,[1-3] while the RECEP formulation as used in this report has been applied to 11 enroute sectors at the Los Angeles and Atlanta Centers.[4-6] In all cases, the resulting RECEP capacity estimates were consistent with estimates made by facility personnel. Although these results may not be considered a formal validation of the RECEP model, they do indicate that it is a reasonable representation of control operations.

D. Organization of This Report

The sections of this report may be grouped in three parts, although these parts are not formally designated. The first part, which includes this section and Sections II, III, and IV, is introductory in nature and describes terminal ATC and workload modeling approaches. The second part is the Oakland Bay TRACON case study, Sections V through VIII. The third part, Sections IX through XII, is the Los Angeles TRACON case study. Further details of the analysis are included in the Appendix.

In the first part, Section II describes TRACON control operations and procedures, and it differentiates between arrival operations (including visual and instrument approaches) and departure operations. Section III describes the ARTS III system and the associated controller operating requirements. Section IV describes the analytical approach used to model terminal operations and sector workload requirements.

In the second part, Section V describes the Oakland Bay TRACON's sectorization structure and arrival and departure procedures. Section VI explains the data collection at Bay TRACON and the construction of RECEP models corresponding to ARTS III operations for the six sectors. Section VII describes the reconstruction of the RECEP models according to

UG3RD system operations. Section VIII gives the sector capacity and manning estimates made for the ARTS III and UG3RD system alternatives.

In the third part, Sections IX, X, XI, and XII are analogous to Sections V, VI, VII, and VIII, respectively, but they address the Los Angeles TRACON.

II TRACON OPERATIONS

In this report we address the potential impact of ATC automation on TRACON operations, as distinguished from airport traffic control tower (ATCT) and air route traffic control center (ARTCC) operations. The terminal airspace controlled by a TRACON operation is a transition zone between airports and enroute airspace, and it is divided into volumes of airspace called sectors. Each sector is under the jurisdiction of a controller or team of controllers who maintain radio contact with and radar surveillance of aircraft within the sector. Sectors are configured according to a system of airport arrival and departure routes, and the control operations for each sector are procedurally structured and integrated with each other to facilitate traffic flow and separation assurance.

In order to provide an overview of terminal ATC, we first discuss the terminal control procedures used to integrate sector control responsibilities; and secondly, the actual operations nature of TRACON sectors. We base the following discussions on our observation of Oakland Bay and Los Angeles TRACON operations.

A. Terminal Control Procedures

Although each sector team is responsible for aircraft within its assigned airspace, air traffic control operations currently depend on a well defined and highly structured system of intersector and interfacility control procedures which facilitate the orderly movement of aircraft through a multisector environment. Between adjoining sectors and facilities both formal letters-of-agreement and informal accords specify the usual aircraft altitudes, speeds, headings, and in-trail separations that should be established when jurisdictional control over aircraft is transferred from one sector team to another at their common boundary; these procedures reinforce an established system of preferential traffic routes and standard terminal arrival and departure patterns.

The intersector agreements provide decision-making guidelines for sector-control by defining the traffic flow strategies and mechanisms by which jurisdiction is delegated to individual sector teams without requiring excessive coordination between them. For example, a control team accepting aircraft at its sector boundary need not be concerned with how the preceding sector team controlled the aircraft, providing it is properly set up in accordance with the intersector procedural agreement. Sector decisions regarding which control techniques (e.g., vectoring, altitude, or speed instructions) should be used in structuring traffic for sector transit and exit are internal functions of each sector team and do not require consultation with a facility authority. The sector teams are essentially autonomous decision-making units operating under the traffic organization requirements of the procedural agreements; supervisory, coordinating, and support personnel are not involved in minute-by-minute issuance of sector control instructions.

The system of procedural agreements and preferential routes structures each sector's traffic flow such that sector control becomes somewhat standardized, resulting in a fairly stable set of control techniques. Controllers make decisions concerning an individual flight plan or conflict avoidance maneuver based on established personal knowledge of what is best for facilitating overall traffic flow; they do not spend time reviewing the direct implications of a single control instruction upon each and all aircraft under their jurisdiction. Familiarity with the procedural requirements of each sector is, therefore, important to a control team's ability to make control decisions with minimum effort.

Procedural agreements clearly document facility traffic control policy and effectively serve as a relatively stable traffic planning device for sector operations. However, flexibility in intersector traffic integration can be introduced directly between adjacent sector teams or facilities; such coordination is often necessary as traffic situations change. A sector team, for example, may request another sector team to adjust spacings between aircraft in order to coordinate aircraft sequences, or one facility may request another to constrain traffic overloading situations. Similarly, altitude and speed restrictions may be applied or removed as situations warrant. Again, it is important to emphasize that personnel not on the sector team do not specify which control techniques should be applied, but only issue specifications or negotiate with the sector team regarding overall traffic flow organization.

B. Terminal Sector Operations

TRACON sector controllers provide separation assurance and traffic flow facilitation services to aircraft arriving and departing from local airports and to aircraft transiting the terminal airspace. Controllers monitor displays of radar-derived situation data, make decisions, voice communicate with pilots to transmit clearances, maneuver instructions, proximate traffic and navigational advisories and the like, communicate with other controllers to coordinate their control actions, and maintain computerized and hard-copy data records describing aircraft flights.

The terminal area route structure is designed to segregate arrival traffic flows from departure traffic flows as much as possible. This policy minimizes conflicts between descending and climbing aircraft, which could become excessively frequent and difficult to control in dense traffic situations. The route segregation is procedurally achieved by means of formal altitude separation (i.e., tunneling one route under another) and geographic separation (i.e., defining arrival and departure corridors). In some terminal areas, especially where numerous airports are served, the complexity of the required route network and the constraints of airspace preclude the complete segregation of arrival and departure traffic. However, a degree of procedural segregation is normally sufficient to enable arrangement of sectors along predominantly inbound and outbound routings. As a result, TRACON sectors often are differentiated according to arrival and departure operations.

1. Arrival Operations

Arrival traffic flows from diverse directions are integrated through a series of merges. These merging operations require arrival sector controllers to determine the order in which the aircraft are to be processed through the merge points while maintaining proper spacing; these operations are aided by a system of procedural specifications. Initial route mergings are conducted in the enroute airspace by the Center in order to organize the traffic according to control specifications required for entering the terminal airspace. By this means, aircraft are brought into TRACON arrival sectors along defined routes in accordance with prespecified or individually negotiated in-trail separations (typically 5 n.m.) and often according to specified altitude and speed restrictions. Arrival sector controllers process the aircraft through a succession of fewer and fewer merge points until the traffic is funneled to the airport final approaches. Control jurisdiction then is transferred to the tower in conformity with the appropriate in-trail separation, speed, and altitude specifications. This process involves the use of speed, altitude, and vectoring controls to slow the descending aircraft to approach speed, clear them along their planned routes, sequence them through the merges, and space them to maintain separation.

At some TRACONs (such as Oakland) arrival operations are based on the "feeder and final" sectorization concept, where a feeder sector's controller accepts aircraft entering from an ARTC Center, processes the aircraft through his airspace, and transfers control jurisdiction of the aircraft to a final sector controller. The final sector controller maintains control of the aircraft until it approaches the airport runways, at which time control jurisdiction is transferred to a tower.

In this operation, a feeder sector's controllers, and not those of the final sector, usually determine the sequence in which aircraft are ordered for landing. Because the feeders control the merges located in their airspace and are responsible for the sequencing and spacing of aircraft through these points, they control the order and spacing of traffic entering the final sectors. Thus the feeder sector's control decisions determine the sequencing of aircraft merging at downstream points located in the final sector. In this way the feeder controllers "set up" the traffic for downstream sequencing, while the final sector controllers "fine-tune" the traffic by issuing directives needed to complete the mergings, maintain separation, and proceed to landing. However, if necessary, the final sector controllers have the option of altering the traffic sequencing plan established by the feeders.

At other TRACONs (such as Los Angeles), control operations are not delineated according to feeder and final sector pairs; these functions are performed by a single designated arrival sector. In any case, the single or the paired sector design can be used for handling traffic in separate and possibly parallel corridors. For example, one arrival sector or pair of sectors may control aircraft destined to a specific runway or runway complex, while another sector operation controls aircraft destined for other runway(s). Both the Oakland Bay and Los Angeles TRACONs basically have such a control scheme: two traffic corridors run into the final approaches to parallel runways. At the Oakland Bay TRACON, each sector feeds into its own runway, while the Los Angeles TRACON sectors feed two pairs of parallel runways. In such cases, an arrival sector or a "feeder and final" pair may operate relatively independent of its complementary sector(s), especially during visual approach conditions. However, if the runway configuration is such that the aircraft on the parallel approach courses are in lateral proximity with each other, special precautions must be taken to assure adequate aircraft separation during instrument approaches. Each final, feeder, or arrival sector's controllers must coordinate their sequencing and spacing operations with those of the parallel sector to integrate traffic for mutual airport approach.

In summary, arrival sector operations depend on the traffic requirements specific to each TRACON site. We see that controllers carry out local merging operations for aircraft directly under their control, but also influence merging situations in downstream sectors. During instrument landing operations, controllers must overtly coordinate approach mergings with other controllers; such coordination may not be needed during visual approach operations. Additionally, sector controllers need to maintain separation assurance for aircraft that are potentially in crossing or overtaking conflict situations, while at the same time facilitating the flight of all aircraft--including those merely crossing the airspace--in accordance with pilot plans and procedural requirements.

2. Departure Operations

Departure sector operations differ from those of arrival sectors only in that aircraft are predominantly diverging rather than merging. Departure sector controllers accept climbing aircraft from an airport tower, process the aircraft through their airspace, and transfer control jurisdiction to an ARTC Center as the aircraft enter enroute airspace. Although the aircraft are received from one or a few origin airports, they normally have different destinations and therefore are usually on divergent routes within a departure sector. However, some local merging may occur in order to integrate take-offs from different runways or airports. Although parallel departure sectors may be designated (as at the Oakland Bay and Los Angeles TRACONs), alternate departure routes are sufficiently separated so that extensive coordination normally need not be carried out between controllers of different departure sectors.

As in the case of arrival sectors, a few aircraft may be crossing through the departure airspace. Controllers need to separate all aircraft in potential crossing and overtaking conflict situations as well as those in local merging situations, and facilitate flight planning.

III ARTS III SYSTEM DESCRIPTION

The current third generation ARTS III system is the base from which the upgraded ATC systems will evolve. To enable an understanding of the potential applications and limitations of automated ATC enhancements, we first describe ARTS III operational equipment and secondly, ARTS III control operations. These descriptions are intended to provide an insight into the operating characteristics of current automation technology. One should bear in mind that the ARTS III system is the technological mechanism currently used by controllers in carrying out the operations described in the preceding section of this report.

A. ARTS III Equipment

ARTS III is a semi-automated terminal ATC support system whose major elements are the computerized data acquisition subsystem (DAS), data processing subsystem (DPS), and data entry and display subsystem (DEDS). The system operates in conjunction with Airport Surveillance Radar (ASR) and Air Traffic Control Beacon Interrogators (ATCBI) to process primary radar and Air Traffic Control Radar Beacon System (ATCRBS) data. ARTS III interfaces with the computerized Flight Data Processing (FPD) system to enable transfer of digitized flight data between ATC facilities.[10]

ARTS III hardware/software apparatus enables:

- Beacon tracking.
- Broadband radar/beacon displays with alphanumeric data blocks (including aircraft identity, Mode C automatic altitude, and ground speed reports).
- Display filtering.
- Simplified clearance/coordination procedures.

1. Equipment Applications

The ARTS III computer system tracks the trajectory of an aircraft's ATCRBS beacon responses to successive ATCBI interrogations (e.g., at 4-second intervals) and correlates this information with computer-stored flight plan data. This flight plan correlation enables the system to recognize the identity of an aircraft replying on a selected discrete beacon code, and to automatically initiate tracking operations; controllers must manually initiate tracking for nondiscrete beacon targets. The ARTS III tracking program stores positional data, calculates beacon target velocity, predicts flight path position, and correlates subsequent beacon responses with these predictions. Concurrently, the computer uses manually entered altimeter setting data to decide altitude data from Mode C transponder responses to interrogations. Tracking is automatically discontinued when an active track passes a prespecified range and azimuth or manually at the controller's discretion.[10]

Flight plan data are obtained automatically from other FDP-equipped facilities through established computer interfaces or are entered manually by TRACON controllers.[10] As indicated in the preceding paragraph, the flight plan data record is used to establish and maintain automatic tracking, and it facilitates target correlation and identification. The correlation process enables the ARTS III system to associate data blocks with beacon targets; such association is useful for display purposes. This display capability and the concurrent computerized data processing are the basic automation attributes of ARTS III; these attributes determine the design of the operational equipment made available to sector teams.

2. Equipment Usage

The ARTS III system supports control operations through the presentation of alphanumeric data on sector controllers' radar displays, the semi-automatic transfer of data between sectors, and the automatic transfer of flight data between the terminal and ARTCC computers. These support capabilities are provided to controllers through the ARTS III automation devices included in each sector team's operating console.

An ARTS III console includes a planned view display (PVD) and keyboard and trackball units, which jointly provide a data entry and display interface between the controllers and the computer system. These automation elements augment sector team voice communications and hard-copy (paper) data processing equipment.

The PVD presents radar-derived aircraft situation data and computer-processed alphanumeric and symbolic data. The presentation may include primary radar targets, beacon targets, control position symbols, aircraft data blocks (from beacon targets only), video maps, tabular lists (i.e., arrival/departure and coast/suspend lists), time, altimeter setting, selected beacon codes, general system information (e.g., ATIS, weather) and the like. The PVD may be vertical (Type I console) or horizontal (Type II console), with adjustment knobs to control brightness range, alphanumeric character size, and so forth.

A trackball and keyboard unit operates in conjunction with the PVD and provides the controller-computer interface mechanisms for data entry and display control. The unit includes a trackball panel, alphanumeric keys and quick-action, special function keys. The trackball is used manually to slew and capture PVD targets, while manual keypunching is used to access the computerized operation. These capabilities enable controllers to select and revise data presented on the PVD, enter flight data, and carry out special control operations (e.g., transfer control jurisdiction, manually initiate or drop beacon tracking). At least one trackball and keyboard unit is built into each console, but additional keyboard-only units may be provided (normally with the Type II horizontal display).[10]

The console designs vary from facility to facility in accordance with local operations. At some facilities (such as the Boston-Logan TRACON), vertical PVDs and associated keyboard and trackball units are arranged in rows, with one PVD console assigned to each sector team. At other facilities, sector team pairs are set up as islands isolated from other sector team pairs. In this case, each team usually is equipped with its own PVD console (as at the Los Angeles TRACON where both horizontal PVD and vertical PVD pairs exist). At least one facility (Oakland Bay TRACON) has a single PVD island shared by two sector teams, but each team is equipped with its own trackball panel and keyboards.

In addition to the ARTS III automation, the sector console includes air/ground (A/G) radio and interphone communications apparatus and workspace for maintaining paper flight progress strips or scratch pad hard-copy data records. A/G communications enable two-way voice conversation between pilot and controller, while interphone communications enable two-way voice conversations between controllers of different sectors as well as between different facilities. Hard-copy records provide flight data information to supplement PVD-displayed data, and they are manually updated in handwriting. Paper flight strips are prepared by FDP printer or prepared manually by sector controllers; some sector teams use paper scratch pads in lieu of formal flight strips.

B. ARTS III Operations

We now examine the way in which the ARTS III equipment is used to carry out sector team control operations and the options available in assigning control responsibilities among sector team members.

1. Sector Control Operations

The sector control team utilizes the ARTS III console to conduct separation assurance and facilitate traffic flow. In this operation, the controllers are the primary decision makers and use the ARTS III console to obtain and transfer information. The ARTS III automation does not make control decisions, but it supports the controllers' decision-making processes by automatically processing and displaying flight data and facilitating communications. The following discussion reviews the means by which a sector controller interacts with the ARTS III system, with pilots, and with other controllers in order to effect control services and implement procedural requirements.

The PVD's alphanumeric aircraft data block information serves as an aid to the controller's awareness of current and planned traffic situations, and it becomes increasingly important as sector traffic levels rise. The data block presents aircraft flight identity, current altitude, and ground speed information that trigger an instant recall of each aircraft's current and planned flight path. This mnemonic effect is particularly useful to a controller who must cope with dynamic traffic data. A controller can concentrate attention on traffic presented in one area of the PVD, while other data are automatically being updated without controller assistance. The alphanumeric data blocks are also useful in establishing the target identities of aircraft not yet under the sector team's jurisdiction.

The controller relies on continuous PVD surveillance to mentally project flight trajectories and conduct limited conflict searches; his picture of current and future traffic situations includes a conceptual overlay of the standardized control procedures (including minimum separation requirements) and preferential routes as well as a thorough knowledge of aircraft performance characteristics (which depend on aircraft design and owner operating policies). In order to formulate control decisions, the controller mentally compares his traffic projections against the traffic structuring guidelines specified by the control procedures. His control decisions are then disseminated by means of A/G communications.

The controller's mental "picture-keeping" process is also supported by hard-copy data, usually paper flight progress strips but sometimes paper scratch pads. The flight strips describe each aircraft's flight identity, route, altitude, speed plans, beacon code assignment, and equipment. This basic information supplements the PVD data blocks by indicating flight plans and aircraft capabilities that a controller must know when an incoming aircraft is added to his mental picture of the traffic situation. Flight strips may be used for manual recording of such control actions as altitude clearance, route revisions, or beacon code changes. In some cases, where sector procedures are extremely structured (e.g., final approach sectors), only the sequence in which aircraft enter and depart the sector need be recorded on scratch pads. Hard-copy data also serve an important failure-mode function for surveillance. In the event of a complete failure in the radar data presentation capability, the paper data may be used in conjunction with pilot reports for on-line flight following by the controllers.

A controller also issues control instructions to pilots by voice communicating over A/G radio. Such verbal instructions include clearances (i.e., assignments or approvals of specific routes, altitudes, and speeds), advisories (i.e., weather, proximate traffic information), and direct navigational control (i.e., heading vectors and altitude or speed revisions). Direct voice communication provides some flexibility because it allows pilots to negotiate with a controller if the instruction issued cannot be readily followed; positive confirmation of instruction compliance is also transmitted by voice. Since most aircraft in a sector are on the same radio frequency, the A/G communication is on a "party-line" with aircraft crews monitoring each other's instructions and responses. Although not studied explicitly here, pilots may perhaps use this capability to communicate among themselves in order to attempt separation assurance should a ground-based A/G system totally fail.

Controllers communicate with each other by means of interphone voice or face-to-face coordination. The interphone system is used to negotiate and confirm procedural controls (i.e., arrival sequences, speed, or altitude restrictions, in-trail separations) and to advise sector teams of some specific traffic condition that may be unusual. Members of a single sector team or, in certain cases, members of adjacent sector teams may communicate directly with each other by face-to-face oral conversations (i.e., without interphone apparatus) or with hand signals (i.e., by pointing to a PVD target or moving a flight strip). As in the case of interphone intersector messages, these communications are needed to coordinate controller actions so that each controller maintains cognizance of overall operations and thereby avoids last-minute surprises.

A sector controller uses the computer data entry and display interface to carry out various control operations and keep the automation system up to date concerning his on-line control operations. For example, manual trackball and keyboard operations are used to effect control jurisdiction transfers between sectors; these transfers are usually performed silently without accompanying interphone voice communication. Such "handoffs" are registered in the computer system, which in turn transfers data file access from one control team to another and updates PVD position symbol displays. In other cases, the controller may use the data entry and display system to manually enter or modify flight plan data into computer storage, assign a discrete beacon code, or establish beacon tracking. A controller may selectively force the presentation of individual data blocks on to his PVD or delete them, or he may force the entire PVD data for another sector onto his display in order to "glance over" that sector's traffic. Controllers also have the option to use an alphanumeric "scratch pad" which electronically displays such data as destination airport, runway, or departure fix designations; this scratch pad information time shares PVD data block display space with the Mode C altitude data. (The PVD "scratch pad" should not be confused with the paper scratch pad.) Other operations enable controllers to display tabular lists, reorient data block presentations, preview flight plan data, present system data on the PVD, and so forth. These examples demonstrate some of the uses made of the trackball and keyboard units, which provide the means to integrate computer processing capabilities with sector control operations.

2. Sector Controller Responsibilities

The lead member of an ARTS III sector team is the radar (R) controller, who is responsible for separation assurance, minute-to-minute decision making, and A/G voice communications. He may be supported by a coordinator, by a handoff (H) controller, or by both. During periods of light traffic, the R controller may man the sector alone and therefore perform all necessary communications and data processing activities. However, as traffic increases, the R controller's workload restricts his performance, necessitating the allocation of some operational activities to one or both of the other team members.

While a single H controller may be assigned to assist an R controller, a coordinator is assigned to a pair of sectors and simultaneously supports both R controllers. As a result of the shared nature of coordinators' services, we refer to sector team manning alternatives according to four regimes: a 1-man team (R controller); a 1.5-man team (R controller and one-half the services of a coordinator); a 2-man team

(R and H controllers); and a 2.5-man team (R and H controllers and one-half the services of a coordinator).

The ARTS III console is usually set up so that each controller and coordinator position is equipped with keyboard and interphone apparatus, while a single PVD and trackball panel is directly accessible by the R controller. Each R controller is equipped with A/G apparatus, while all sector team members may handle flight strips or paper scratch pads depending on local operating procedures. These equipment arrangements enable the effective division of control responsibility among team members. In the following paragraphs we briefly review the operational role of each member of the team and address other support positions.

a. <u>1-Man Team</u>

The R-controller performs all the sector control operations necessary for separation assurance and traffic flow facilitation. These operations include surveillance, A/G communications, data entry and display, flight strip (or paper scratch pad) processing, intersector interphone and face-to-face coordination, and related decision making.

b. <u>1.5-Man Team</u>

The R-controller maintains responsibility for separation assurance and minute-to-minute decision making, but shares decision making about traffic planning with the coordinator. The coordinator performs intersector coordination wnd some data entry operations, while the R controller performs separation assurance, surveillance and related data processing operations. Based on our observations of control activities, the coordinator is usually able to perform the interphone communications for both the sectors he supports and half the computerized handoffs for each sector. However, these activities do induce some additional face-to-face communications with the R controllers since he must advise the R controller regarding the intersector negotiations completed. A coordinator supporting a pair of arrival sectors determines the sequence in which aircraft should be mutually merged and advises each R controller of his plan; each R controller sets up this traffic in accordance with the coordinator's plan. A coordinator supporting a pair of departure sectors integrates tower departure operations with those of each sector. Such interfacility coordination is also performed for arrival sectors, and also is conducted with adjacent ARTC Centers. Also, the coordinator may assist in distributing flight strips to the appropriate R controller.

c. 2-Man Team

The R controller maintains responsibility for separation assurance and traffic flow facilitation, and shares some of the mechanical aspects of control operations with the H controller. In this case, the H controller supports only one R controller and should have time to perform the routine interphone communications and computer handoff operations. However, the R controller must himself coordinate separation assurance and sequencing for aircraft merging into other sectors while performing surveillance and communications and data processing activities. Again, intrasector face-to-face communications is needed to maintain operational cognizance of each team member's activities. The H controller may also assist the R controller by arranging and correcting flight strips. We should note that we have not observed a 2-man team in actual operations, indicating that TRACON personnel prefer the manning strategies which involve a coordinator. However, since 2-man teams are physically and operationally possible, we do consider this manning option to be feasible.

d. 2.5-Man Team

The R controller maintains responsibility for separation assurance and minute-to-minute decision making, but he shares decision making about traffic planning with the coordinator and affords some of the mechanical control tasks to the H controller. The coordinator is primarily concerned with integrating intersector and interfacility operations and is therefore active in interphone and face-to-face communications; he also assists in flight strip distribution where appropriate. The H controller performs interphone communications not handled by the coordinator, carries out computer data entry and display operations, and may assist the R controller with flight strip preparation.

e. Other Support Positions

Although not directly associated with a specific sector, a controller may normally man a flight data position, where flight progress strips are printed. He checks and corrects flight strip data and delivers the flight strips to the proper sector team or team pair. In some cases, the delivery is made to an arrival or departure coordinator, who selectively distributes strips to an R controller when aircraft entry is about to occur. In at least one facility (Los Angeles TRACON), flight strip printers are located at each departure sector and are operated by the sector H controllers. In this case, no separate flight data positions are currently manned, and the arrival sectors must manually write their own flight strips. In other cases (such as final arrival sectors at Oakland Bay TRACON), R controllers use paper scratch pads to keep track of aircraft entries and exits; FDP printed flight strips for arrival aircraft are delivered to the feeder sectors but not to the finals.

At the Los Angeles TRACON, parallel monitor (PM) positions are manned during instrument approach operations. A PM controller maintains surveillance of aircraft on a set of parallel final approach courses and intervenes on the arrival sector's A/G radio frequency to correct potential violations of minimum separations. A PM position is located at a PVD console other than one being used by the regular sector teams.

IV WORKLOAD MODELING

The preceding two sections have described terminal ATC control procedures, operations, and operational technology. In this section we present a methodology for quantitatively relating these procedures, operations, and technology to the traffic handling capabilities of sector controllers. This methodology models controller workload requirements based on observations of ARTS III operations, and enables estimation of sector controller traffic capacities corresponding to various operating strategies. The resulting RECEP models will facilitate subsequent extrapolations and analysis of the impact on control operations of ATC enhancement alternatives.

A. Model Overview

In order to relate sector traffic handling capabilities to the various operating strategies, we will develop workload models corresponding to each of the four alternative sector manning regimes: 1-man, 1.5-man, 2-man, and 2.5-man teams. Our modeling approach will follow that of our previous ATC analyses[4-7] in which we used data collected from field observations of sector teams to construct the models, and thereby to describe controller work characteristics.

A major assumption of our approach is that the workload on the controller due to his operational requirements is the factor which limits the number of aircraft that he can handle during any given period of time; this thus determines the traffic capacity of the sector. Our past observations of air traffic control activities indicate that within a given time period (i.e., one hour) there is a maximum total time that a controller can spend performing control tasks. Through previous field observations and data calibration efforts,[1-5] we have found that an R controller's workload threshold is typically 48 man-min of work per hour; the number of aircraft per hour that generates this amount of work represents his traffic capacity. The objective of our models is to correlate workload time requirements with traffic flow rates so that we may identify the traffic flow rate (i.e., capacity) corresponding to the workload threshold (48 man-min/hr). We use an hourly time period as a basis for estimating capacity since this interval is the time a controller normally spends at a sector position before being relieved.

The following discussion reviews the procedures for field data collection and describes the methods and rationale with which the data were used to structure workload models.

1. Field Experimentation

Using as a guideline our previous data collection exercises at NAS Stage A enroute ATC facilities,[1-5] we have developed a parallel data collection/reduction procedure for ARTS III terminal ATC facilities based on the following data sources:

- Videotape recordings of PVD data, using an auxiliary console to duplicate in real time the presentation on an operational PVD.
- Audiotape (including videotape sound track) recordings of A/G and interphone communications.
- Manual recordings of the frequency of observed controller actions, including data entry and display operations, flight strip or paper scratch pad processing, and face-to-face communications.
- Manual stopwatch recordings of observed controller actions.
- Reproductions of flight strips and paper scratch pads, used and marked on by controllers.

These data were collected during a one-hour observation of a selected sector's control activities. Each observation session was followed by a one-hour structured interview with the sector's controllers. The interviewer used videotape playback during examination and discussion of the operational strategies, procedures, and techniques employed by the controllers. This information was supplemented by published facility operations manuals, letters-of-agreement, maps, and the like, as well as consultations with facility supervisory personnel.

Reducing the field observation data involved assembling the data measurements into a format that facilitates cross-reference of the observed activities and permits a reconstruction, in part, of the various control activities. The information on operational procedures obtained during the controller interview, along with the data observations, provided perspective on control requirements that was useful in the logical reconstruction of control activity.

Also, as part of the data reduction efforts, we obtained stop-watch measurements of recorded communications, to supplement the activity-time measurements made at the facility. For each identified task, we selected from the data measurements a "reasonable" minimum task performance time to represent task work requirements. In determining minimum performance times, we considered only those observed or recorded activities that we judged were performed completely (that is, they satisfied the requirements of information transaction or message content) and with efficiency (without delay, interruption, or extraneous information). Since the field data collection sessions were generally conducted during moderate-to-heavy conditions, we have assumed that our reconstruction of control activities is representative of control requirements during capacity conditions (during which nonessential activities are minimized).

2. Model Rationale

Using our observations on control operations and interviews with facility controller and supervisory personnel, we conclude that the R controller's workload is the critical determinant of sector team traffic capacity. That is, the R controller, rather than the coordinator or H controller, is the team member whose workload requirements will limit traffic handling capabilities. We base these conclusions on the observation that a significant proportion of terminal ATC control work is centered on surveillance, minute-to-minute decision making, and A/G communications; these tasks are not off-loaded to other positions under any of the alternative sector team manning regimes. Therefore, we will develop an R controller workload model corresponding to each of the four sector manning regimes; the regimes will be differentiated by changes in the model reflecting the revised operations of the R controllers each time an additional controller or coordinator is added to the team. In each case, the R controller's workload threshold will be used to define the sector team's traffic capacity.

Out emphasis on the R controller model differs from the approach we used in modeling enroute operations;[4-7] then we modeled R controller and sector team work separately. Our field observations indicate that enroute operations make more extensive use of computer data entry and flight strip processing than terminal operations. The distribution of work among enroute sector team members would in some instances cause a sector data (D) controller to experience heavier work loading than the R controller at comparable traffic levels. In this case, the overall team work requirements rather than those of the R controller alone would limit traffic handling capability.

B. Model Structure

In a preceding section we described the various operational activities (i.e., decision making, surveillance, communications, data processing) that are required of the R controller. These activities are mutually integrated and interactive and are very difficult to model as independent entities. Therefore, we aggregate the various control work requirements into activity categories that represent operational/procedural relationships. For our modeling purposes, we organize control requirements according to:

- Routine work
- Surveillance work
- Conflict processing work.

Routine work includes the A/G, interphone, and face-to-face communications, data entry/display operations, and flight strip or paper scratch pad data processing tasks needed to facilitate traffic flow. Surveillance work is the visual observations of the PVD data to facilitate flight-following. Conflict processing work includes the decision making and communications needed to detect and assess potential conflicts, resolve the conflicts by means of A/G communications, and coordinate the assessment and resolution actions with other controllers. We further categorize potential conflicts according to crossing, local merging, overtaking, and coordinated approach merging situa‥ons.

R controller workload time, W_R, measured in man-min/hr, corresponding to a specified hourly traffic rate is calculated using the following additive formulation:

$$W_R = \left[k_1 N + c t_s N + \left(k_2 + k_3 + k_4 + k_5 \right) N^2 \right] \Big/ 60$$

where

N is the number of aircraft/hr through the sector.

t_s is the average sector flight time, measured in min.

c is the surveillance workload constant, measured in man-sec/aircraft-min.

k_1 is the routine workload weighting, measured in man-sec/aircraft.

k_2 is the crossing conflict workload weighting, measured in (man-sec/hr)/(aircraft/hr)^2.

k_3 is the local merging conflict workload weighting, measured in (man-sec/hr)/(aircraft/hr)^2.

k_4 is the overtaking conflict workload weighting, measured in (man-sec/hr)/(aircraft/hr)^2.

k_5 is the coordinated approach merging conflict workload weighting, measured in (man-sec/hr)/(aircraft/hr)^2.

60 is the factor to convert man-sec/hr of work to man-min/hr.

A set of four R-controller workload times (W_R's) is calculated for each sector corresponding to the four manning regimes. The regimes are distinguished by adjusting the workload weighting parameters (k's).

The importance of the workload component structure of the R controller model is the capability of distinguishing the control work requirements of different sectors in a manner that is sensitive to each sector's operational characteristics. Sector routine workload time (k_1N) increases in direct proportion to the traffic flow rate, but varies from one sector to another depending on the pattern of traffic flow through each sector as well as each sector's procedural rules. For example, the routine workload weighting (k_1) for an arrival sector (where speed control instructions are frequent) would differ from that of a departure sector (where speed control is not as frequent).

The surveillance workload time (ct_sN) increases in direct proportion to sector flight time; therefore, surveillance work is sensitive to the geographic size of a sector as well as the traffic flow rate. The flight time parameter (t_s) distinguishes the surveillance work requirements of different sectors since the same surveillance workload constant (c) applies to each sector. We note that the product, ct_s, may be considered to be the surveillance workload weighting measured in man-min/aircraft.

Potential crossing, local merging, overtaking, and coordinated approach merging conflict processing workload times (k_2N^2, k_3N^2, k_4N^2, and k_5N^2) increase with the square of the traffic flow rate. The conflict workload weightings (k_2, k_3, k_4, and k_5) calculated for one sector would differ from those of another, depending on the complexity of each sector's route structure and its procedural rules. In particular, the derivations of the conflict workload weightings can model a variety of aircraft crossing and merging situations including level/level, level/climb, climb/climb, level/descent, and so forth.

In the following paragraphs we review the derivation of the workload weightings.

1. Routine Work

The routine workload time (k_1N) represents the ordinarily occurring control events required to clear aircraft through the sector; it is generated in some form by every flight. Using the field data collected for each sector, we identify the routine control events, specify the set of tasks required to effect each event, determine minimum task performance times, and measure the frequency of each event by sector.

Each routine event is included in one of the following functional categories:

- Control jurisdiction transfer
- Traffic structuring
- Pilot request
- General intersector coordination
- General system operation.

Control jurisdiction transfer encompasses the collection of control events required to handoff an aircraft from one sector to another. Traffic structuring refers to the procedural-based, decision-making process of guiding aircraft through a sector. Pilot requests result in real-time flight modifications, adding work. General intersector coordination includes those informational transfers that are performed to remain cognizant of multisector traffic movement, but are not part of handoff, traffic structuring, pilot request, or pointout activities. General system operation refers to the remaining activities not included in the above categories, activities such as PVD display maintenance.

A routine event consists of a single task or sequence of tasks that must be performed to complete the event. The tasks are:

- A/G communications
- Data entry/display operations
- Paper flight strip (or paper scratch pad) processing
- Interphone communications
- Face-to-face communications.

For example, one control event routinely required for control jurisdiction transfer is handoff acceptance. This event requires the controller to perform manual data entry/display operations and flight strip processing tasks. On the other hand, an altitude instruction event issued by the controller as part of the traffic structuring function might involve only the A/G communication task.

Our field observation results enable us to specify individual task times and the frequency of each event by sector for any given manning regime. We use these data to calculate the routine workload weighting, k_1:

$$k_1 = \sum_i \sum_j r_i \, t_{ij} \quad .$$

where

r_i is the frequency of occurrence of type i routine event measured in events/aircraft.

t_{ij} is the minimum performance time required for each type j task included in routine event i, measured in man-min/event. (In subsequent modeling applications, we will describe task times by man-sec; conversion to man-min is implicit in the modeling equations.)

2. <u>Surveillance Work</u>

Surveillance workload time (ct_sN) is the time spent scanning the PVD. We were not able to measure in the field the number of times a controller looks at the PVD or the duration of each glance. Instead, we inferentially formulated assumptions regarding surveillance frequency and time duration; these assumptions are developed from interviews with controllers and reflect their perceptions.

To maintain a mental picture of traffic movement, we assume that the R controller is likely to look at an aircraft's data display once every minute, 1 to 1.5 sec per look being sufficient time to identify aircraft and recognize or recall situations. These assumptions--1.25 man-sec/look and 1 look/aircraft-min--set the surveillance workload constant (c) equal to 1.25 man-sec/aircraft-min. The corresponding surveillance workload weighting is 1.25 t_s man-sec/aircraft (which is implicitly converted to man-min/aircraft in the workload model equations).

3. <u>Conflict Processing Work</u>

The workload times for processing crossing, merging, and overtaking conflicts (k_2N^2, k_3N^2, k_4N^2, and k_5N^2) represent the time spent, including communications and decision making, to maintain separation assurance. Aircraft conflict situations arise when there is a prospective violation of the minimum separation allowable between aircraft. Because prevention of such situations requires corrective action in advance, conflict avoidance by the controller necessitates a rather well-developed capability to mentally project flight trajectories and to perceive potential conflict. The R controller activities are detection and assessment, then resolution and coordination of potential conflicts.

The detection and assessment task entails situation recognition and action selection based on traffic data derived from PVD surveillance and flight strips; the resolution is the issuance and negotiation of control instructions through A/G communication. Effective detection and assessment depend, to a large extent, on judgment and familiarity with procedures developed through control experience. Observations reveal that journeymen R controllers have refined these capabilities to such a degree that situation resolution instructions are typically issued when conflicting aircraft first enter the sector. The corrective actions, which usually occur five or so minutes before violation would be imminent, are performed as soon as possible to avoid possible controller distractions by other critical situations. In merging situations, some intersector coordination (usually face-to-face communication) is needed to integrate aircraft sequencing and spacing.

To estimate conflict processing workload weightings, we use the duration of each conflict processing event and its frequency of occurrence:

$$k_2 = t_c e_c$$

$$k_3 = t_m e_m$$

$$k_4 = t_o e_o$$

$$k_5 = t_a e_a$$

where

t_c, t_m, t_o, t_a are the minimum performance times required for crossing, local merging, overtaking, and coordinated approach merging conflict processing, measured in man-sec/conflict.

e_c, e_m, e_o, e_a are conflict event frequency factors that measure the rates of occurrence of crossing, local merging, overtaking, and coordinated approach merging conflict events, measured in (conflicts/hr)/(aircraft/hr)^2.

We determine the conflict processing time (t_c, t_m, t_o, and t_a) by estimating and summing the minimum times typically needed for the detection and assessment, resolution, and coordination tasks. These task times are based upon field observation of control activity and subsequent interviews of controllers using the videotape playback of the observed situation to review controller actions.

The hourly conflict frequency factors (e_c, e_m, e_o, and e_a) determine the number of conflicts per hour (e_cN^2, e_mN^2, e_oN^2, and e_aN^2) for any hourly traffic flow rate, N, and represent the total number of conflicts that may be occurring at one or more conflict points in the sector. These factors are calibrated for each sector using mathematical models (developed by SRI[4-7]) that determine the expected frequency of each conflict type at each selected location or along each selected route. The models define conflict frequencies as functions of aircraft speeds, route intersection angle, route lengths, and minimum separation requirements. These relationships are formulated as a summation of the probability of pairwise conflicts between aircraft; the models are further described in Appendix A.

