puts, which are more appropriate in looking at longer term considerations such as implementation of FAA engineering and development program products.

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Capacity of Terminal Airspace Sectors

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Current air traffic control facilities in terminals that operate with automated radar terminal system III equipment require controllers to (a) monitor displays of radar-derived situation data; (b) make decisions; (c) voice communicate with pilots to transmit clearances, maneuver instructions, proximate traffic, and navigational advisories; (d) communicate with other controllers to coordinate their control actions; and (e) maintain computerized and hard-copy data records describing aircraft flights. The time spent performing these activities depends on local traffic routing characteristics and related procedural control requirements, including visual versus instrument airport approach operations. The work-load models differentiate the work activity characteristics of various airspace sectors and quantify traffic capacity (aircraft per hour) according to the number of persons assigned to a sector control team. The modeling approach demonstrated uses field data collected at the Oakland Bay Terminal radar approach control facility. Traffic capacities are calculated for various sector operational alternatives that represent current and proposed automated control systems.

Various Federal Aviation Administration-sponsored studies examined the potential impact of automation on air traffic control operations (1, 2, 3, 4). Techniques were developed that relate the traffic-handling capabilities of air traffic controllers to their operational work requirements. This paper describes the methodology used to model terminal airspace capacity corresponding to controller work-load constraints. Specifically, I examine the airspace under the jurisdiction of high-density terminal radar approach control (TRACON) facilities that currently are operating with automated radar terminal system (ARTS) III equipment.

The methodology uses field observations to define operational requirements of TRACON facilities and identify the control work activities associated with the current ARTS III equipment. The field data are used to structure and apply mathematical descriptions of control work requirements, which are adjusted to represent postulated future air traffic control automations.

OPERATING CHARACTERISTICS OF TRACON FACILITIES

This paper addresses the traffic capacity aspects of TRACON operations, as distinguished from airport traffic control tower and air route traffic control center operations. The TRACON-controlled terminal airspace is a transition zone between airports and en route airspace, which 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 in the sector's airspace. Sectors are configured according to a system of airport arrival and departure routes; the control operations for each sector are procedurally structured and integrated to facilitate traffic flow and separation assurance.

The terminal area route structure is designed to segregate the major arrival traffic flows from departure traffic flows. This minimizes conflicts between descending and climbing aircraft, which could become frequent and difficult to control in dense traffic situations. Route segregation is achieved procedurally by means of formal altitude separation (tunneling one route under another) and geographic separation (defining arrival and departure corridors). In some terminal areas, especially those serving numerous airports, the complexity of the required route network and airspace constraints preclude the complete segregation of arrival and departure traffic. The degree of procedural segregation achievable, however, is normally sufficient to arrange sectors along predominant inbound and outbound routings.

Arrival Operations

Arrival traffic flows from diverse directions are integrated by means of a series of merges. The merging operations require arrival sector controllers to determine the sequence for processing aircraft through the merge points while maintaining proper spacing. The controller is guided by a system of procedural specifications. The center conducts initial route mergings in order to organize the traffic according to control specifications required for entry to the terminal airspace. By this means, aircraft are brought into TRACON arrival sectors along defined routes according to prespecified or negotiated in-trail separations 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 airport final approaches. Control jurisdiction is then transferred to the tower, in accordance with the appropriate in-trail separation, speed, and altitude specifications. Radio communications are necessary for issuing speed, altitude, and vectoring commands to slow all descending aircraft to approach speed, clear them along their planned routes, sequence them through the merges, and space them to maintain separation.

At some TRACON facilities, such as at Oakland Bay, which controls traffic into San Francisco International Airport (Figure 1), arrival operations are based on the feeder and final sector concept. Under this concept, a feeder sector's controller accepts aircraft entering from a center, processes the aircraft through its airspace, and transfers control jurisdiction to a final sector's controllers. The latter continue controlling the aircraft until the aircraft approach airport runways, when control jurisdiction is transferred to a tower. In this operation, a feeder sector's controllers establish the arrival traffic organization plan, since they determine the sequence in which aircraft are cleared for landing.

