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ADVANCED PRODUCTIVITY ANALYSIS METHODS FOR AIR TRAFFIC CONTROL OPERATIONS

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FINAL REPORT

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16. Abstract

This report gives a description of the Air Traffic Control (ATC) productivity analysis methods developed, implemented, and refined by the Stanford Research Institute (SRI) under the sponsorship of FAA and TSC. Two models are included in the productivity analysis methodology. The first is the Relative Capacity Estimating Process (RECEP) that models the traffic handling capabilities of individual ATC sectors in terms of routine, surveillance, and conflict-processing workloads. The second model is the Air Traffic Flow (ATF) model that simulates a multisector ATC network by tracing aircraft flows from sector to sector; and measuring traffic loadings, workload requirements, and delays under given sets of traffic input parameters and congestion-relief strategy. The report covers the background and application experiences of the two models as well as technical descriptions of their input/output specifications, modle structures, field data collection and reduction techniques, and potential model applications. Finally, a hypothetical example illustrating a typical RECEP/ATF application, together with post-simulation output analyses, are given. A general survey of other similar models and techniques, and their comparisons with RECEP and ATF, are also included in the report.

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PREFACE

Over the past years the Stanford Research Institute (SRI) has developed evaluation methodologies and successive versions of computer models that were used as tools in air traffic control productivity analyses performed for the FAA. Although the results of these analyses were documented in various SRI reports, the evaluation tools themselves and their associated backgrounds and utilities heretofore have not been documented and published as an integrated whole. Under this project, SRI was given the opportunity to examine the models and their applications in order to revise and consolidate those features that deemed to be desirable for both current and future applications and to produce a document that would assist the users in the utilizations of these tools.

Acknowledgement is given to the TSC project technical monitor, Mr. Robert Wiseman, for his effective guidance, participation, and contribution to many technical areas, particularly in the development of new approaches to maximize the efficiency of field data collection and reduction, data base update, and model verification. We also wish to acknowledge the contributions of Dr. Mitchell Grossberg of TSC who investigated and documented the feasibility of new procedures for automatic source data reduction; and Mr. William Petruzel of FAA who gave us much needed guidance and advice in the preparation of this report.

This project was directed by Dr. Paul Tuan, the Project Leader, under the supervision of Dr. Robert Ratner, SRI's Transportation Center Director. Mr. Steven Procter was responsible for the refinements, modifications, and documentation of the Air Traffic Flow (ATF) model; and Dr. George Couluris

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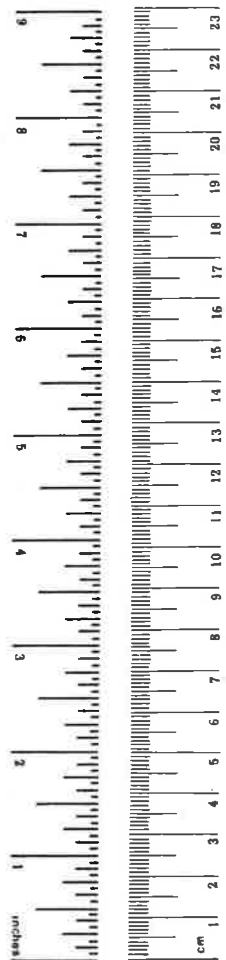
ACRONYM LIST

A/G	Air/Ground
ARTCC	Air Route Traffic Control Center
ARTS	Automated Radar Terminal System
ATC	Air Traffic Control
ATF	Air Traffic Flow
CRD	Computer Readout Device
DART	Data Analysis and Reduction Tool
DSF	Digital Simulation Facility
FAA	Federal Aviation Facility
FDP	Flight Data Processing
GPSS	General Purpose System Simulation
NAFEC	National Air Facility Experimental Center
NAS	National Aviation System
PVD	Plan View Display
RDP	Radar Data Processing
RECEP	Relative Capacity Estimating Process
SAR	System Analysis and Recording
SRI	Stanford Research Institute
TATF	Terminal Automatic Test Facility
TRACON	Terminal Radar Approach Control
TSC	Transportation Systems Center
UG3RD	Upgraded Third Generation
VCU	Voice Channel Utilization
WA	Work Activity
WP	Workpace

METRIC CONVERSION FACTORS

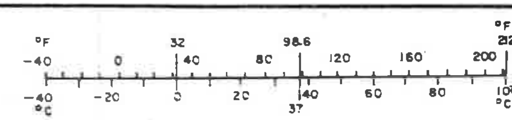
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



EXECUTIVE SUMMARY

Introduction

This report is a description of the evaluation methodologies that have been used by SRI in air traffic control (ATC) productivity analyses performed for the FAA. The models and techniques involved in these analyses have been successively modified and refined over the past years. More recently, under a contract awarded by the Transportation Systems Center, SRI was given the opportunity to examine the models and their applications in order to consolidate and improve those features that are considered to be desirable for both current and future applications. The purpose of this report is to document the major application areas and the analysis method used with an integrated approach in order to assist the FAA in the use of these tools.