C. Sector Capacity Estimation

The R controller workload formulations are used to quantify sector traffic capacity. We estimated sector capacity by identifying the hourly traffic rate (ac/hr) that generates 48 man-min/hr of R controller work. One procedure was to determine R controller workload for a range of traffic flow rates, and search for the flow rate corresponding to the workload threshold. The R controller workload is the sum of routine, surveillance, and conflict work as defined by the workload weighting parameters, for a specific sector operation. We calculated workload at successive 5 ac/hr increments in traffic flow, and obtained the sector traffic capacity by interpolation.

V BAY TRACON OPERATIONS

The airspace under the jurisdiction of Bay TRACON is designated as a Group I Terminal Control Area (TCA) within which all aircraft are controlled.* Bay TRACON provides control services to aircraft arriving and departing three major civil, two military, and numerous lesser airports, as well as enroute aircraft transiting the TCA. Final approach and related airport control services are provided by separate ATC tower facilities located at each airport and coordinated with Bay TRACON.† Airspace above that of Bay TRACON is controlled by the Oakland ARTC Center. San Francisco International Airport (SFO), which generates mainly air carrier traffic, is the primary airport and is included in the TCA; other airports underlay the designated TCA airspace. Two major civil airports, Oakland International (OAK) and San Jose Municipal (SJC), also generate commercial traffic but with significant general aviation activity, while the Alameda (NGZ) and Moffet (NUQ) Naval Air Stations (NAS) generate military and related governmental air traffic. The remaining airports under the TCA generate general aviation air traffic, with some commercial and military helicopter activity.

To accommodate the complexity of traffic patterns required by the various airports, Bay TRACON is configured into ten sectors. Six of these sectors, AR-1, AR-2, AR-9, AR-10, DR-1, and DR-2, primarily handle the SFO approach and departure traffic and are shown in the Figure 1

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*The TCA designation requires all aircraft operating in its airspace to be subject to ATC operating rules (thereby eliminating uncontrolled flights), and requires equipment and pilot to meet certain qualifications. The Group I designation currently requires: an aircraft to be equipped with ATCRBS and Mode C transponders (unless it is a helicopter or an IFR flight not to or from the primary airport), 2-way radio, and VOR or TACAN receiver; the take-off or landing pilot to hold at least a private pilot certificate; a large turbine-powered aircraft to operate within designated airspace limits; and the flight to be ATC authorized. Group II requirements are less stringent.[9]

†Bay TRACON is located on the property of Oakland International Airport, but is not collocated with the Oakland Airport Traffic Control Tower, nor with the Oakland Flight Service Station.

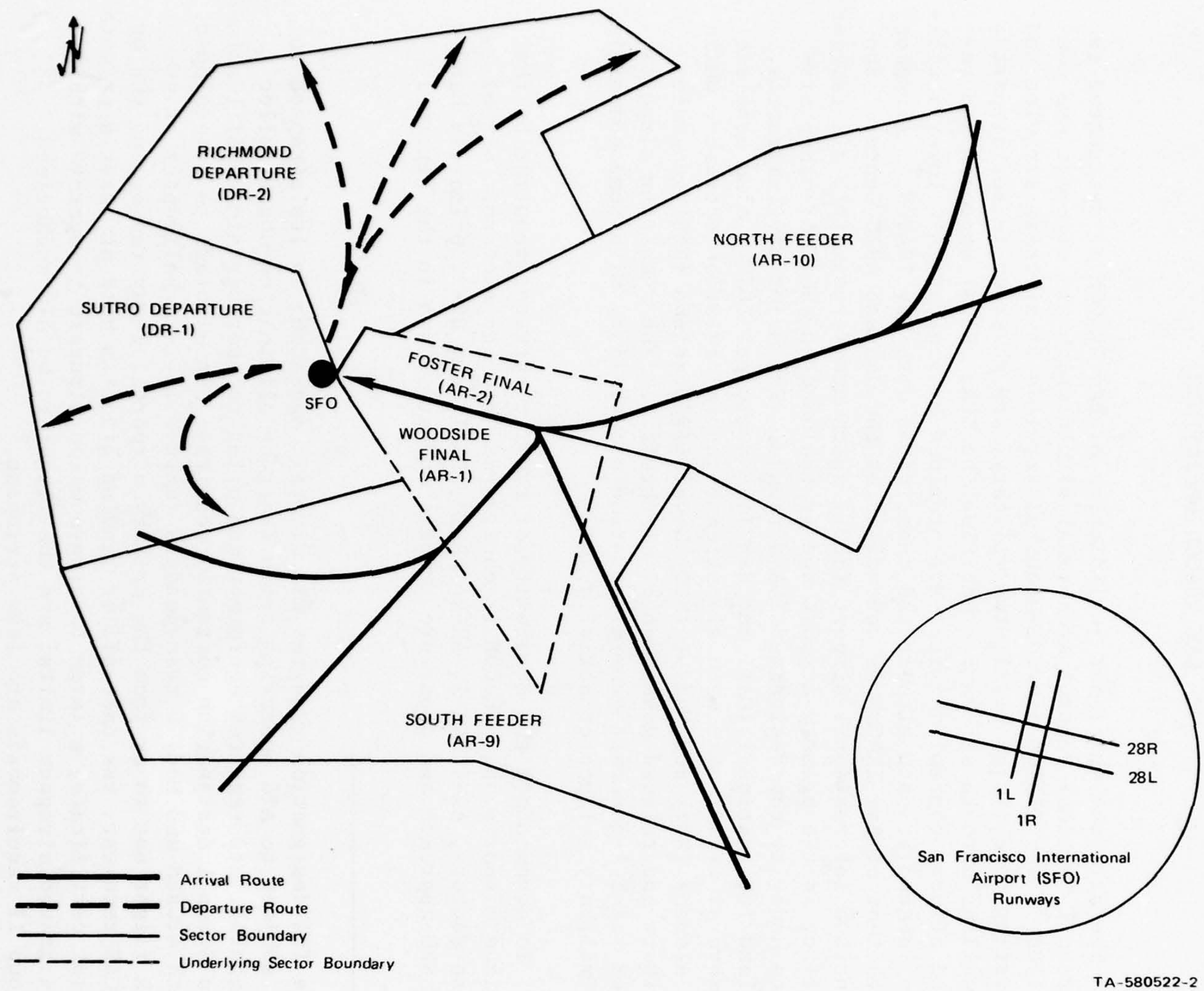

FIGURE 1 WEST PLAN PRIMARY ARRIVAL AND DEPARTURE ROUTES FOR OAKLAND BAY TRACON

schematic; two sectors, AR-3 and AR-4, handle predominantly OAK and NGZ traffic, and the remaining two sectors, DR-5 and DR-6, handle predominantly SJC and NUQ traffic. Small general aviation aircraft operating out of other airports normally remain below the TCA airspace and therefore are not controlled by Bay TRACON.

Figure 1 presents the West Plan sectorization scheme used during the predominant wind conditions. An alternative Southeast Plan is generally associated with weather frontal activity in the Bay Area, and it is used less frequently. The West Plan sectors are structured into a shelf-like inverted conical configuration focused on SFO, with some sectors overlaying others in order to accommodate the typically climbing or descending aircraft.*

In the remainder of this section, we first describe the overall operational integration of the six sectors serving SFO traffic under the West Plan configuration. This plan was in operation during the period of our observation and data collection at Bay TRACON. We then present more detailed descriptions of the six sector operations.

A. Operational Overview

Aircraft landing at SFO are handled by the four arrival (AR) sectors, which also handle some aircraft destined to other airports (e.g., OAK and NGZ). These other aircraft are on approach routes (not shown in Figure 1) that diverge from or cross the primary SFO arrival routes. Aircraft taking off from SFO are handled by the departure (DR) sectors; the DR sectors also handle some aircraft from other airports, which are on departure routes (not shown in Figure 1) merging or crossing the primary SFO departure routes.

The geographic segregation of arrival and departure traffic exemplifies the procedural separation concept whereby preplanned routes (rather than individual aircraft on opposing courses) are kept apart. At those points where arrivals and departures might intersect each other, procedural separation is almost always applied by means of altitude restrictions which tunnel traffic streams around others. This highly structured system of separated routings is effected through the routine use of standard instrument departure (SID) and arrival (STAR) assignments.

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*We designate the routes shown in Figure 1 as "primary" in accordance with our field observations in order to facilitate the textual descriptions given in this report; this designation does not necessarily conform to FAA official terminology.

The following discussions of arrival and departure operations pertain to the primary routings shown in Figure 1. We will subsequently present more detailed descriptions of primary and secondary route interactions for each of the six sectors.

1. Arrival Operations

Bay TRACON arrival operations are based on the "feeder and final" sectorization concept, but with the final sectors sharing jurisdiction of the final approach corridor to parallel runways. Two feeder sectors (AR-9 and AR-10) set up traffic to be processed by the two final sectors (AR-1 and AR-2), and the two final sectors fine-tune the traffic. AR-9 feeds aircraft to AR-1, and AR-10 feeds AR-2.

The integration of traffic flows from a single feeder to a single final (e.g., AR-9 to AR-1) is relatively direct and a minimum of intersector coordination is usually required. The feeder sector controller implements the sequencing plan by issuing clearances to the pilots, while the final sector controller generally recognizes the sequencing plan by observing on his radar display the relative positions and speeds of incoming aircraft. Control negotiations between feeder and final controller regarding individual pairwise mergings are not routine.

However, integrating traffic from the different feeders (i.e., AR-9 and AR-10) for merging at the final approaches to SFO requires a well defined procedural control structure to enable both feeders to integrate their traffic into mutually compatible sequencings and spacings. The control procedures depend on whether the final approach is conducted according to visual or instrument approach operations.

a. Visual Side-by-Side Approach Operations

Final approaches to SFO are primarily for landing on either runway 28R or 28L, which are shown in Figure 1. Sector AR-1 controls aircraft on the final approach course to 28L and Sector AR-2 controls aircraft on the parallel approach course to 28R. Under visual conditions, one final sector controller clears aircraft for a visual approach to the appropriate runway after pilots have confirmed visual sighting of the airport and of other aircraft in the vicinity; controllers continue radar surveillance of aircraft on the final approaches and issue advisories as necessary to facilitate separation. This procedure enables aircraft to be cleared for simultaneous approaches to the two parallel runways, resulting in side-by-side approach operations.

b. Instrument In-Trail Approach Operations

Although both 28R and 28L are equipped with instrument landing systems (ILS), there is not sufficient lateral separation between the two runways to allow simultaneous side-by-side instrument approaches. Under instrument conditions, minimum in-trail separations are maintained between successive aircraft regardless of which runway approaches are used. That is, an aircraft on the 28L approach course is kept at least 3 n.m. (more for wake turbulence spacing) behind a preceding aircraft whether the latter is on the 28R or 28L approach courses. In essence, aircraft on both parallel approaches are treated as if they are merged into a single stream of separated traffic, resulting in in-trail approach operations.

In-trail approach operations require coordination between the two feeder as well as between the two final sectors' controllers to enable sequencing and spacing of aircraft on the final approach. In this case, the two feeder controllers (AR-9 and AR-10) need to integrate their traffic so that one feeder's aircraft will be properly sequenced on final approach with those of the other, rather than bringing in their traffic independently as under visual conditions. Using radar display data, a feeder sector controller uses speed or vectoring controls to fit his aircraft into holes the other controller has built into his traffic stream. Otherwise, the two feeder sector controllers negotiate the pairwise ordering of aircraft and decide which aircraft will be first, second, and so forth. The two final sector controllers must similarly use radar display data to be aware of each others' traffic in order to maintain spacings between aircraft. A final sector controller must keep aircraft under his control separated from each other, and also keep his aircraft separated in-trail from parallel aircraft in the other final sector.

2. Departure Operations

As shown in Figure 1, departure traffic climbing from SFO diverge into various routings. The primary departure runways are 1L and 1R, from which aircraft climb directly into Sector DR-2 airspace or turn left into sector DR-1 airspace. Departures are also conducted off runways 28R and 28L and these are handled by Sector DR-1.

The airport tower hands off aircraft directly to the appropriate sector, which controls the climbing aircraft until they enter enroute airspace. Little coordination is required between the two departure sector controllers, and TRACON control procedures for departures do not distinguish between visual and instrument conditions.

B. Sector Traffic Operations

We wish to describe the traffic routing geometrics specific to each of the six sectors, with emphasis on the potential conflict situations inherent in each. For descriptive convenience, we first address arrival operations for visual approaches on a sector-by-sector basis; secondly, the effect of instrument approaches on overall arrival operations; and, thirdly, departure operations on a sector-by-sector basis.

1. Arrival Sectors--Visual Approaches

The traffic routing and potential conflict characteristics for visual approach operations at the two feeder and two final sectors are given below.

a. South Feeder (AR-9) Sector

Figure 2 depicts the major air routes used in the South Feeder (AR-9) Sector. We have numbered these routes separately within each sector for purposes of identification and description. They are used as follows:

- Route 1 for inbounds to SFO from Southern California.
- Routes 2 and 3 for inbounds to SFO from the Northwest and the Pacific.

As indicated in the figure, most of the traffic on Route 1 enters the sector from the Oakland ARTCC descending to or level at 10,000 ft and leaves the sector descending to or level at 6,000 ft. On Route 2, most of the traffic enters descending to or level at 11,000 ft and leaves the sector descending to or level at 6,000 ft; while most traffic on Route 3 enters descending to or level at 6,000 ft and leaves at 5,000 ft. Since all of the aircraft are landing at SFO, they must be locally merged by the South Feeder controller before handoff to the Woodside Final sector. Although the air routes actually merge in Woodside Final airspace, as indicated in Figure 2 by the two circles where the dashed route lines converge, the sequencing and spacing, merging, and resolution of any potential conflicts at these points are performed by the South Feeder controller. There are potential overtake conflicts on nearly all of the route segments.

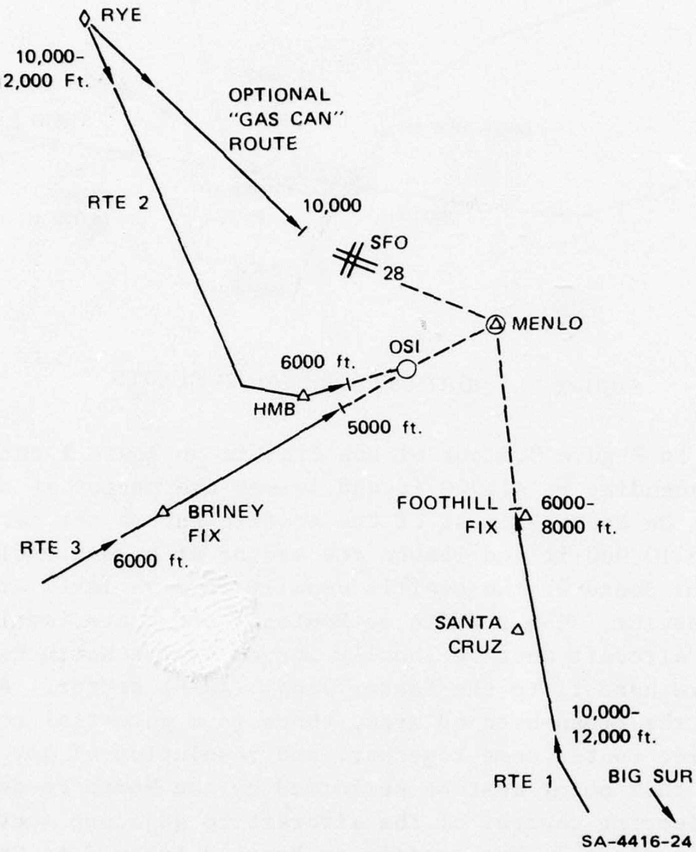

FIGURE 2 SOUTH FEEDER (AR-1) ROUTES

b. North Feeder (AR-10) Sector

Figure 3 shows the major air routes used in the North Feeder (AR-10) Sector. Again, we designate the routes by number as follows:

- Route 1 for inbounds to SFO from the South and East.
- Route 2 for inbounds to SFO from the North and East.
- Route 3 for inbounds to OAK and Alameda NAS from the Southeast.

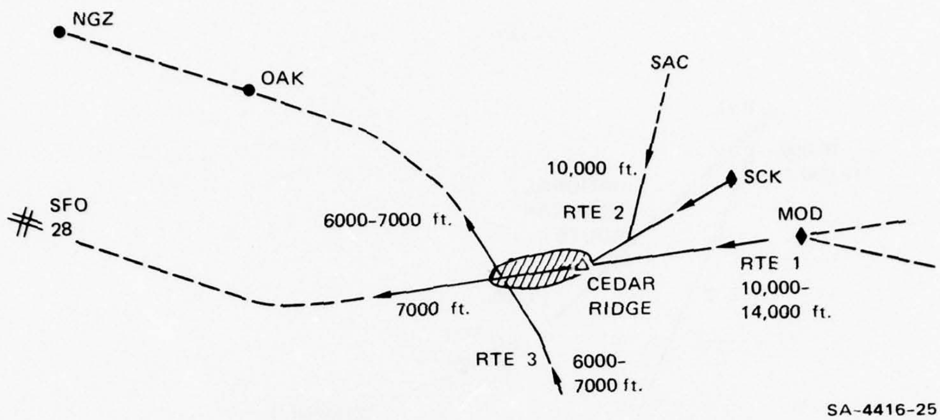

FIGURE 3 NORTH FEEDER (AR-2) ROUTES

As indicated in Figure 3, most of the traffic on Route 1 enters the sector at or descending to 11,000 ft and leaves the sector at or descending to 7,000 ft. On Route 2, most of the traffic enters the sector at or descending to 10,000 ft and leaves the sector at or descending to 7,000 ft. For Route 3, the traffic usually remains level at 7,000 ft through the sector. The traffic on Routes 1 and 2 are landing at SFO; hence, these aircraft must be locally merged by the North Feeder controller before handoff to the Foster Final (AR-6) sector. Also, as indicated by the cross-hatched area, there is a potential conflict zone where all three routes come together, and resolution of any potential conflicts at this point must be performed by the North Feeder controller before transferring control of the aircraft to adjacent sectors. Our observations indicated that traffic on Route 3 inbound to Oakland and Alameda NAS tended to be procedurally separated by altitude from the inbound SFO streams, with Route 3 traffic crossing Cedar Ridge on the average of 2,000 to 3,000 ft lower than the 10,000 to 12,000 ft altitudes at which Route 1 and 2 traffic crosses this area. We do not show several minor routes through the sector which are primarily used by aircraft flying to and from the San Jose and Sacramento areas. Their contribution to controller conflict processing activities is usually negligible due to light traffic volumes and the routine altitude separation at route crossings. When potential crossing conflicts do occur between these aircraft and the high volume inbound streams, climbing directives are issued to the aircraft crossing the inbound corridor.

The sequence and space maintenance activities associated with aircraft on the major inbound routes through both feeder sectors involves a significant amount of overtake conflict processing. For aircraft transitions into SFO and OAK, controllers will generally allow the use of pilot discretion in descending through the feeder sectors to 7,000 ft and slowing to 250 knots. The resulting, unique deceleration and descent profiles of each inbound aircraft are characteristic of feeder sector operations and contribute greatly to the overtaking workloads of these sectors.

c. Woodside Final (AR-1) Sector

Figure 4 shows the major routes used in the Woodside Final sector.

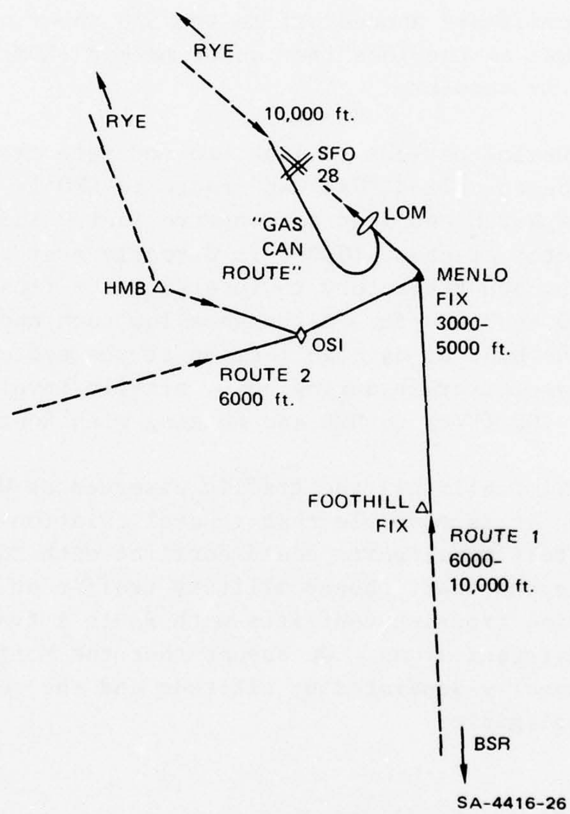

FIGURE 4 WOODSIDE FINAL (AR-9) ROUTES

Although the routes designated as 1 and 2 in the figure are physically separate, they are considered by the Woodside Final controller as one flow by the time they enter the sector. Preliminary sequencing and spacing of the merging traffic on the two routes has been performed by the South Feeder controller before handing over the aircraft to the Woodside Sector; the Woodside Final controller fine tunes the inbound streams so that the sequence established upstream is maintained at the appropriate in-trail separation, which will be three, four, five, or six miles in trail, depending on the size and types of the aircraft involved. The Woodside controller also makes adjustments of speeds and altitudes in order to prepare aircraft for handoff to tower on final approach.

Aircraft enter the sector on Route 1 from the South between 9,000 and 10,000 ft and descend to approximately 5,000 ft and 250 kts at the Menlo fix. Aircraft from the North and West enter near OSI at about 6,000 ft and reach Menlo at 3,000 to 4,000 ft and 250 kts. All inbound aircraft are handed off to the SFO tower at 2,000 to 3,000 ft and 200 to 250 kts at the localizer outer marker (LOM) about 5 miles from the runway 19 complex.

During periods of light-to-moderate traffic and relatively good weather, the so-called "Gas Can" route to SFO is used by aircraft inbound from the North and West to conserve fuel. These aircraft enter the Woodside Sector at about 10,000 ft directly over the SFO VOR and make a "teardrop" approach trajectory to intercept the final approach path at the LOM at 2,000 to 3,000 ft. Although a few such approaches were observed during the hour of data collection at the sector, the prescribed approach for these aircraft during heavy traffic involves flying from the Point Reyes VOR (RYE) to HMB and merging with Route 2 at OSI.

Virtually all the traffic observed at Woodside was inbound to SFO, although it is possible that general aviation traffic entering the TCA from satellite airports could conflict with "Gas Can" and Final approach traffic and that inbound military traffic at Moffett Field could generate potential crossing conflicts with Route 1 traffic over the Boulder Creek-Saratoga areas. We assume that the Moffett-Route 1 crossings are procedurally separated by altitude and the general aviation conflicts to be negligible.

d. Foster Final (AR-2) Sector

The primary purpose of the Foster City Sector controller is to ensure the proper in-trail separation and to maintain the arrival sequence of aircraft on the inbound arrival stream coming to SFO from the east through the North Feeder Sector. Most aircraft follow Route 1, entering the sector west of the Cedar Ridge fix, descending through 7,000 ft, and are radar vectored to the SFO localizer, reaching the LOM at altitudes between 2,000 to 3,000 ft where they are handed off to the tower. Route 2 carries some low speed, general aviation or commuter traffic which is inbound to SFO over the Oakland and Hayward areas; this route merges with the primary inbound stream at the LOM. Additionally, an occasional "Gas Can" arrival over SFO from the Northwest transitioning through the South Feeder Sector will be turned over the Bay and handled by the Foster controller as either a noise abatement procedure or as an attempt to balance traffic workload between final sectors. Separation standards are the same as those used by Woodside controllers. Figure 5 depicts the route structure observed in the Foster Final Sector.

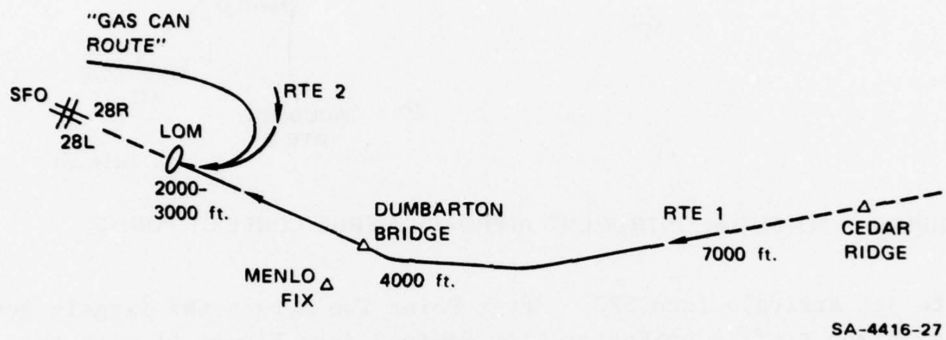

FIGURE 5 FOSTER FINAL (AR-10) ROUTES

Under visual conditions, when simultaneous landings on the 28 runway complex at SFO are performed, we have assumed that the two feeder/final pairs, South Feeder/Menlo Final and North Feeder/Foster Final are operationally independent, with Foster City traffic using Runway 28 and Woodside traffic using 28L. It follows, therefore, that potential merge conflicts in the localizer area will be negligible and that both final approach controllers will be engaged chiefly in the processing of overtaking conflicts.

2. Instrument Approach Characteristics

When instrument landings are necessary, side-by-side approaches cannot be performed and aircraft must be spaced in trail for landings on either of the parallel runways, 28R or 28L. Figure 6 shows the two potential merge conflict points in the localizer area. (We have assigned all "Gas Can" traffic to the standard arrival route from the northwest over OSI.)

Merge Point One is the most critical potential conflict zone, since it combines Woodside Route 1 and 2 traffic with Foster City Route 1 traffic; these routes contain virtually all the commercial and

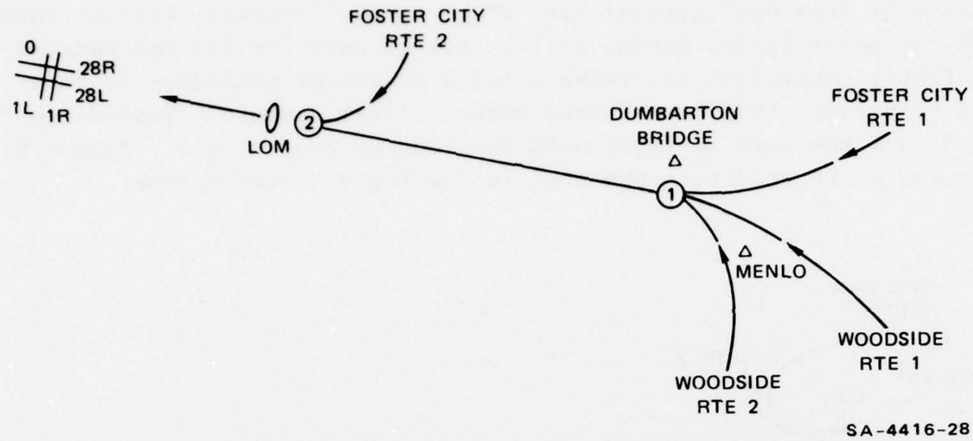

FIGURE 6 POTENTIAL INTRUMENT APPROACH MERGE CONFLICT POINTS

private jet arrivals into SFO. Merge Point Two merges the largely general aviation traffic on Foster City Route 2 (see Figure 5) with the traffic combined at Merge Point One.

As mentioned previously, the merging activities of the Foster and Woodside Final controllers are negligible during visual conditions. However, during instrument operations, merging operations at Merge Points One and Two must be coordinated by the feeder sectors, to ensure the proper alternate in-trail spacing of aircraft within the approach routes. These coordinated mergings are in addition to the local mergings performed by each sector during both visual and instrument conditions. Also, the necessity of mutually sequencing traffic from both feeder and final pairs implies a necessity for each sector to selectively increase in-trail spacings; this in turn increases overtaking conflict work.

3. Departure Sectors

The traffic routing and potential conflict characteristics of the two departure sectors are given below.

a. Sutro Departure (DR-1) Sector

Figure 7 shows the major departure and crossing routes used in the Sutro Departure Sector.

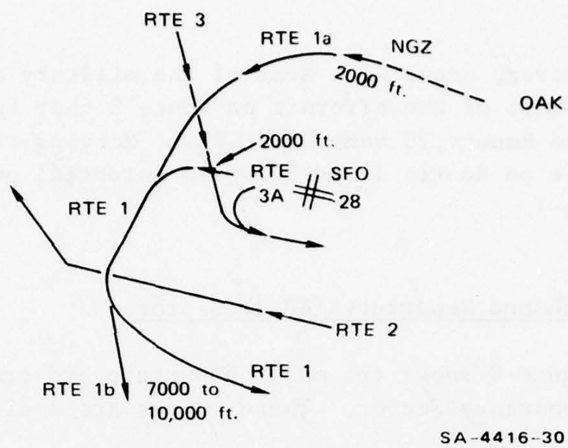

FIGURE 7 SUTRO DEPARTURE (DR-1) ROUTES

These routes are used as follows:

- Route 1, the most heavily used flight path in the sector, for departures from SFO to the west, south, and southeast.
  - Route 1a for departures to the south and west from OAK, that merge in trail, but are altitude separated from SFO departures.
  - Route 1b, for oceanic departures separating from the main body of Route 1 traffic.
- Route 2, for departures from Moffett Field and San Jose area airports to the Northwest toward Point Reyes.
- Route 3, primarily for general aviation and commuter aircraft arriving at SFO (STOL air, SFO helicopters) and Peninsula airports; and Route 3a, for general aviation and commuter aircraft departing SFO to the west and turning sharply to the southeast.

Aircraft on departure routes 1 and 1b generally enter the sector at or climbing to 2,000 ft at about 250 kts, and they are handed off to the Oakland ARTC Center at or climbing to altitudes between 7,000 and 10,000 ft and with airspeeds near 300 kts for commercial jet aircraft. Route 1 aircraft climb rapidly and are therefore above many other aircraft in the sector at points where their routes intersect, thereby minimizing the potential for crossing conflicts. Route 1 crossing conflicts can, however, occur with some of the military aircraft on Route 2, and with most of the aircraft on Route 3 that intersect Route 1 departures from the Runway 28 complex at SFO. Merging conflicts are, of course, possible on Routes 1 and 3, while potential overtakes exist primarily on Route 1.

b. Richmond Departure (AR-2) Sector

Figure 8 shows the major departure and crossing routes used in the Richmond Departure Sector. These routes are designated and used as follows:

- Route 1 for all departures to the north and east via the OAK VOR, where it branches into three branches. They are:
  - Route 1a, an aggregation of routes with regional destinations such as Stockton and Fresno, and nationwide destinations east of Sacramento and Reno.
  - Route 1b for traffic to the Sacramento area and points north and east.
  - Route 1c, toward Napa for departures to Portland, Seattle, and other points to the north and west.
- Routes 2a, 2b, and 2c for departures from OAK and NAS Alameda to the west, east, and north, respectively.
- Route 3, representing an aggregation of radar vector routes involving general aviation and commercial commuter aircraft flying through the TCA from the Sausalito area toward OAK and beyond.
- Route 4, similar in structure and aircraft mix to Route 3, but lying in a more northerly and southerly heading.

Nearly all the departing aircraft on these routes enter the sector at or climbing to 2,000 ft and are handed off to Oakland ARTC Center at or climbing to altitudes between 5,000 and 10,000 ft; the lower performance aircraft in the sector airspace tend to fly at or below 5,000 ft. Potential crossing conflicts between low level enroute aircraft and fast climbing departures out of SFO and OAK are minimized by routine altitude separation. Some crossing conflict processing appears necessary to separate random pairs of low level and enroute aircraft on Routes 3 and 4, while potential overtakes exist on each of the SFO and OAK departure routes.

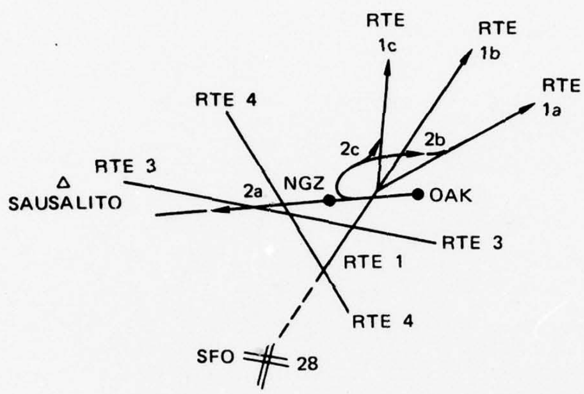

FIGURE 8 RICHMOND DEPARTURE (DR-2) ROUTES

VI BAY TRACON ARTS III MODEL

SRI conducted field observations at Bay TRACON during the week of March 29, 1976. We collected operations data for the six sectors controlling SFO arrival and departure aircraft; these include two final sectors (AR-1 and AR-2), two feeder sectors (AR-9 and AR-10) and two departure sectors (DR-1 and DR-2). Data from one session at each of the six sectors was reduced to obtain the information necessary to model R Controller routine, surveillance, and potential conflict processing workload for the 1-man, 1.5-man, 2-man, and 2.5-man sector team manning regimes corresponding to current ARTS III operations.

A. Routine Work

Our R controller model requires estimation of routine workload weighting (k_1) using the routine event frequencies and task performance times measured from field data collection and reduction. In the following paragraphs, we present the results of our data measurements and workload weighting calculations.

1. Routine Event Frequencies

Our measurements of routine event frequencies (r_{ij}'s) are summarized in Table 1 for the six Bay TRACON sectors. Each frequency value is the ratio of the total number of routine events observed during one hour to the total number of aircraft generating those events; therefore, each frequency value is an empirically derived representation of the expected rate of event occurrence associated with each aircraft.

We distinguish the routine events in Table 1 according to basic and supplemental events; supplemental events are indented in the table's listing of event descriptions. The basic events are "parent" events, each of which may have one or more supplemental events associated with it. A supplemental event will occur as frequently or less frequently than its parent basic event, but never more frequently. This phenomena is due to the nature of the task structure which we use to define each event; this structure will be explained in the discussion of event performance times which follows.

Table 1

ROUTINE EVENT FREQUENCY ESTIMATES

OAKLAND BAY TRACON

Routine Control Event Description		Event Frequency by Sector (event/aircraft)					
Event Function	Basic Event and Supplemental Event	AR-1 Woodside Final	AR-2 Foster Final	AR-9 South Feeder	AR-10 North Feeder	DR-1 Sutro Departure	DR-2 Richmond Departure
Control jurisdiction transfer	Handoff acceptance	1.00	1.00	1.00	0.96	0.80	0.79
	Manual acceptance-silent	1.00	1.00	1.00	0.96	0	0
	Tower departure call	0	0	0	0	0.80	0.79
	Controller coordination	0.08	0.13	0.13	0.05	0.10	0.11
	Handoff initiation-silent	0	0	1.00	1.00	1.00	1.00
	Controller coordination	0	0	0	0.09	0.30	0.21
Traffic structuring	Initial pilot call-in	1.00	1.00	1.00	1.00	1.00	1.00
	TCA clearance request	0	0	0	0.04	0.20	0.21
	Initial controller response	1.00	1.00	1.00	1.00	1.00	1.00
	Altitude instruction	0.33	0.13	0.94	0.68	0.40	0.21
	Data update	0	0	0.50	0.23	0.20	0.21
	Heading/route instruction	0.92	0.33	0.94	0.86	0.10	0.21
	Speed instruction	0	0.07	0.63	0	0	0
	Approach/runway advisory	0.92	0.27	0.94	0.86	0.05	0.05
	PVD display update	0	0	0.94	0.86	0.05	0.05
	Traffic advisory	0.08	0.20	0	0	0.10	0.05
	ATIS advisory	0.08	0.07	0.13	0.14	0.10	0.11
	Altimeter setting advisory	0	0	0	0	0.30	0.21
	Transponder code assignment	0	0	0	0.04	0.20	0.21
	Controller coordination	0	0	0.07	0	0.20	0
	Altitude instruction	1.17	0.87	0.13	0.73	0.25	0.79
	Data update	0	0	0.13	0.14	0.10	0.21
	Controller coordination	0	0	0	0	0.05	0.05
	Heading/route instruction	0.33	0.13	0	0.45	0.50	0.95
	Controller coordination	0	0	0	0	0.10	0
	Speed instruction	0	0.20	0.25	0.09	0	0
	Approach clearance	1.08	0.93	0	0	0	0.05
	Runway assignment	0.33	0.53	0.13	0.05	0.15	0.11
	Traffic advisory	1.17	1.00	0.19	0.18	0.55	0.89
	Pilot altitude report	0.08	0.20	0.19	0.09	0.45	0.84
	Pilot heading/position report	0.08	0	0	0	0.10	0.16
	Pilot speed report	0.17	0	0	0.09	0.05	0
	Miscellaneous A/G communication	0	0	0.07	0.09	0.15	0.26
	Frequency change	1.00	1.00	1.00	1.00	1.00	1.00
	Transponder code change	0	0	0	0	0.10	0.11
	Approach/runway advisory	0.58	0.60	0.13	0.09	0	0
Pilot request	Altitude revision	0	0	0.19	0.05	0.15	0.11
	Controller coordination	0	0	0.06	0	0	0.05
	Route/heading revision	0	0	0	0	0.20	0.21
	Controller coordination	0	0	0	0	0.05	0.11
	Miscellaneous pilot request	0.17	0.20	0.13	0.05	0	0.26
General intersector coordination	Pointout acceptance	0.17	0.13	0.06	0	0.15	0.26
	Pointout initiation	0	0	0.25	0	0.50	0.42
	Control instruction approval	0	0	0.06	0.09	0.25	0.37
	Planning advisory	0.17	0	0.06	0.09	0.15	0.05
	Aircraft status advisory	0.25	0.07	0.13	0.18	0.25	0.11
General system operation	Data block forcing/removal	0.67	0.53	0.50	0.96	0.20	0.84
	PVD display adjustment	0.25	0	0.19	0.18	0	0.05

The event frequencies are a convenient means to distinguish the routine work characteristics of different sectors. This property is demonstrated in Table 1 by the differences between sectors in the frequencies measured for all but a few of the individual events. For example, the frequency of an "altitude instruction" event (included as part of the "traffic structuring" function) differs from one sector to the other. Also, some events, including basic events, may be performed by some sector teams but not by others, as evidenced by the "handoff-initiation-silent event.