At other TRACON facilities, such as at Los Angeles, operations in a designated arrival sector are not delineated according to feeder and final sector pairs. However, either design concept may be used to handle traffic in separate or parallel routing corridors. For example, one feeder and final pair or one arrival sector may control aircraft destined for a specific runway or runway complex of an airport, while an identical sector operation may control aircraft destined for other runways. At some TRACON facilities, such as both Oakland Bay and Los Angeles, two traffic corridors converge to final approaches to parallel runways. Here, a feeder and final pair or an arrival sector may operate relatively independently of its complementary sectors, especially during visual approach conditions. However, if the runway configuration design is such that aircraft on the parallel approach courses are in lateral proximity, special precautions must be taken to ensure adequate aircraft separation during instrument approaches (where poor visibility precludes the pilot's separation assistance). Each final feeder or arrival sector's controllers must coordinate their sequencing and spacing operations with those of the parallel sector to integrate their traffic for airport approach.

In summary, arrival sector operations depend on the traffic requirements of each TRACON site. Controllers handle local merging operations for aircraft directly under their control and also influence merging situations in downstream sectors. During instrument landing operations, controllers coordinate approach mergings with other controllers. Such coordination may be unnecessary during visual approach operations. Additionally, controllers must maintain separation assurance for aircraft that are potentially in conflicting situations while at the same time facilitating the flight of aircraft in accordance with pilot plans and procedural requirements.

Departure Operations

Departure sector operations differ from those of arrival sectors only in that (a) aircraft are usually diverging rather than merging and (b) control requirements do not depend on visual versus instrument approaches. Departure sector controllers accept climbing aircraft from an airport tower, process the aircraft through their airspaces, and transfer control jurisdiction to a center when the aircraft enter en route airspace. Some local merging may occur in order to integrate takeoffs from other runways or airports. Although parallel departure sectors may be designated (as at the Oakland Bay TRACON site), departure routings are usually sufficiently separated so that extensive coordination between controllers of different departure sectors is unnecessary.

ARTS III OPERATIONS

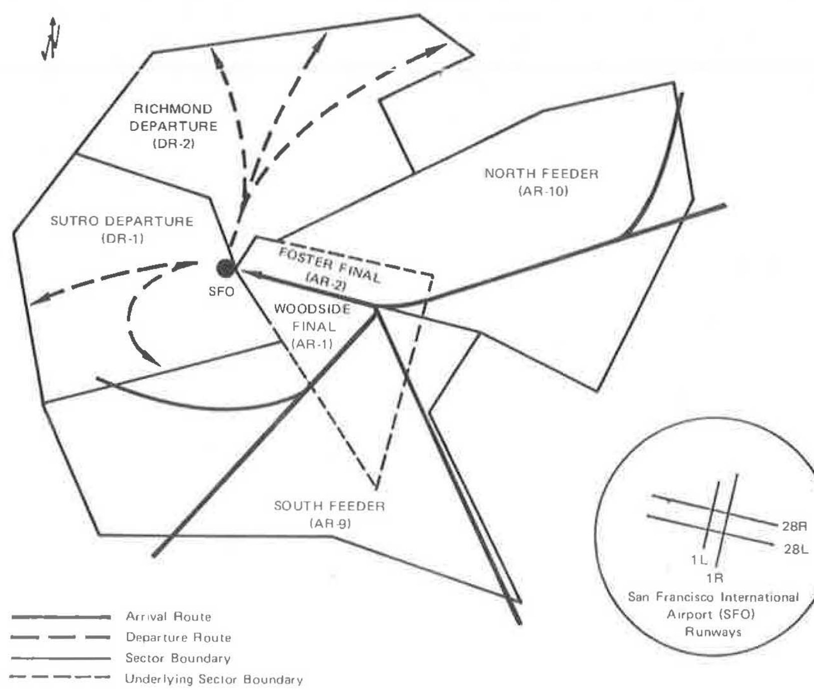
ARTS III is a semiautomated terminal air traffic control support system composed of a computerized data acquisition subsystem, data processing subsystem, and data entry and display subsystem. ARTS III equipment design affects the control actions performed and the allocation of work duties among a controller team.