2. Routine Event Performance Times

We identified the task components of each event as summarized in Table 2. The individual task performance times ($_{ij}$'s) shown in Table 2 are stopwatch measurements of observed minimum execution times; these represent work requirements during capacity traffic conditions, when controllers are assumed to be operating at peak efficiency.

During our observation sessions, each of the four arrival sectors was operating under visual approach conditions as a 1-man team (R controller only), while both departure sectors were operating as 1.5-man teams (one R controller for each sector, sharing a coordinator between them). By carefully cross-referencing the various data collection sources (i.e., communications recordings, flight strips or paper scratch pads, and manual observation records), we were able to extrapolate the tasks necessary to carry out each event regardless of which controller is performing them, and whether the operations occur under visual or instrument conditions. The resulting task items in Table 2 therefore represent the requirements of a "composite team," and do not describe the specific R controller task requirements for either of the 1-man, 1.5-man, 2-man, or 2.5-man team regimes.

We will subsequently use the composite team tasks structure of Table 2 to allocate specific tasks to the R controller for each of the four regimes. We observed that the minimum task performance times did not vary between sectors, and the composite team task times of Table 2 thus apply to each of the six sectors. The data regarding task times are used to distinguish the work time requirements of events under the alternative team manning regimes; moreover, task time data are also used in conjunction with event frequency data to develop work requirements for each individual sector. Before describing the R controller requirements for each regime, we will examine the underlying task structure for the composite team.

Table 2
COMPOSITE TEAM
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 1--ARTS III BASE

Routine Control Event Description		Performance Time by Task (man-sec/event)				
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing*	Interphone Communication	Face-to-Face Communication
Control jurisdiction transfer	Handoff acceptance			2		
	Manual acceptance-silent		2			
	Tower departure call				2	
	Controller coordination				6	3
	Handoff initiation-silent		3			
	Controller coordination				6	3
Traffic structuring	Initial pilot call-in	4		1		
	TCA clearance request	4	10	6		
	Initial controller response	2				
	Altitude instruction	3				
	Data update			2		
	Heading/route instruction	3				
	Speed instruction	3				
	Approach/runway advisory	3				
	PVD display update		3			
	Traffic advisory	3				
	ATIS advisory	3				
	Altimeter setting advisory	3				
	Transponder code assignment	3	3	2		
	Controller coordination				5	3
	Altitude instruction	5				
	Data update			2		
	Controller coordination				5	3
	Heading/route instruction	5				
	Controller coordination				5	3
	Speed instruction	5				
	Approach clearance	6				
	Runway assignment	5				
	Traffic advisory	5				
	Pilot altitude report	5				
	Pilot heading/position report	5				
	Pilot speed report	5				
	Miscellaneous A/G communication	5				
	Frequency change	4		1		
	Transponder code change	2				
	Approach/runway advisory	3				
Pilot request	Altitude revision	6		2		
	Controller coordination				5	3
	Route/heading revision	8		2		
	Controller coordination				5	3
	Miscellaneous pilot request	6				
General intersector coordination	Pointout acceptance		3		6	3
	Pointout initiation				6	3
	Control instruction approval				5	3
	Planning advisory				5	3
	Aircraft status advisory				5	
General system operation	Data block forcing/removal		3			
	PVD display adjustment		3			

*Flight strip processing includes paper scratch-pad processing.

a. Composite Team Routine Tasks

Table 2 identifies the tasks associated with the basic and supplemental events first presented in Table 1. Each basic event is comprised of a parent set of tasks necessary for event execution; each supplemental event is associated with an additional set of tasks that are performed only when required.

Control Jurisdiction Transfer--Under the control jurisdiction transfer function, the basic handoff acceptance event requires 2 man-sec of flight strip processing or paper scratch pad processing (which is included under the "flight strip processing" task category in Table 2). In this case, the flight strip processing is performed by the feeder and departure sector teams who arrange or distribute the strips, or scratch pad processing is performed by the final sector teams who handwrite the aircraft's flight identity onto the scratch pad. These actions are considered basic tasks since they are performed whenever a handoff acceptance occurs. In contrast, the supplemental events associated with handoff acceptance are not always performed. For instance, the feeder and final sectors manually accept (silently, without interphone contact) handoffs from other sectors by means of a 2 man-sec keyboard data entry/display operation; this operation increases the total handoff acceptance time to 4 man-sec. The departure sectors need not perform this supplemental operation for climbing aircraft whose tracks are automatically acquired by the ARTS III system. However, departure sector teams receive interphone calls from towers, e.g., SFO ATCT), advising of each aircraft take-off. This supplemental event (tower departure call) takes 2 man-sec and enables the TRACON controllers to initiate flight-strip handling and confirm that each aircraft is correctly acquired, tracked, and displayed on the PVD. Another supplemental event, controller coordination, may accompany a handoff acceptance and typically requires a 6 man-sec interphone communication between different sector teams and a 3 man-sec face-to-face message relay (voice or hand-signal) or consultation between controllers within a sector.

A basic handoff initiation event is performed silently, requiring a 3 man-sec manual data entry/display operation, and it may be accompanied by supplemental controller coordination. Since the tracks of aircraft descending to airports are automatically dropped by the ARTS III system, final sectors need not initiate handoffs to towers for aircraft on final approach. This operational characteristic of the final sector does not alter the task requirements of the basic handoff initiation event in Table 2 but is represented under the event frequency tabulations of Table 1 (where handoff initiation events are shown not to occur in the final sectors).

This rather detailed discussion of handoff events is intended to demonstrate the application of the basic and supplemental event concepts and the relationships between event frequencies and performance times. These concepts apply to the models of the remaining routine events, which we now briefly describe.

Traffic Structuring and Pilot Requests--All basic events under structuring and pilot request are initiated by an A/G communication and sometimes include flight strip marking. The performance time of each A/G communication task, which entails negotiation and confirmation between pilot and controller, is measured from the beginning transmission to the ending transmission for both parties and includes time devoted to decision making. Similarly, interphone and face-to-face communication includes both decision-making and transmission time.

The first traffic structuring event for an aircraft is the pilots initial flight identity and altitude call-in on the sector's A/G radio frequency, taking 4 man-sec. The occurrence of the call-in is manually "checked" on the paper scratch pad or flight strip (or at least generates flight strip review or rearrangement), requiring 1 man-sec. In a few cases, an unexpected aircraft "pop-up" involving a pilot's request to enter the TCA requires an additional 4 man-sec for the A/G radio call-in. Such a supplemental TCA clearance request also causes the controller to spend 10 man-sec to hand write a new flight strip, and 6 man-sec to enter the appropriate flight and tracking data by means of keyboard data entry/display operations. The controller's initial response to the pilot takes 2 man-sec of A/G communications to acknowledge the call-in and is followed by one or more supplemental events. Such events typically are part of a single lengthy A/G communication used to issue altitude, heading or speed clearances; approach and runway, traffic, ATIS, and altimeter setting advisories; or transponder code assignments. Each one of these A/G messages takes an additional 3 man-sec and may require other tasks. For example, data entry/display operations taking 3 man-sec are used to enter expected runway assignment data for PVD display or to request or enter a transponder discrete code assignment. Flight strip processing tasks taking 2 man-sec may be needed to hand write altitude or transponder code revisions. Also, occasional controller coordination of the pilot call-in requires 5 man-sec and 3 man-sec, respectively, for interphone or face-to-face communications.

These controller-to-pilot traffic structuring events may be performed, revised, or repeated at some time after the initial pilot call-in, in which case they may require 5 to 6 man-sec of A/G communications, depending on the transaction. Other A/G communications involving pilot reports and requests regarding altitude, position, or speed, and other miscellaneous messages (such as weather reports) are performed as needed.

A 4 man-sec controller-to-pilot instruction to change radio frequency to that of the next sector or tower culminates the traffic structuring and pilot request activity for an aircraft. It is manually recorded by crossing-out the aircraft flight identity on a paper scratch pad or filing the flight strip; each such task requires 1 man-sec. In addition, a 2 man-sec transponder code change (normally to establish a VFR non-discrete code) or a 3 man-sec approach/runway advisory may be issued to supplement the basic frequency change A/G communication.

General Intersector Coordination--These events include informational transfers performed by controllers to maintain mutual cognizance of multisector traffic movement and are not part of handoff, traffic structuring, or pilot request functions. Pointout actions are required by a sector team to retain control of aircraft briefly in or near another sector's airspace. Both pointout acceptance and initiation typically require 6 man-sec of interphone communication between different sector teams to coordinate and effect the operation, and 3 man-sec of face-to-face communication between members of a sector team. The pointout acceptance operation also involves a 3 man-sec keyboard data entry/display operation to force the aircraft's data block on to the receiving sector team's PVD display.

The remaining general intersector coordination events involve 5 man-sec interphone and 3 man-sec face-to-face communications. Control instruction approvals are issued in response to other sector team's traffic structuring and pilot request activities. Planning advisories are used to negotiate or transmit procedural requirements, while aircraft status advisories clarify individual aircraft situations and do not necessitate intrasector face-to-face communications.

General System Operation--This category includes those activities not mentioned in the above descriptions, such as data block forcing removal and PVD display adjustment. General system operation events are performed entirely by 3 man-sec data entry/display operations and are needed for minute-by-minute PVD display maintenance.

b. R Controller Routine Tasks

We now assign the composite team task requirements specific to the R controller under each of the four sector team manning regimes. These allocations are made in accordance with the operational assumptions given in a previous section of this report regarding sector control responsibilities under the ARTS III system, and they are summarized in Tables 3, 4, 5, and 6 for the 1-man, 1.5-man, 2-man, and 2.5-man teams, respectively

1-man Team--Under the 1-man team shown in Table 3, the R controller is assigned all the tasks necessary for event execution except face-to-face communication; this is not performed since there is no other team member to communicate with. The Table 3 task time entries correspond to the Table 1 composite team entries, excluding the face-to-face tasks. The resulting minimum time required to execute each event is obtained by summing the component task times, as shown in the right-hand column of Table 3.

1.5-man Team--We assume that the addition of a coordinator supporting a pair of sectors enables each R controller to assign interphone communications tasks to the coordinator. However, an R controller must be kept advised of the intersector negotiations being conducted by the coordinator, and face-to-face communications between R controller and coordinator are necessary. The resulting R controller task requirements for the 1.5-man team are summarized in Table 4; these requirements were obtained by eliminating the interphone communication tasks from the 1-man team operation in Table 3, and introducing face-to-face communications tasks, from the composite team tasks in Table 2.

The coordinator also participates in handoff activities by distributing flight strips to the appropriate R controller and (according to our observations) performing half the manual keyboard silent handoff acceptance and initiation events. Therefore, we eliminate from the R controller requirements the handoff acceptance flight strip processing task as shown in Table 4. The coordinator's contribution to handoff requirements is signified by reducing by one-half the frequency of silent manual acceptance and silent handoff initiation events presented in Table 1. This adjustment to the handoff event frequencies applies only to the 1.5-man team regime.

2-man Team--The R and H controllers share task responsibilities for a single sector, and no coordinator position is manned. In this case, we assume the R controller assigns the H controller all interphone communication tasks, some of the keyboard data entry/display operation tasks, and flight-strip processing (or paper scratch pad) processing tasks required for handoffs. This reallocation of responsibilities results in the set of R controller tasks shown in Table 5. These task time entries are obtained from Table 3 by eliminating those entries relating

Table 3

R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 1, 1-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance			2			2
	Manual acceptance-silent		2				2
	Tower departure call				2		2
	Controller coordination				6		6
	Handoff initiation-silent		3				3
	Controller coordination				6		6
Traffic structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4	10	6			20
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update			2			2
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update		3				3
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3	3	2			8
	Controller coordination				5		5
	Altitude instruction	5					5
	Data update			2			2
	Controller coordination				5		5
	Heading/route instruction	5					5
	Controller coordination				5		5
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4		1			5
	Transponder code change	2					2
	Approach/runway advisory	3					3
Pilot request	Altitude revision	6		2			8
	Controller coordination				5		5
	Route/heading revision	8		2			10
	Controller coordination				5		5
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3		6		9
	Pointout initiation				6		6
	Control instruction approval				5		5
	Planning advisory				5		5
	Aircraft status advisory				5		5
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 4

R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 1, 1.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent		2				2
	Tower departure call						0
	Controller coordination					3	3
	Handoff initiation-silent		3				3
	Controller coordination					3	3
Traffic structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4	10	6			20
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update			2			2
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update		3				3
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3	3	2			5
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update			2			2
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4		1			5
	Transponder code change	2					2
	Approach/runway advisory	3					3
Pilot request	Altitude revision	6		2			8
	Controller coordination					3	3
	Route/heading revision	8		2			10
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3			3	6
	Pointout initiation						3
	Control instruction approval						3
	Planning advisory					3	3
	Aircraft status advisory						0
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 5

R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 1, 2-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent						0
	Tower departure call						0
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4		6			10
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update			2			2
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update		3				3
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3		2			5
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update			2			2
	Controller coordination					3	3
	Heading/route instruction	5					4
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4		1			5
	Transponder code change	2					2
	Approach/runway advisory	3					3
Pilot request	Altitude revision	6		2			8
	Controller coordination					3	3
	Route/heading revision	8		2			10
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance					3	3
	Pointout initiation					3	3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 6

R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 1, 2.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent						0
	Tower departure call						0
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4		6			10
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update			2			2
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update						0
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3					5
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update			2			2
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					[illegible]	3
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4		1			5
	Transponder code change	2					2
	Approach/runway advisory	3					4
Pilot request	Altitude revision	6		2			8
	Controller coordination					3	3
	Route/heading revision	8		2			10
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance					3	3
	Pointout initiation					3	3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General system operation	Data block forcing/removal						0
	PVD display adjustment						0

to the interphone communication tasks, the data processing tasks required for handoffs, and those data entry/display tasks that are not required for minute-by-minute PVD display update and maintenance. However, some face-to-face communication tasks between R and H controllers are now necessary.

2.5-man Team--We assume the R controller offloads some flight strip processing and all data entry/display operation and interphone communication tasks to the H controller and the coordinator. The resulting R controller tasks in Table 6 are obtained from Table 5 by eliminating all task entries other than A/G communication, flight strip processing and face-to-face communication tasks. Also, those flight strip processing tasks (including handoff and transponder code assignment) not directly concerned with minute-by-minute traffic data maintenance are allocated to positions other than the R controller.

c. R Controller Event Performance Times

The controller minimum performance times required to execute each event are presented in Table 7 for each of the four sector team manning regimes. Each event time entry is the sum of the component task times as shown in the right-hand columns of Tables 3, 4, 5, and 6; these summaries are collated in Table 7 to facilitate comparisons between event times under each regime.

3. Routine Workload Weighting

The R controller routine workload weighting (k_1) is calculated by multiplying event frequencies (Table 1) by corresponding event performance times (Table 7) and summing the products obtained for each sector manning regime for each of the six sectors. The resulting workload weightings are listed in Table 8.

B. Surveillance Work

As discussed earlier, surveillance workload modeling is based on the assumption that 1.25 man-sec/aircraft-min of PVD scanning work is needed to maintain cognizance of traffic movements. Surveillance workload weighting is obtained by multiplying this scanning work constant by the average aircraft transit time for each sector; this is summarized in Table 9. The transit times in Table 9 are those reported[11] for each sector by Oakland Bay TRACON and correspond to the average time aircraft were on each sector's A/G radio frequency during out data collection sessions.

Table 7

R Controller

ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES

OAKLAND BAY TRACON
SYSTEM 1--ARTS III BASE

Routine Control Event Description		Performance Time by Team (man-sec/event)			
Event Function	Basic Event and Supplemental Event	1.0-Man Team	1.5-Man Team	2.0-Man Team	2.5-Man Team
Control jurisdiction transfer	Handoff acceptance	2	0	0	0
	Manual acceptance-silent	2	2*	0	0
	Tower departure call	2	0	0	0
	Controller coordination	6	3*	3	3
	Handoff initiation-silent	3	3	0	0
	Controller coordination	6	3	3	3
Traffic structuring	Initial pilot call-in	5	5	5	5
	TCA clearance request	20	20	10	10
	Initial controller response	2	2	2	2
	Altitude instruction	3	3	3	3
	Data update	2	2	2	2
	Heading/route instruction	3	3	3	3
	Speed instruction	3	3	3	3
	Approach/runway advisory	3	3	3	3
	PVD display update	3	3	3	0
	Traffic advisory	3	3	3	3
	ATIS advisory	3	3	3	3
	Altimeter setting advisory	3	3	3	3
	Transponder code assignment	8	8	5	5
	Controller coordination	5	3	3	3
	Altitude instruction	5	5	5	5
	Data update	2	2	2	2
	Controller coordination	5	3	3	3
	Heading/route instruction	5	5	5	5
	Controller coordination	5	3	3	3
	Speed instruction	5	5	5	5
	Approach clearance	6	6	6	6
	Runway assignment	5	5	5	5
	Traffic advisory	5	5	5	5
	Pilot altitude report	5	5	5	5
	Pilot heading/position report	5	5	5	5
	Pilot speed report	5	5	5	5
	Miscellaneous A/G communication	5	5	5	5
	Frequency change	5	5	5	5
	Transponder code change	2	2	2	2
	Approach/runway advisory	3	3	3	3
Pilot request	Altitude revision	8	8	8	8
	Controller coordination	5	3	3	3
	Route/heading revision	10	10	10	10
	Controller coordination	5	3	3	3
	Miscellaneous pilot request	6	6	6	6
General Intersector coordination	Pointout acceptance	9	6	3	3
	Pointout initiation	6	3	3	3
	Control instruction approval	5	3	3	3
	Planning advisory	5	3	3	3
	Aircraft status advisory	5	0	0	0
General system operation	Data block forcing/removal	3	3	3	0
	PVD display adjustment	3	3	3	0

*Indicated event occurs at one-half the frequency rate shown in Table 1.

Table 8

R CONTROLLER ROUTINE WORKLOAD WEIGHTINGS
OAKLAND BAY TRACON, SYSTEM 1--ARTS III BASE

Sector	R Controller Routine Workload Weighting, k_1, by team (man-sec/aircraft)			
	1-Man Team	1.5-Man Team	2-Man Team	2.5-Man Team
AR-1, Woodside Final	56	50	49	46
AR-2, Foster Final	46	42	41	39
AR-9, South Feeder	48	41	38	34
AR-10, North Feeder	47	41	38	32
DR-1, Sutro Departure	55	43	39	39
DR-2, Richmond Departure	66	56	51	48

C. <u>Conflict Processing Work</u>

Our formulation of the conflict processing workload requires estimating the frequency of potential conflict events and their processing task times.

1. <u>Conflict Event Frequency</u>

The traffic operation and route pattern characteristics for each of the six sectors were described in a preceding section of this report. We use the mathematical relations described in Appendix A to model each sector's traffic patterns and calculate the expected number of potential conflicts. These calculations give the frequency factors (e_c, e_m, e_o, and e_a, respectively), that measure the frequency of potential crossing, local merging, overtaking, and coordinated approach merging conflicts. These calculated frequency factors are summarized

Table 9

R CONTROLLER SURVEILLANCE WORKLOAD WEIGHTING
OAKLAND BAY TRACON, SYSTEM 1--ARTS III BASE

Sector	Aircraft Average Transit Time, t_s (min)	Surveillance Workload Weighting, ct_s (man-sec/aircraft)*
AR-1, Woodside Final	5	6.25
AR-2, Foster Final	5	6.25
AR-9, South Feeder	4	5
AR-10, North Feeder	3	4.75
DR-1, Sutro Departure	5	6.25
DR-2, Richmond Departure	4	5

*Surveillance workload constant, c, = 1.25 man-sec/aircraft-min.

for each sector in Table 10. Since approach control procedures vary according to visibility conditions, we model both visual approach and instrument approach operations.

a. Visual Approach Operations

Under visual approach conditions, simultaneous side-by-side approaches to the SFO parallel runways are normal. For modeling purposes, we assume the two feeder-and-final pairs, South Feeder/Woodside Final (AR-9/AR-1) and North Feeder/Foster Final (AR-10/AR-2) are operationally independent; AR-9/AR-1 traffic uses Runway 28L and AR-10/AR-2 traffic uses Runway 28R. Therefore, traffic along one of these approach courses need not be sequenced and spaced with traffic along the other approach course, and no coordinated approach merging conflict situations exist. Thus, under visual approach operations, the corresponding frequency factor in Table 10 is zero for each sector.

The remaining frequency factors shown in Table 10 reflect the conflict situations internal to each sector (i.e., those potential conflicts are resolved by each sector team without formal intersector coordination). For example, we find that overtaking situations are most frequent in the final sectors. The feeder sectors must resolve crossing and overtaking conflicts and conduct local mergings of traffic under their jurisdiction. The departure sectors primarily resolve crossing situations, but are also concerned with overtaking and local merging conflicts.

b. Instrument Approach Operations

In this case, all traffic approaching the SFO parallel runway complex must be mutually sequenced and spaced, and the resolution of potential approach merging conflicts must be coordinated by the two feeder sector teams. Our mathematical modeling for this potential conflict situation obtains a frequency factor of 3.8 (conflicts/hr)/(aircraft/hr).[2] However, since both feeder sectors are involved in the resolution of each coordinated approach merge, this frequency factor applies to both sectors, as shown in Table 10. (The resulting double counting of approach merge frequencies will be counteracted by the methodology we use to estimate conflict event times, which we will explain subsequently.)

Except for arrival sector overtaking situations, we assume that the frequency of each sector's remaining potential conflicts is the same under instrument approaches as for visual approaches, since their

Table 10

CONFLICT EVENT FREQUENCY ESTIMATES
OAKLAND BAY TRACON, SYSTEM 1 - ARTS III BASE

Sector	Conflict Event Frequency Factor [(Conflicts/Hr) / (Aircraft/Hr)^2]			
	Visual Approach Operations			
Sector	Crossing, e_c	Local Merging, e_m	Overtaking, e_o	Coordinated Approach Merging, e_a
AR-1, Woodside Final	0	0	6.5×10^{-3}	0
AR-2, Foster Final	0	3.2×10^{-3}	10.6×10^{-3}	0
AR-9, South Feeder	0	4.6×10^{-3}	1.4×10^{-3}	0
AR-10, North Feeder	1.5×10^{-3}	3.3×10^{-3}	3.7×10^{-3}	0
DR-1, Sutro Departure	5.7×10^{-3}	0.7×10^{-3}	2.3×10^{-3}	0
DR-2, Richmond Departure	4.5×10^{-3}	0	0.8×10^{-3}	0
	Instrument Approach Operations			
Sector	Crossing, e_c	Local Merging, e_m	Overtaking, e_o	Coordinated Approach Merging, e_a
AR-1, Woodside Final	0	0	13.0×10^{-3}	0
AR-2, Foster Final	0	3.2×10^{-3}	21.2×10^{-3}	0
AR-9, South Feeder	0	4.6×10^{-3}	2.8×10^{-3}	3.8×10^{-3}
AR-10, North Feeder	1.5×10^{-3}	3.3×10^{-3}	7.4×10^{-3}	3.8×10^{-3}
DR-1, Sutro Departure	5.7×10^{-3}	0.7×10^{-3}	2.3×10^{-3}	0
DR-2, Richmond Departure	4.5×10^{-3}	0	0.8×10^{-3}	0

corresponding procedural requirements do not change. However, each final-and-feeder pair must increase in-trail aircraft spacings in order to integrate its traffic with those of the other sector pair along the parallel final approach courses. To approximate this situation, we assume that the in-trail aircraft spacings required will be double those of the visual approach case, such as would occur if each feeder alternated aircraft deliveries to the final approach course with the other. This assumption will double the calculated frequency factor estimates, which are adjusted accordingly in Table 10 for the feeder and final sectors under instrument approach operations.

2. Conflict Event Performance Time

The minimum time required for potential conflict event processing is the sum of the minimum times required to perform detection and assessment, coordination, and resolution tasks. Our estimates of the minimum task performance and event times required by the composite sector team are summarized in Table 11 for crossing, local merging, overtaking, and coordinated approach merging situations.

Table 11

COMPOSITE TEAM
CONFLICT EVENT PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 1--ARTS III BASE

Conflict Event	Minimum Performance Time by Task (man-sec/conflict)			
	Detection and Assessment	Coordination	Resolution	Total
Crossing	20	0	20	40
Local Merging	20	0	15	35
Overtaking	20	0	10	30
Coordinated Approach	20	5	15	40

a. Composite Team Conflict Tasks

The detection and assessment task time estimate (which is 20 man-sec for each conflict event) corresponds to the results obtained from our previous enroute ATC data analyses[4-7] in which we reviewed with controllers video-tape playbacks of their conflict processing activities. Spot checks of Bay TRACON controller activities found that no change was warranted in this previous estimate of detection and assessment task time.

The estimates of coordination and resolution task time were obtained directly from data measurements made at Bay TRACON. Table 11 shows that intersector coordination (5 man-sec) is needed between feeder sector teams to negotiate (by means of face-to-face oral conversation or hand signals) and agree on the order in which each sector's aircraft are sequenced onto the final approaches during instrument approach operations. Such communications apply only to the coordinated approach mergings. The resolution task times vary according to the type of potential conflict event. The crossing conflict resolution time (20 man-sec) is longer than that of the others because controllers rely on vectoring, altitude, and speed controls to correct conflicts and often later instruct an aircraft to return to its original course. Merging conflict resolution time (15 man-sec) normally consists of speed controls with some vectoring, while overtaking conflict resolution time (10 man-sec) generally consists of only speed controls.

b. R Controller Conflict Tasks

The tasks represented in Table 11 for crossing, local merging, and overtaking situations are performed by each sector's R controller, no matter what team manning regime is in effect, and the corresponding task times represent his workload requirement for each such conflict event. However, the R controller workload associated with a coordinated approach merging situation will vary under different manning regimes. Consider the situations presented in Table 12 where R controller task requirements are shown dependent on whether or not a coordinator is involved and to which of the two feeder R controllers overtly resolves the approach merging. With reference to the non-coordinator operation (i.e., 1-man or 2-man teams), we assume each approach merging conflict will require both feeder R controllers to detect, assess, and coordinate the situation; therefore, both R controllers spend time on these tasks even though only one approach merging conflict is involved. In our field observations, however, we found that generally only one of the two R controllers is needed to resolve the merge via A/G communications. He issues the appropriate instructions to

Table 12

COORDINATED APPROACH MERGING

R CONTROLLER CONFLICT EVENT PERFORMANCE TIME ESTIMATES

OAKLAND BAY TRACON, SYSTEM 1--ARTS III BASE

Sector Operation	R-Controller Minimum Performance Time by Task (man-sec/coordinated merging event)				
	Detection and Assessment	Coordination	Resolution	Total	Average
Without Coordinator*					
AR-9 (or -10)	20	5	15	40	32.5
AR-10(or -9)	20	5	0	25	
With Coordinator†					
AR-9 (or -10)	10	3	15	28	20.5
AR-10(or -9)	10	3	0	13	

*1-man and 2-man sector team manning regimes

†1.5-man and 2.5-man sector team manning regimes

fit his aircraft into spacings built into the other controller's traffic stream. (Additional control work required to maintain aircraft in proper relative positions is assumed to be represented by our models of overtaking conflict work.) Therefore, the total work time required by both R controllers to process a single coordinated approach merging conflict is 65 man-sec, which results in an average event performance time of 32.5 man-sec for each R controller.

Regarding the coordinator-supported operations (i.e., 1.5-man or 2.5-man team regimes) in Table 11, we assume the coordinator will make the sequencing decisions, and this would reduce each R controller's detection and assessment task time requirements to 10 man-sec. The coordinator will issue sequencing directives simultaneously to each R controller, taking 3 man-sec of each of their time for coordination. The resulting average event performance time is 20.5 man-sec for each R controller.

For our modeling purposes, the R controller's performance times (t_c, t_m, t_o, and t_a, respectively) for the potential conflict events in crossing, local merging, overtaking, and coordinated approach merging situations measured in man-sec/conflict are:

t_c = 40, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_m = 35, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_o = 30, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_a = 32.5, for 1-man and 2-man teams;

= 20.5, for 1.5-man and 2.5-man teams.

3. Conflict Workload Weighting

R controller conflict workload weightings (k_2, k_3, k_4, and k_5) are estimated by multiplying the conflict event frequencies (Table 10) by the corresponding performance time (see above). Results of these calculations for visual and instrument approach conditions in each of the six sectors are presented in Table 13.

D. Workload Weighting Application

The routine, surveillance, and conflict workload weighting data are used to estimate sector capacities for each sector team manning regime. We defer to a subsequent section of this report the presentation of the resulting sector capacity estimates for ARTS III operations so that we may then make comparisons between these capacity estimates and those corresponding to the UG3RD system alternatives.

Table 13

R CONTROLLER CONFLICT WORKLOAD WEIGHTING
OAKLAND BAY TRACON, SYSTEM 1-- ARTS III BASE

Sector	R Controller Conflict Workload Weighting $[(\text{Man-Sec/Hr})/(\text{Aircraft/Hr})^2]$				
	Visual Approach Operations				
	Crossing,* k_2	Merging,* k_3	Overtaking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Woodside Final	0	0	19.5×10^{-2}	0	0
AR-2, Foster Final	0	11.2×10^{-2}	31.8×10^{-2}	0	0
AR-9, South Feeder	0	16.1×10^{-2}	4.2×10^{-2}	0	0
AR-10, North Feeder	6.0×10^{-2}	11.6×10^{-2}	11.1×10^{-2}	0	0
DR-1, Sutro Departure	22.8×10^{-2}	2.5×10^{-2}	6.9×10^{-2}	0	0
DR-2, Richmond Departure	18.0×10^{-2}	0	2.4×10^{-2}	0	0
	Instrument Approach Operations				
Sector	Crossing,* k_2	Merging,* k_3	Overtaking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Woodside Final	0	0	39.0×10^{-2}	0	0
AR-2, Foster Final	0	11.2×10^{-2}	63.6×10^{-2}	0	0
AR-9, South Feeder	0	16.1×10^{-2}	8.4×10^{-2}	12.4×10^{-2}	7.8×10^{-2}
AR-10, North Feeder	6.0×10^{-2}	11.6×10^{-2}	22.2×10^{-2}	12.4×10^{-2}	7.8×10^{-2}
DR-1, Sutro Departure	22.8×10^{-2}	2.5×10^{-2}	6.9×10^{-2}	0	0
DR-2, Richmond Departure	18.0×10^{-2}	0	2.4×10^{-2}	0	0

*Indicated crossing, local merging and overtaking conflict workload weightings are for any of the 1-man, 1.5-man, 2-man, and 2.5-man sector team manning regimes.

VII BAY TRACON UG3RD SYSTEMS MODELS

In this section we describe the technological and operational aspects of various proposed UG3RD automation features and assess their impact on R controller workload for the six Bay TRACON sectors. These systems are:

- Automated data handling (ADH)
- Basic metering and spacing (M&S)
- Conflict probe
- Area navigation (RNAV)
- Discrete address beacon system (DABS) data link
- DABS-based intermittent positive control (IPC).

Our UG3RD feature descriptions are based on FAA engineering and operational preliminary design plans[7] for terminal ATC and UG3RD ATC System, on consultations with FAA Oakland Bay TRACON, Los Angeles TRACON and Headquarters personnel, and on our experience and judgment. We consider each feature, in the order of the above list, to be added incrementally to the preceding feature. This procedure obtains a set of alternative ATC systems, each of which includes the features of its predecessor system, as well as its own additional feature.

The current ARTS III System modeled in the preceding section of this report is taken as the base system. Beginning with the ARTS III model, we will incrementally adjust the event frequency and performance time parameters to describe the operational characteristics of each successive UG3RD system. This process will provide revised workload weightings for each successive UG3RD system and enable determination of sector capacities under each system. The workload descriptions stem from our views on how the various features might be implemented.

A. Automated Data Handling (System 2)

Automated data handling provides for the automatic distribution of flight data among sectors and facilities. The main automation aspect of this feature is the addition at sector positions of an electronic tabular flight data display system.

The tabular display can be highly important because of its impact on sector controller activities and its implications for sector configuration redesign. The tabular display, an electronic alphanumeric presentation of flight data, would replace the flight progress strips and paper scratch pads on which flight data are currently found. The display is assumed to be automatically refreshed by the FDP computer system and to be accessible by sector team keyboard entry devices. It is designed to eliminate manual flight strip processing by consolidating all on-line data presentation and maintenance into computer interactive format (thus eliminating the current system requirement for redundant simultaneous keyboard and flight strip processing operations) and to facilitate sector team handoff and pointout operations.

The automatic transfer of flight data and the elimination of current paper flight strip processing would mean that a flight data position would no longer be necessary, provided that the automated system operates with a high degree of failure recovery. We expect that, with the advent of advanced microprocessing technology, continuity of tabular display operations could be provided through redundant ADH software/hardware equipment. Otherwise, if such fault tolerance were not provided, an important productivity benefit of automated data handling could not be realized, because flight strip printers and flight data processors would probably be needed for back-up purposes. (Of course, the flight data position is also used for on-the-job training of controllers, and eliminating this position would require adjustments in controller training programs.)

Quite apart from the issue of sector team manpower support, the tabular display should reduce R controller workload requirements and thereby increase sector traffic capacities. We discuss R controller workload changes in the following paragraphs.

1. ADH Workload Model

The ADH tabular display will primarily affect routine work by altering many of the sector team's data maintenance activities. We foresee no effect on our surveillance or conflict work models.

a. Composite Team Routine Tasks

Our interpretations of the effects of tabular display on the composite team's routine task performance time are summarized in Table 14. The parenthesis around entries in the table indicates task times under the ARTS III Base System (Table 2). Entries adjacent to the parenthesis are the revised task times corresponding to automated data handling.

Table 14
COMPOSITE TEAM
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 2--AUTOMATED DATA HANDLING

Routine Control Event Description		Performance Time by Task (man-sec/event)*				
Event Function	Basic Event and Supplemental Event	A/C Communication	Data Entry/ Display Operation	Flight Strip Processing*	Interphone Communication	Face-to-Face Communication
Control jurisdiction transfer	Handoff acceptance			0(2)		
	Manual acceptance-silent		2			
	Tower departure call				0(2)	
	Controller coordination				6	3
	Handoff initiation-silent		1(3)			
	Controller coordination				6	3
Traffic structuring	Initial pilot call-in	4	1(0)	0(1)		
	TCA clearance request	4	10	0(6)		4(0)
	Initial controller response	2				
	Altitude instruction	3				
	Data update		3(0)	0(2)		
	Heading/route instruction	3				
	Speed instruction	3				
	Approach/runway advisory	3				
	PVD display update		3			
	Traffic advisory	3				
	ATIS advisory	3				
	Altimeter setting advisory	3				
	Transponder code assignment	3	3	0(2)		
	Controller coordination				5	3
	Altitude instruction	5				
	Data update		3(0)	0(2)		
	Controller coordination				5	3
	Heading/route instruction	5				
	Controller coordination				5	3
	Speed instruction	5				
	Approach clearance	6				
	Runway assignment	5				
	Traffic advisory	5				
	Pilot altitude report	5				
	Pilot heading/position report	5				
	Pilot speed report	5				
	Miscellaneous A/G communication	5				
	Frequency change	4	1(0)	0(1)		
	Transponder code change	2				
	Approach/runway advisory	3				
Pilot request	Altitude revision	6	3(0)	0(2)		
	Controller coordination				5	3
	Route/heading revision	8	3(0)	0(2)		
	Controller coordination				5	3
	Miscellaneous pilot request	6				
General intersector coordination	Pointout acceptance		3		0(6)	0(3)
	Pointout initiation		3(0)		0(6)	0(3)
	Control instruction approval				5	3
	Planning advisory				5	3
	Aircraft status advisory				5	
General system operation	Data block forcing/removal		3			
	PVD display adjustment		3			

*System 1 performance times are indicated in parentheses.

All other entries in Table 14 are identical to those in Table 2, since we assume that these tasks will not be affected by tabular display operations and must be performed.

With reference to the tasks under the control jurisdiction transfer function shown in Table 14, we assume the FDP computer system will be capable of recognizing handoff initiation and acceptance events and automatically indicating their occurrence on a tabular display of flight data for each aircraft. This capability eliminates the 2 man-sec flight strip processing currently needed to manually arrange or distribute the strips (or to mark paper scratch pads). However, the keyboard data entry/display operations are still needed for silently initiating or accepting handoffs (and thereby triggering an update of the computerized tabular display). Tower departure calls would not be needed if the tower controllers used simplified button-pushing operations to report aircraft takeoff; the ADH system would use these reports for automatically updating TRACON tabular flight data displays and to check for correct track acquisition. Silent handoff initiation could be manually performed on the aircraft's electronic flight data tabulation by a 1 man-sec button-pushing operation rather than by the current 3 man-sec data entry/display operation.

For traffic structuring and pilot request events, the flight strip processing tasks become keyboard data entry/display operations. Event recording tasks (e.g., recording the occurrence of a pilot call-in or frequency change instruction) are assumed to be accomplished by simple direct entry devices on the tabular display; they would not take longer than the current flight strip performance times of 1 man-sec each. However, preparation of new flight files for unexpected aircraft "pop-ups" would still need to be performed, requiring a 10 man-sec data entry/display operation; however, the 6 man-sec flight strip preparation is eliminated. Under 2-man or 2.5-man sector team operations, we assume the H controller performs the necessary keyboard operations for the "pop-ups", and we allow an additional 4 man-sec face-to-face communication so that the H controller may obtain the necessary flight data from the R controller (who has obtained the data from the pilot via A/G communication).