ARTS III supports control operations through (a) the presentation of alphanumeric data on sector controllers' radar displays, (b) the semiautomatic transfer of data between sectors, and (c) the automatic transfer of flight data between the terminal and center computers. Each sector teams's operating console contains the ARTS III automation devices.

An ARTS III console includes a plan view display (PVD) and keyboard and track-ball units that jointly provide a data entry and display interface between the controllers and the computer system. The PVD is the sector team's primary display device and presents radar-derived aircraft situation and computer-processed alphanumeric and symbolic data. The presentation includes

1. Primary radar targets,
2. Beacon targets,
3. Control position symbols,
4. Aircraft data blocks (from beacon targets only),
5. Video maps,
6. Tabular lists (arrival-departure and coast-suspend lists),

Figure 1. Primary arrival and departure routes for Oakland Bay TRACON.



7. Time,
8. Altimeter setting,
9. Selected beacon codes, and
10. General system information (e.g., weather).

A track-ball and keyboard unit operates in conjunction with the PVD to provide the controller-computer interface mechanisms for data entry and display control. The unit includes a track-ball panel, alphanumeric keys, and quick action, special function keys. The track ball is used manually to slue and capture PVD targets; 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 and manually initiate or drop beacon tracking).

In addition to the ARTS III automation, the sector console includes air to ground (A/G) radio and interphone communication apparatus and work space needed to maintain flight strip or paper scratch pad data records. A/G communications enable two-way voice conversation between pilot and controller; interphone communications enable two-way voice conversation between controllers of different sectors or facilities. Hard copy records provide flight data to supplement PVD-displayed data and are updated by hand.

Sector Control Responsibilities

The lead member of an ARTS III sector team is the radar controller, who is responsible for separation assurance, minute-to-minute decision making, and A/G voice communications. The radar controller may be supported by a coordinator, a hand-off controller, or both. During periods of light traffic, the radar controller may be the only controller in the sector and performs all necessary communications and related data processing activities. As traffic increases, the radar controller's work-load requirements become restrictive, necessitating the allocation of some operational activities to one or both of the other team members.

A single hand-off controller may be assigned to assist a radar controller, but a coordinator is assigned to a pair of sectors and simultaneously supports both radar controllers. As a result of the shared nature of coordinators' services, there are four sector team regimes:

1. A 1-person team (radar controller);
2. A 1.5-person team (radar controller and 0.5 coordinator);
3. A 2-person team (radar and hand-off controllers); or
4. A 2.5-person team (radar and hand-off controllers and 0.5 coordinator).

The ARTS III console is organized so that each controller and coordinator is equipped with keyboard and interphone apparatus and the radar controller has direct access to a single PVD and track-ball panel. Each radar controller is equipped with A/G apparatus and all sector team members may handle flight strips or paper scratch pads, depending on local operating procedures. The equipment arrangements enable the effective division of control responsibility among sector team members.

Roles of Sector Control Members

In a one-person team the radar controller performs all of the sector control operations necessary to ensure separation and facilitate traffic flow. These operations include PVD surveillance, A/G communications, data entry and display, flight strip or paper scratch pad data processing, intersector interphone and face-to-face coordination, and related decision making.

In a 1.5-person team the radar controller maintains responsibility for ensuring separation and minute-to-minute decision making, but shares traffic planning decision making with the coordinator. The coordinator performs intersector coordination and some data entry operations, while the radar controller performs separation assurance, surveillance, and related data processing operations. Based on observed control activities, the coordinator is usually able to perform the interphone communications for both sectors he or she is supporting and half of the computerized hand offs for each sector. However, these activities induce some additional face-to-face communications with the radar controller because he or she must advise the radar controller about the completed intersector negotiations. A coordinator supports a pair of arrival sectors, determines the sequence for merging aircraft, and advises each radar controller of his or her plan. Each radar controller sets up 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 is also conducted with adjacent centers. The coordinator may assist in distributing flight strips to the appropriate radar controller.