Certain data update operations currently recorded on flight strips (e.g., altitude and route/heading instructions or requests) would need to be replaced by new keyboard data entry/display operations. Since current keyboard operations for computer data entries require 3 man-sec to perform, it is assumed that data entry operations using the tabular display would also take this long. Therefore, implementing the tabular display would actually increase data entry operations by 1 man-sec over the current flight strip entries. The 3 man-sec data entry time may be an over-estimate if one considers the possibility of designing improved man-machine interaction devices as part of the tabular display, but it is nevertheless adopted for lack of more precise data.

The keyboard data entry/display operations required for accepting handoffs could also give a visual signal (e.g., blinking light) which could be removed by pushing a button after issuing the radio frequency change. We assume that a 1 man-sec manual button push would replace the current 1 man-sec flight strip marking associated with a frequency change instruction.

Pointouts currently initiated by interphone communications cause the recipient sector team to force a data block onto its own PVD display as part of the pointout acceptance event. The receiving sector has no flight strip on the aircraft in question, and verbal intersector communications are used to transmit needed flight data as well as to confirm pointout recognition. The interphone and associated face-to-face communications could be eliminated by the tabular display if both the pointout initiation and acceptance events are performed by silent keyboard data entry/display operations. The pointout initiation would automatically force the PVD data block display and simultaneously force pertinent flight data onto the receiving sector's tabular display, thus eliminating the need for voice consultations. A manual silent pointout acceptance would confirm pointout recognition. As shown in Table 14, we assume the ADH pointout initiation and acceptance events require 3 man-sec data entry/display operations but no interphone or face-to-face communications.

No effect on A/G communication task requirements is projected since the tabular display automates controller data maintenance activities rather than the controller/pilot interface.

b. <u>R Controller Routine Tasks</u>

We allocate the composite team routine task time requirements to the R controller for each of the four sector team manning regimes as shown in Tables 15, 16, 17, and 18. The allocations parallel those made for the ARTS III Base System: The coordinator performs routine interphone tasks and, for the 1.5-man team, half the handoff events; the H controller performs keyboard data entry/display tasks where appropriate and interphone communications if the coordinator position is not manned; face-to-face communications apply only to the multi-man team regimes. Regarding pointout acceptance and initiation events for the 2-man and 2.5-man teams, we assume the necessary manual tasks are performed by the H controller, but the R controller must observe the pointout-related

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Table 15

R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 2, 1-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent		2				2
	Tower departure call						0
	Controller coordination				6		6
	Handoff initiation-silent		1				1
	Controller coordination				6		6
Traffic structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4	10				14
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update		3				3
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update		3				3
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3	3				6
	Controller coordination				5		5
	Altitude instruction	5					5
	Data update		3				3
	Controller coordination				5		5
	Heading/route instruction	5					5
	Controller coordination				5		5
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4	1				5
	Transponder code change	2					2
	Approach/runway advisory	3					3
Pilot request	Altitude revision	6	3				9
	Controller coordination				5		5
	Route/heading revision	8	3				11
	Controller coordination				5		5
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3				3
	Pointout initiation		3				3
	Control instruction approval				5		5
	Planning advisory				5		5
	Aircraft status advisory				5		5
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 16

R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 2, 1.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent		2				2
	Tower departure call						0
	Controller coordination					3	3
	Handoff initiation-silent		1				1
	Controller coordination					3	3
Traffic structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4	10				14
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update		3				3
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update		3				3
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3					3
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update		3				3
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4	1				5
	Transponder code change	2					2
	Approach/runway advisory	3					3
Pilot request	Altitude revision	6	3				9
	Controller coordination					3	3
	Route/heading revision	8	3				11
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3				3
	Pointout initiation		3				3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 17

R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 2, 2-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communi-cation	Data Entry/ Display Opera-tion	Flight Strip Process-ing	Inter-phone Communi-cation	Face-to-Face Communi-cation	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent						0
	Tower departure call						0
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4				4	8
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update						0
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update		3				3
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3					3
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update						0
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4	1				5
	Transponder code change	2					2
	Approach/runway advisory	3					3
Pilot request	Altitude revision	6	3				9
	Controller coordination					3	3
	Route/heading revision	8	3				11
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3 *				3
	Pointout initiation		3 *				3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

*Operational Cognizance

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OAKLAND BAY TRACON AND LOS ANGELES TRACON: CASE STUDIES OF UPGR--ETC(U)

MAR 77 G J COULURIS, J M JOHNSON DOT-FA75WA-3714

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Table 18

R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 2, 2.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent						0
	Tower departure call						0
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4				4	8
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update						0
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update						0
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3					3
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update						0
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4	1				5
	Transponder code change	2					2
	Approach/runway advisory	3					3
Pilot request	Altitude revision	6					6
	Controller coordination					3	3
	Route/heading revision	8					8
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3*				3
	Pointout initiation		3*				3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General system operation	Data block forcing/removal						0
	PVD display adjustment						0

*Operational cognizance

display data to maintain cognizance of these activities. Therefore, the R controller's "operation cognizance" requirements are considered to result in 3 man-sec data entry/display tasks, as shown in Tables 17 and 18. The derivations of the remaining R controller task allocations in Tables 15, 16, 17, and 18 are the same as under the ARTS III Base System.

The resulting R controller routine event minimum performance times for the 1-man, 1.5-man, 2-man, and 2.5-man team regimes are summarized in Table 19.

2. ADH Workload Weightings

R controller routine workload weightings are calculated using the routine event frequencies in Table 1. The Table 1 entries are based on current ARTS III Base System operations and are assumed to be representative of ADH operations since no revisions in the frequency of routine control requirements are anticipated. We multiply the Table 1 event frequencies by the corresponding event performance times in Table 19 to obtain the R controller routine workload weightings shown in Table 20 for each sector under the four sector team regimes.

The R controller surveillance workload weighting (Table 9) and conflict workload weighting (Table 13) calculated for the ARTS III Base System also apply to the automated data handling system.

B. Basic Metering and Spacing (System 3)

Basic metering and spacing (M&S) is a terminal ATC computerized operation to maximize runway system utilization by precisely controlling the delivery time of arrival aircraft to a runway system's threshold and thereby minimizing interarrival times.[7] The computer operation processes FDP- and radar-derived aircraft situation data, determines sequencing and spacing requirements along the inbound routes, and displays control maneuver suggestions to the controllers. Final decisions regarding minute-by-minute control instructions, as well as their actual issuance via A/G communications, are the responsibility of the R controllers. The controllers manage the computerized operation by manually specifying algorithm parameters describing operational or procedural constraints (i.e., in-trail separation, altitude, speed, and route-merging requirements, runway usage, restrictions, and so forth).[7]

Basic metering and spacing is intended to replace part of the decision making involved in merging aircraft from divergent directions into

Table 19

R Controller

ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES

OAKLAND BAY TRACON
SYSTEM 2--AUTOMATED DATA HANDLING

Routine Control Event Description		Performance Time by Team (man-sec/event)			
Event Function	Basic Event and Supplemental Event	1.0-Man Team	1.5-Man Team	2.0-Man Team	2.5-Man Team
Control jurisdiction transfer	*Handoff acceptance*	0	0	0	0
	Manual acceptance-silent	2	2*	0	0
	Tower departure call	0	0	0	0
	Controller coordination	6	3	3	3
	Handoff initiation-silent	1	1*	0	0
	Controller coordination	6	3	3	3
Traffic structuring	Initial pilot call-in	5	5	5	5
	TCA clearance request	14	14	8	8
	Initial controller response	2	2	2	2
	Altitude instruction	3	3	3	3
	Data update	3	3	0	0
	Heading/route instruction	3	3	3	3
	Speed instruction	3	3	3	3
	Approach/runway advisory	3	3	3	3
	PVD display update	3	3	3	0
	Traffic advisory	3	3	3	3
	ATIS advisory	3	3	3	3
	Altimeter setting advisory	3	3	3	3
	Transponder code assignment	6	3	3	3
	Controller coordination	5	3	3	3
	Altitude instruction	5	5	5	5
	Data update	3	3	0	0
	Controller coordination	5	3	3	3
	Heading/route instruction	5	5	5	5
	Controller coordination	5	3	3	3
	Speed instruction	5	5	5	5
	Approach clearance	6	6	6	6
	Runway assignment	5	5	5	5
	Traffic advisory	5	5	5	5
	Pilot altitude report	5	5	5	5
	Pilot heading/position report	5	5	5	5
	Pilot speed report	5	5	5	5
	Miscellaneous A/G communication	5	5	5	5
	Frequency change	5	5	5	5
	Transponder code change	2	2	2	2
	Approach/runway advisory	3	3	3	3
Pilot request	Altitude revision	9	9	9	9
	Controller coordination	5	3	3	3
	Route/heading revision	11	11	11	11
	Controller coordination	5	3	3	3
	Miscellaneous pilot request	6	6	6	6
General Intersector coordination	*Pointout acceptance*	3	3	3	3
	Pointout initiation	3	3	3	3
	Control instruction approval	5	3	3	3
	Planning advisory	5	3	3	3
	Aircraft status advisory	5	0	0	0
General system operation	Data block forcing/removal	3	3	3	0
	PVD display adjustment	3	3	3	0

*Indicated event occurs at *one-half* the rate shown in Table 1.

Table 20

R CONTROLLER ROUTINE WORKLOAD WEIGHTINGS
OAKLAND BAY TRACON, SYSTEM 2--AUTOMATED DATA HANDLING

Sector	R Controller Routine Workload Weighting, k_1, by Team (man-sec/aircraft)			
	1-Man Team	1.5-Man Team	2-Man Team	2.5-Man Team
AR-1, Woodside Final	53	50	49	46
AR-2, Foster Final	44	42	41	39
AR-9, South Feeder	44	41	37	32
AR-10, North Feeder	43	40	37	31
DR-1, Sutro Departure	46	41	38	38
DR-2, Richmond Departure	57	53	50	47

one or more final approach sequences and defining their order or sequence on a time-integrated basis. The computer algorithm must meter the flow of aircraft across the various merge points and allow for the longitudinal spacing of aircraft along the routes through these merge points. However, the basic metering and spacing algorithm determines sequencing and spacing requirements for aircraft destined to a specific runway complex, and it may not encode knowledge of all aircraft in the sectors. Therefore, controllers must constantly compare the displayed instructions against their own detailed minute-by-minute mental projections of aircraft trajectories in order to satisfy separation assurance needs. Accordingly, the R controller may issue A/G directives that to do necessarily correspond to those that are automatically generated.[7]

The potential incompatibility between actual and automatically generated control instruction suggests that the basic metering and spacing operation (i.e., without comprehensive automated conflict processing) could not be expected to fully automate the decision-making activities needed in spacing aircraft arrival traffic. But regardless of the content of the automatically generated commands, the automated operation could determine the sequencing requirements needed to optimize runway utilization, display to controllers the order in which successive aircraft are to be processed through merge points, and update the sequence orderings as traffic situations change. This updating function includes the ability to automatically detect sequencing incompatibilities as they develop. Therefore, the basic metering and spacing operation is capable of alleviating some of the decision making needed to structure and update the sequencing plan, although controllers must still decide the minute-by-minute instructions needed to effect the preferred sequences and maintain spacing. Such control instructions may correspond to or be partly based on commands suggested by the automated operation.

In the following paragraphs, we develop an R controller workload model corresponding to our operational description of basic metering and spacing. We assume that controllers will respond to sequencing directives automatically issued and updated by the computerized system, will mentally determine action requirements, and will transact the A/G voice communications to resolve the situation.

1. M&S Workload Model

Since controller sequencing operations are generated by pairwise interactions between merging aircraft, basic metering and spacing will alter the decision-making task times that we have incorporated into our conflict work model. We expect no impact on routine or surveillance work requirements.

a. Composite Team Conflict Tasks

Our projections of the effect of basic metering and spacing on the composite team's potential conflict processing task times are summarized in Table 21. Since the computerized operation is designed to facilitate only arrival traffic flows, we assume that task time reductions will be experienced for local merging, overtaking, and coordinated approach merging situations along inbound routes in feeder and final sectors; departure sectors will not be affected. We assume no effect on crossing conflict task performance because such conflicts are not normally part of the arrival traffic merging operation. Since the automated operation does not completely alleviate the controller's need to decide on appropriate

Table 21

ARRIVAL SECTOR COMPOSITE TEAM

CONFLICT EVENT PERFORMANCE TIME ESTIMATES

OAKLAND BAY TRACON, SYSTEM 3--BASIC METERING AND SPACING

Conflict Event	Minimum Performance Time by Task* (man-sec/conflict)			
	Detection and Assessment	Coordination	Resolution	Total
Crossing	20	0	20	40
Local Merging	10 (20)	0	15	25 (35)
Overtaking	10 (20)	0	10	20 (30)
Coordinated Approach Merging	10 (20)	5	15	30 (40)

*System 2 task times are indicated in parentheses. Revisions apply only to arrival (feeder and final) sectors.

control instructions, we assume the detection and assessment task time for the three conflict situations of interest will be reduced from 20 to 10 man-sec/conflict. This reduction in man-sec/conflict is due to the assistance given to controllers by the automatic detection of sequencing conflicts and the automatic suggestion of aircraft orderings. With this automation, controllers do not have to spend time searching for a specific pairwise conflict and then determining which aircraft should be merged ahead of another, but must only decide how to accomplish the merge.

In overtaking situations, more time is normally required for mentally detecting the problem than with a merging conflict, but the sequencing decision here is obvious. Therefore, a 10 man-sec/event time reduction results from the automatic detection of the overtaking conflict.

We assume that automatic detection and assessment of overtaking situations is incorporated into the basic metering and spacing operation because all pairs of successive aircraft must be properly spaced at the runway threshold whether or not each aircraft is on identical or merging inbound routings.

We do not adjust conflict coordination and resolution task times because basic metering and spacing is not expected to affect the communication activities necessary for these tasks.

b. <u>R Controller Conflict Tasks</u>

As in the case of our analysis of the ARTS III Base System, we assume the tasks represented in Table 21 for crossing, local merging, and overtaking situations are performed by the R controller. The impact of basic M&S on the R controller's coordinated approach merging tasks are shown in Table 22. The detection and assessment task time reductions attributed to basic metering and spacing offset much of task support that otherwise would have been provided by the coordinator. That is, metering and spacing essentially automates the sequencing decisions made by the coordinator. However, the coordinator still reduces the R controller's coordination time required to confirm sequencing plans between feeder sectors, although only by 2 man-sec/event (and the coordinator is still needed to support R controller routine work requirements as defined in the ARTS III Base System).

To summarize the effects of basic metering and spacing upon our workload model, the R controller's potential conflict event performance times (t_c, t_m, t_o, and t_a, respectively) for crossing, local merging, overtaking, and coordinated approach merging situations measured in man-sec/event are:

t_c = 40, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_m = 25, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_o = 20, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_a = 22.5, for 1-man and 2-man teams,

= 20.5, for 1.5-man and 2.5-man teams.

2. <u>M&S Workload Weightings</u>

No revisions to frequency of conflict events are associated with basic metering and spacing, and the conflict event frequencies in Table 10

Table 22

COORDINATED APPROACH MERGING

R CONTROLLER CONFLICT EVENT PERFORMANCE TIME ESTIMATES

OAKLAND BAY TRACON, SYSTEM 3--BASIC METERING AND SPACING

Sector Operation	R Controller Minimum Performance Time by Task * (man-sec/coordinated merging event)				
	Detection and Assessment	Coordination	Resolution	Total	Average
Without Coordinator †					
AR-9 (or -10)	10 (20)	5	15	30 (40)	22.5(32.5)
AR-10 (or -9)	10 (20)	5	0	15 (25)	
With Coordinator ‡					
AR-9 (or -10)	10	3	15	28	20.5
AR-10 (or -9)	10	3	0	13	

* System 2 task times are indicated in parentheses.

† 1-man and 2-man sector team manning regimes

‡ 1.5-man and 2.5-man sector team manning regimes

calculated for the current ARTS III Base System apply; these frequencies also apply to the automated data handling system which we assume to precede the basic metering and spacing system. We multiply the conflict event performance times (see above) by the corresponding Table 10 event frequencies to obtain the R controller conflict workload weightings shown in Table 23 for basic metering and spacing.

The R controller routine workload weightings (Table 20) and surveillance workload weightings (Table 19) corresponding to the predecessor systems also apply to the basic metering and spacing system.

C. Conflict Probe (System 4)

Projections of aircraft flight trajectories by computer calculations of the FDP and radar-derived situation data might be used in two ways to assist controllers in processing potential conflict situations: first, to alert controllers of imminent potential conflicts and to suggest corrective actions; second, to probe for conflicts over a long-term horizon to enable early resolution. In either case, A/G communications are required to transmit control instructions.

The current enroute ATC conflict alert device provides warning of an imminent potential conflict that occasionally may be missed by the controllers. It does not affect the routine sector control workload because the conflict alert projects minimum separation violation a few minutes or less ahead of its occurrence, while the controller generally projects conflicts further ahead in time. We will not examine this device further with regard to terminal ATL workload impact, although safety is the area of benefit potential.

A conflict probe with longer look-ahead capabilities is difficult to assess. To avoid excessive "false alarms," a degree of flight plan description that is not currently part of the computerized data-files may be required. The projection of the minute-by-minute variation in aircraft trajectories, which are grasped by controllers for short-term projection purposes, would need to be incorporated into a conflict probe device. This capability is particularly critical in a terminal ATC environment such as that of the Bay TRACON, in which merging traffic flows are a major part of basic operational procedures, or in any high-density traffic operation in which turning maneuvers are standard.

Since the computerized conflict probe must be knowledgeable of the flight trajectories routinely followed by aircraft in the terminal airspace, a rather extensive description of the operational route geometrics and procedural restrictions needs to be incorporated into the probe. This

Table 23

R CONTROLLER CONFLICT WORKLOAD WEIGHTING
OAKLAND BAY TRACON, SYSTEM 3--BASIC METERING AND SPACING

Sector	R Controller Conflict Workload Weighting [(Man-Sec/Hr)/(Aircraft/Hr)^2]				
	Visual Approach Operations				
	Crossing,* k_2	Local Merging,* k_3	Overtaking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Woodside Final	0	0	13.0×10^{-2}	0	0
AR-2, Foster Final	0	8.0×10^{-2}	21.2×10^{-2}	0	0
AR-9, South Feeder	0	11.5×10^{-2}	2.8×10^{-2}	0	0
AR-10, North Feeder	6.0×10^{-2}	8.3×10^{-2}	7.4×10^{-2}	0	0
DR-1, Sutro Departure	22.8×10^{-2}	2.5×10^{-2}	6.9×10^{-2}	0	0
DR-2, Richmond Departure	18.0×10^{-2}	0	2.4×10^{-2}	0	0
	Instrument Approach Operations				
Sector	Crossing,* k_2	Local Merging,* k_3	Overtaking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Woodside Final	0	0	26.0×10^{-2}	0	0
AR-2, Foster Final	0	8.0×10^{-2}	42.4×10^{-2}	0	0
AR-9, South Feeder	0	11.5×10^{-2}	5.6×10^{-2}	8.6×10^{-2}	7.8×10^{-2}
AR-10, North Feeder	6.0×10^{-2}	8.3×10^{-2}	14.8×10^{-2}	8.6×10^{-2}	7.8×10^{-2}
DR-1, Sutro Departure	22.8×10^{-2}	2.5×10^{-2}	6.9×10^{-2}	0	0
DR-2, Richmond Departure	18.0×10^{-2}	0	2.4×10^{-2}	0	0

*Indicated crossing, local merging and overtaking conflict workload weightings are for any of the 1-man, 1.5-man, 2-man, and 2.5-man sector team manning regimes.

knowledge is essential to enable projection of conflicts along the curved and straight-line flight paths, which may be in descending, ascending, or horizontal configurations with speed or altitude restrictions in effect. The complexity and scope of the route geometry and procedural data encoded into the probe's software may restrict the conflict prediction capability to that of a sector-specific projection horizon. A longer look-ahead horizon over an integrated multisector routing environment may not prove feasible because of data processing constraints and prediction inaccuracies (i.e., excessive false alarms).

Operationally, a sector conflict probe may be used for automatically assessing clearance decisions immediately when aircraft enter into a sector and for updating these assessments continuously until the aircraft exit. The probe warns controllers of potential conflicts projected within a sector and may display resolution alternatives. The automated operation could be integrated with basic metering and spacing to facilitate compatibility between approach sequencing and spacing requirements and each sector's separation assurance responsibilities. The integration of the two systems would enhance the validity of the basic metering and spacing operation as a mechanism for automatically generating spacing commands acceptable to controllers. (Recall that we assume that basic metering and spacing is useful for automatically generating sequencing plans, but lacks the resolution needed to automatically generate reliable spacing commands.)

Controller acceptance of the automatically generated conflict avoidance data depends on the accuracy history of the probe and on controllers' ability to quickly integrate the probe's conclusions with their own mental comprehension of traffic situations. The probe would be of limited value in terms of workload reduction if the controllers duplicated the automatic conflict processing activities. Questions concerning the realistic limits on interfacing computer-derived control decisions with human cognitive processes is beyond the scope of this work, and for the purpose of our analyses, we assume that a conflict probe is operationally feasible. We make this assumption with the understanding that the technological ability of a conflict probe to perform accurately and its acceptance by controllers are not yet proven or disproven.

1. Conflict Probe Workload Model

The sector conflict probe will alter the sector teams task performance time requirements that we have included as part of our conflict work model. We foresee no impact on our routine work or PVD surveillance work models.

a. Composite Team Conflict Tasks

The sector conflict probe's effects on composite team task performance times are estimated as shown in Table 24 for all sectors. Detection and assessment are performed by the computerized probe, and resolution suggestions are displayed to controllers. We judge that 5 man-sec

Table 24

COMPOSITE TEAM

CONFLICT EVENT PERFORMANCE TIME ESTIMATES

OAKLAND BAY TRACON, SYSTEM 4--SECTOR CONFLICT PROBE

Conflict Event	Minimum Performance Time by Task (Man-Sec/Conflict)*			
	Detection and Assessment	Coordination	Resolution	Total
Crossing	5(20)	0	20	25(40)
Local Merging	5(10)	0	15	20(25)
Overtaking	5(10)	0	10	15(20)
Coordinated Approach Merging	5(10)	5	15	25(30)

*System 3 performance times are indicated in parentheses.

will be sufficient to assimilate this information. Similar to current operations, actual resolution is performed via A/G communications. A reduction of 15 man-sec in total conflict processing time results.

b. R Controller Conflict Tasks

We allocate the composite team tasks to the R controller in the manner described for the predecessor basic metering and spacing system (and the same as for the ARTS III Base System). The R controller's potential conflict event performance times (t_c, t_m, t_o, and t_a, respectively) for crossing, local merging, overtaking, and approach merging situations measured in man-sec/conflict are:

t_c = 25, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_m = 20, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_o = 15, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_a = 17.5, for 1-man and 2-man teams,

= 15.5, for 1.5-man and 2.5-man teams.

As in the case of basic metering and spacing, the conflict probe automates much of the support work of the coordinator. The coordinator reduces the R controller's coordinated approach merging event time by only 2 man-sec (although other R controller work reductions are attributed to the coordinator in the routine work model).

2. Conflict Probe Workload Weightings

Since the sector conflict probe does not affect the frequency of potential conflict events, the event frequencies used to model the predecessor basic metering and spacing system apply. These frequencies are shown in Table 10. We multiply the Table 10 event frequencies by the appropriate event performance (see above) to obtain the conflict workload weightings shown in Table 25.

The R controller routine workload weightings (Table 20) and surveillance work weightings (Table 9) used under the predecessor system also apply to sector conflict probe system.

Table 25

R CONTROLLER CONFLICT WORKLOAD WEIGHTING
OAKLAND BAY TRACON, SYSTEM 4--SECTOR CONFLICT PROBE

Sector	R Controller Conflict Workload Weighting $[(\text{Man-Sec/Hr})/(\text{Aircraft/Hr})^2]$				
	Visual Approach Operations				
	Crossing,* k_2	Merging,* k_3	Overtaking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Woodside Final	0	0	9.8×10^{-2}	0	0
AR-2, Foster Final	0	6.4×10^{-2}	15.9×10^{-2}	0	0
AR-9, South Feeder	0	9.2×10^{-2}	2.1×10^{-2}	0	0
AR-10, North Feeder	3.8×10^{-2}	6.6×10^{-2}	5.6×10^{-2}	0	0
DR-1, Sutro Departure	14.3×10^{-2}	1.4×10^{-2}	3.5×10^{-2}	0	0
DR-2, Richmond Departure	11.3×10^{-2}	0	1.2×10^{-2}	0	0
	Instrument Approach Operations				
Sector	Crossing,* k_2	Merging,* k_3	Overtaking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Woodside Final	0	0	19.5×10^{-2}	0	0
AR-2, Foster Final	0	6.4×10^{-2}	31.8×10^{-2}	0	0
AR-9, South Feeder	0	9.2×10^{-2}	4.2×10^{-2}	6.7×10^{-2}	5.9×10^{-2}
AR-10, North Feeder	3.8×10^{-2}	6.6×10^{-2}	11.1×10^{-2}	6.7×10^{-2}	5.9×10^{-2}
DR-1, Sutro Departure	14.3×10^{-2}	1.4×10^{-2}	3.5×10^{-2}	0	0
DR-2, Richmond Departure	11.3×10^{-2}	0	1.2×10^{-2}	0	0

*Indicated crossing, local merging and overtaking conflict workload weightings are for any of the 1-man, 1.5-man, 2-man, and 2.5-man sector team manning regimes.

D. Area Navigation (System 5)

RNAV incorporates navigation devices to achieve closely spaced arrival and departure and multi-lane direct routes for high-density terminal and enroute airspace. Enroute airspace uses are not considered here. The concept we consider includes the establishment of an RNAV route system using fixed waypoints to facilitate computerized navigation.

The RNAV waypoint network could be configured to conform closely to traffic routing patterns. Since analogous NAVAID locations are currently in effect, the number of routine instructions required to clear aircraft through the navigation network should not be significantly reduced. Use of RNAV to reduce crossing conflict resolution A/G instructions may not be feasible because of the difficulty of integrating vectoring maneuvers with an established waypoint network; it might be as difficult to vector the aircraft as it is to establish and transmit temporary waypoint fixes (e.g., latitude and longitude) to the pilot.

The main workload-related benefit of terminal RNAV appears to be the ability to reduce overtaking conflicts by establishing closely spaced parallel routes. By assigning successive aircraft to offset routes or segregating variable speed traffic onto the separate lanes, controllers could eliminate aircraft overtaking situations.[7] However, we suggest that this RNAV advantage would probably not be realized in arrival sectors where convergent routings dominate operations and where spacing must be maintained to facilitate merging at final approach; overtakings and passings would not routinely be permitted even though arrival aircraft are on parallel offset routes. Overtakings and passings in closely spaced parallel routes through departure sectors does appear feasible since the route corridors are diverging and requirements to satisfy metering and spacing specifications do not exist.

1. RNAV Workload Model

RNAV will alter a portion of the event frequency data that we have included as part of our conflict model. We project no impact on our routine or surveillance work models.

We assume RNAV will eliminate the occurrence of overtaking conflicts in departure sectors, as shown in Table 26. The Table 26 entries are obtained by adjusting the conflict event frequency entries in Table 10 which we used to model the predecessor sector conflict probe system. We assume RNAV will not eliminate or reduce conflict event occurrences in the arrival sectors nor will it eliminate or reduce crossing and merging conflict occurrences in the departure sectors.

Table 26

CONFLICT EVENT FREQUENCY ESTIMATES
OAKLAND BAY TRACON, SYSTEM 5 - RNAV

Sector	Conflict Event Frequency Factor* [(Conflicts/Hr) / (Aircraft/Hr)^2]			
	Visual Approach Operations			
Sector	Crossing, e_c	Local Merging, e_m	Overtaking, e_o	Coordinated Approach Merging, e_a
AR-1, Woodside Final	0	0	6.5×10^{-3}	0
AR-2, Foster Final	0	3.2×10^{-3}	10.6×10^{-3}	0
AR-9, South Feeder	0	4.6×10^{-3}	1.4×10^{-3}	0
AR-10, North Feeder	1.5×10^{-3}	3.3×10^{-3}	3.7×10^{-3}	0
DR-1, Sutro Departure	5.7×10^{-3}	0.7×10^{-3}	0(2.3×10^{-3})	0
DR-2, Richmond Departure	4.5×10^{-3}	0	0(0.8×10^{-3})	0
	Instrument Approach Operations			
Sector	Crossing, e_c	Local Merging, e_m	Overtaking, e_o	Coordinated Approach Merging, e_a
AR-1, Woodside Final	0	0	13.0×10^{-3}	0
AR-2, Foster Final	0	3.2×10^{-3}	21.2×10^{-3}	0
AR-9, South Feeder	0	4.6×10^{-3}	2.8×10^{-3}	3.8×10^{-3}
AR-10, North Feeder	1.5×10^{-3}	3.3×10^{-3}	7.4×10^{-3}	3.8×10^{-3}
DR-1, Sutro Departure	5.7×10^{-3}	0.7×10^{-3}	0(2.3×10^{-3})	0
DR-2, Richmond Departure	4.5×10^{-3}	0	0(0.8×10^{-3})	0

* System 4 event frequencies are indicated in parenthesis.

2. RNAV Workload Weightings

RNAV does not affect the conflict event performance times calculated for the predecessor system (Table 24). R controller conflict workload weighting may be obtained by multiplying these task performance times by the RNAV conflict event frequencies in Table 26. The results are identical to the workload weightings shown in Table 25, except that the four entries shown for departure sector overtakings are equal to zero.

The R controller routine workload weightings (Table 20) and surveillance workload weighting (Table 9) used for the predecessor system also apply to the RNAV system.

E. DABS Data Link (System 6)

The DABS data link transmits digital data to pilots, including general control instructions and collision avoidance directives.[7] It is not intended to transmit extensive nonstandard messages in a high-density environment.

The data link integrated with extensive computerization is the basis for the so-called "control-by-exception" concept. We view this concept as somewhat more revolutionary than evolutionary, since it would transform the controller into a systems manager who is not routinely engaged in minute-by-minute tactical decision making. Rather, he would monitor and regulate a computerized sector control operation; the latter would automatically issue, by means of data link, many routine and conflict processing clearances and instructions according to traffic situations and procedural rules. The controller would intervene when necessary to adjust procedural rules, to respond to pilot requests, to resolve non-standard situations, and to transmit A/G messages that are too long for the DABS data link. In essence, he would concentrate on minute-by-minute procedural decision making and perform minute-by-minute tactical decision making only when required. We assume that sectors will be retained as the basic control jurisdictional unit to provide fault tolerance in the event of data link or computer system malfunction (where operations fall back to a nondata-link ATC system).

Under the control-by-exception concept, we assume that a sector controller need not review and approve each instruction. If he were required to read, mentally assimilate, and approve each instruction (duplicating the automated operation), workload advantages would not be realized. This concept assumes the implementation of refined and advanced metering and spacing (which extend basic metering and spacing services to integrated multi-airport arrival and departure operations) and automatic conflict processing computerization, using data link to deliver situation resolution instructions. By this means, sequencing, spacing, and potential conflict situations are resolved without dependence on human decision making. However, assuming human controllers retain responsibility for separation assurance, the question arises as to the degree to which controllers would actually remove themselves from the capability to perform minute-by-minute tactical decision making. Therefore, we assume that controllers will continue to perform intensive PVD surveillance to retain real-time mental picture-keeping (which would be vital in the event of some computer-processing failures) and to maintain cognizance of computer-generated traffic structuring and conflict processing strategies.

1. Data Link Workload Model

The data link-based control-by-exception operation will alter many of the sector team's communication and data maintenance activities that we have included as part of our routine and conflict work models. We foresee no impact on our surveillance work model. In the following paragraphs we adjust our routine and conflict work models to represent control-by-exception operations under the assumption that all aircraft are equipped with DABS data link.

a. Routine Work

Composite Team Routine Tasks--Our revisions to the route task performance times for the composite team are shown in Table 27. The parentheses enclose task time entries that apply to the predecessor RNAV system (which were originally established as part of the ADH system routine work model and presented in Table 14).

With reference to task time revisions in Table 27, we assume the control-by-exception computerization performs much of the mechanical data maintenance activities associated with the assimilation and updating of traffic control operations data. Controllers need not perform the 2 man-sec keyboard manual silent handoff acceptance because the computerization will automatically begin to process control refinements.

A/G voice communications for the standard altitude, heading, speed, approach and runway advisory, transponder code change, and frequency change instructions are assumed to be replaced by data link transmissions. These automatic transmissions eliminate controller time

Table 27
COMPOSITE TEAM
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 6--DABS DATA LINK

Routine Control Event Description		Performance Time by Task (man-sec/event)*				
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/Display Operation	Flight Strip Processing *	Interphone Communication	Face-to-Face Communication
Control jurisdiction transfer	Handoff acceptance					
	Manual acceptance-silent		0(2)			
	Tower departure call					
	Controller coordination				6	3
	Handoff initiation-silent		1			
	Controller coordination				6	3
Traffic structuring	Initial pilot call-in	4	1			
	TCA clearance request	4	10			4
	Initial controller response	2	5†(0)			
	Altitude instruction	0(3)				
	Data update		0(3)			
	Heading/route instruction	0(3)				
	Speed instruction	0(3)				
	Approach/runway advisory	0(3)				
	PVD display update		0(3)			
	Traffic advisory	3				
	ATIS advisory	0(3)				
	Altimeter setting advisory	0(3)				
	Transponder code assignment	3	0(3)			
	Controller coordination				5	3
	Altitude instruction	0(5)	3†(0)			
	Data update		0(3)			
	Controller coordination	5(0)	3(0)		5	3
	Heading/route instruction	0(5)	3†(0)			
	Controller coordination	5(0)	3(0)		5	3
	Speed instruction	0(5)	3†(0)			
	Approach clearance	0(6)	3†(0)			
	Runway assignment	0(5)	3†(0)			
	Traffic advisory	5				
	Pilot altitude report	5				
	Pilot heading/position report	5				
	Pilot speed report	5				
	Miscellaneous A/G communication	5				
	Frequency change	0(4)	3†(1)			
	Transponder code change	0(2)				
	Approach/runway advisory	0(3)				
Pilot request	Altitude revision	6	3			
	Controller coordination				5	3
	Route/heading revision	8	3			
	Controller coordination				5	3
	Miscellaneous pilot request	6				
General intersector coordination	Pointout acceptance		3†	3		
	Pointout initiation		3†			
	Control instruction approval				5	3
	Planning advisory				5	3
	Aircraft status advisory				5	
General system operation	Data block forcing/removal		3			
	PVD display adjustment		3			

*System 5 performance times are indicated in parenthesis.

†Operational cognizance

spent in these A/G voice communications. However, when such activities are nonstandard and require intersector coordination, we assume that A/G voice communications and manual keyboard data entry/display operations will be required. The duration of each nonstandard A/G communications depends on the message transaction involved, and our estimate varies from 3 to 5 man-sec, in accordance with the communication time requirements determined for the predecessor systems. Similarly, we use 3 man-sec to account for keyboard data entry/display actions since it is typical of observed controller capabilities. We note that data entry/display operations required for updating altitude and runway data and changing transponder codes are assumed to be performed automatically, thus eliminating these 3 man-sec manual task time requirements.

Also shown in Table 27 under the data entry/display heading are "operational cognizance" activities. These reflect the controller monitoring work required to maintain awareness of the computerized traffic structuring strategies. Although keyboard activities are not necessarily assumed, these task items provide a surrogate mechanism for estimating the controller monitoring work associated with each data link message transmission. In actuality, rather than reviewing each individual transmission, controllers would probably be provided with a data display describing the overall traffic-oriented procedural intentions of the computer operation, and thereby maintain their mental picture of control operations.

We judge that 3 man-sec is a reasonable time to allow for the operational cognizance activities associated with a standard data link message transmission and pointout (the latter function would also be automatically performed). This time span is not as long as a typical A/G voice message, but should be sufficient for the controller to recognize the procedural intentions of the computerized operation. We associate a 5 man-sec operation cognizance time with the controller's initial response to a pilot call-in in order to account for the time controllers need to mentally assimilate the aircraft's operational requirements in relation to the computerized procedural intentions.

<u>R Controller Routine Tasks</u>--We allocate the composite team routine task time requirements to the R controller for each of the four sector team manning regimes using the same allocation guidelines described for the ARTS III base and the automated data handling system. Results are presented in Tables 28, 29, 30, and 31.

The corresponding R controller routine event minimum performance times for the 1-man, 1.5-man, 2-man, and 2.5-man team regimes are summarized in Table 32. We note that no R controller event time

Table 28

R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 6, 1-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent						0
	Tower departure call						0
	Controller coordination				6		6
	Handoff initiation-silent		1				1
	Controller coordination				6		6
Traffic structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4	10				14
	Initial controller response	2	5*				7
	Altitude instruction						0
	Data update						0
	Heading/route instruction						0
	Speed instruction						0
	Approach/runway advisory						0
	PVD display update						0
	Traffic advisory	3					3
	ATIS advisory						0
	Altimeter setting advisory						0
	Transponder code assignment	3					3
	Controller coordination				5		5
	Altitude instruction		3*				3
	Data update						0
	Controller coordination	5	3		5		13
	Heading/route instruction		3*				3
	Controller coordination	5	3		5		13
	Speed instruction		3*				3
	Approach clearance		3*				3
	Runway assignment		3*				3
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change		3*				3
	Transponder code change						0
	Approach/runway advisory						0
Pilot request	Altitude revision	6	3				9
	Controller coordination				5		5
	Route/heading revision	8	3				11
	Controller coordination				5		5
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3*				3
	Pointout initiation		3*				3
	Control instruction approval				5		5
	Planning advisory				5		5
	Aircraft status advisory				5		5
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

*Operational cognizance

Table 29

R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 6, 1.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent						0
	Tower departure call						0
	Controller coordination					3	3
	Handoff initiation-silent		1				1
	Controller coordination					3	3
Traffic structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4	10				14
	Initial controller response	2	5*				7
	Altitude instruction						0
	Data update						0
	Heading/route instruction						0
	Speed instruction						0
	Approach/runway advisory						0
	PVD display update						0
	Traffic advisory	3					3
	ATIS advisory						0
	Altimeter setting advisory						0
	Transponder code assignment	3					3
	Controller coordination					3	3
	Altitude instruction		3*				3
	Data update						0
	Controller coordination	5	3			3	11
	Heading/route instruction		3*				3
	Controller coordination	5	3			3	11
	Speed instruction		3*				3
	Approach clearance		3*				3
	Runway assignment		3*				3
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change		3*				3
	Transponder code change						0
	Approach/runway advisory						0
Pilot request	Altitude revision	6	3				9
	Controller coordination					3	3
	Route/heading revision	8	3				11
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3*				3
	Pointout initiation		3*				3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

*Operational cognizance

Table 30

R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 6, 2-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent						0
	Tower departure call						0
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4				4	8
	Initial controller response	2	5*				7
	Altitude instruction						0
	Data update						0
	Heading/route instruction						0
	Speed instruction						0
	Approach/runway advisory						0
	PVD display update						0
	Traffic advisory	3					3
	ATIS advisory						0
	Altimeter setting advisory						0
	Transponder code assignment	3					3
	Controller coordination					3	3
	Altitude instruction		3*				3
	Data update						0
	Controller coordination	5				3	8
	Heading/route instruction		3*				3
	Controller coordination	5				3	8
	Speed instruction		3*				3
	Approach clearance		3*				3
	Runway assignment		3*				3
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change		3*				3
	Transponder code change						0
	Approach/runway advisory						0
Pilot request	Altitude revision	6					6
	Controller coordination					3	3
	Route/heading revision	8					8
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3*				3
	Pointout initiation		3*				3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General system operation	Data block forcing/removal						0
	PVD display adjustment						0

*Operational cognizance

Table 31

R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 6, 2.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent						0
	Tower departure call						0
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4				4	8
	Initial controller response	2	5*				7
	Altitude instruction						0
	Data update						0
	Heading/route instruction						0
	Speed instruction						0
	Approach/runway advisory						0
	PVD display update						0
	Traffic advisory	3					3
	ATIS advisory						0
	Altimeter setting advisory						0
	Transponder code assignment	3					3
	Controller coordination					3	3
	Altitude instruction		3*				3
	Data update						0
	Controller coordination	5				3	8
	Heading/route instruction		3*				3
	Controller coordination	5				3	8
	Speed instruction		3*				3
	Approach clearance		3*				3
	Runway assignment		3*				3
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change		3*				3
	Transponder code change						0
	Approach/runway advisory						0
Pilot request	Altitude revision	6					6
	Controller coordination					3	3
	Route/heading revision	8					8
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3*				3
	Pointout initiation		3*				3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General system operation	Data block forcing/removal						0
	PVD display adjustment						0

*Operational cognizance

Table 32

R Controller

ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES

OAKLAND BAY TRACON
SYSTEM 6--DABS DATA LINK

Routine Control Event Description		Performance Time by Team (man-sec/event)			
Event Function	Basic Event and Supplemental Event	1.0-Man Team	1.5-Man Team	2.0-Man Team	2.5-Man Team
Control jurisdiction transfer	Handoff acceptance	0	0	0	0
	Manual acceptance-silent	0	0*	0	0
	Tower departure call	0	0	0	0
	Controller coordination	6	3	3	3
	Handoff initiation-silent	1	1*	0	0
	Controller coordination	6	3	3	3
Traffic structuring	Initial pilot call-in	5	5	5	5
	TCA clearance request	14	14	8	8
	Initial controller response	7	7	7	7
	Altitude instruction	0	0	0	0
	Data update	0	0	0	0
	Heading/route instruction	0	0	0	0
	Speed instruction	0	0	0	0
	Approach/runway advisory	0	0	0	0
	PVD display update	0	0	0	0
	Traffic advisory	3	3	3	3
	ATIS advisory	0	0	0	0
	Altimeter setting advisory	0	0	0	0
	Transponder code assignment	3	3	3	3
	Controller coordination	5	3	3	3
	Altitude instruction	3	3	3	3
	Data update	0	0	0	0
	Controller coordination	13	11	8	8
	Heading/route instruction	3	3	3	3
	Controller coordination	13	11	8	8
	Speed instruction	3	3	3	3
	Approach clearance	3	3	3	3
	Runway assignment	3	3	3	3
	Traffic advisory	5	5	5	5
	Pilot altitude report	5	5	5	5
	Pilot heading/position report	5	5	5	5
	Pilot speed report	5	5	5	5
	Miscellaneous A/G communication	5	5	5	5
	Frequency change	3	3	3	3
	Transponder code change	0	0	0	0
	Approach/runway advisory	0	0	0	0
Pilot request	Altitude revision	9	9	9	9
	Controller coordination	5	3	3	3
	Route/heading revision	11	11	11	11
	Controller coordination	5	3	3	3
	Miscellaneous pilot request	6	6	6	6
General Intersector coordination	Pointout acceptance	3	3	3	3
	Pointout initiation	3	3	3	3
	Control instruction approval	5	3	3	3
	Planning advisory	5	3	3	3
	Aircraft status advisory	5	0	0	0
General system operation	Data block forcing/removal	3	3	0	0
	PVD display adjustment	3	3	0	0

*Indicated event occurs at one-half the rate shown in Table 1.

reductions are obtained by increasing from 2-man to 2.5-man team operations. In the 2-man regime, the H controllers perform the interphone communications and those few data entry/display operations that are not performed automatically by the computerized system. Therefore, there are no additional tasks that may be offloaded effectively from the R controller to a coordinator under the 2.5-man regime.

b. Conflict Work

Composite Team Conflict Tasks--Our revisions to the composite team conflict tasks performance times for DABS control-by-exception operation are shown in Table 33. We assume that, in accordance with their separation assurance responsibilities, controller will maintain close

Table 33

COMPOSITE TEAM
CONFLICT EVENT PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 6 -- DABS DATA LINK

Conflict Event	Minimum Performance Time by Task* (man-sec/conflict)			
	Detection and Assessment	Coordination	Resolution	Total
Crossing	5	0	10† (20)	15(25)
Local Merging	5	0	10† (15)	15(20)
Overtaking	5	0	10†	15
Coordinated Merging	5	0(5)	10† (15)	15(25)

*System 5 performance times are indicated in parentheses.

†Conformance confirmation

surveillance of conflict processing operations. Since actual conflict resolution instructions would be issued by data link, we estimate that 10 man-sec in resolution time is needed by controllers to confirm aircraft conformance. This time enables controllers to check aircraft responses to the automatically transmitted conflict avoidance directives. Also, the computerized operation obviates the need for coordinating approach mergings between sector.

R Controller Conflict Tasks--The R controller conflict event performance times (t_c, t_m, t_o, and t_a, respectively) for crossing local merging, overtaking, and coordinated approach merging situations are identical to those shown for the composite team in Table 33, all of which equal 15 man-sec per conflict. In these cases, the conflict support work of the coordinator effectively is automated by the control-by-exception operation.

2. Data Link Workload Weightings

The R controller routine and conflict event frequencies used to model the predecessor system apply to DABS data link modeling since the rates of occurrence of these events are not affected by control-by-exception automation. We use the appropriate routine event frequencies (Table 1) and performance times (Table 32) to calculate the routine workload weighting summarized in Table 34. The conflict event performance times (Table 33) and RNAV-based conflict event frequencies (Table 26) are used to calculate the conflict workload weightings shown in Table 35.

The R controller surveillance workload weightings (Table 9) used for the predecessor systems also apply to the DABS data link system.

Recall that routine and conflict task time reductions could not be obtained by increasing sector manning to the 2.5-man level. The routine, conflict, and surveillance workload weightings reflect these results, indicating that simultaneous use of a coordinator and H controller is not an effective way of operating control-by-exception.

F. DABS Intermittent Positive Control

IPC provides traffic advisories and threat avoidance commands to VFR pilots on an as-needed basis.[7] Extended to IFR operations, IPC would operate on imminent (e.g., load-time of 1 to 2 min) conflict situations that are "missed" by controllers. This is assumed to be a safety enhancement device that would not affect the capacity considerations associated with normal sector task activities.

Table 34

R CONTROLLER ROUTINE WORKLOAD WEIGHTINGS
OAKLAND BAY TRACON, SYSTEM 6--DABS DATA LINK

Sector	R Controller Routine Workload Weighting, k_1, by Team (man-sec/aircraft)			
	1-Man Team	1.5-Man Team	2-Man Team	2.5-Man Team
AR-1, Woodside Final	38	37	34	34
AR-2, Foster Final	34	33	32	32
AR-9, South Feeder	28	26	23	23
AR-10, North Feeder	30	28	23	23
DR-1, Sutro Departure	44	39	37	37
DR-2, Richmond Departure	52	49	44	44

However, DABS IPC may be needed to provide fault tolerance in the event of failures in the other enhancement operations (particularly conflict processing automation). Therefore, IPC would be necessary for the successful implementation of these other features. We do not further evaluate IPC; it is considered to be an incremental add-on to the data link system but with no independent capacity impact.

Table 35

R CONTROLLER CONFLICT WORKLOAD WEIGHTING
OAKLAND BAY TRACON, SYSTEM 6 -- DABS DATA LINK

Sector	R Controller Conflict Workload Weighting $[(\text{Man-Sec/Hr})/(\text{Aircraft/Hr})^2]$				
	Visual Approach Operations				
	Crossing,* k_2	Merging,* k_3	Overtaking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Woodside Final	0	0	9.8×10^{-2}	0	0
AR-2, Foster Final	0	4.8×10^{-2}	15.9×10^{-2}	0	0
AR-9, South Feeder	0	6.9×10^{-2}	2.1×10^{-2}	0	0
AR-10, North Feeder	2.3×10^{-2}	5.0×10^{-2}	5.6×10^{-2}	0	0
DR-1, Sutro Departure	8.6×10^{-2}	1.1×10^{-2}	0	0	0
DR-2, Richmond Departure	6.8×10^{-2}	0	0	0	0
Sector	Instrument Approach Operations				
	Crossing,* k_2	Merging,* k_3	Overtaking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Woodside Final	0	0	19.5×10^{-2}	0	0
AR-2, Foster Final	0	4.8×10^{-2}	31.8×10^{-2}	0	0
AR-9, South Feeder	0	6.9×10^{-2}	4.2×10^{-2}	5.7×10^{-2}	5.7×10^{-2}
AR-10, North Feeder	2.3×10^{-2}	5.0×10^{-2}	11.1×10^{-2}	5.7×10^{-2}	5.7×10^{-2}
DR-1, Sutro Departure	8.6×10^{-2}	1.1×10^{-2}	0	0	0
DR-2, Richmond Departure	6.8×10^{-2}	0	0	0	0

*Indicated crossing, local merging and overtaking conflict workload weightings are for any of the 1-man, 1.5-man, 2-man, and 2.5-man sector team manning regimes.

VIII BAY TRACON SECTOR CAPACITY AND MANNING

In this section, we estimate traffic capacities for six Bay TRACON sectors for each sector team manning regime under each of the six ATC system alternatives. We use these capacities to estimate multisector minimum manning requirements for a range of traffic levels, which enable comparisons of UG3RD systems effects on facility operations.

A. Sector Capacity

Recall that we define sector traffic capacity as the hourly traffic rate (ac/hr) that generates 48 man-min/hr of R controller work. We use the routine, surveillance and conflict workload weightings quantified in the two preceding sections of this report to calculate R controller workload for successive increments in traffic flow, and interpolate the sector traffic capacity.

We apply this procedure to estimate sector capacities for both visual and instrument approach conditions, for each of the four sector team manning regimes, and for each of the six ATC system alternatives. The resulting capacity estimates are presented in Tables 36, 37, 38, 39, 40, and 41, respectively, for each of the six sectors of interest. (We note that these capacity estimates were judged to be "realistic" and "reasonable" by a Bay TRACON supervisory staff member.)

These sector capacities directly reflect the R controller activity requirements defined by the workload weightings. We see that feeder and final sector capacities for instrument approach operations are less than those for visual operations because of the additional approach merging work, while departure sector capacities are not affected by approach conditions. The sector capacities generally increase for each successive increment in sector team manning because the R controller usually offloads some portion of routine or conflict work to the added team member(s). In some situations, the amount of work offloaded is not sufficiently significant to increase sector capacity; in the case of 2-man versus 2.5-man team regimes under the DABS data link system, no work offloading is projected and sector capacities are identical under the two regimes. Therefore, the 2-man team is the practical sector manning limit under System 6 operations.

Table 36

WOODSIDE FINAL (AR-1) CAPACITY ESTIMATES

ATC System	Sector Capacity by Team (ac/hr)*							
	Visual Approach Operations†				Instrument Approach Operations‡			
	1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0-Man	1.5-Man	2.0-Man	2.5-Man
1. Current ARTS III	41	44	45	47	37	40	41	42
2. + Automated Data Handling	43	44	45	47	39	40	41	42
3. + Basic Metering and Spacing	44	46	47	49	39	40	41	42
4. + Conflict Probe	45	47	48	50	43	44	45	47
5. + RNAV (100% Avionics)	45	47	48	50	43	44	45	47
6. + DABS Data-Link (100% Avionics)	58	59	62	62	53	54	56	56

*Sector traffic capacity corresponds to R-controller workload threshold (48 man-min/hr)

†Side-by-side operations on parallel final approach courses

‡In-trail operations on parallel final approach courses

Table 37

FOSTER FINAL (AR-2) CAPACITY ESTIMATES

ATC System	Sector Capacity by Team (ac/hr)*							
	Visual Approach Operations†				Instrument Approach Operations‡			
	1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0-Man	1.5-Man	2.0-Man	2.5-Man
1. Current ARTS III	41	43	44	45	36	38	38	39
2. + Automated Data Handling	42	43	44	45	37	38	38	39
3. + Basic Metering and Spacing	45	47	47	48	41	42	42	43
4. + Conflict Probe	47	49	49	51	43	44	45	46
5. + RNAV (100% Avionics)	47	49	49	51	43	44	45	46
6. + DABS Data-Link (100% Avionics)	56	57	57	57	49	50	51	51

*Sector traffic capacity corresponds to R-controller workload threshold (48 man-min/hr)

†Side-by-side operations on parallel final approach courses

‡In-trail operations on parallel final approach courses

Table 38

SOUTH FEEDER (AR-9) CAPACITY ESTIMATES

ATC System	Sector Capacity by Team (ac/hr)*							
	Visual Approach Operations†				Instrument Approach Operations‡			
	1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0-Man	1.5-Man	2.0-Man	2.5-Man
1. Current ARTS III	46	51	53	57	42	47	48	52
2. + Automated Data Handling	49	51	54	59	44	47	48	53
3. + Basic Metering and Spacing	51	54	57	63	47	49	52	56
4. + Conflict Probe	52	55	59	65	49	51	54	59
5. + RNAV (100% Avionics)	52	55	59	65	49	51	54	59
6. + DABS Data-Link (100% Avionics)	73	76	81	81	65	68	72	72

*Sector traffic capacity corresponds to R-controller workload threshold (48 man-min/hr)

†Side-by-side operations on parallel final approach courses

‡In-trail operations on parallel final approach courses

Table 39

NORTH FEEDER (AR-1) CAPACITY ESTIMATES

ATC System	Sector Capacity by Team (ac/hr)*							
	Visual Approach Operations†				Instrument Approach Operations‡			
	1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0-Man	1.5-Man	2.0-Man	2.5-Man
1. Current ARTS III	45	49	51	56	40	44	44	49
2. + Automated Data Handling	48	50	52	57	42	44	45	49
3. + Basic Metering and Spacing	50	52	55	60	45	47	49	53
4. + Conflict Probe	52	55	58	64	48	50	52	57
5. + RNAV (100% Avionics)	52	55	58	64	48	50	52	57
6. + DABS Data-Link (100% Avionics)	68	71	78	78	60	62	67	67

*Sector traffic capacity corresponds to R-controller workload threshold (48 man-min/hr)

†Side-by-side operations on parallel final approach courses

‡In-trail operations on parallel final approach courses

Table 40

SUTRO DEPARTURE (DR-1) CAPACITY ESTIMATES

ATC System	Sector Capacity by Team (ac/hr)*							
	Visual Approach Operations†				Instrument Approach Operations‡			
	1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0-Man	1.5-Man	2.0-Man	2.5-Man
1. Current ARTS III	39	45	48	48	39	45	48	48
2. + Automated Data Handling	43	46	48	48	43	46	48	48
3. + Basic Metering and Spacing	43	46	48	48	43	46	48	48
4. + Conflict Probe	47	51	53	53	47	51	53	53
5. + RNAV (100% Avionics)	48	52	55	55	48	52	55	55
6. + DABS Data-Link (100% Avionics)	52	57	59	59	52	57	59	59

*Sector traffic capacity corresponds to R-controller workload threshold (48 man-min/hr)

†Side-by-side operations on parallel final approach courses

‡In-trail operations on parallel final approach courses

Table 41

RICHMOND DEPARTURE (DR-2) CAPACITY ESTIMATES

ATC System	Sector Capacity by Team (ac/hr)*							
	Visual Approach Operations†				Instrument Approach Operations‡			
	1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0-Man	1.5-Man	2.0-Man	2.5-Man
1. Current ARTS III	37	41	44	46	37	41	44	46
2. + Automated Data Handling	41	43	45	47	41	43	45	47
3. + Basic Metering and Spacing	41	43	45	47	41	43	45	47
4. + Conflict Probe	43	45	47	50	43	45	47	50
5. + RNAV (100% Avionics)	43	46	48	50	43	46	48	50
6. + DABS Data-Link (100% Avionics)	48	50	55	55	48	50	55	55

*Sector traffic capacity corresponds to R-controller workload threshold (48 man-min/hr)

†Side-by-side operations on parallel final approach courses

‡In-trail operations on parallel final approach courses

Each UG3RD ATC system successor to the ARTS III Base system includes an automation feature that is added onto the operational features of its predecessors. Since each UG3RD feature further reduces R controller workload requirements to varying extents, sector capacity generally increases as each successive system evolves. However, some of the automation features do not alleviate workload in certain operational environments. For example, basic metering and spacing supports approach operations, but it does not increase departure sector capacity. Similarly, RNAV was not assumed effective in reducing work requirements for arrival operations, and it does not increase feeder or final sector capacity.

We note that our workload analyses assume 100 percent deployment of RNAV and DABS data link airborne equipment for the aircraft fleet under TRACON control. We do not explicitly assess the effect on capacity of partial deployment of such avionics equipment. However, based on our previous analyses of enroute ATC aircraft equipment deployments, first-cut capacity estimates for partial deployment may be made by linear interpolations between systems. For example, a 100 percent RNAV and 50 percent data-link aircraft equipment deployment is expected to obtain sector capacity estimates midway between those shown in Tables 36 through 41 for RNAV and DABS data link.

B. Multi-Sector Manning

Subject to the traffic handling constraints imposed by our sector capacity calculations, we wish to compare the relative manning requirements of each of the six alternative ATC systems associated with the joint operation of the six sectors. These comparisons require estimating multi-sector minimum manning over a range of traffic activity projections so that the relative effectiveness of each system's traffic service capability may be assessed. We use sector capacities calculated for instrument approach conditions rather than visual because instrument conditions are more critical constraints to controller traffic handling capabilities.

1. Manning Calculations

Our intention is to calculate for each system the minimum number of manned control positions required to process various levels of traffic through each sector without exceeding our R controller workload-based capacity constraints. Manning estimates might be made simply by comparing the traffic through each sector during some specific hour against the hourly capacity of each sector team manning regime. However, certain aspects of TRACON operations complicate this manning estimation procedure.

The first of these complicating factors is that a coordinator does not support one single sector team, but operates interactively with two specific sector teams. Therefore, we need to account for coordinator manning requirements on a sector pairwise basis, rather than on an individual sector basis. Second, sector manning requirements are determined by the peak hour traffic during an 8-hour work shift. We need to account for the peak hour manning needs even though each sector's peak hour does not necessarily occur at the same time as another's. Third, flight data positions support control operations even though they are not necessarily part of any specific sector team. We need to account for flight data manning needs on a facility-wide basis.

The estimation procedure we use to account for these manning needs is as illustrated in Tables 42, 43, 44, 45, 46, and 47 for the six alternative ATC systems, respectively. These tables are worksheets that trace our calculations.

Consider Table 42, which represents the ARTS III Base system. Our traffic base is the 1975 statistics reported for the 8-hour day shift for the Bay TRACON busy day (90th percentile).[11] The traffic statistics shown in Table 42 are the peak hour traffic counts for each sector. Our sector capacity estimates for each team manning regime are also listed. We determine a traffic handling growth potential factor (relative to the 1975 day shift, peak hour traffic) for each sector's manning regime by dividing the corresponding sector traffic capacity by the peak hour traffic. For example, the 1-man team regime for AR-1 is shown to have a traffic growth potential factor equal to 1.37, which means this sector operation is assumed capable of handling a 37 percent increase to the 1975 day shift, peak hour traffic.

We use the traffic growth potential factors to estimate sector manning needs for 25 percent increments in day-shift traffic projections As shown in Table 42, we compare each traffic factor increment against a sector's growth potential for each team manning regime, and identify the sector manning required to handle the projected traffic. By this means, we find that AR-1 needs a 2-man team to handle a 50 percent traffic increase, and a 2.5-man team to handle a 75 percent traffic increase. However, the coordinator in this latter regime supports AR-2 as well as AR-1, even though AR-2 can handle the 75 percent traffic increase with a 1-man team. To account for the sector pairwise services of the coordinator, we assign a 1.5-man team to AR-2 at this traffic level.

With reference to the sector team manning requirement calculated for the DABS data link system in Table 47, the two final sectors are shown not to be manned at low traffic activity levels. In this case, the large

Table 42

DAY-SHIFT, PEAK-HOUR MANNING CALCULATIONS
OAKLAND BAY TRACON
SYSTEM 1--ARTS III BASE

Sector	1975 Busy-day, Day-shift, Peak-hour Traffic (ac/hr)*	IFR Sector Capacity by Team (ac/hr)				Traffic Growth Potential Factor† by Team				Manning Requirement by Traffic Factor (controllers/team)								
		1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0 Man	1.5-Man	2.0-Man	2.5-Man	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
AR-1 Woodside Final	27	37	40	41	42	1.37	1.48	1.52	1.56	1	1	2	2.5	2.5	2.5	2.5	2.5	2.5
AR-2 Foster Final	20	36	38	38	39	1.80	1.90	1.90	1.95	1	1	1	1.5[‡]	2.5	2.5	2.5	2.5	2.5
AR-9 South Feeder	18	42	48	48	52	2.33	2.61	2.67	2.89	1	1	1	1.5[‡]	1.5[‡]	1.5[‡]	1.5	2.5	2.5
AR-10 North Feeder	26	40	44	44	49	1.54	1.69	1.69	1.88	1	1	1	2.5	2.5	2.5	2.5	2.5	2.5
DR-1 Sutro Departure	23	39	45	48	48	1.70	1.96	2.09	2.09	1.5[‡]	1.5[‡]	1.5[‡]	1.5	2.5[‡]	2.5	2.5	2.5	2.5
DR-2 Richmond Departure	38	37	41	44	46	0.97	1.08	1.16	1.21	1.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Subtotal (Men)										7	8	9	12	14	14	14	15	15
Flight data positions (Men)										1	1	1	1	2	2	2	2	2
Total (Men)										8	9	10	13	16	16	16	17	17
Manning factor (1975 Base)										1.0	1.13	1.25	1.63	2.0	2.0	2.0	2.13	2.13

*Source: "Application of ATC Terminal Standard for FY 1975," computer printout manuscript, Air Traffic Service, FAA (1976)

†Traffic Growth Potential = Capacity ÷ 1975 Busy-day Traffic

‡Coordinator (1/2-man) required for companion sector

Table 43

DAY-SHIFT, PEAK-HOUR MANNING CALCULATIONS
OAKLAND BAY TRACON
SYSTEM 2--AUTOMATED DATA HANDLING

Sector	1975 Busy-day, Day-shift, Peak-hour Traffic (ac/hr)*	IFR Sector Capacity by Team (ac/hr)				Traffic Growth Potential Factor by Team[†]				Manning Requirement by Traffic Factor (controllers/team)								
		1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0 Man	1.5-Man	2.0-Man	2.5-Man	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
AR-1 Woodside Final	27	39	40	41	42	1.44	1.48	1.52	1.56	1	1	2	2.5	2.5	2.5	2.5	2.5	2.5
AR-2 Foster Final	20	37	38	38	39	1.85	1.90	1.90	1.95	1	1	1	1.5[‡]	2.5	2.5	2.5	2.5	2.5
AR-9 South Feeder	18	44	47	48	53	2.44	2.61	2.67	2.94	1	1	1	1.5[‡]	1.5[‡]	1.5[‡]	1.5	2.5	2.5
AR-10 North Feeder	26	42	44	45	49	1.62	1.69	1.73	1.88	1	1	1	2.5	2.5	2.5	2.5	2.5	2.5
DR-1 Sutro Departure	23	43	46	48	48	1.87	2.00	2.09	2.09	1	1.5[‡]	1.5[‡]	1.5[‡]	1.5	2.5	2.5	2.5	2.5
DR-2 Richmond Departure	38	41	43	45	47	1.08	1.13	1.18	1.24	1	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Subtotal (Men)										6	8	9	12	13	14	14	15	15
Flight data positions (Men)										0	0	0	0	0	0	0	0	0
Total (Men)										6	8	9	12	13	14	14	15	15
Manning factor (1975 Base)										0.75	1.00	1.13	1.50	1.63	1.75	1.75	1.88	1.88

*Source: "Application of ATC Terminal Standard for PY 1975," computer printout manuscript, Air Traffic Service, FAA (1976)

[†]Traffic Growth Potential = Capacity ÷ 1975 Busy-day Traffic

[‡]Coordinator (1/2-man) required for companion sector

Table 44

DAY-SHIFT, PEAK-HOUR MANNING CALCULATIONS
OAKLAND BAY TRACON
SYSTEM 3--BASIC METERING AND SPACING

Sector	1975 Busy-day, Day-shift, Peak-hour Traffic (ac/hr)*	IFR Sector Capacity by Team (ac/hr)				Traffic Growth Potential Factor by Team †				Manning Requirement by Traffic Factor (controllers/team)								
		1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0 Man	1.5-Man	2.0-Man	2.5-Man	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
AR-1 Woodside Final	27	41	43	43	45	1.52	1.59	1.59	1.67	1	1	1	2.5	2.5	2.5	2.5	2.5	2.5
AR-2 Foster Final	20	41	42	42	43	2.05	2.10	2.10	2.15	1	1	1	1.5[‡]	1.5[‡]	2.5	2.5	2.5	2.5
AR-9 South Feeder	18	47	49	52	56	2.61	2.72	2.89	3.11	1	1	1	1.5[‡]	1.5[‡]	1.5[‡]	1.5[‡]	2.5[‡]	2.5
AR-10 North Feeder	26	45	47	49	53	1.73	1.81	1.88	2.04	1	1	1	1.5	2.5	2.5	2.5	2.5	2.5
DR-1 Sutro Departure	23	43	46	48	48	1.87	2.00	2.09	2.09	1	1.5[‡]	1.5[‡]	1.5[‡]	1.5	2.5	2.5	2.5	2.5
DR-2 Richmond Departure	38	41	43	45	47	1.08	1.13	1.18	1.24	1	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Subtotal (Men)										6	8	8	11	12	14	14	15	15
Flight data positions (Men)										0	0	0	0	0	0	0	0	0
Total (Men)										6	8	8	11	12	14	14	15	15
Manning factor (1975 Base)										0.75	1.00	1.00	1.38	1.50	1.75	1.75	1.88	1.88

*Source: "Application of ATC Terminal Standard for PY 1975," computer printout manuscript, Air Traffic Service, FAA (1976)

†Traffic Growth Potential = Capacity ÷ 1975 Busy-day Traffic

‡Coordinator (1/2-man) required for companion sector

Table 45

DAY-SHIFT, PEAK-HOUR MANNING CALCULATIONS
OAKLAND BAY TRACON
SYSTEM 4--SECTOR CONFLICT PROBE

Sector	1975 Busy-day, Day-shift, Peak-hour Traffic (ac/hr)*	IFR Sector Capacity by Team (ac/hr)				Traffic Growth Potential Factor by Team†				Manning Requirement by Traffic Factor (controllers/team)								
		1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0 Man	1.5-Man	2.0-Man	2.5-Man	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
AR-1 Woodside Final	27	43	44	45	47	1.59	1.63	1.67	1.74	1	1	1	2.5	2.5	2.5	2.5	2.5	2.5
AR-2 Foster Final	20	43	44	45	46	2.15	2.20	2.25	2.30	1	1	1	1.5‡	1.5‡	2.5‡	2.5	2.5	2.5
AR-9 South Feeder	18	49	51	54	59	2.72	2.83	3.00	3.28	1	1	1	1	1	1.5‡	1.5‡	1.5	2.5‡
AR-10 North Feeder	26	48	50	52	57	1.85	1.92	2.00	2.19	1	1	1	1	2	2.5	2.5	2.5	2.5
DR-1 Sutro Departure	23	47	51	53	53	2.04	2.22	2.30	2.30	1	1.5‡	1.5‡	1.5‡	1.5‡	2.5‡	2.5	2.5	2.5
DR-2 Richmond Departure	38	43	45	47	50	1.13	1.18	1.24	1.32	1	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Subtotal (Men)										6	8	8	10	11	14	14	14	15
Flight data positions (Men)										0	0	0	0	0	0	0	0	0
Total (Men)										6	8	8	10	11	14	14	14	15
Manning factor (1975 Base)										0.75	1.00	1.00	1.25	1.38	1.75	1.75	1.75	1.88

*Source: "Application of ATC Terminal Standard for PY 1975," computer printout manuscript, Air Traffic Service, FAA (1976)

†Traffic Growth Potential = Capacity ÷ 1975 Busy-day Traffic

‡Coordinator (1/2-man) required for companion sector

Table 46

DAY-SHIFT, PEAK-HOUR MANNING CALCULATIONS
OAKLAND BAY TRACON
SYSTEM 5--RNAV

Sector	1975 Busy-day, Day-shift, Peak-hour Traffic (ac/hr)*	IFR Sector Capacity by Team (ac/hr)				Traffic Growth Potential Factor by Team[†]				Manning Requirement by Traffic Factor (controllers/team)								
		1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0 Man	1.5-Man	2.0-Man	2.5-Man	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
AR-1 Woodside Final	27	43	44	45	47	1.59	1.63	1.67	1.74	1	1	1	2.5	2.5	2.5	2.5	2.5	2.5
AR-2 Foster Final	20	43	44	45	46	2.15	2.20	2.25	2.30	1	1	1	1.5[‡]	1.5[‡]	2.5[‡]	2.5	2.5	2.5
AR-9 South Feeder	18	49	51	54	59	2.27	2.83	3.00	3.28	1	1	1	1	1	1.5[‡]	1.5[‡]	1.5	2.5[‡]
AR-10 North Feeder	26	48	50	52	57	1.85	1.92	2.00	2.19	1	1	1	1	2	2.5	2.5	2.5	2.5
DR-1 Sutro Departure	23	48	52	55	55	2.09	2.26	2.39	2.39	1	1	1.5[‡]	1.5[‡]	1.5[‡]	1.5	2.5	2.5	2.5
DR-2 Richmond Departure	38	43	46	48	50	1.13	1.21	1.26	1.32	1	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5
									Subtotal (Men)	6	7	8	10	11	13	14	14	15
									Flight data positions (Men)	0	0	0	0	0	0	0	0	0
									Total (Men)	6	7	8	10	11	13	14	14	15
									Manning factor (1975 Base)	0.75	0.88	1.00	1.25	1.38	1.63	1.75	1.75	1.88

*Source: "Application of ATC Terminal Standard for PY 1975," computer printout manuscript, Air Traffic Service, FAA (1976)

†Traffic Growth Potential = Capacity ÷ 1975 Busy-day Traffic

‡Coordinator (1/2-man) required for companion sector

Table 47

DAY-SHIFT, PEAK-HOUR MANNING CALCULATIONS
OAKLAND BAY TRACON
SYSTEM 6--DABS DATA LINK

Sector	1975 Busy-day, Day-shift, Peak-hour Traffic (ac/hr)*	IFR Sector Capacity by Team (ac/hr)				Traffic Growth Potential Factor by Team†				Manning Requirement by Traffic Factor (controllers/team)								
		1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0 Man	1.5-Man	2.0-Man	2.5-Man	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
AR-1 Woodside Final	27	53	54	56	56	1.96	2.00	2.07	2.07	0	0	1	1	1.5	2	2.5‡	2	2
AR-2 Foster Final	20	49	50	51	51	2.45	2.50	2.55	2.55	0	0	1	1	1.5†	1	1.5	2	2
AR-9 South Feeder	18	65	68	72	72	3.61	3.78	4.00	4.00	1	1	1	1	1	1	1	1‡	1‡
AR-10 North Feeder	26	60	62	67	67	2.31	2.38	2.58	2.58	1	1	1	1	1	1	2	2	2
DR-1 Sutro Departure	23	52	57	59	59	2.26	2.48	2.57	2.57	1	1	1†	1‡	1‡	1†	2‡	2	2
DR-2 Richmond Departure	38	48	50	55	55	1.26	1.32	1.45	1.45	1	1	2	2	2	2	2	2	2
Subtotal (Men)										4	4	7	7	8	8	11	11	11
Flight data positions (Men)										0	0	0	0	0	0	0	0	0
Total (Men)										4	4	7	7	8	8	11	11	11
Manning factor (1975 Base)										0.50	0.50	0.88	0.88	1.00	1.00	1.38	1.38	1.38

*Source: "Application of ATC Terminal Standard for PY 1975," computer printout manuscript, Air Traffic Service, FAA (1976)

†Traffic Growth Potential = Capacity ÷ 1975 Busy-day Traffic

‡Coordinator (1/2-man) required for companion sector

traffic growth potentials associated with control-by-exception software for the two feeder sectors represent considerable capacity excess for their 1-man team operations. We assume tha feeder sector workload requirements are sufficiently low to enable a feeder R controller to handle a feeder-and-final sector pair at low traffic levels.

We next estimate the manning requirements for the flight data position needed to operate the flight strip printers. Two flight data positions are currently established at Bay TRACON, of which one is routinely manned (regardless of training activities). Based on consultations with facility supervisory personnel, we conservatively assume that manning of the second flight data position under the ARTS III base system could be delayed at most until traffic activity doubles, as shown in Table 42. However, automated data handling is assumed to eliminate flight strip printers and the attendant manning, and thus flight data position manning is set at zero in Tables 43 through 47 for the alternative UG3RD systems.

The total multi-sector day-shift minimum manning requirements are calculated by summing the sector team and flight data manning for each traffic factor. (The manning estimates do not include staffing allowances[12] for administration, relief, annual and sick leaves, excess shift capacity, training, and special assignments.) Under the ARTS III Base system, we estimate that a total of eight manned positions correspond to the 1975 day-shift traffic (1.0 traffic factor), as shown in Table 42. This 1975 manning level defines the base manning factor (1.0 in Table 42) and is used as the reference for calculating manning factors for each traffic-factor increment under each alternative ATC system. That is, the manning factor data shown in Tables 42 through 47 relate each projected manning requirement to that of the 1975 ARTS III base system.

2. Manning Comparisons

Our manning factor calculations corresponding to selected traffic factors are summarized by ATC system in Table 48. The manning factor estimates are made under the assumption of a fixed six-sector configuration, and these estimates represent adjustments to the six sector teams and flight data positions needed to handle increases to the 1975 traffic activity.

This manning estimation procedure as applied to Bay TRACON does not account for possible resectorizations or possible traffic constraining delays induced by terminal airspace capacity limitations. Our consultations with Bay TRACON personnel indicate that the current

Table 48

OAKLAND BAY TRACON MANNING FACTOR ESTIMATES

Traffic Factor / ATC System	Day Shift Manning Factor by Traffic Growth Factor (1975 Base)						
	1.0	1.25	1.5	1.75	2.0	2.5	3.0
1. Current ARTS III	1.00	1.13	1.25	1.63	2.0	2.13	2.13
2. + Automated Data Handling	0.75	1.00	1.13	1.50	1.63	1.75	1.88
3. + Basic Metering and Spacing	0.75	1.00	1.00	1.38	1.50	1.75	1.88
4. + Sector Conflict Probe	0.75	1.00	1.00	1.25	1.38	1.75	1.88
5. + RNAV (100% Avionics)	0.75	0.88	1.00	1.25	1.38	1.75	1.88
6. + DABS Data Link (100% Avionics)	0.50	0.50	0.88	0.88	1.00	1.38	1.38

six sector design concept used to handle SFO operations is not likely to be reconfigured into additional sectors, since potential terminal area capacity gains are not expected to result from such a reconfiguration. The current pairwise arrangements of feeder-and-final and departure sectors is considered the most efficient sectorization design operationally feasible for SFO traffic.

Based on our consultations with Bay TRACON personnel, field observations, and operations analyses, we conclude that whatever critical delay-producing bottleneck situations may exist are related currently to SFO airport constraints rather than terminal airspace constraints.

In regard to delay-related implications of future operations, the manning requirements in Table 48 are shown generally to increase as traffic approaches twice the 1975 level and to gradually level off as traffic increases beyond the 2.0 factor (or thereafter, depending on the alternative UG3RD system). The leveling-off is due to the inability of adding controllers to those sector teams operating at their maximum manning level (i.e., 2 men for DABS data-link, 2.5 men for the other systems). Therefore, certain sectors are workload saturated and cannot handle additional traffic. In fact, some delays may be induced earlier by one departure sector (DR-2) which reaches maximum manning for ARTS III well before the traffic projection doubles. However, delays generated by terminal airspace should not be significant since SFO traffic is projected to increase only by 65 percent (relative to 1975) by the year 2000.*

Since major workload saturation situations would occur if traffic increases significantly beyond the 2.0 factor, such traffic disruptions would cause significant change to the operations assumptions we have made in modeling sector capacity and manning. Therefore, as far as the manning factor estimates in Table 48 are concerned, we suggest that comparisons using these data be made between systems only for those traffic factors at or below 2.0. Comparisons at the higher traffic levels would have no realistic meaning, particularly since Bay TRACON is not expected to operate at these levels. In the following paragraph we do examine manning requirements at the 1.0 and 2.0 traffic factors for the sake of comparing the potential operational impacts of the alternative ATC systems.