In a two-person team the radar controller maintains responsibility for ensuring separation and facilitating traffic flow and shares some of the mechanical aspects of control operations with the hand-off controller. The hand-off controller supports only one radar controller and should have time, therefore, to perform the routine interphone communications and computer hand-off operations. The radar controller must coordinate sequencing and spacings for merges with other sector teams while performing surveillance and the remaining communications and data processing activities. Again, direct intrasector communications are needed to maintain operational cognizance of each team member's activities. The hand-off controller may also assist the radar controller by arranging and correcting flight strips.

In a 2.5-person team the radar controller maintains responsibility for ensuring separation and minute-to-minute decision making, but shares traffic planning decision making with the coordinator and delegates some of the mechanical control tasks to the hand-off controller. The coordinator is primarily concerned with integrating intersector and interfacility operations and is active, therefore, in interphone and face-to-face communications. Where appropriate, he or she also assists in flight strip distribution. The hand-off controller performs interphone communications not handled by the coordinator, carries out computer data entry and display operations, and may assist the radar controller with flight strip preparation.

WORK-LOAD MODELING

The work-load modeling approach estimates the traffic-handling capabilities of an individual sector by encoding the controller work associated with the sector's operational requirements. This approach develops work-load models for each of the four team regimes during instrument and visual approach operations. The models are based on the frequency of occurrence of specific control events and the minimum time required to perform each event. These data are obtained by observation at a TRACON study site.

A major work-load modeling assumption is that the controller's work load, determined by his or her operational requirements, is the factor limiting the number of aircraft that can be handled by the controller during any given period of time and, thus, determining the traffic capacity of the sector. Past observations (1) of air traffic control activities indicate that within a given period of time there is a maximum total time that a controller can spend performing control tasks. For instance, a radar controller's work-load threshold has been found to be typically 48 person-min/h, and the number of aircraft per hour that generates this amount of work represents his or her traffic capacity. In effect, over a long period of time, such as 1 h, radar controllers can be expected to spend, at most, 80 percent of the 60 min available doing control work. This work-load limit enables them to handle the very intense traffic and work-load surges that typically occur over a short period of time (5 to 10 min) but that could not be handled if they worked more than the 48 person-min/h limit.

The objective of a work-load model is to correlate work time requirements with traffic flow rates to identify the traffic flow rate (capacity) corresponding to the work-load threshold. The 1-h period is used as a base for capacity estimation because this is the time a controller normally spends at a sector position.

In modeling terminal sector operations, the radar controller's work load (with a 48 person-min/h threshold) is considered the critical determinant of the traffic capacity of a sector team. That is, the radar controller, rather than the coordinator or the hand-off controller, is the team member whose work-load requirements will limit traffic-handling capabilities. These conclusions are based on the observation that a significant proportion of terminal air traffic control work is centered on surveillance, quick decision making, and A/G communications that are not delegated to other positions under any of the alternate sector team regimes. Therefore, the radar controller work-load model incorporates each of the four regimes. The regimes will be differentiated by remodeling the radar controller's operational requirements each time an additional controller or coordinator is added to the team. In each case, the radar controller's work-load threshold will be used to define the sector team's traffic capacity.

Model Structure

Operational activities are mutually integrated and interactive and are very difficult to model as independent entities. Therefore, the various control work requirements are aggregated into activity categories that represent operational relations. For modeling purposes, control requirements are organized according to routine work, surveillance work, and conflict processing work.

Routine work includes A/G, interphone, and face-to-face communications; data entry and display operations; and flight strip or paper scratch pad data processing tasks needed to facilitate traffic flow. Surveillance work is the visual observation of the PVD data to facilitate following flights. 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 these actions with other controllers. The potential conflicts are categorized further according to crossing, local merging, overtaking, and coordinated approach merging. Radar controller work-load time (W_R) measured in person-minutes per hour and corresponding to a specified hourly traffic rate, is calculated by using the following additive formulation:

$$W_R = [k_1 N + ct_s N + (k_2 + k_3 + k_4 + k_5)N^2]/60 \quad (1)$$

where

- N = number of aircraft per hour through the sector,
- t_s = average sector flight time (min),
- c = surveillance work-load constant (person-s/aircraft-min),
- k_1 = routine work-load weighting (person-s/aircraft),
- k_2 = crossing conflict work-load weighting [(person-s/h)/(aircraft/h)^2],
- k_3 = local merging conflict work-load weighting [(person-s/h)/(aircraft/h)^2],
- k_4 = overtaking conflict work-load weighting [(person-s/h)/(aircraft/h)^2], and
- k_5 = coordinated approach merging conflict work-load weighting [(person-s/h)/(aircraft/h)^2].

A set of four radar controller work-load times (W_R), corresponding to the four regimes, is calculated for each sector. The regimes are distinguished by adjusting the work-load weighting parameters (k).

The importance of the work-load component structure of the radar controller model is its capability to distinguish the control work requirements of different sectors in a manner that is sensitive to each sector's operational characteristics. Sector routine work-load 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 work-load 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 less frequent.

The surveillance work-load 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 to traffic flow rate. The flight time parameter (t_s) distinguishes the surveillance work requirements of different sectors, since the same surveillance work-load constant (c) applies to each sector. The product (ct_s) is the surveillance work-load weighting measured in person-seconds per aircraft.

In the processing of potential crossing, local merging, overtaking, and coordinated approach merging conflicts, work-load 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 work-load weightings (k_2, k_3, k_4, and k_5) calculated for one sector 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 work-load weightings can model a variety of aircraft crossing and merging situations (e.g., level to level, level to climb, climb to climb, level to descent).

The routine work-load time (k_1N) represents the time required by normal control events to clear aircraft through the sector. Field data collected for each sector are used to identify the routine control events, specify the set of tasks required for each event, determine task performance times (minimum times), and measure the frequency of occurrence of each event by sector.

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

1. Control jurisdiction transfer,

2. Traffic structuring,
3. Pilot request,
4. General intersector coordination, and
5. General system operation.

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

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

1. Air-to-ground communications,
2. Computer data entry and display operations,
3. Flight strip or paper scratch pad data processing,
4. Interphone communications, and
5. Face-to-face direct voice communications.

For example, one control event routinely required for control jurisdiction transfer is hand-off acceptance. This event requires that the controller perform manual data entry and display operations and flight strip data 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.

Results of field experiments enable the specification of individual task times and the frequency of occurrence of each event by sector for any given team regime. These data are used to calculate the routine work-load weighting (k_1).

$$k_1 = \sum_i \sum_j r_i t_{ij} \qquad (2)$$

where

r_i = frequency of occurrence of type i routine events (events/aircraft), and
t_{ij} = minimum performance time required for each type j task included in routine event i (person-s/event).

Surveillance work-load time (ct_sN) is the time spent scanning the PVD. Past field data collection efforts were unable to measure the number of times a controller looks at the PVD or the duration of each look. The following assumptions were developed from interviews with controllers and reflect their perceptions.

To maintain a mental picture of traffic movement, the radar controller is likely to look at an aircraft's data display once every minute; 1 to 1.5 s/look is sufficient time to identify aircraft and recognize or recall situations. The assumptions (1.25 person-s/look and 1 look/aircraft-min) set the surveillance work-load constant (c) equal to 1.25 person-s/aircraft-min. The corresponding surveillance work-load weighting is 1.25 t_s person-s/aircraft.

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

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

$$k_2 = t_c e_c \quad k_3 = t_m e_m \quad k_4 = t_o e_o \quad k_5 = t_a e_a \qquad (3)$$

where

t_c, t_m, t_o, t_a = minimum performance times required for crossing, local merging, overtaking, and coordinated processing of approach merging conflicts (person-s/conflict), and
e_c, e_m, e_o, e_a = conflict event frequency factors that measure the rates of occurrence of crossing, local merging, overtaking, and coordinated processing of approach merging conflicts [(conflicts/h)/(aircraft/h)^2].