In Table 48, the ARTS III base system is shown to be capable of handling a doubling of 1975 traffic if manning is also doubled. Significant reductions in these manning requirements appear under the automated

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*Airport traffic activity forecast provided by FAA(AVP), October 1975.

data handling and DABS data link operations, while the intermediate UG3RD systems show incremental gains of lower magnitude. Automated data handling reduces manning (relative to ARTS III) by 25 percent for the 1.0 traffic factor, and by 82 percent for the 2.0 traffic factor. DABS data link reduces manning (relative to ARTS III) by 50 percent and 100 percent, respectively, for the 1.0 and 2.0 traffic factors. This shows that the fully upgraded system is capable of handling twice the 1975 traffic with the current manning complement.

IX LOS ANGELES TRACON OPERATIONS

The Los Angeles TRACON, a Group I TCA facility, is designed primarily to serve aircraft arrivals and departures at Los Angeles International Airport (LAX). The facility also provides separation assurance for traffic enroute through the area and for instrument traffic using satellite airports outside the TCA at Hawthorne, Santa Monica, Culver City, and Torrance. The coverage area of L.A. TRACON extends for approximately 20 miles to the east and west of LAX and 10 miles to the north and south. It is bordered by the Hollywood-Burbank TRACON on the north, the Ontario TRACON on the east, the Coast (Long Beach) TRACON on the south, and by Los Angeles ARTC Center airspace above 10,000 ft. and to the west. A separate contingent of controllers man the Los Angeles ATCT, although both the Los Angeles tower and TRACON controllers are part of a single administrative facility, the Los Angeles Tower-TRACON. The tower and TRACON are not collocated.

A. Operational Overview

The map in Figure 9 shows the geographic coverage and sectorization structure of the facility. The sector structure shown conforms to a standard "West" wind plan in which aircraft land in a westerly direction on either of the Runway 25 or Runway 24 complexes; both complexes are closely spaced dual parallel runways. This sector structure will shift to accommodate wind and weather conditions that call for landings in the "opposite," easterly direction.

L.A. TRACON also participates in a unique noise abatement procedure in which downward approaches and standard, upward departures require aircraft to proceed in opposite headings during those night and early morning hours when total traffic volume at LAX is extremely light. However, during the periods of our observation and data collection at the facility, the West plan was in operation.

Measurements were taken and observations noted at all four of the sectors shown in Figure 9; the Downey Arrival (AR-1) and Stadium Arrival (AR-2) sectors and the South Departure (DR-1) and North Departure (DR-2) sectors. Both the 24 and 25 runway complexes are each used for landings and take-offs. Generally, the AR-1 sector controls aircraft approaching

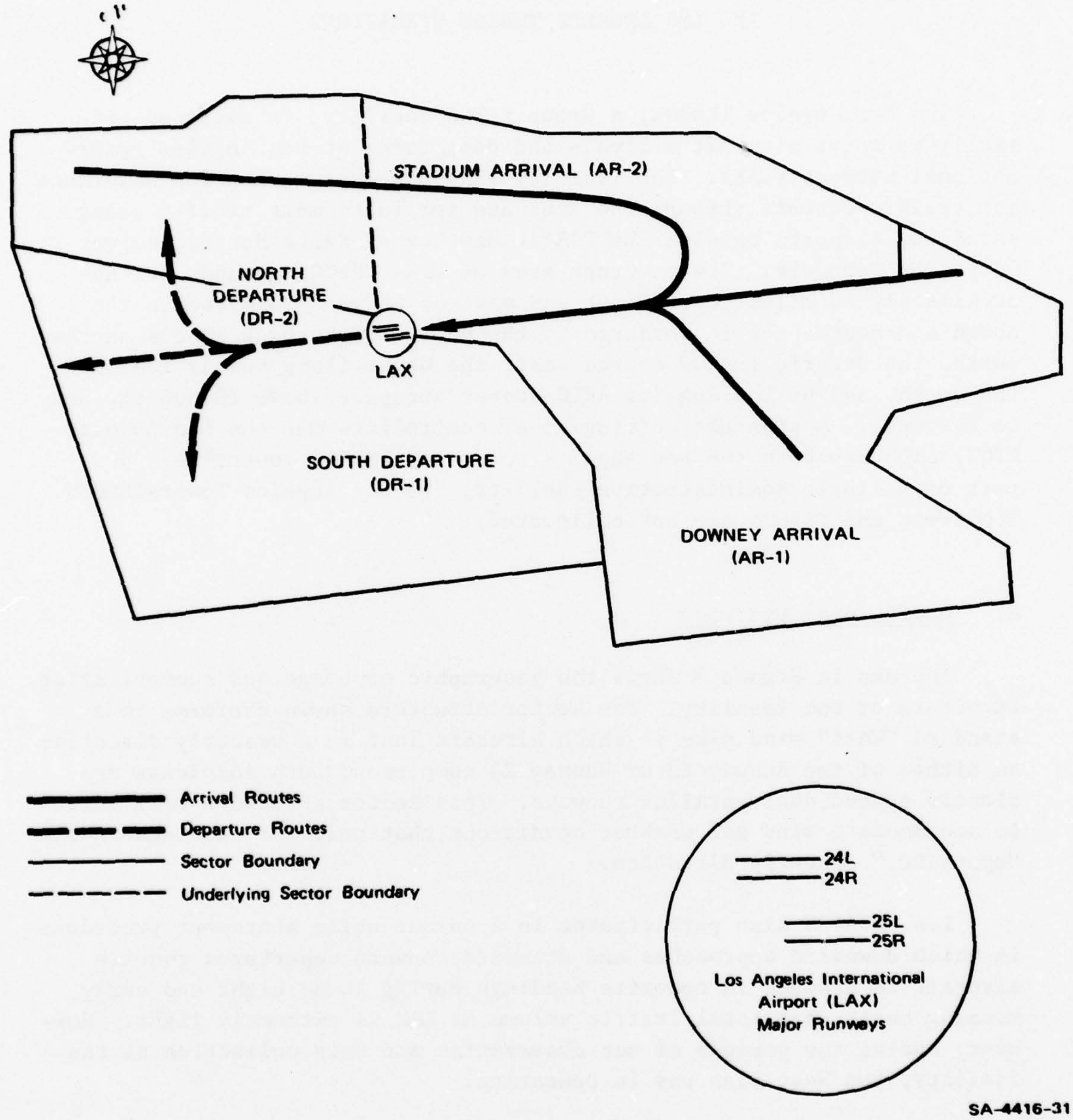

FIGURE 9 WEST PLAN PRIMARY ARRIVAL AND DEPARTURE ROUTES FOR LOS ANGELES TRACON

straight-in from the east and landing on the 25 runway, while the AR-2 sector controls aircraft turning into the 24 runway complex. However, aircraft under control of one sector may use the airport approaches normally controlled by the other sector. For example, because of airport ground taxi routing restrictions and terminal design, weight limited heavy (including jumbo) and general aviation aircraft must land in the 24 runway complex, normally landing on runway 24R.

Under visual approach operations, simultaneous side-by-side landings to both runways on each complex are permitted. Under instrument condition, in-trail operations to both the 24 and 25 complexes are performed, but not simultaneously side-by-side to 24R and 24L runways, nor simultaneously to 25R and 25L runways. In effect, simultaneous side-by-side approaches to each complex are allowed, but not to the closely spaced parallel runways within each complex. During periods of heavy traffic under instrument conditions, two parallel monitor positions, PM-1 and PM-2, are deployed to ensure lateral and intrail separation of approaching aircraft. PM-1 monitors aircraft to the 25 runway complex, and PM-2 monitors the 24 runway complex.

Brief descriptions of the four sectors and the instrument and visual approach operations are given below.

B. Sector Traffic Operations

1. Arrival Sectors

a. Downey Arrival Sector (AR-1)

The Downey Arrival Sector processes the typically heavy traffic arriving at LAX from the east and south and all instrument operations at the Hawthorne (HHR) Airport. Where parallel approaches are in progress at LAX, the Downey Controllers will usually sequence traffic to the Runway 25 complex. In general, controller duties are similar to those exercised by Stadium Sector personnel.

Figure 10 shows the principal arrival and crossing routes used in the Downey Sector.

These routes are designated by number as follows:

- Route 1c for arrivals at LAX from the east. This is the primary arrival corridor through the Downey Sector and is used by high speed commercial jets.

* Route 1d for arrivals at LAX from the south over SBI. It too, is used mainly by commercial jet aircraft.
* Route 2 for instrument traffic arriving at and departing HHR.
* Route 3, for north-south traffic through the sector. It is largely altitude separated from Routes 1c and 1d traffic.

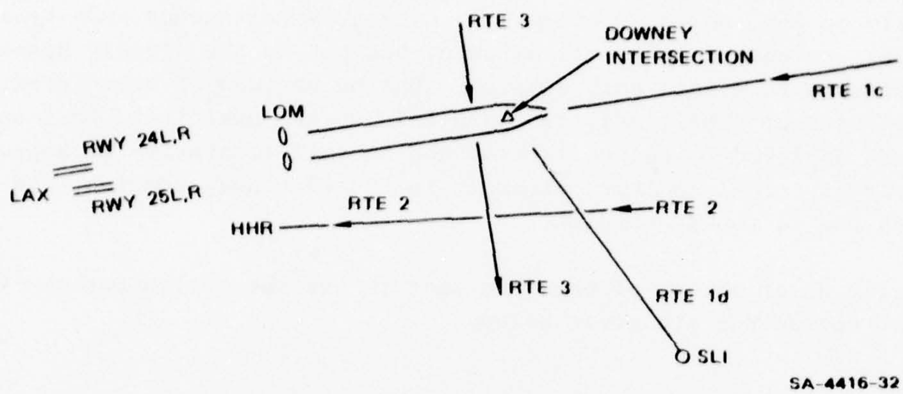

FIGURE 10 DOWNEY ARRIVAL (AR-1) ROUTES

As indicated in Figure 10, most traffic on Route 1c enters the sector at the LAX localizer heading about 25 miles east of the airport. Most jet traffic on 1c enters the sector at or descending to 10,000 feet, crosses the Downey Intersection (about 15 miles from LAX) at or descending to 4,000 ft., and is handed off to the L.A. tower near the LOM at about 2,000 ft. Route 1d jet traffic enters over the Seal Beach VORTAC (SLI) at or descending to 7,000 ft. and is typically vectored to the localizer final approach heading, intersecting it and merging with the Route 1c and Stadium arrival flows at 4,000 to 6,000 feet. The relatively high volumes through the Downey Sector require frequent speed control directives, particularly to aircraft on Route 1c. Most LAX arrival jet traffic on Routes 1c and 1d crosses the Downey Intersection between 230 and 270 knots, with aircraft in potential overtaking situations occasionally reduced to 200 kts or less.

Both Routes 1c and 1d contain small amounts of relatively low speed general aviation and commuter air traffic inbound to LAX; this traffic usually remains altitude separated from the higher, faster traffic on these routes until the Downey intersection is reached. The slower traffic is generally assigned to the Runway 24 complex for easy access to the LAX commuter terminal. It proceeds through the sector at speeds between 130 and 170 kts.

The potential for overtaking conflicts between aircraft under Downey Sector Control is especially high on Route 1c inbound to Downey Intersection and fairly high for the Route 1d inbounds to Downey, while overtaking conflicts on Routes 2 and 3 appear to be insignificant. Crossing conflicts in the sector appear to be minimized through the strict, altitude separated structuring of intersecting air routes and arrival corridors. This is especially true of the intersection of Route 3 with the LAX arrivals on Routes 1c and 1d. Merging conflicts, which occur between Downey Intersection and the LOM create special problems for both Downey and Stadium arrival controllers since these conflict situations depend on runway assignments, instrument or visual approach conditions, and the traffic volume and aircraft type mix in both sectors at a given time. Our analysis of the potential merging conflicts for each type of approach condition is described shortly.

b. Stadium Arrival Sector (AR-2)

The Stadium Arrival Sector handles arrival flights to LAX from the north and west plus instrument approaches to the Santa Monica airport and miscellaneous crossing traffic. Controller responsibilities include the full positive control of all instrument approaches to LAX plus the sequencing of all visual approaches so that the appropriate separation standards are met and maintained. This involves the use of radar vectoring and speed control directives for all traffic and the issuance of runway assignment and traffic identification instructions to visual approach traffic.

Figure 11 shows the principal arrival and crossing routes used in the stadium sector.

These routes are designated by number as follows:

- Route 1a for arrivals to LAX from San Francisco and other points north and west. This is the primary arrival corridor through the Stadium sector, and is used mainly by commercial, high performance jet aircraft.

- Route 1b for arrivals to LAX from the Ventura area and points west. This usually includes a high percentage of general aviation and commuter aircraft that is altitude separated from the faster Route 1a traffic between Saddle and SMO.

- Route 2, an aggregation of routes for traffic using Santa Monica Airport.

- Route 3, roughly corresponding to the V459 airway, for aircraft arriving at Hawthorne and other satellite airports, or crossing the sector on north or south headings. It is altitude separated from most of the traffic on the localizer approach path to LAX.

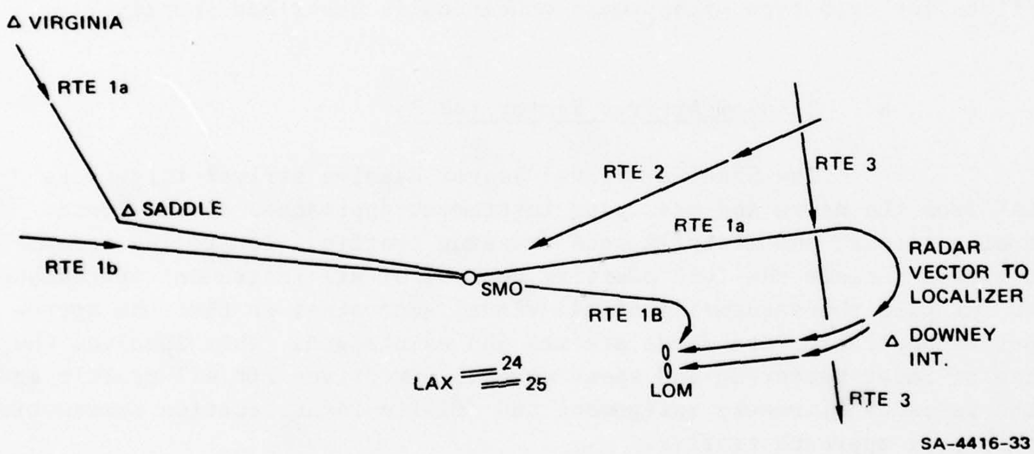

FIGURE 11 STADIUM ARRIVAL (AR-2) ROUTES

As indicated in Figure 11, most of the traffic on Route 1a enters the sector near the Virginia Fix at or descending to 11,000 ft., turns east over Saddle at 9,000 to 10,000 ft., and crosses SMO at approximately 7,000 ft. Aircraft proceed east of SMO and at 4,000 to 5,000 ft. are radar vectored to the base and final approaches, reaching the localizer outer marker (LOM) at about 2,000 ft., where they are handed off to the tower. Under light-to-moderate traffic conditions, Route 1a aircraft are allowed to decelerate at the pilot's discretion, with most aircraft slowing to around 250 kts at SMO and 200 kts at LOM.

Route 1b traffic crosses Saddle at 7,000 ft. and the SMO area at less than 5,000 ft. Most aircraft on this route are turned inbound on the base approach leg at the LOM, which effectively removes much of the overtaking conflict potential with the faster Route 1a traffic, leaving instead a potential merging conflict point with Route 1b traffic and other inbound traffic at the localizer. Most Route 1b traffic uses the Runway 24 complex.

Major potential conflicts in this sector include a significant amount of overtaking on Route 1a and the merging of 1a traffic at the LAX localizer with inbounds from the east and south through the Downey arrival sector. (Both the instrument and visual approach conflict potentials at the LAX localizer are discussed below.) The potential for crossing conflicts is quite high between 1a traffic and departures out of LAX heading east through the North Departure sector, as will be discussed shortly. Some crossing conflicts are possible between aircraft on Routes 2 and 3, while some overtake conflict potential exists on both routes.

Aircraft separation minimums are 3 to 6 miles, depending on the pairwise aircraft size and type mixes involved on relative aircraft headings.

2. Approach Characteristics

a. Instrument Approach Merges

Figure 12 below shows the five distinct merge points that are assumed to exist at the LAX localizer during instrument approach conditions, when simultaneous IFR landings are performed on the Runway 24 and 25 ILS's.

The traffic composition of each of the five merge points, which can involve aircraft from both arrival sectors, is briefly described below. They are:

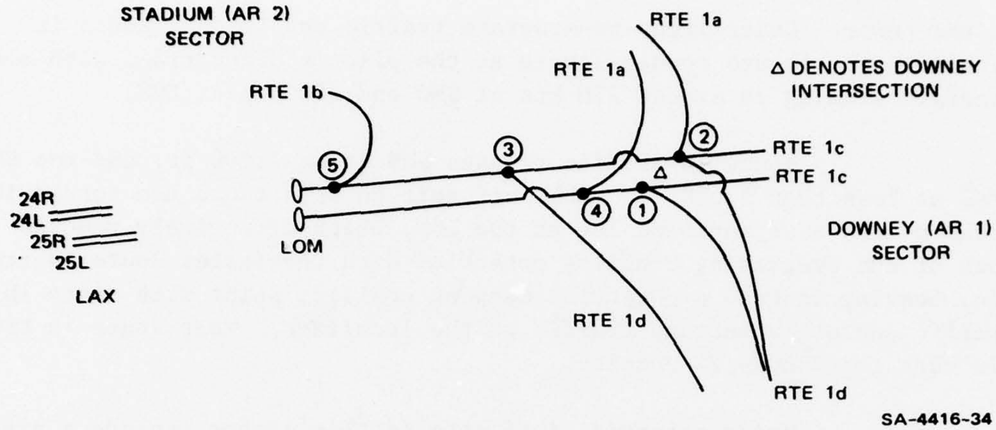

FIGURE 12 INSTRUMENT APPROACH MERGE POINTS

- Point 1, which combines most jet traffic (except jumbos) on Route 1c with most jet traffic on Route 1d (except jumbos) at Downey Intersection for landing on Runway 25. (Jumbos and some other larger aircraft are usually too heavy to use the Runway 25 complex.)
- Point 2, which combines some Route 1d heavy jets and all Route 1d and 1c jumbos with approximately half the jet traffic inbound from the Northwest on Route 1a. Merging takes place at or near the Downey intersection for landing on Runway 24. Route 1d traffic is assumed to cross over Route 1c traffic to Runway 25.
- Point 3, which combines all point 2 traffic with the slower Route 1d general aviation and commuter traffic for landing on Runway 24. Merging is assumed to take place halfway between Downey Intersection and LOM. This Route 1d traffic is assumed to cross beneath Runway 25 traffic by 1,000 to 2,000 feet.
- Point 4, which adds about half the Route 1a jet traffic to the Runway 25 stream at a near Downey intercept. The Route 1a traffic is assumed to cross under the Runway 24 traffic. (The Runway 25 complex is a convenient terminal access for several airlines flying into LAX from the northwest.)

* Point 5, which combines Runway 24 traffic with Marina arrivals through the Stadium sector Route 1b. Merging is assumed to take place at the LOM.

For our analysis purposes, the overtake conflict workload is allocated to each arrival controller based on the traffic composition of each route segment in the merge area. For example, if half the traffic on the Runway 25 localizer between Downey Intersection and LOM entered the Downey sector, then that arrival controller is assumed to retain control of those aircraft only, and he is therefore assigned half the overtake conflict processing necessary on that segment. The remaining workload would be assigned to the Stadium sector controller.

c. Visual Approach Merges

Figure 13 shows the merge points assumed to remain in effect under visual, side-by-side approach conditions. Merge points 2 and 4 have been largely eliminated by the assignment of Route 1a traffic

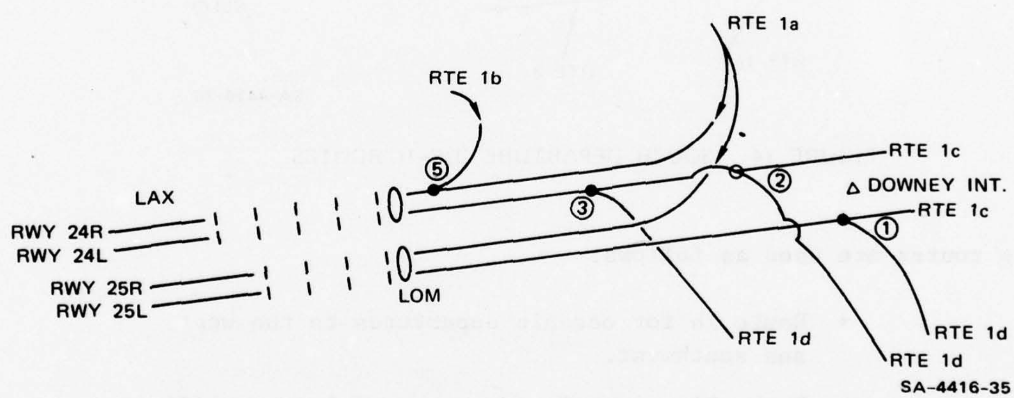

FIGURE 13 VISUAL APPROACH MERGE POINTS

under Stadium control to Runways 25R and 24R. A small amount of merging at point 2 will occasionally be necessary to combine Route 1c and 1d jumbo and heavy jet traffic. All altitude crossing separations for instrument approaches are assumed to hold for visual approaches; these are indicated by the loops in Figure 13. The remaining merging and overtaking conflict workloads are distributed among controllers and coordinators as before, although much conflict avoidance work will be replaced by routine "see and be seen" visual approach instructions.

3. Departure Sectors

a. South Departure Sector (DR-1)

Figure 14 shows the major departure and crossing routes used in the South Departure Sector.

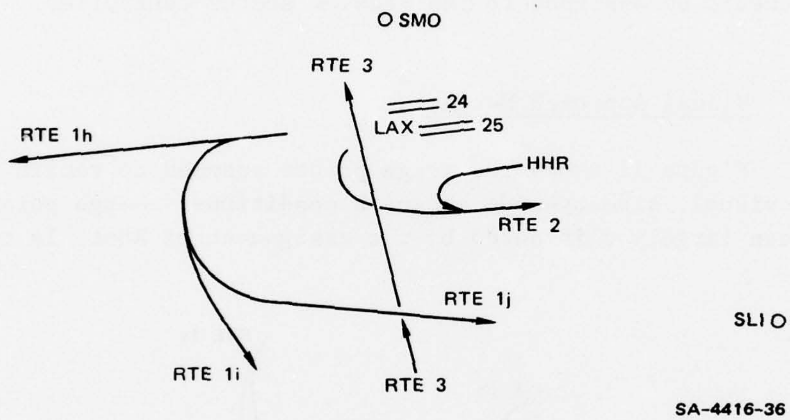

FIGURE 14 SOUTH DEPARTURE (DR-1) ROUTES

These routes are used as follows:

- Route 1h for oceanic departures to the west and southwest.
- Route 1i primarily for commercial jet traffic to San Diego and points south and east.
- Route 1j primarily for commercial jet traffic over the Seal Beach VORTAC to the east and southeast.
- Route 2 for general aviation and commuter traffic to Ontario, Santa Ana and points east, and instrument departures from Hawthorne.
- Route 3, as a continuation of North Departure Route 3 for enroute traffic north to the Hollywood-Burbank area.

Aircraft departing LAX on Routes 1h, 1i and 1j enter the sector at or climbing to 2,000 ft. and are handed off to the Los Angeles ARTC Center at or climbing to altitudes between 7,000 and 10,000 ft. Aircraft on Route 2 departing LAX climb to and maintain altitudes under 4,000 ft. in TRACON airspace, while HHR departures often climb to 7,000 in a circling pattern, leaving the TRACON at 7,000 ft. above the airport. Route 3 traffic maintains 4,000 to 5,000 ft. altitudes through the sector.

Route 1 aircraft tend to climb rapidly through the sector and are therefore above most other aircraft at points where their routes intersect, thereby minimizing the potential for crossing conflicts. The potential for overtaking conflicts, however, is high on Routes 1i and 1j and moderate on Routes 1h, 2 and 3.

b. North Departure Sector (DR-2)

Figure 15 shows the major departure and crossing routes used in the North Departure sector. These routes are designated and used as follows:

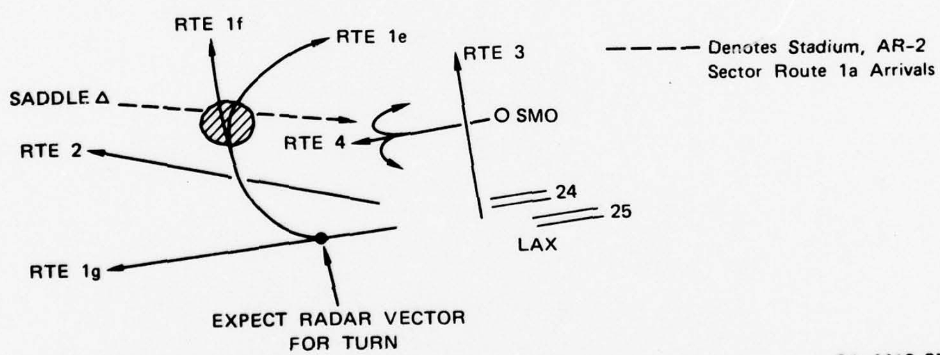

FIGURE 15 NORTH DEPARTURE (DR-2) ROUTES

- Route 1e for departures to the east.
- Route 1f for departures to the north and northwest.
- Route 1g for oceanic departures.
- Route 2 for low level, general aviation and commuter traffic to Ventura, Santa Barbara, and other points north and west.

- Route 3 for traffic enroute through the TRACON to the Hollywood-Burbank area and points north.
- Route 4 for instrument departures from Santa Monica (SMO) and Hughes (OVR) Airports.

X LOS ANGELES TRACON ARTS III MODEL

SRI conducted a field experiment at Los Angeles TRACON during the week of May 3, 1976, which included observations of the operations of the two arrival sectors (AR-1 and AR-2) and the two departure sectors (DR-1 and DR-2). Workload modeling data are based on data measurements taken during one 1-hour observation session for each of the four sectors. During these observation sessions, AR-1 was operating with a 1.5-man team, AR-2 with a 2.5-man team, and the two departure sectors were each operating as 2.5-man teams; visual operations were in effect, and parallel monitoring positions (PM-1 and PM-2) were not manned. Two additional 1-hour sessions observed each arrival sector, during which instrument operations were in effect part of the time with the PM-1 and PM-2 manned. Although detailed task activity measurements were not obtained during these latter sessions, these observations aided our modeling of instrument operations.

Our Los Angeles TRACON field observation, data reduction, and workload model formulations closely parallel those we made for the Oakland Bay TRACON. In this section, we describe the Los Angeles TRACON models, but to avoid repetition do not discuss many of the modeling details. Such details have already been explained during our analysis of the Bay TRACON. However, where Los Angeles and Bay TRACON operations differ, we do delineate our modeling approach.

A. Routine Work

1. Composite Team Routine Event Data

Measurements of routine event frequencies for each sector are summarized in Table 49, and corresponding minimum task performance times for the composite team are shown in Table 50. The basic and supplemental control events correspond in general to those identified for the Oakland Bay TRACON (Tables 1 and 2), but some differences should be noted.

For example, three additional handoff acceptance events--flight strip preparation, flight strip printer servicing, and clearance delivery--were observed at the Los Angeles TRACON and are included as supplemental events in Tables 49 and 50. These events account for the departure controllers' requirement to service the flight strip printer (one of which is located near each departure sector console), and the arrival controllers'

Table 49

COMPOSITE TEAM
ROUTINE EVENT FREQUENCY ESTIMATES
LOS ANGELES TRACON

Routine Control Event Description		Event Frequency Sector (event/aircraft)			
Event Function	Basic Event and Supplemental Event	AR-1 Downey	AR-2 Stadium	DR-1 South Departure	DR-2 North Departure
Control Jurisdiction Transfer	Handoff acceptance	0.92	0.86	0.94	0.91
	Manual acquisition-silent	0.92	0.86	0	0
	Flight strip preparation	0.92	0.86	0	0
	Flight strip printer servicing	0	0	0.94	0.91
	Tower departure call (run down)	0	0	0.94	0.91
	Clearance delivery coordination	0	0	0.06	0.09
	Controller coordination	0.23	0.18	0.17	0.06
	Handoff initiation-silent	0.08	0.14	1.00	1.00
	Controller coordination	0.15	0	0.14	0.18
Traffic Structuring	Initial pilot call-in	1.00	1.00	1.00	1.00
	TCA clearance request	0.08	0.14	0.06	0.09
	Initial controller response	1.00	1.00	1.00	1.00
	Altitude instruction	0.62	0.64	0.31	0.56
	Data update	0.62	0.64	0.25	0.38
	Heading/route instruction	0.23	0.82	0.39	0.09
	Speed instruction	0.62	0.23	0	0
	Approach/runway advisory	0.54	0.82	0	0
	Data update	0	0.82	0	0
	Traffic advisory	0.08	0.09	0.08	0.06
	ATIS Advisory	0	0	0	0
	Altimeter setting advisory	0	0.05	0	0.06
	Transponder code assignment	0.08	0.14	0.06	0.09
	Controller coordination	0	0.05	0.03	0
	Altitude instruction	1.27	2.41	0.67	0.59
	Data update	0.58	1.23	0.31	0.18
	Controller coordination	0	0.14	0.17	0.06
	Heading/route instruction	0.62	2.27	1.50	1.47
	Controller coordination	0	0.14	0.08	0.03
	Speed instruction	0.85	2.09	0.08	0.12
	Approach clearance	0.85	0.64	0	0
	PVD display update	0.85	0	0	0
	Runway assignment	0.27	0.14	0	0
	Controller coordination	0.15	0.14	0	0
	Traffic advisory	1.38	1.27	0.72	0.65
	Pilot altitude report	0.12	0.27	0.92	1.21
	Pilot heading/position report	0	0.14	0.19	0.15
	Pilot speed report	0.04	0.18	0.08	0.03
	Miscellaneous A/G communication	0.04	0.18	0.14	0
	Frequency change	1.00	1.00	1.00	1.00
	Transponder code change	0	0	0.11	0.06
	Approach/runway advisory	0.23	0.68	0	0
	Altitude/heading/speed instruction	0.62	1.00	0.06	0.59
Pilot Request	Altitude revision	0.12	0.18	0.06	0.15
	Controller coordination	0	0.09	0	0.06
	Route/heading revision	0	0	0.06	0.06
	Controller coordination	0	0	0	0.06
	Miscellaneous pilot request	0.08	0	0.11	0.06
General Intersector Coordination	Pointout acceptance	0.04	0.05	0.03	0.03
	Pointout initiation	0.08	0.09	0	0
	Control instruction approval	0.04	0.05	0.06	0.12
	Planning advisory	0.35	0.27	0.08	0.06
	Aircraft status advisory	0.19	0.18	0.11	0.12
General System Operation	Data block forcing/removal	0.92	0.36	0.61	0.71
	PVD display adjustment	0.08	0	0.14	0.03

Table 50
COMPOSITE TEAM
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 1--ARTS III BASE

Routine Control Event Description		Performance Time by Task (man-sec/event)				
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication
Control Jurisdiction Transfer	Handoff acceptance			2		
	Manual acquisition-silent		2			
	Flight strip preparation			6		
	Flight strip printer servicing			15		
	Tower departure call (run down)				2	
	Clearance delivery			2	10	3
	Controller coordination				6	3
	Handoff initiation-silent		3			
	Controller coordination				6	3
Traffic Structuring	Initial pilot call-in	4		1		
	TCA clearance request	4	10	6		
	Initial controller response	2				
	Altitude instruction	3				
	Data update			2		
	Heading/route instruction	3				
	Speed instruction	3				
	Approach/runway advisory	3				
	Data update			2		
	Traffic advisory	3				
	ATIS Advisory	3				
	Altimeter setting advisory	3				
	Transponder code assignment	3	3	2		
	Controller coordination				5	3
	Altitude instruction	5				
	Data update			2		
	Controller coordination				5	3
	Heading/route instruction	5				
	Controller coordination				5	3
	Speed instruction	5				
	Approach clearance	6				
	PVD display update		3			
	Runway assignment	5				
	Controller coordination				5	3
	Traffic advisory	5				
	Pilot altitude report	5				
	Pilot heading/position report	5				
	Pilot speed report	5				
	Miscellaneous A/G communication	5				
	Frequency change	4				
	Transponder code change	2				
	Approach/runway advisory	3				
	Altitude/heading/speed instruction	3				
Pilot Request	Altitude revision	6		2		
	Controller coordination				5	3
	Route/heading revision	8		2		
	Controller coordination				5	3
	Miscellaneous pilot request	6				
General Intersector Coordination	Pointout acceptance		3		6	3
	Pointout initiation				6	3
	Control instruction approval				5	3
	Planning advisory				5	3
	Aircraft status advisory				5	
General System Operation	Data block forcing/removal		3			
	PVD display adjustment		3			

requirement to handwrite their own flight strips (no printed flight strips are delivered to the arrival sectors and paper scratch pads are not used). Also, clearance delivery coordination is conducted by the departure sectors with some local towers (other than LAX) regarding certain aircraft that will enter the TCA after take-off from these lesser airports; in these cases, a tower is advising the TRACON controllers of an aircraft's flight intention. These flights, as well as other "pop-ups," enter the TCA without formal silent handoffs because other ARTS III or NAS Stage A equipped facilities are not involved, and they require a TCA clearance request A/G communication from the pilot (which is treated as a supplemental event to the basic pilot call-in, as in the Bay TRACON analysis).

Some minor differences occur between Bay TRACON and Los Angeles TRACON traffic structuring events. The AR-2 controllers were usually observed to perform the data update event by marking their flight strips (rather than using keyboard data entry/display operations) to record the issuance of approach/runway advisories during the initial controller response to a pilot call-in. The AR-1 controllers, however, were observed to record the issuance of an approach clearance by using data entry/display operations (a PVD display update event). Both Los Angeles TRACON arrival sectors conduct some routine interphone coordination with tower controllers regarding specific runway assignments (the LAX approaches are more complex than those of SFO). These arrival sectors in some cases issue approach/runway advisories to pilots, supplementing a basic frequency change event (this repeating of the approach clearance is analogous to instructions given by both feeder and final sectors at Bay TRACON).

2. R Controller Routine Event Data

We allocate the composite team task requirements to the R controller for each of the four manning regimes in accordance with the allocation rules defined for the Bay TRACON analysis: the coordinator performs routine interphone tasks and, for the 1.5-man team, performs half the handoff events; the H controller performs keyboard data entry/display tasks where appropriate (including departure sector flight strip printer servicing), and interphone communications if the coordinator position is not manned; and face-to-face communications apply only to the multi-man team regimes. The resulting R controller task allocations are shown in Tables 51, 52, 53, and 54 for the 1-man, 1.5-man, 2-man, and 2.5-man teams respectively. The corresponding R controller routine event minimum performance times are summarized in Table 55.