Conflict processing times (t_c, t_m, t_o, and t_a) are determined by estimating and summing the minimum times needed for the detection and assessment, resolution, and coordination tasks. These task times are based on field observation of control activity and subsequent interviews of controllers; videotape playback of the observed situation is used 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 occur at one or more conflict points in the sector. These factors are calibrated for each sector through the use of mathematical models that determine the expected frequency of occurrence 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 as perceived by controllers. These relations are formulated as the summation of the probability of pairwise conflicts between aircraft and are described by Siddiqee (5, 6).

OAKLAND BAY TRACON CASE STUDY

A field experiment conducted at the Oakland Bay TRACON site during March 1976 examined the operational activities of the six sectors handling arrival and departure traffic to and from San Francisco International Airport. Data sources included (a) videotape recordings of PVD data; (b) audiotape recordings of A/G and interphone communications; (c) manual observations and stopwatch measurements of controller actions; (d) flight strips and paper scratch pads; and (e) structured interviews with controller and supervisory personnel.

Control event frequencies of occurrence and minimum performance time data needed to calculate the routine, surveillance, and potential conflict work-load weightings for ARTS III operations were determined (4). The work-load weightings were used to calculate radar controller

Table 1. Estimates of sector capacity by team regimes for Oakland Bay TRACON ARTS III.

Sector	Visual Approach Operations (aircraft/h)				Instrument Approach Operations (aircraft/h)			
	1.0-Person	1.5-Persons	2.0-Persons	2.5-Persons	1.0-Person	1.5-Persons	2.0-Persons	2.5-Persons
AR-1, Woodside final	41	44	45	47	37	40	41	42
AR-2, Foster final	41	43	44	45	36	38	38	39
AR-9, South feeder	46	51	53	57	42	47	48	52
AR-10, North feeder	45	49	51	56	40	44	44	49
DR-1, Sutro departure	39	45	48	48	39	45	48	48
DR-2, Richmond departure	37	41	44	46	37	41	44	46

work load for successive 5 aircraft/h increments in traffic flow and to interpolate the sector traffic capacity corresponding to 48 person-min/h of radar controller work. The resulting capacity estimates, by visual and instrument approach operations, are presented in Table 1 for each of the six sectors.

These sector capacities reflect the characteristics of the radar controller activity defined by the work-load 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, but departure sector capacities are not affected by approach conditions. The sector capacities generally increase for each successive increment in the sector team members because the radar controller usually delegates some portion of routine or conflict work to the added team member.

In the modeling of possible future operations, the work-load event frequencies and performance times were judgmentally revised to represent various automation concepts (4). The corresponding work-load weightings and traffic capacities for each sector were determined. Results for sector AR-9 are given below for instrument approach operations under a one-person team.

Air Traffic Control System	Sector Capacity (aircraft/h)
Current ARTS III	42
Plus basic metering and spacing	47
Plus data link	65
Total	154

Under the above conditions, the radar controller's traffic capacity is estimated to increase by 12 percent relative to ARTS III operations when basic metering and spacing is implemented. This automation generates and displays control instructions, which are relayed to arrival aircraft by the radar controller; automatic flight data displays are included. The data link system, which automatically transmits digital messages to aircraft, is estimated to increase capacity by an additional 38 percent.

A similar analysis of automation effects on the capacities of other Oakland Bay TRACON arrival and departure sectors enabled a study of the number of controllers required for each air traffic control system (4).

This study estimated that, with metering and spacing, the same number of controllers required to operate the six ARTS III sectors could handle 50 percent more traffic than they handled in 1975 during a day of heavy traffic. With data link automation, the same number of controllers could handle twice as much traffic. These results depend heavily on the judgments made in constructing the work-load models and should be considered as first order estimates of automation impact.

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