Table 51
R CONTROLLER
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 1, 1-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Inter-phone Communication	Face-to-Face Communication	Total
Control Jurisdiction Transfer	Handoff acceptance			2			2
	Manual acquisition-silent		2				2
	Flight strip preparation			6			6
	Flight strip printer servicing			15			15
	Tower departure call (run down)				2		2
	Clearance delivery			2	10		12
	Controller coordination				6		6
	Handoff initiation-silent		3				3
	Controller coordination					6	6
Traffic Structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4	10	6			20
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update			2			2
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	Data update			2			2
	Traffic advisory	3					3
	ATIS Advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3	3	2			8
	Controller coordination				5		5
	Altitude instruction	5					5
	Data update			2			2
	Controller coordination				5		5
	Heading/route instruction	5					5
	Controller coordination				5		5
	Speed instruction	5					5
	Approach clearance	6					6
	PVD display update		3				3
	Runway assignment	5					5
	Controller coordination				5		5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4		1			5
	Transponder code change	2					2
	Approach/runway advisory	3					3
	Altitude/heading/speed instruction	3					3
Pilot Request	Altitude revision	6		2			8
	Controller coordination				5		5
	Route/heading revision	8		2			10
	Controller coordination				5		5
	Miscellaneous pilot request	6					6
General Intersector Coordination	Pointout acceptance		3		6		9
	Pointout initiation				6		6
	Control instruction approval				5		5
	Planning advisory				5		5
	Aircraft status advisory				5		5
General System Operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 52
R CONTROLLER
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 1, 1.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control Jurisdiction Transfer	Handoff acceptance						0
	Manual acquisition-silent		2				2
	Flight strip preparation			6			6
	Flight strip printer servicing			15			15
	Tower departure call (run down)						0
	Clearance delivery			2	10		12
	Controller coordination					3	3
	Handoff initiation-silent		3				3
	Controller coordination					3	3
Traffic Structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4	10	6			20
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update			2			2
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	Data update			2			2
	Traffic advisory	3					3
	ATIS Advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3	3	2			8
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update			2			2
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	PVD display update		3				3
	Runway assignment	5					5
	Controller coordination					3	3
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4		1			5
	Transponder code change	2					2
	Approach/runway advisory	3					3
	Altitude/heading/speed instruction	3					3
Pilot Request	Altitude revision	6		2			8
	Controller coordination					3	3
	Route/heading revision	8		2			10
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General Intersector Coordination	Pointout acceptance		3			3	6
	Pointout initiation					3	3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General System Operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 53
R CONTROLLER
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 1, 2-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Inter-phone Communication	Face-to-Face Communication	Total
Control Jurisdiction Transfer	Handoff acceptance						0
	Manual acquisition-silent						0
	Flight strip preparation						0
	Flight strip printer servicing						0
	Tower departure call (run down)						0
	Clearance delivery					3	3
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic Structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4		6			10
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update			2			2
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	Data update			2			2
	Traffic advisory	3					3
	ATIS Advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3		2			5
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update			2			2
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	PVD display update		3				3
	Runway assignment	5					5
	Controller coordination					3	3
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4		1			5
	Transponder code change	2					2
	Approach/runway advisory	3					3
	Altitude/heading/speed instruction	3					3
Pilot Request	Altitude revision	6		2			8
	Controller coordination					3	3
	Route/heading revision	8		2			10
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General Intersector Coordination	Pointout acceptance					3	3
	Pointout initiation					3	3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General System Operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 54
R CONTROLLER
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 1, 2.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control Jurisdiction Transfer	Handoff acceptance						0
	Manual acquisition-silent						0
	Flight strip preparation						0
	Flight strip printer servicing						0
	Tower departure call (run down)						0
	Clearance delivery					3	3
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic Structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4		6			10
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update			2			2
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	Data update	2					2
	Traffic advisory	3					3
	ATIS Advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3		2			5
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update			2			2
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	PVD display update						0
	Runway assignment	5					5
	Controller coordination					3	3
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4		1			5
	Transponder code change	2					2
	Approach/runway advisory	3					3
	Altitude/heading/speed instruction	3					3
Pilot Request	Altitude revision	6		2			8
	Controller coordination					3	3
	Route/heading revision	8		2			10
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General Intersector Coordination	Pointout acceptance					3	3
	Pointout initiation					3	3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General System Operation	Data block forcing/removal						0
	PVD display adjustment						0

Table 55
R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 1--ARTS III BASE

Routine Control Event Description		Performance Time by Team (man-sec/event)			
Event Function	Basic Event and Supplemental Event	1.0-Man Team	1.5-Man Team	2.0-Man Team	2.5-Man Team
Control Jurisdiction Transfer	Handoff acceptance	2	2	0	0
	Manual acquisition-silent	2	2*	0	0
	Flight strip preparation	6	6	0	0
	Flight strip printer servicing	15	15	0	0
	Tower departure call (run down)	2	0	0	0
	Clearance delivery coordination	12	12	3	3
	Controller coordination	6	3	3	3
	Handoff initiation-silent	3	3*	0	0
	Controller coordination	6	3	3	3
Traffic Structuring	Initial pilot call-in	5	5	5	5
	TCA clearance request	20	20	10	10
	Initial controller response	2	2	2	2
	Altitude instruction	3	3	3	3
	Data update	2	2	2	2
	Heading/route instruction	3	3	3	3
	Speed instruction	3	3	3	3
	Approach/runway advisory	3	3	3	3
	Data update	2	2	2	2
	Traffic advisory	3	3	3	3
	ATIS Advisory	3	3	3	3
	Altimeter setting advisory	3	3	3	3
	Transponder code assignment	8	8	5	5
	Controller coordination	5	3	3	3
	Altitude instruction	5	5	5	5
	Data update	2	2	2	2
	Controller coordination	5	3	3	3
	Heading/route instruction	5	5	5	5
	Controller coordination	5	3	3	3
	Speed instruction	5	5	5	5
	Approach clearance	6	6	6	6
	PVD display update	3	3	3	0
	Runway assignment	5	5	5	5
	Controller coordination	5	3	3	3
	Traffic advisory	5	5	5	5
	Pilot altitude report	5	5	5	5
	Pilot heading/position report	5	5	5	5
	Pilot speed report	5	5	5	5
	Miscellaneous A/G communication	5	5	5	5
	Frequency change	5	5	5	5
	Transponder code change	2	2	2	2
	Approach/runway advisory	3	3	3	3
	Altitude/heading/speed instruction	3	3	3	3
Pilot Request	Altitude revision	8	8	8	8
	Controller coordination	5	3	3	3
	Route/heading revision	10	10	10	10
	Controller coordination	5	3	3	3
	Miscellaneous pilot request	6	6	6	6
General Intersector Coordination	Pointout acceptance	9	6	3	3
	Pointout initiation	6	3	3	3
	Control instruction approval	5	3	3	3
	Planning advisory	5	3	3	3
	Aircraft status advisory	5	0	0	0
General System Operation	Data block forcing/removal	3	3	3	0
	PVD display adjustment	3	3	3	0

* Indicated event occurs at half the frequency rate shown in Table 49.

3. Routine Workload Weightings

The R controller routine workload weighting is calculated by multiplying event frequencies (Table 49) by corresponding event performance times (Table 55) and summing the products. The resulting workload weightings are listed in Table 56 for the four sector manning regimes at each of the four sectors.

B. Surveillance Work

Surveillance workload weightings based on the assumption of 1.25 man-sec/aircraft-min for PVD scanning is shown in Table 57 for the four sectors. The transit times in Table 57 are those reported[11] for each sector by Los Angeles TRACON. The transit times shown for the arrival sectors do not include that portion of time aircraft spend on the final approach during which separation is maintained by parallel monitors under instrument operations or by pilots under visual operations; this time would increase by 2.5 min the sector transit times shown in Table 57 for both arrival sectors.

Table 56

R CONTROLLER ROUTINE WORKLOAD WEIGHTINGS
LOS ANGELES TRACON, SYSTEM 1--ARTS III BASE

Sector	R Controller Routine Workload Weighting, k_1, by Team (man-sec/aircraft)			
	1-Man Team	1.5-Man Team	2-Man Team	2.5-Man Team
AR-1, Downey Arrival	77	72	63	57
AR-2, Stadium Arrival	102	97	87	86
DR-1, South Departure	69	63	45	42
DR-2, North Departure	71	65	46	44

Table 57

R CONTROLLER SURVEILLANCE WORKLOAD WEIGHTING
LOS ANGELES TRACON, SYSTEM 1--ARTS III BASE

Sector	Aircraft Average Transit Time, t_s (min)	Surveillance Workload Weighting, ct_s (man-sec/aircraft)*
AR-1, Downey Arrival	7.5	9.38
AR-2, Stadium Arrival	7.5	9.38
DR-1, South Departure	5	6.25
DR-2, North Departure	5	6.25

*Surveillance workload constant, c = 1.25 man-sec/aircraft-min.

C. Conflict Work

1. Conflict Event Data

Application of the potential conflict modeling relationships (Appendix A) to the traffic operation and route pattern characteristics for each of the four Los Angeles TRACON sectors provides the conflict event frequencies shown in Table 58. Distinction is made between visual and instrument approach operations to account for coordinated approach mergings and increased overtaking work during instrument conditions.

In accordance with the operational descriptions given for the two arrival sectors, coordinated approach mergings are made at fewer merge points during visual rather than instrument approach operations, causing the frequency of such events to be less during visual than during instrument conditions. The overtaking conflict frequencies calculated in Table 58 for the two arrival sectors during instrument approach operations are double twice calculated for visual operations, because increased

Table 58

CONFLICT EVENT FREQUENCY ESTIMATES
LOS ANGELES TRACON, SYSTEM 1--ARTS III BASE

Sector	Conflict Event Frequency Factor $[(\text{conflicts/hr})/(\text{aircraft/hr})^2]$			
	Crossing, e_c	Local Merging, e_m	Overtaking, e_o	Coordinated Approach Merging, e_a
	Visual approach Operations			
AR-1, Downey Arrival	0	0.5×10^{-3}	1.3×10^{-3}	0.8×10^{-3}
AR-2, Stadium Arrival	0	3.6×10^{-3}	2.3×10^{-3}	0.8×10^{-3}
DR-1, South Departure	0	0	1.2×10^{-3}	0
DR-2, North Departure	3.8×10^{-3}	0	2.6×10^{-3}	0
	Instrument Approach Operations			
AR-1, Downey Arrival	0	0.5×10^{-3}	2.5×10^{-3}	2.4×10^{-3}
AR-2, Stadium Arrival	0	3.6×10^{-3}	4.5×10^{-3}	2.4×10^{-3}
DR-1, South Departure	0	0	1.2×10^{-3}	0
DR-2, North Departure	3.8×10^{-3}	0	2.6×10^{-3}	0

in-trail spacings are assumed necessary during instrument operations for coordinated approach mergings of both sectors' traffic.

Spot checks of conflict task minimum performance times observed at Los Angeles TRACON showed them to be consistent with those of Bay TRACON. For our modeling purposes, we use the R controller conflict event times previously defined for Bay TRACON. These minimum performance times (t_c, t_m, t_o, and t_a, respectively) for crossing, local merging, overtaking, and coordinated approach merging situations measured in man-sec/conflict are:

t_c = 40, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_m = 35, for 1-man, 1 5-man, 2-man, and 2.5-man teams;

t_o = 30, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_a = 32.5, for 1-man and 2-man teams

= 20.5, for 1.5-man and 2.5-man teams.

Recall that the R controller time for coordinated approach merging (t_a) varies by team manning regime because the coordinator decides aircraft sequences and calls them out to each R controller.

2. Conflict Workload Weighting

Conflict workload weightings are estimated by multiplying the conflict event frequencies (Table 58) by the corresponding performance time (Table 11). Results of these calculations are presented in Table 59 for visual and instrument approach conditions for the four sectors.

Table 59
R CONTROLLER CONFLICT WORKLOAD WEIGHTING
LOS ANGELES TRACON, SYSTEM 1--ARTS III BASE

Sector	R Controller Conflict Workload Weighting $[(\text{man-sec/hr})/(\text{aircraft/hr})^2]$				
	Visual Approach Operations				
	Crossing,* k_2	Local Merging,* k_3	Overtaking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Downey Arrival	0	1.8×10^{-2}	3.9×10^{-2}	2.6×10^{-2}	1.6×10^{-2}
AR-2, Stadium Arrival	0	12.6×10^{-2}	6.9×10^{-2}	2.6×10^{-2}	1.6×10^{-2}
DR-1, South Departure	0	0	$3.6.10^{-2}$	0	0
DR-2, North Departure	15.2×10^{-2}	0	7.8×10^{-2}	0	0
	Instrument Approach Operations				
	Crossing,* k_2	Local Merging,* k_3	Overtaking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Downey Arrival	0	1.8×10^{-2}	7.5×10^{-2}	7.8×10^{-2}	4.9×10^{-2}
AR-2, Stadium Arrival	0	12.6×10^{-2}	13.5×10^{-2}	7.8×10^{-2}	4.9×10^{-2}
DR-1, South Departure	0	0	3.6×10^{-2}	0	0
DR-2, North Departure	15.2×10^{-2}	0	7.8×10^{-2}	0	0

*Indicated crossing, local merging, and overtaking conflict workload weightings are for any of the 1-man, 1.5-man, 2-man, and 2.5-man sector team-manning regimes.

XI LOS ANGELES TRACON UG3RD SYSTEM MODELS

In this section we describe the operational impacts of the UG3RD automation features using our models of R controller workload for the four Los Angeles TRACON sectors. These features, including their assumed technological and operational characteristics, are the same as those addressed in our Bay TRACON analysis:

- Automated data handling (ADH)
- Basic metering and spacing (M&S)
- Area navigation (RNAV)
- Discrete address beacon system (DABS) data link
- DABS-based intermittent positive control (IPC).

The basic modeling assumptions used to analyze the UG3RD systems are the same as for our Bay TRACON study. Thus, we present here only the workload modeling data pertinent to the Los Angeles TRACON sectors.

A. Automated Data Handling (System 2)

The primary element of automated data handling is the electronic tabular display system which eliminates paper flight strip processing and consolidates on-line data presentation and maintenance into a computer interactive format.

1. ADH Workload Model

The tabular display will alter many of the sector team's data maintenance activities that we have included as part of our routine workload model. We foresee no impact on our surveillance or conflict work models.

Our interpretations of effects of the tabular display on the composite team's routine task performance times are summarized in Table 60. The corresponding R controller routine task performance times for the four team manning regimes are shown in Tables 61, 62, 63, and 64.

Table 60
COMPOSITE TEAM
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 2--AUTOMATED DATA HANDLING

Routine Control Event Description		Performance Time by Task (man-sec/event)*				
Event Function	Basic Event and Supplemental Event	A/G Communi-cation	Data Entry/ Display Operation	Flight Strip Process-ing	Interphone Communi-cation	Face-to-Face Communi-cation
Control Jurisdiction Transfer	Handoff acceptance			0(2)		
	Manual acquisition-silent		2			
	Flight strip preparation			0(6)		
	Flight strip printer servicing			0(15)		
	Tower departure call (run down)				0(2)	
	Clearance delivery			0(2)	10	3
	Controller coordination				6	3
	Handoff initiation-silent		1(3)			
	Controller coordination				6	3
Traffic Structuring	Initial pilot call-in	4	1(0)	0(1)		
	TCA clearance request	4	10	0(6)		4(0)
	Initial controller response	2				
	Altitude instruction	3				
	Data update		3(0)	0(2)		
	Heading/route instruction	3				
	Speed instruction	3				
	Approach/runway advisory	3				
	Data update		3(0)	0(2)		
	Traffic advisory	3				
	ATIS Advisory	3				
	Altimeter setting advisory	3				
	Transponder code assignment	3	3	0(2)		
	Controller coordination				5	3
	Altitude instruction	5				
	Data update		3(0)	0(2)		
	Controller coordination				5	3
	Heading/route instruction	5				
	Controller coordination				5	3
	Speed instruction	5				
	Approach clearance	6				
	PVD display update		3			
	Runway assignment	5				
	Controller coordination				5	3
	Traffic advisory	5				
	Pilot altitude report	5				
	Pilot heading/position report	5				
	Pilot speed report	5				
	Miscellaneous A/G communication	5				
	Frequency change	4	1(0)	0(1)		
	Transponder code change	2				
	Approach/runway advisory	3				
	Altitude/heading/speed instruction	3				
Pilot Request	Altitude revision	6	3(0)	0(2)		
	Controller coordination				5	3
	Route/heading revision	8	3(0)	0(2)		
	Controller coordination				5	3
	Miscellaneous pilot request	6				
General Intersector Coordi-nation	Pointout acceptance		3		0(6)	0(3)
	Pointout initiation		3(0)		0(6)	0(3)
	Control instruction approval				5	3
	Planning advisory				5	3
	Aircraft status advisory				5	
General System Operation	Data block forcing/removal		3			
	PVD display adjustment		3			

*System 1 performance times are indicated by parentheses.

Table 61
R CONTROLLER
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 2, 1-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control Jurisdiction Transfer	Handoff acceptance						0
	Manual acquisition-silent		2				2
	Flight strip preparation						0
	Flight strip printer servicing						0
	Tower departure call (run down)						0
	Clearance delivery				10		10
	Controller coordination				6		6
	Handoff initiation-silent		1				1
	Controller coordination				6		6
Traffic Structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4	10				14
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update		3				3
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	Data update		3				3
	Traffic advisory	3					3
	ATIS Advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3	3				6
	Controller coordination				5		5
	Altitude instruction	5					5
	Data update		3				3
	Controller coordination				5		5
	Heading/route instruction	5					5
	Controller coordination				5		5
	Speed instruction	5					5
	Approach clearance	6					6
	PVD display update		3				3
	Runway assignment	5					5
	Controller coordination				5		5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4	1				5
	Transponder code change	2					2
	Approach/runway advisory	3					3
	Altitude/heading/speed instruction	3					3
Pilot Request	Altitude revision	6	3				9
	Controller coordination				5		5
	Route/heading revision	8	3				11
	Controller coordination				5		5
	Miscellaneous pilot request	6					6
General Intersector Coordination	Pointout acceptance		3				3
	Pointout initiation		3				3
	Control instruction approval				5		5
	Planning advisory				5		5
	Aircraft status advisory				5		5
General System Operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 62
R CONTROLLER
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 2, 1.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control Jurisdiction Transfer	Handoff acceptance						0
	Manual acquisition-silent		2				2
	Flight strip preparation						0
	Flight strip printer servicing						0
	Tower departure call (run down)						0
	Clearance delivery				10		10
	Controller coordination					3	3
	Handoff initiation-silent		1				1
	Controller coordination					3	3
Traffic Structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4	10				14
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update		3				3
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	Data update		3				3
	Traffic advisory	3					3
	ATIS Advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3					3
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update		3				3
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	PVD display update		3				3
	Runway assignment	5					5
	Controller coordination					3	3
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4	1				5
	Transponder code change	2					2
	Approach/runway advisory	3					3
	Altitude/heading/speed instruction	3					3
Pilot Request	Altitude revision	6	3				9
	Controller coordination					3	3
	Route/heading revision	8	3				11
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General Intersector Coordination	Pointout acceptance		3				3
	Pointout initiation		3				3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General System Operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 63
R CONTROLLER
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 2, 2-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communi-cation	Data Entry/ Display Operation	Flight Strip Process-ing	Inter-phone Communi-cation	Face-to-Face Communi-cation	Total
Control Jurisdiction Transfer	Handoff acceptance						0
	Manual acquisition-silent						0
	Flight strip preparation						0
	Flight strip printer servicing						0
	Tower departure call (run down)						0
	Clearance delivery					3	3
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic Structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4				4	8
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update						0
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	Data update		3				3
	Traffic advisory	3					3
	ATIS Advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3					3
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update						0
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	PVD display update		3				3
	Runway assignment	5					5
	Controller coordinati^n					3	3
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4	1				5
	Transponder code change	2					2
	Approach/runway advisory	3					3
	Altitude/heading/speed instruction	3					3
Pilot Request	Altitude revision	6	3				9
	Controller coordination					3	3
	Route/heading revision	8	3				11
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General Intersector Coordi-nation	Pointout acceptance		3				3
	Pointout initiation		3				3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General System Operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 64
R CONTROLLER
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 2, 2.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communi-cation	Data Entry/ Display Operation	Flight Strip Process-ing	Inter-phone Communi-cation	Face-to-Face Communi-cation	Total
Control Jurisdiction Transfer	Handoff acceptance						0
	Manual acquisition-silent						0
	Flight strip preparation						0
	Flight strip printer servicing						0
	Tower departure call (run down)						0
	Clearance delivery					3	3
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic Structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4				4	8
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update						0
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	Data update						0
	Traffic advisory	3					3
	ATIS Advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3					3
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update						0
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	PVD display update						0
	Runway assignment	5					5
	Controller coordination					3	3
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4	1				5
	Transponder code change	2					2
	Approach/runway advisory	3					3
	Altitude/heading/speed instruction	3					3
Pilot Request	Altitude revision	6	3				9
	Controller coordination					3	3
	Route/heading revision	8	3				11
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General Intersector Coordi-nation	Pointout acceptance		3*				3
	Pointout initiation		3*				3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General System Operation	Data block forcing/removal						0
	PVD display adjustment						0

*Operational cognizance

The resulting R controller routine event performance times for each regime are summarized in Table 65.

2. ADH Workload Weightings

The R controller routine workload weightings are obtained by multiplying the Table 49 event frequencies by the corresponding event performance times in Table 65. The resulting routine workload weightings for each sector under four sector team manning regimes are shown in Table 66.

The R controller surveillance workload weighting (Table 57) and conflict workload weighting (Table 59) calculated for the ARTS III base system also apply to the automated data handling system.

B. Basic Metering and Spacing (System 3)

Basic metering and spacing performs part of the decision making required to merge aircraft from divergent directions into one or more final approach sequences.

1. M&S Workload Model

The M&S feature will alter the decision making task times that we have incorporated into our conflict work model. We expect no impact on routine or surveillance work requirements.

Our Bay TRACON estimates of conflict task performance times assume that metering and spacing will automate that part of the merging and overtaking detection and assessment tasks devoted to situation and sequence identification. Thus, under this system, the R controller's potential conflict event performance times (t_c, t_m, t_o, and t_a, respectively) for crossing, local merging, overtaking, and coordinated approach merging situations measured in man-sec/event are:

t_c = 40, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_m = 25, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_o = 20, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_a = 22.5, for 1-man and 2-man teams

= 20.5, for 1.5-man and 2.5-man teams.

Table 65
R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 2--AUTOMATED DATA HANDLING

Routine Control Event Description		Performance Time by Team (man-sec/event)			
Event Function	Basic Event and Supplemental Event	1.0-Man Team	1.5-Man Team	2.0-Man Team	2.5-Man Team
Control Jurisdiction Transfer	Handoff acceptance	0	0	0	0
	Manual acquisition-silent	2	2*	0	0
	Flight strip preparation	0	0	0	0
	Flight strip printer servicing	0	0	0	0
	Tower departure call (run down)	0	0	0	0
	Clearance delivery coordination	10	10	3	3
	Controller coordination	6	3	3	3
	Handoff initiation-silent	1	1*	0	0
	Controller coordination	6	3	3	3
Traffic Structuring	Initial pilot call-in	5	5	5	5
	TCA clearance request	14	14	8	8
	Initial controller response	2	2	2	2
	Altitude instruction	3	3	3	3
	Data update	3	3	0	0
	Heading/route instruction	3	3	3	3
	Speed instruction	3	3	3	3
	Approach/runway advisory	3	3	3	3
	Data update	3	3	3	0
	Traffic advisory	3	3	3	3
	ATIS Advisory	3	3	3	3
	Altimeter setting advisory	3	3	3	3
	Transponder code assignment	6	3	3	3
	Controller coordination	5	3	3	3
	Altitude instruction	5	5	5	5
	Data update	3	3	0	0
	Controller coordination	5	3	3	3
	Heading/route instruction	5	5	5	5
	Controller coordination	5	3	3	3
	Speed instruction	5	5	5	5
	Approach clearance	6	6	6	6
	PVD display update	3	3	3	0
	Runway assignment	5	5	5	5
	Controller coordination	5	3	3	3
	Traffic advisory	5	5	5	5
	Pilot altitude report	5	5	5	5
	Pilot heading/position report	5	5	5	5
	Pilot speed report	5	5	5	5
	Miscellaneous A/G communication	5	5	5	5
	Frequency change	5	5	5	5
	Transponder code change	2	2	2	2
	Approach/runway advisory	3	3	3	3
	Altitude/heading/speed instruction	3	3	3	3
Pilot Request	Altitude revision	9	9	9	9
	Controller coordination	5	3	3	3
	Route/heading revision	11	11	11	11
	Controller coordination	5	3	3	3
	Miscellaneous pilot request	6	6	6	6
General Intersector Coordination	Pointout acceptance	3	3	3	3
	Pointout initiation	3	3	3	3
	Control instruction approval	5	3	3	3
	Planning advisory	5	3	3	3
	Aircraft status advisory	5	0	0	0
General System Operation	Data block forcing/removal	3	3	3	0
	PVD display adjustment	3	3	3	0

*Indicated event occurs at half the frequency rate shown in Table 49.

Table 66

R CONTROLLER ROUTINE WORKLOAD WEIGHTINGS
LOS ANGELES TRACON, SYSTEM 2--AUTOMATED DATA HANDLING

Sector	R Controller Routine Workload Weighting, k_1, by Team (man-sec/aircraft)			
	1-Man Team	1.5-Man Team	2-Man Team	2.5-Man Team
AR-1, Downey Arrival	69	65	60	54
AR-2, Stadium Arrival	96	91	84	80
DR-1, South Departure	49	46	43	41
DR-2, North Departure	51	48	45	43

2. M&S Workload Weightings

Basic metering and spacing system does not alter frequency of conflict events, and the conflict event frequencies in Table 58 calculated for the current ARTS III Base System apply. We multiply the conflict event performance (see above) by the corresponding Table 58 event frequencies to obtain the R controller conflict workload weighting shown in Table 67 for basic metering and spacing.

The R controller routine workload weighting (Table 66) and surveillance workload weighting (Table 57) corresponding to the predecessor system also apply to the basic metering and spacing system.

C. Conflict Probe (System 4)

A sector conflict probe projects aircraft flight trajectories by computer calculations and warns controllers of potential conflict situations.

Table 67

R CONTROLLER CONFLICT WORKLOAD WEIGHTING
LOS ANGELES TRACON, SYSTEM 3--BASIC METERING AND SPACING

Sector	R Controller Conflict Workload Weighting [(man-sec/hr)/(aircraft/hr)^2]				
	Visual Approach Operations				
	Crossing,* k_2	Local Merging,* k_3	Over-taking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Downey Arrival	0	1.3×10^{-2}	2.6×10^{-2}	1.8×10^{-2}	1.6×10^{-2}
AR-2, Stadium Arrival	0	9.0×10^{-2}	4.6×10^{-2}	1.8×10^{-2}	1.6×10^{-2}
DR-1, South Departure	0	0	2.4×10^{-2}	0	0
DR-2, North Departure	15.2×10^{-2}	0	5.2×10^{-2}	0	0
	Instrument Approach Operations				
Sector	Crossing,* k_2	Local Merging,* k_3	Over-taking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Downey Arrival	0	1.3×10^{-2}	5.0×10^{-2}	5.4×10^{-2}	4.9×10^{-2}
AR-2, Stadium Arrival	0	9.0×10^{-2}	9.0×10^{-2}	5.4×10^{-2}	4.9×10^{-2}
DR-1, South Departure	0	0	2.4×10^{-2}	0	0
DR-2, North Departure	15.2×10^{-2}	0	5.2×10^{-2}	0	0

*Indicated crossing, local merging, and overtaking conflict workload weightings are for any of the 1-man, 1.5-man, 2-man, and 2.5-man sector team-manning regimes.

1. Conflict Probe Workload Model

The sector conflict probe will alter the sector team's task performance time requirements which are included in the conflict work model. We foresee no impact on our routine work or PVD surveillance work models.

The conflict probe is assumed to automate detection and assessment tasks in the manner described in the Bay TRACON analysis. Therefore, using a conflict probe, the R controller's potential conflict event performance times (t_c, t_m, t_o, t_a, respectively) for crossing, local merging, overtaking, and approach merging situations measured in man-sec/conflict are:

t_c = 25, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_m = 20, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_o = 15, for 1-man, 1.5-man, 2-man, and 2.5-man teams;

t_a = 17.5, for 1-man and 2-man teams

= 15.5, for 1.5-man and 2.5-man teams.

2. Conflict Probe Workload Weightings

No revisions to the rate of occurrence of conflict events are associated with the conflict probe, and the conflict event frequencies in Table 58 for the predecessor system apply. We multiply the Table 58 event frequencies by the appropriate event performance time (see above) to obtain the conflict workload weightings shown in Table 68.

The R controller routine workload weightings (Table 66) and surveillance work weightings (Table 57) used for the predecessor system also apply to sector conflict probe system.

D. Area Navigation (System 5)

RNAV incorporates navigation devices to achieve closely spaced arrival and departure and multi-lane direct routes for high-density airspace.

Table 68

R CONTROLLER CONFLICT WORKLOAD WEIGHTING
LOS ANGELES TRACON, SYSTEM 4--SECTOR CONFLICT PROBE

Sector	R Controller Conflict Workload Weighting $[(\text{man-sec/hr})/(\text{aircraft/hr})^2]$				
	Visual Approach Operations				
	Crossing,* k_2	Local Merging,* k_3	Over-taking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Downey Arrival	0	1.0×10^{-2}	2.0×10^{-2}	1.4×10^{-2}	1.2×10^{-2}
AR-2, Stadium Arrival	0	7.2×10^{-2}	3.5×10^{-2}	1.4×10^{-2}	1.2×10^{-2}
DR-1, South Departure	0	0	1.8×10^{-2}	0	0
DR-2, North Departure	9.5×10^{-2}	0	3.9×10^{-2}	0	0
	Instrument Approach Operations				
Sector	Crossing,* k_2	Local Merging,* k_3	Over-taking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Downey Arrival	0	1.0×10^{-2}	3.8×10^{-2}	4.2×10^{-2}	3.7×10^{-2}
AR-2, Stadium Arrival	0	7.2×10^{-2}	6.8×10^{-2}	4.2×10^{-2}	3.7×10^{-2}
DR-1, South Departure	0	0	1.8×10^{-2}	0	0
DR-2, North Departure	9.5×10^{-2}	0	3.9×10^{-2}	0	0

*Indicated crossing, local merging, and overtaking conflict workload weightings are for any of the 1-man, 1.5-man, 2-man, and 2.5-man sector team-manning regimes.

1. RNAV Workload Model

RNAV will alter a portion of the event frequency data that we have included as part of our conflict model. We project no impact on our routine or surveillance work models.

In accordance with our analysis of Bay TRACON, we assume RNAV will eliminate the occurrence of overtaking conflicts in departure sectors as shown in Table 69. The Table 69 entries are obtained by adjusting the conflict event frequency entries in Table 58 which we used to model the predecessor sector conflict probe system. We assume RNAV will not eliminate or reduce conflict event occurrences in the arrival sectors nor will it eliminate or reduce crossing and merging conflict occurrences in the departure sectors.

2. RNAV Workload Weightings

RNAV does not affect the conflict event performance times calculated for the predecessor system. R controller conflict workload weighting may be obtained by multiplying these task performance times by the RNAV conflict event frequencies in Table 69. The results will be identical to the workload weightings shown in Table 68, except that the four entries shown for departure sector overtakings will each equal zero.

The R controller routine workload weightings (Table 66) and surveillance workload weighting (Table 57) used for the predecessor system also apply to the RNAV system.

E. DABS Data Link (System 6)

The DABS data link transmits digital data to pilots, including general control instructions and collision avoidance directives. The data link integrated via extensive computerization is the basis for such control-by-exception operations. Here, the controller becomes a system manager who is not actively engaged in minute-by-minute tactical decision making, but monitors and regulates the computerized operation.

1. Data Link Workload Model

The data link based control-by-exception operation will alter many of the sector team's communication and data maintenance activities

Table 69

CONFLICT EVENT FREQUENCY ESTIMATES
LOS ANGELES TRACON, SYSTEM 5--RNAV

Sector	Conflict Event Frequency Factor* [(Conflicts/Hr) / (Aircraft/Hr)^2]			
	Visual Approach Operations			
	Crossing, e_c	Local Merging, e_m	Overtaking, e_o	Coordinated Approach Merging, e_a
AR-1, Downey Arrival	0	0.5×10^{-3}	1.3×10^{-3}	0.8×10^{-3}
AR-2, Stadium Arrival	0	3.6×10^{-3}	2.3×10^{-3}	0.8×10^{-3}
DR-1, South Departure	0	0	0(1.2×10^{-3})	0
DR-2, North Departure	3.8×10^{-3}	0	0(2.6×10^{-3})	0
	Instrument Approach Operations			
	Crossing, e_c	Local Merging, e_m	Overtaking, e_o	Coordinated Approach Merging, e_a
AR-1, Downey Arrival	0	0.5×10^{-3}	2.5×10^{-3}	2.4×10^{-3}
AR-2, Stadium Arrival	0	3.6×10^{-3}	4.5×10^{-3}	2.4×10^{-3}
DR-1, South Departure	0	0	0(1.2×10^{-3})	0
DR-2, North Departure	3.8×10^{-3}	0	0(2.6×10^{-3})	0

*System 4 event frequencies are indicated in parenthesis.

that we have included in our routine and conflict work models. We foresee no impact on our surveillance work model. In the following paragraphs we follow the methodology described in the Bay TRACON analysis for adjusting our routine and conflict work models, under the assumption that all aircraft are equipped with DABS data link.

Our interpretations of the tabular display effect upon the composite team's routine task performance time are summarized in Table 70. The corresponding R controller routine task performance times for the four team manning regines are shown in Tables 71, 72, 73, and 74. The resulting R controller routine event performance times for each regime are summarized in Table 75.

Conflict resolution instructions are assumed to be transmitted by the data link while controllers maintain cognizance of the computerized operation. The R controllers conflict event performance times (t_c, t_m, t_o, and t_a, respectively) for crossing, local merging, overtaking and coordinated approach merging situations are each reduced to 15 man-sec/conflict.

2. Data Link Workload Weightings

The R controller routine and conflict event frequencies used to model the predecessor system apply to DABS data link modeling since the rates of occurrence of these events are not affected by control-by-exception automation. We use the appropriate routine event frequencies (Table 49) and performance times (Table 57) to calculate the routine workload weighting summarized in Table 76. The conflict event performance times (see above) and the predecessor RNAV-based event frequencies (Table 69) are used to calculate the conflict workload weightings shown in Table 77.

The R controller surveillance workload weightings (Table 57) used for the predecessor systems also apply to the DABS data link system.

F. DABS Intermittent Positive Control

IPC provides traffic advisors and threat avoidance commands to VFR pilots on an as-needed basis. Extended to IFR operations IPC would operate on imminent (e.g., lead-time of 1 to 2 min) conflict situations that are "missed" by controllers. This is assumed to be a safety enhancement device that would not effect the capacity considerations associated

Table 70
COMPOSITE TEAM
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 6--DABS DATA LINK

Routine Control Event Description		Performance Time by Task (man-sec/event)†				
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication
Control Jurisdiction Transfer	Handoff acceptance		0(2)			
	Manual acquisition-silent					
	Flight strip preparation					
	Flight strip printer servicing					
	Tower departure call (run down)					
	Clearance delivery		3*(0)		0(10)	0(3)
	Controller coordination				6	3
	Handoff initiation-silent		1			
	Controller coordination				6	3
Traffic Structuring	Initial pilot call-in	4	1			
	TCA clearance request	4	10			4
	Initial controller response	2	5*(0)			
	Altitude instruction	0(3)				
	Data update		0(3)			
	Heading/route instruction	0(3)				
	Speed instruction	0(3)				
	Approach/runway advisory	0(3)				
	Data update		0(3)			
	Traffic advisory	3				
	ATIS Advisory	0(3)				
	Altimeter setting advisory	0(3)				
	Transponder code assignment	3	0(3)			
	Controller coordination				5	3
	Altitude instruction	0(5)	3*(0)			
	Data update		0(3)			
	Controller coordination	5(0)	3(0)		5	3
	Heading/route instruction	0(5)	3*(0)			
	Controller coordination	5(0)	3(0)		5	3
	Speed instruction	5(0)	3*(0)			
	Approach clearance	3(6)	3*(0)			
	PVD display update		0(3)			
	Runway assignment	0(50	3*(0)			
	Controller coordination	5(0)	3(0)		5	3
	Traffic advisory	5				
	Pilot altitude report	5				
	Pilot heading/position report	5				
	Pilot speed report	5				
	Miscellaneous A/G communication	5				
	Frequency change	0(4)	3*(1)			
	Transponder code change	0(2)				
	Approach/runway advisory	0(3)				
	Altitude/heading/speed instruction	0(3)				
Pilot Request	Altitude revision	6	3			
	Controller coordination				5	3
	Route/heading revision	8	3			
	Controller coordination				5	3
	Miscellaneous pilot request	6				
General Intersector Coordination	Pointout acceptance		3*			
	Pointout initiation		3*			
	Control instruction approval				5	3
	Planning advisory				5	3
	Aircraft status advisory				5	
General System Operation	Data block forcing/removal		3			
	PVD display adjustment		3			

*Operational cognizance

†System 5 performance times are indicated in parenthesis.

Table 71
R CONTROLLER
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 6, 1-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communi-cation	Data Entry/ Display Operation	Flight Strip Process-ing	Inter-phone Communi-cation	Face-to-Face Communi-cation	Total
Control Jurisdiction Transfer	Handoff acceptance						0
	Manual acquisition-silent						0
	Flight strip preparation						0
	Flight strip printer servicing						0
	Tower departure call (run down)						0
	Clearance delivery		3*				3
	Controller coordination				6		6
	Handoff initiation-silent		1				1
	Controller coordination				6		6
Traffic Structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4	10				14
	Initial controller response	2	5*				7
	Altitude instruction						0
	Data update						0
	Heading/route instruction						0
	Speed instruction						0
	Approach/runway advisory						0
	Data update						0
	Traffic advisory	3					3
	ATIS Advisory						0
	Altimeter setting advisory						0
	Transponder code assignment	3					3
	Controller coordination				5		5
	Altitude instruction		3*				3
	Data update						0
	Controller coordination	5	3		5		13
	Heading/route instruction		3*				3
	Controller coordination	5	3		5		13
	Speed instruction		3*				3
	Approach clearance		3*				3
	PVD display update						0
	Runway assignment		3*				3
	Controller coordination	5	3		5		13
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change		3*				3
	Transponder code change						0
	Approach/runway advisory						0
	Altitude/heading/speed instruction						0
Pilot Request	Altitude revision	6	3				9
	Controller coordination				5		5
	Route/heading revision	8	3				11
	Controller coordination				5		5
	Miscellaneous pilot request	6					6
General Intersector Coordi-nation	Pointout acceptance		3*				3
	Pointout initiation		3*				3
	Control instruction approval				5		5
	Planning advisory				5		5
	Aircraft status advisory				5		5
General System Operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

*Operational cognizance

Table 72
R CONTROLLER
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 6, 1.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control Jurisdiction Transfer	Handoff acceptance						0
	Manual acquisition-silent						0
	Flight strip preparation						0
	Flight strip printer servicing						0
	Tower departure call (run down)						0
	Clearance delivery		3*				3
	Controller coordination					3	3
	Handoff initiation-silent		1				1
	Controller coordination					3	3
Traffic Structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4	10				14
	Initial controller response	2	5*				7
	Altitude instruction						0
	Data update						0
	Heading/route instruction						0
	Speed instruction						0
	Approach/runway advisory						0
	Data update						0
	Traffic advisory	3					3
	ATIS Advisory						0
	Altimeter setting advisory						0
	Transponder code assignment	3					3
	Controller coordination					3	3
	Altitude instruction		3*				3
	Data update						0
	Controller coordination	5	3			3	11
	Heading/route instruction		3*				3
	Controller coordination	5	3			3	11
	Speed instruction		3*				3
	Approach clearance		3*				3
	PVD display update						0
	Runway assignment		3*				3
	Controller coordination	5	3			3	11
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change		3*				3
	Transponder code change						0
	Approach/runway advisory						0
	Altitude/heading/speed instruction						0
Pilot Request	Altitude revision	6	3				9
	Controller coordination					3	3
	Route/heading revision	8	3				11
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General Intersector Coordination	Pointout acceptance		3*				3
	Pointout initiation		3*				3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General System Operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

*Operational cognizance

Table 73
R CONTROLLER
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 6, 2-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control Jurisdiction Transfer	Handoff acceptance						0
	Manual acquisition-silent						0
	Flight strip preparation						0
	Flight strip printer servicing						0
	Tower departure call (run down)						0
	Clearance delivery		3*				3
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic Structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4				4	8
	Initial controller response	2	5*				7
	Altitude instruction						0
	Data update						0
	Heading/route instruction						0
	Speed instruction						0
	Approach/runway advisory						0
	Data update						0
	Traffic advisory	3					3
	ATIS Advisory						0
	Altimeter setting advisory						0
	Transponder code assignment	3					3
	Controller coordination					3	3
	Altitude instruction		3*				3
	Data update						0
	Controller coordination	5				3	8
	Heading/route instruction		3*				3
	Controller coordination	5				3	8
	Speed instruction		3*				3
	Approach clearance		3*				3
	PVD display update						0
	Runway assignment		3*				3
	Controller coordination	5	3				8
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change		3*				3
	Transponder code change						0
	Approach/runway advisory						0
	Altitude/heading/speed instruction						0
Pilot Request	Altitude revision	6	3				9
	Controller coordination					3	3
	Route/heading revision	8	3				11
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General Intersector Coordination	Pointout acceptance		3*				3
	Pointout initiation		3*				3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General System Operation	Data block forcing/removal						0
	PVD display adjustment						0

*Operational cognizance

Table 74
R CONTROLLER
ROUTINE TASK MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 6, 2.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Inter-phone Communication	Face-to-Face Communication	Total
Control Jurisdiction Transfer	Handoff acceptance						0
	Manual acquisition-silent						0
	Flight strip preparation						0
	Flight strip printer servicing						0
	Tower departure call (run down)						0
	Clearance delivery		3*				3
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic Structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4				4	8
	Initial controller response	2	5*				7
	Altitude instruction						0
	Data update						0
	Heading/route instruction						0
	Speed instruction						0
	Approach/runway advisory						0
	Data update						0
	Traffic advisory	3					3
	ATIS Advisory						0
	Altimeter setting advisory						0
	Transponder code assignment	3					3
	Controller coordination					3	3
	Altitude instruction		3*				3
	Data update						0
	Controller coordination	5				3	8
	Heading/route instruction		3*				3
	Controller coordination	5				3	8
	Speed instruction		3*				3
	Approach clearance		3*				3
	PVD display update						0
	Runway assignment		3*				3
	Controller coordination	5	3				8
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change		3*				3
	Transponder code change						0
	Approach/runway advisory						0
	Altitude/heading/speed instruction						0
Pilot Request	Altitude revision	6	3				9
	Controller coordination					3	3
	Route/heading revision	8	3				11
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General Intersector Coordination	Pointout acceptance		3*				3
	Pointout initiation		3*				3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General System Operation	Data block forcing/removal						0
	PVD display adjustment						0

*Operational cognizance

Table 75
R CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
LOS ANGELES TRACON, SYSTEM 6--DABS DATA LINK

Routine Control Event Description		Performance Time by Team (man-sec/event)			
Event Function	Basic Event and Supplemental Event	1.0-Man Team	1.5-Man Team	2.0-Man Team	2.5-Man Team
Control Jurisdiction Transfer	Handoff acceptance	0	0	0	0
	Manual acquisition-silent	0	0	0	0
	Flight strip preparation	0	0	0	0
	Flight strip printer servicing	0	0	0	0
	Tower departure call (run down)	0	0	0	0
	Clearance delivery coordination	12	12	3	3
	Controller coordination	6	3	3	3
	Handoff initiation-silent	1	1*	0	0
	Controller coordination	6	3	3	3
Traffic Structuring	Initial pilot call-in	5	5	5	5
	TCA clearance request	20	20	10	10
	Initial controller response	2	2	2	2
	Altitude instruction	3	3	3	3
	Data update	2	2	2	2
	Heading/route instruction	3	3	3	3
	Speed instruction	3	3	3	3
	Approach/runway advisory	3	3	3	3
	Data update	2	2	2	2
	Traffic advisory	3	3	3	3
	ATIS Advisory	3	3	3	3
	Altimeter setting advisory	3	3	3	3
	Transponder code assignment	8	5	5	5
	Controller coordination	5	3	3	3
	Altitude instruction	5	5	5	5
	Data update	2	2	2	2
	Controller coordination	5	3	3	3
	Heading/route instruction	5	5	5	5
	Controller coordination	5	3	3	3
	Speed instruction	5	5	5	5
	Approach clearance	6	6	6	6
	PVD display update	3	3	3	0
	Runway assignment	5	5	5	5
	Controller coordination	5	3	3	3
	Traffic advisory	5	5	5	5
	Pilot altitude report	5	5	5	5
	Pilot heading/position report	5	5	5	5
	Pilot speed report	5	5	5	5
	Miscellaneous A/G communication	5	5	5	5
	Frequency change	5	5	5	5
	Transponder code change	2	2	2	2
	Approach/runway advisory	3	3	3	3
	Altitude/heading/speed instruction	3	3	3	3
Pilot Request	Altitude revision	8	8	8	8
	Controller coordination	5	3	3	3
	Route/heading revision	10	10	10	10
	Controller coordination	5	3	3	3
	Miscellaneous pilot request	6	6	6	6
General Intersector Coordination	Pointout acceptance	9	6	3	3
	Pointout initiation	6	3	3	3
	Control instruction approval	5	3	3	3
	Planning advisory	5	3	3	3
	Aircraft status advisory	5	0	0	0
General System Operation	Data block forcing/removal	3	3	3	0
	PVD display adjustment	3	3	3	0

* Indicated event occurs at half the frequency rate shown in Table 49.

Table 76

R CONTROLLER ROUTINE WORKLOAD WEIGHTINGS
LOS ANGELES TRACON, SYSTEM 6--DABS DATA LINK

Sector	R Controller Routine Workload Weighting, k_1, by Team (man-sec/aircraft)			
	1-Man Team	1.5-Man Team	2-Man Team	2.5-Man Team
AR-1, Downey Arrival	48	45	41	41
AR-2, Stadium Arrival	64	60	57	57
DR-1, South Departure	45	42	38	38
DR-2, North Departure	44	42	38	38

with normal sector task activities. As in the case of the Bay TRACON analysis, we do not further evaluate IPC; it is considered to be an incremental add-on to the data link system but with no independent effect upon workload.

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Table 77

R CONTROLLER CONFLICT WORKLOAD WEIGHTING

LOS ANGELES TRACON, SYSTEM 6--DABS DATA LINK

Sector	R Controller Conflict Workload Weighting $[(\text{man-sec/hr})/(\text{aircraft/hr})^2]$				
	Visual Approach Operations				
	Crossing,* k_2	Local Merging,* k_3	Over-taking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Downey Arrival	0	0.8×10^{-2}	2.0×10^{-2}	1.2×10^{-2}	1.2×10^{-2}
AR-2, Stadium Arrival	0	5.4×10^{-2}	3.5×10^{-2}	1.2×10^{-2}	1.2×10^{-2}
DR-1, South Departure	0	0	0	0	0
DR-2, North Departure	5.7×10^{-2}	0	0	0	0
	Instrument Approach Operations				
Sector	Crossing,* k_2	Local Merging,* k_3	Over-taking,* k_4	Coordinated Approach Merging, k_5	
				1-Man, 2-Man Teams	1.5-Man, 2.5-Man Teams
AR-1, Downey Arrival	0	0.8×10^{-2}	3.8×10^{-2}	3.6×10^{-2}	3.6×10^{-2}
AR-2, Stadium Arrival	0	5.4×10^{-2}	6.8×10^{-2}	3.6×10^{-2}	3.6×10^{-2}
DR-1, South Departure	0	0	0	0	0
DR-2, North Departure	5.7×10^{-2}	0	0	0	0

*Indicated crossing, local merging, and overtaking conflict workload weightings are for any of the 1-man, 1.5-man, 2-man, and 2.5-man sector team-manning regimes.

XII LOS ANGELES TRACON SECTOR CAPACITY AND MANNING

In this section, we estimate traffic capacities at the four Los Angeles TRACON sectors for each sector team manning regime under each of the six ATC system alternatives. We use these capacities to estimate multi-sector minimum manning requirements for a range of traffic levels; these estimates enable comparisons of the impact of the various UG3RD systems on facility operations.

A. Sector Capacity

We use the routine, surveillance, and conflict workload weightings established for the Los Angeles TRACON and follow the procedure previously described for the Bay TRACON analysis to estimate sector capacities. These estimated sector capacities for both visual and instrument approach operations are presented in Tables 78, 79, 80, and 81, respectively, for each of the four sectors.

These sector capacities directly reflect the R controller activity requirements defined by the workload weightings. We see that feeder and final sector capacities for instrument approach operations are slightly less than those for visual operations because of the additional approach merging work, while departure sector capacities are not affected by approach conditions. The sector capacities generally increase for each successive increment in sector team manning because the R controller usually offloads some portion of routine or conflict work to the added team members. In some situations, the amount of work offloaded does not sufficiently increase sector capacity; in the case of 2-man versus 2.5-man team regimes for the DABS data link system, no work offloading is projected and sector capacities are identical for the two regimes. Therefore, the 2-man team is the practical manning limit under System 6 operations.

Each UG3RD ATC system successor to the ARTS III Base System includes an automation feature that is added onto the operational features of its predecessor. Since each UG3RD automation feature further reduces R controller workload requirements to varying extents, sector capacity generally increases as each successive system evolves. However, some of the automation features do not alleviate workload in certain operational environments. For example, basic metering and spacing supports

Table 78

DOWNEY (AR-1) CAPACITY ESTIMATES

ATC System	Sector Capacity by Team (ac/hr)							
	VFR Approach Rules				IFR Approach Rules			
	1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0-Man	1.5-Man	2.0-Man	2.5-Man
1. Current ARTS III	32	34	38	41	31	33	37	40
2. + Automated Data Handling	35	37	40	43	34	36	38	42
3. + Metering and Spacing	36	38	40	44	35	37	39	42
4. + Conflict Probe	36	38	40	44	35	37	39	43
5. + RNAV (100% Avionics)	36	38	40	44	35	37	39	43
6. + DABS Data-Link (100% Avionics)	49	51	55	55	47	49	53	53

Table 79

STADIUM (AR-2) CAPACITY ESTIMATES

ATC System	Sector Capacity by Team (ac/hr)							
	VFR Approach Rules				IFR Approach Rules			
	1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0-Man	1.5-Man	2.0-Man	2.5-Man
1. Current ARTS III	25	26	28	28	24	25	27	28
2. + Automated Data Handling	26	27	29	30	25	27	28	29
3. + Metering and Spacing	26	28	29	31	26	27	29	30
4. + Conflict Probe	27	28	29	31	26	27	29	30
5. + RNAV (100% Avionics)	27	28	30	31	26	27	29	30
6. + DABS Data-Link (100% Avionics)	37	39	41	41	36	38	40	40

Table 80

SOUTH DEPARTURE (DR-1) CAPACITY ESTIMATES

ATC System	Sector Capacity by Team (ac/hr)							
	VFR Approach Rules				IFR Approach Rules			
	1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0-Man	1.5-Man	2.0-Man	2.5-Man
1. Current ARTS III	38	41	54	57	38	41	54	57
2. + Automated Data Handling	50	53	56	58	50	53	56	58
3. + Metering and Spacing	50	53	56	58	50	53	56	58
4. + Conflict Probe	51	54	57	60	51	54	57	60
5. + RNAV (100% Avionics)	52	55	58	61	52	55	58	61
6. + DABS Data-Link (100% Avionics)	56	60	65	65	56	60	65	65

Table 81

NORTH DEPARTURE (DR-2) CAPACITY ESTIMATES

ATC System	Sector Capacity by Team (ac/hr)							
	VFR Approach Rules				IFR Approach Rules			
	1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0-Man	1.5-Man	2.0-Man	2.5-Man
1. Current ARTS III	34	36	46	47	34	36	46	47
2. + Automated Data Handling	43	45	46	48	43	45	46	48
3. + Metering and Spacing	43	45	46	48	43	45	46	48
4. + Conflict Probe	45	47	50	51	45	47	50	51
5. + RNAV (100% Avionics)	47	49	51	53	47	49	51	53
6. + DABS Data-Link (100% Avionics)	54	56	60	60	54	56	60	60

approach operations, but is not shown to increase departure sector capacity. Similarly, RNAV is not assumed to be effective in reducing work requirements for arrival operations, and is not shown to increase arrival sector capacity.

We note that our workload analyses assume 100 percent deployment of RNAV and DABS data link airborne equipment for the aircraft fleet under TRACON control. We do not explicitly assess the effect on capacity of partial deployment of avionics equipment. However, based on our previous analyses of enroute ATC aircraft equipment deployments, first-cut capacity estimates for partial deployment may be made by linear interpolations in Tables 78, 79, 80, and 81, as was explained under the Bay TRACON analysis.

B. Multi-Sector Manning

Subject to the traffic handling constraints imposed by our sector capacity calculations, we wish to compare the relative manning requirements of each of the six alternative ATC systems associated with the joint operation of the four sectors.

We use sector capacities calculated for instrument approach conditions rather than visual because instrument conditions are more critical constraints to controller traffic handling capabilities.

1. Manning Calculations

Again using the previously described Bay TRACON analysis procedure, we calculate for each system the minimum number of manned control positions required to process various levels of traffic through each sector, without exceeding our R controller workload-based capacity constraints. The calculation worksheets including the manning estimates are shown in Tables 82, 83, 84, 85, 86, and 87, respectively, for the six alternative ATC systems. The traffic base is the 1975 statistics reported for the 8-hour day shift for the Los Angeles TRACON busy day (90th percentile).[11]

Controller manning requirements are made for 25 percent increments in day-shift, peak-hour traffic projections. Manning estimates for each of the four sectors are made by comparing each traffic increment against the sector teams' growth potentials, and identifying the team needed to handle the projected traffic. Allowances are made for sharing a coordinator between two arrival or two departure sectors, even though

Table 82

DAY-SHIFT, PEAK-HOUR MANNING CALCULATIONS
LOS ANGELES TRACON
SYSTEM 1--ARTS III BASE

Sector	1975 Busy-day, Day-shift, Peak-hour Traffic (ac/hr)*	IFR Sector Capacity by Team (ac/hr)				Traffic Growth Potential by Team†				Manning Requirement by Traffic Growth Factor (controllers/team)								
		1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0 Man	1.5-Man	2.0-Man	2.5-Man	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
AR-1 Downey Arrival	34	31	33	37	40	0.91	0.97	1.09	1.18	2	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
AR-2 Stadium Arrival	20	24	25	27	28	1.20	1.25	1.35	1.40	1	1.5‡	2.5	2.5	2.5	2.5	2.5	2.5	2.5
DR-1 South Departure	24	38	41	54	57	1.58	1.71	2.25	2.38	1	1	1	2	2.5‡	2.5‡	2.5	2.5	2.5
DR-2 North Departure	26	34	36	46	47	1.31	1.38	1.77	1.81	1	1	2	2	2.5	2.5	2.5	2.5	2.5
Subtotal (Men)										5	6	8	9	10	10	10	10	10
Parallel monitoring positions (Men)										2§	2§	4**	4**	4**	4**	4**	4**	4**
Flight data positions (Men)										0	1	1	1	2	2	2	2	2
Total (Men)										7	9	13	14	16	16	16	16	16
Manning factor (1975 Base)										1.0	1.29	1.85	2.0	2.29	2.29	2.29	2.29	2.29

*Source: "Application of ATC Terminal Standard for PY 1975," computer printout manuscript, Air Traffic Service, FAA (1976)
†Traffic growth potential = capacity/1975 traffic
‡Coordinator (1/2-man) required for companion sector
§Performance monitoring function only assumed
**Final sector function assumed

Table 83

DAY-SHIFT, PEAK-HOUR MANNING CALCULATIONS
LOS ANGELES TRACON
SYSTEM 2--AUTOMATED DATA HANDLING

Sector	1975 Busy-day, Day-shift, Peak-hour Traffic (ac/hr)*	IFR Sector Capacity by Team (ac/hr)				Traffic Growth Potential by Team†				Manning Requirement by Traffic Growth Factor (controllers/team)								
		1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0 Man	1.5-Man	2.0-Man	2.5-Man	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
AR-1 Downey Arrival	34	34	36	38	42	1.00	1.06	1.12	1.24	1	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
AR-2 Stadium Arrival	20	25	27	28	29	1.25	1.35	1.40	1.45	1	1.5‡	2.5	2.5	2.5	2.5	2.5	2.5	2.5
DR-1 South Departure	24	50	53	56	58	2.08	2.21	2.33	2.42	1	1	1	1	1.5‡	2.5‡	2.5	2.5	2.5
DR-2 North Departure	26	43	45	46	48	1.65	1.73	1.77	1.85	1	1	1	2	2.5	2.5	2.5	2.5	2.5
Subtotal (Men)										4	6	7	8	9	10	10	10	10
Parallel monitoring positions (Men)										2§	2§	4**	4**	4**	4**	4**	4**	4**
Flight data positions (Men)										0	0	0	0	0	0	0	0	0
Total (Men)										6	8	11	12	13	14	14	14	14
Manning factor (1975 Base)										0.86	1.14	1.57	1.71	1.86	2.00	2.00	2.00	2.00

*Source: "Application of ATC Terminal Standard for PY 1975," computer printout manuscript, Air Traffic Service, FAA (1976)
†Traffic growth potential = capacity/1975 traffic
‡Coordinator (1/2-man) required for companion sector
§Performance monitoring function only assumed
**Final sector function assumed

Table 84

DAY-SHIFT, PEAK-HOUR MANNING CALCULATIONS
LOS ANGELES TRACON
SYSTEM 3--BASIC METERING AND SPACING

Sector	1975 Busy-day, Day-shift, Peak-hour Traffic (ac/hr)*	IFR Sector Capacity by Team (ac/hr)				Traffic Growth Potential by Team†				Manning Requirement by Traffic Growth Factor (controllers/team)								
		1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0 Man	1.5-Man	2.0-Man	2.5-Man	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
AR-1 Downey Arrival	34	35	37	39	42	1.03	1.09	1.15	1.24	1	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
AR-2 Stadium Arrival	20	26	27	29	30	1.30	1.35	1.45	1.50	1	1.5‡	2.5‡	2.5	2.5	2.5	2.5	2.5	2.5
DR-1 South Departure	24	50	53	56	58	2.08	2.21	2.33	2.42	1	1	1	1	1.5‡	2.5‡	2.5	2.5	2.5
DR-2 North Departure	26	43	45	46	48	1.65	1.73	1.77	1.85	1	1	1	2	2.5	2.5	2.5	2.5	2.5
Subtotal (Men)										4	6	7	8	9	10	10	10	10
Parallel monitoring positions (Men)										2§	2§	2§	4**	4**	4**	4**	4**	4**
Flight data positions (Men)										0	0	0	0	0	0	0	0	0
Total (Men)										6	8	9	12	13	14	14	14	14
Manning factor (1975 Base)										0.86	1.14	1.29	1.71	1.86	2.00	2.00	2.00	2.00

*Source: "Application of ATC Terminal Standard for FY 1975," computer printout manuscript, Air Traffic Service, FAA (1976)
†Traffic growth potential = capacity/1975 traffic
‡Coordinator (1/2-man) required for companion sector
§Performance monitoring function only assumed
**Final sector function assumed

Table 85

DAY-SHIFT, PEAK-HOUR MANNING CALCULATIONS
LOS ANGELES TRACON
SYSTEM 4--SECTOR CONFLICT PROBE

Sector	1975 Busy-day, Day-shift, Peak-hour Traffic (ac/hr)[*]	IFR Sector Capacity by Team (ac/hr)				Traffic Growth Potential by Team[†]				Manning Requirement by Traffic Growth Factor (controllers/team)								
		1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0 Man	1.5-Man	2.0-Man	2.5-Man	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
AR-1 Downey Arrival	34	35	37	39	43	1.03	1.09	1.15	1.26	1	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
AR-2 Stadium Arrival	20	26	27	29	30	1.30	1.35	1.45	1.50	1	1.5[‡]	2.5[‡]	2.5	2.5	2.5	2.5	2.5	2.5
DR-1 South Departure	24	51	54	57	60	2.13	2.25	2.38	2.50	1	1	1	1.5[‡]	1.5[‡]	1.5	2.5	2.5	2.5
DR-2 North Departure	26	45	47	50	51	1.73	1.81	1.92	1.96	1	1	1	1.5	2.5	2.5	2.5	2.5	2.5
Subtotal (Men)										4	6	7	8	9	9	10	10	10
Parallel monitoring positions (Men)										2[§]	2[§]	2[§]	4[**]	4[**]	4[**]	4[**]	4[**]	4[**]
Flight data positions (Men)										0	0	0	0	0	0	0	0	0
Total (Men)										6	8	9	12	13	13	14	14	14
Manning factor (1975 Base)										0.86	1.14	1.29	1.71	1.86	1.86	2.00	2.00	2.00

*Source: "Application of ATC Terminal Standard for PY 1975," computer printout manuscript, Air Traffic Service, FAA (1976)
†Traffic growth potential = capacity/1975 traffic
‡Coordinator (1/2-man) required for companion sector
§Performance monitoring function only assumed
**Final sector function assumed

Table 86

DAY-SHIFT, PEAK-HOUR MANNING CALCULATIONS
LOS ANGELES TRACON
SYSTEM 5--RNAV

Sector	1975 Busy-day, Day-shift, Peak-hour Traffic (ac/hr)*	IFR Sector Capacity by Team (ac/hr)				Traffic Growth Potential by Team†				Manning Requirement by Traffic Growth Factor (controllers/team)								
		1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0 Man	1.5-Man	2.0-Man	2.5-Man	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
AR-1 Downey Arrival	34	35	37	39	43	1.03	1.09	1.15	1.26	1	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
AR-2 Stadium Arrival	20	26	27	29	30	1.30	1.35	1.45	1.50	1	1.5‡	2.5‡	2.5	2.5	2.5	2.5	2.5	2.5
DR-1 South Departure	24	52	55	58	61	2.17	2.29	2.42	2.54	1	1	1	1	1.5‡	1.5	2.5	2.5	2.5
DR-2 North Departure	26	47	49	51	53	1.81	1.88	1.96	2.04	1	1	1	1	2.5	2.5	2.5	2.5	2.5
Subtotal (Men)										4	6	7	7	9	9	10	10	10
Parallel monitoring positions (Men)										2§	2§	2§	4**	4**	4**	4**	4**	4**
Flight data positions (Men)										0	0	0	0	0	0	0	0	0
Total (Men)										6	8	9	11	13	13	14	14	14
Manning factor (1975 Base)										0.86	1.14	1.29	1.57	1.86	1.86	2.00	2.00	2.00

*Source: "Application of ATC Terminal Standard for PY 1975," computer printout manuscript, Air Traffic Service, FAA (1976)
†Traffic growth potential = capacity/1975 traffic
‡Coordinator (1/2-man) required for companion sector
§Performance monitoring function only assumed
**Final sector function assumed

Table 87

DAY-SHIFT, PEAK-HOUR MANNING CALCULATIONS
LOS ANGELES TRACON
SYSTEM 6--DABS DATA LINK

Sector	1975 Busy-day, Day-shift, Peak-hour Traffic (ac/hr)*	IFR Sector Capacity by Team (ac/hr)				Traffic Growth Potential by Team†				Manning Requirement by Traffic Growth Factor (controllers/team)								
		1.0-Man	1.5-Man	2.0-Man	2.5-Man	1.0 Man	1.5-Man	2.0-Man	2.5-Man	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
AR-1 Downey Arrival	34	47	49	53	53	1.38	1.44	1.56	1.56	1	1	2	2	2	2	2	2	2
AR-2 Stadium Arrival	20	36	38	40	40	1.80	1.90	2.00	2.00	1	1	1	1	2	2	2	2	2
DR-1 South Departure	24	56	60	65	65	2.33	2.50	2.71	2.71	1	1	1	1	1	1	2	2	2
DR-2 North Departure	26	54	56	60	60	2.08	2.15	2.31	2.31	1	1	1	1	1	2	2	2	2
Subtotal (Men)										4	4	5	5	6	7	8	8	8
Parallel monitoring positions (Men)										0	0	0	0	2**	2**	2**	2**	2**
Flight data positions (Men)										0	0	0	0	0	0	0	0	0
Total (Men)										4	4	5	5	8	9	10	10	10
Manning factor (1975 Base)										0.57	0.57	0.71	0.71	1.14	1.29	1.43	1.43	1.43

*Source: "Application of ATC Terminal Standard for PY 1975," computer printout manuscript, Air Traffic Service, FAA (1976)
†Traffic growth potential = capacity/1975 traffic
‡Coordinator (1/2-man) required for companion sector
§Performance monitoring function only assumed
**Final sector function assumed

only one of the sectors may actually need the coordinator (i.e., to match team capacity with the traffic projection).

In regard to arrival operations, we assume that some special manning expansions may be applied to handle traffic growth beyond the traffic level at which both the arrival sectors reach their team manning limit (i.e., 2-men for DABS data link, and 2.5-man for the other systems). For our purpose, we assume that each parallel monitor position will be expanded (possibly by being transformed into the equivalent of two final sectors), and we add one controller to each. For example, under ARTS III operations in Table 82, we assume four controllers will replace the two parallel monitors at the 1.5 traffic factor in order to alleviate the workload of the two arrival sectors.

We next estimate the flight data position manning requirements needed to operate the flight progress strip printers. No flight data positions were manned during our observations at Los Angeles TRACON; two flight strip pointers are serviced by the two departure sector teams, and computer printed strips are not delivered to the arrival sectors. As in our Bay TRACON analysis, we assume that under the ARTS III Base System, manning of two flight data positions (to distribute arrival and departure flight strips) could be delayed at most until traffic activity doubles, as shown in Table 82. Also in Table 82, we assume that one of these positions would be manned earlier to support arrival operations when these sector teams reach their manning levels. However, the automated data handling system is assumed to eliminate flight strip printers and attendant manning, and flight data position manning equals zero in Tables 83 through 87 for all the alternative UG3RD systems.

The total multi-sector day-shift minimum manning requirements are calculated by summing the sector team, parallel monitor and flight data manning for each traffic factor. (The manning estimates do not include staffing allowances[12] for administration, relief, annual and sick leave, excess shift capacity, training, and special assignments.) We estimate that a total of seven manned positions correspond to the 1975 day-shift traffic (1.0 traffic factor) for the ARTS III base system, as shown in Table 82. This 1975 manning level defines the base manning factor (1.0 in Table 82), and is used as the reference for calculating manning factors for each traffic-factor increment under each alternative ATC system. That is, the manning factor data shown in Tables 82 through 87 relate each projected manning requirement to that calculated for the 1975 ARTS III base system.

2. Manning Comparisons

Our manning factor calculations corresponding to selected traffic factors are summarized by ATC system in Table 88. The manning factor estimates represent adjustments to sector, parallel monitor, and flight data positions needed to handle increases in 1975 traffic activity. Consultation with Los Angeles TRACON personnel showed that they envisioned no further reconfiguration beyond the current four-sector/two-parallel feeders design. Therefore, the expansion of the parallel monitor manning assumed in this analyses is based on our judgment regarding the need for position additions if significant traffic growth were to occur.

This manning estimation procedure as applied to Los Angeles TRACON does not account for the possible traffic constraining delays induced by terminal airspace capacity limitations. Based on our consultations with the TRACON personnel, field observations, and operations analyses, we conclude that whatever critical delay-producing bottleneck situations may exist are related to LAX airport constraints rather than terminal airspace constraints.

In regard to delay-related implications of future operations, the manning requirements in Table 88 are shown generally to increase as traffic approaches twice the 1975 level and to gradually level off as traffic increases beyond the 2.0 factor (or thereafter, depending on the alternative UG3RD system). The leveling-off is due to the inability of adding controllers to those sector teams operating at their maximum manning level. Therefore, certain sectors are workload saturated and cannot handle additional traffic. In fact, delays may be induced earlier by the arrival sectors, which reach maximum manning before the traffic projection doubles. However, delays generated by terminal airspace should not be significant because traffic at LAX is forecast to increase only by 30 percent (relative to 1975) by the year 2000.*

Since major workload saturation situations would occur if traffic increases significantly beyond the 2.0 factor, such traffic disruptions would cause significant change to the operational assumptions we have made in modeling sector capacity and manning. Therefore, as far as the manning factor estimates in Table 88 are concerned, we suggest that comparisons using these data be made between systems only for those traffic factors at or below 2.0. Comparisons at the higher traffic levels

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*Airport traffic activity forecast provided by FAA (AVP), October 1975.

Table 88

LOS ANGELES TRACON MANNING FACTOR ESTIMATES

	Day Shift Manning Factor by Traffic Growth Factor (1975 Base)						
ATC System \ Traffic Factor	1.0	1.25	1.5	1.75	2.0	2.5	3.0
1. Current ARTS III	1.00	1.29	1.85	2.00	2.29	2.29	2.29
2. + Automated Data Handling	0.86	1.14	1.57	1.71	1.86	2.0	2.0
3. + Basic Metering and Spacing	0.86	1.14	1.29	1.71	1.86	2.0	2.0
4. + Sector Conflict Probe	0.86	1.14	1.29	1.71	1.86	2.0	2.0
5. + RNAV (100% Avionics)	0.86	1.14	1.29	1.57	1.86	2.0	2.0
6. + DABS Data Link (100% Avionics)	0.57	0.57	0.71	0.71	1.14	1.43	1.43

would have no realistic meaning, particularly since Los Angeles TRACON is not expected to operate at these levels. In the following paragraph, we do examine manning requirements at the 1.0 and 2.0 traffic factors for sake of comparing the potential operational impacts of the alternative ATC systems.

In Table 88, the ARTS III base system is shown to be capable of handling a doubling of 1975 traffic if manning is more than doubled (i.e., increased by 129 percent relative to 1975 manning). Significant reductions in these manning requirements are associated with the automated data handling and DABS data link operations. Automated data handling reduces manning (relative to ARTS III) by 14 percent for the 1.0 traffic factor, and by 37 percent for the 2.0 traffic factor. DABS data link reduces manning (relative to ARTS III) by 43 percent and 115 percent, respectively, for the 1.0 and 2.0 traffic factors. This shows that the fully upgraded system is capable of handling twice the 1975 traffic with only a 14 percent increase in the current manning complement.

Appendix

POTENTIAL CONFLICT MODELS AND APPLICATIONS

This appendix describes mathematical models for estimating the expected frequency of potential conflicts and their applications to the eleven selected sectors of the Bay TRACON. This examination of sector potential conflict situations was performed using techniques based on the RECEP methodology developed during previous SRI research, and adapted to the Bay TRACON operations in accordance with our on-site observations, data collection and controller interviews.

A. Potential Conflict Frequency Models

Potential conflicts are projected violations of separation minimums perceived by controllers. Since this project was concerned with radar environment, the ATC radar separation minimums are the criteria to be maintained. These criteria, based on our observations of the actual separations exercised by controllers, are:

- Aircraft are separated by at least 1,000 feet in altitude.
- Aircraft on departure routes about to enter ARTCC airspace are separated by at least five nautical miles.
- All other aircraft are separated by three to six nautical miles, depending on the sizes and vortex generating capabilities of the aircraft involved.

The three primary means by which these separation minimums can be violated are by (1) the intersection of two aircraft flight paths, (2) one aircraft overtaking another, or (3) the merging of two or more flight paths into one. The possible events resulting from these violations are listed in Table A-1. Since there are differences in the difficulty of resolving the potential conflicts resulting from these events, the events should also be classified by type of aircraft involved, such as nonmilitary versus nonmilitary, military versus nonmilitary, and military versus military. However, during this project, there were not sufficient data to make these distinctions meaningful.

Table A-1

EVENTS RESULTING IN VIOLATION OF RADAR SEPARATION MINIMA

Crossing conflicts	Intersection of two aircraft flight paths at the same altitude. Intersection of a transitioning (climbing or descending) aircraft with a level aircraft at altitude. Intersection of two transitioning aircraft.
Overtake conflicts	Aircraft at the same latitude. Aircraft transitioning on the same track. Aircraft on separate but merging tracks where the merge sequence has been set up at an upstream area, requiring "holes" to be maintained in each feeder traffic stream.
Merging conflicts	The aggregation of two or more "feeder" flight paths at the same point in space.

SRI has developed a number of simple mathematical models for predicting the expected number of such conflict events. Data acquired in our hour-long measurement phases were used to estimate the expected frequencies of conflict events for the air routes comprising each investigated sector. The actual development of the models used to predict the expected number of conflicts within and between air routes is described in Reference 13. Only the resulting expressions are presented here.

1. <u>Crossing Conflict Events</u>

The frequency of conflict events at an air route intersection depends on the aircraft flow rate and velocity along each route, the minimum separation requirements, the angle of intersection between the routes, and the number of flight levels at which conflicts would potentially occur. The average frequency of conflicts at an intersection can be found from:

$$C_x = \sum_i^2 \frac{n_{i1} n_{i2} s \sqrt{v_{i1}^2 + v_{i2}^2 - 2v_{i1} v_{i2} \cos \alpha}}{v_{i1} v_{i2} \sin \alpha}$$

where

- C_x = average number of crossing conflicts per hour at intersection x
- n_{i1} = flow of aircraft at flight level i along route 1 (aircraft per hour)
- n_{i2} = flow of aircraft at flight level i along route 2 (aircraft per hour)
- s = separation minimum used by controllers (nautical 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
- Σ = indicates the summation over all flight levels at which conflicts may occur.

Intersections of more than two air routes were treated by finding the sum of the expected number of conflicts between all possible pairs of air routes. The expected number of conflicts were calculated for each flight level considered, and summed over all flight levels to determine the total conflict frequency associated with that interaction.

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. A transitioning aircraft can conflict not only with air traffic at the actual route crossing altitude, but also, because of 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-to-level crossings at the "blocked" altitudes. Therefore, calculating the expected number of such conflicts entails summing the expected number of crossing conflicts at each flight level affected by the transitioning route. The number of altitudes that are affected is a function of climb/descent angle and separation criteria. Procedures developed[3] can be used to determine the vertical distance required (and therefore the number of flight levels affected) by a transitioning aircraft flow while crossing an air route. Knowing this value and the vertical separation minimum, it is possible to determine which flight levels are affected by this event. The number of potential conflicts resulting between the aircraft flow on each of these flight levels and the flow on the transitioning route can then be determined and summed.

2. <u>Merging Conflict Events</u>

The frequency of conflict events at each flight level of an air route merge point is assumed to be one-half that of a full air route intersection with similar flow rates, velocities, separation requirements, and angles of intersection. Potential violations of separation minimums downstream from the common merge point are treated as overtaking conflicts since the interacting aircraft traffic streams are in trail, or overlapping in this area. The average frequency of merging conflicts per hour, M_y, at merge point, y, is simply

$$M_y = \sum \frac{n_{i1}\, n_{i2}\, s \sqrt{v_{i1}^2 + v_{i2}^2 - 2v_{i1}v_{i2}\cos\alpha}}{v_{i1}v_{i2}\sin\alpha} \tag{2}$$

where Equation (2) parameters are the same as defined for Equation (1).

3. <u>Overtake Conflict Events</u>

The expected frequency of overtakes along a level or transitioning route and between level and transitioning routes in the same direction can be determined from the following relationship

$$O_t = \sum_{i=1}^{m-1} \frac{(\ell + 2s)n_i}{v_i} \sum_{k=i+1}^{m} \frac{n_k}{v_k} \left| v_i - v_k \right| \quad , \tag{3}$$

where

O_t = average number of overtakes per hour along route z

m = number of discrete speed categories along the route

ℓ = length of air route (nautical miles)

n_i = flow rate of aircraft travelling at the i^{th} speed (aircraft per hour)

v_i = average speed of the i^{th} speed class (knots)

n_k = flow rate of aircraft travelling at the k^{th} speed (aircraft per hour)

v_k = average speed of the k^{th} speed class (knots)

s = separation minimum used by controllers (nautical miles)

$|v_i - v_k|$ = magnitude of the difference in velocities of the two speed categories.

In this relationship, the summation symbol (Σ) indicates 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.

B. Sector Conflict Frequency Factors

Equations (1), (2), and (3) estimate the expected number of potential conflict occurrences at a single confliction point or route for a given rate of flow within each route. These relationships may be used to calibrate a generalized conflict occurrence model in which sector conflict event frequencies are related to overall sector traffic

Number of crossing conflicts/hour = $e_a N^2$

Number of local merging conflicts/hour = $e_m N^2$

Number of overtaking conflicts/hour = $e_o N^2$

Number of coordinated approach merging conflicts/hour = $e_a N^2$

where:

N is the number of aircraft/hr through the sector

e_c, e_m, e_o and e_a respectively are frequency factors that measure the rates of occurrence of crossing, local merging, overtaking, and coordinated approach merging conflicts for the sector measured in (conflicts/hr)/(aircraft/hr)^2

The frequency factors, e_c, e_m, e_o, and e_a are calculated (as described below) using Equations (1), (2), and (3) for a single set of traffic route flow, route distribution and speed class data for a sector. This data set describes the mutually occurring conflict events associated with one specific hourly traffic flow rate through the sectors. The conflict occurrence results are summed over all conflict points and routes to obtain the expected number of potential crossing (E_c), local merging (E_m), overtaking (E_o), and coordinated approach merging (E_a) conflicts/hr for the entire sector:

$$E_c = \sum_x C_x \text{ for all intersection points } x = 1,2,\ldots$$

$$E_m = \sum_y M_y \text{ for all local merge points } y = 1,2,\ldots$$

$$E_o = \sum_z O_z \text{ for all routes } z = 1,2,\ldots$$

$$E_a = \sum_y M_y \text{ for all approach merge points } y = 1,2,\ldots$$

Recall that C_x, M_y and O_z are calculated as functions of pairwise products or bilinear functions of traffic flow rates on individual routes through the sector. The corresponding sector traffic flow rate, n, measured in aircraft/hr. is:

$$n = \sum_z n_z \text{ for all routes } z = 1,2,\ldots$$

The frequency factors as a function of sector traffic are calculated as follows:

$$e_c = \frac{E_c}{n_e^2}$$

$$e_m = \frac{E_m}{n_e^2}$$

$$e_o = \frac{E_o}{n^2}$$

$$e_a = \frac{E_a}{n^2}$$

Assuming the traffic along each route will vary in direct proportion to the traffic distribution used in our calibrations (and that other parameters also remain fixed), the products e_cN^2, e_mN^2, e_oN^2, and e_aN^2 estimate the number of conflicts per hour corresponding to any value of N aircraft/hour through the sector. We need not calculate individual values of C_k, M_k, and O_k for each intersection, merge and route for each value of N.

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