The techniques of modeling have long been an important tool to engineers, scientists, and operational analysts. The basic motivation for using models in air traffic control productivity analysis is the search for more knowledge about current systems and to predict the behavior of future systems. Examples of such applications are: (1) the modeling of increased (or decreased) traffic demand of an existing system; (2) the testing of a modified sector organization; (3) the evaluation of a new congestion-relief strategy that has yet to be proven prior to actual field implementation; and (4) the evaluation of the impact of proposed future automation packages. The models described here include the Relative Capacity Estimating Process (RECEP), which relates controller workload to sector traffic capacities, and the Air Traffic Flow (ATF) network simulation model, which assesses traffic capacity and delay in a multisector environment.

Relative Capacity Estimating Process (RECEP)

The RECEP modeling approach estimates the traffic-handling capabilities of an individual sector by encoding, as a set of discrete events, the controller work associated with the sector's operational requirements. RECEP models are mathematical representation of the routine, surveillance, and conflict-processing workload components of a sector team. Routine work tasks involve air/ground (A/G) voice communications; flight data processing (FDP) and radar data processing (RDP) manual data entry/display operations; flight-strip data processing, intersector interphone voice communications; and intrasector direct (face-to-face) voice communications. Surveillance work is visual observation of radar-derived aircraft situation data on a plan view display (PVD). The surveillance workload time 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. Conflict processing work (for potential crossing and overtake conflicts) includes potential-conflict recognition, assessment, and resolution decision making and A/G voice communications. The conflict-workload weightings calculated for one sector would differ from those of another, depending on the complexity of each sector's route structure. The workload weighting is derived by using a potential of four separate equator's modeling a variety of aircraft crossing and merging situations (level-level, level-transitional, transitional-transitional, and overtake).

A sector RECEP model is an additive reconstruction of the above three workload components measured in time-based units (e.g., man-minutes of work) which include minimum task performance and are associated with the sectors' control operations. The advantages of using minimum performance times are: (1) to avoid the necessity of a detailed and extremely difficult accounting of overlapping task situations, and (2) that the minimum performance time is more likely to be invariant over time and location; therefore, it is a much more reliable measure than average or actual times.

RECEP is used to estimate the traffic capacities of individual sectors under alternative operating modes. The capacity estimates correspond to baseline and proposed system operations, as well as feasible sector manning strategies (i.e., one-man, or two-man sector teams). RECEP is also used as the basis for first-order estimation of the capacity effects of sector splitting.

As a result of various ATC-related data collection exercises, SRI has developed a data collection/reduction procedure for NAS Stage A equipped enroute facilities that is based on the following data sources:

- Video tape recordings of PVDs.
- Audio (including video tape sound track) recordings of A/G and interphone communications.
- Manual recordings of observed controller physical actions.
- NAS Stage A data analysis and reduction tool (DART) computer printout records of R and D position FDP/RDP operations.
- Flight strips, used and marked-on by the controller.

It is important to note that a significant portion of the work performed by the controller involves routine tasks. For this reason, a special data reduction process is developed. This process requires that data measurements be assembled into a format that facilitates cross-reference of theobserved activities and permits a reconstruction, in part, of the routine control events. The information on operational procedures obtained during the controller interviews, along with the data observations, is essential to identify the control requirements that are in the logical reconstruction of routine events. The RECEP data base update and model verification are required periodically to maintain its validity as a reliable measuring and predicting tool. A number of procedures are suggested in this report to accomplish this task.

Air Traffic Flow Model (ATF)

ATF is a computerized network simulation of multisector air traffic route flows in which the air route network is partitioned into control sectors. That is, the route network is represented by a connected series of route segments (arcs), where each segment represents a directed flow of aircraft through one sector. Every sector contains a set of route segments, each of which is connected at either end to route segments of adjacent sectors; the first and last route segments connect to sector boundaries that include terminals. For the purpose of proper accounting, when two or more separate route segments are merged into or demerged from a single route within a sector, these route segments are defined as separate routes. The connected route segments enable ATF to trace, over time, aggregate traffic flows from sector to sector, and thereby represent multisector traffic activity without actually tracking individual aircraft trajectories (an attribute that reduces calculation requirements and computer run costs).

Because the route segments are partitioned into sectors, the number of aircraft on each route segment during some small time increment (e.g., one-minute) provides a convenient means to calculate readily the number of aircraft through each sector. These data, together with RECEP-based sector workload capacity relationships, are used in ATF to determine the degree of traffic saturation of each sector team. The ATF model operation loads traffic onto the multisector network, moves traffic from sector to sector at successive time increments, and searches for sector team traffic saturation conditions. When imminent saturation situations are found, an ATF congestion-relief algorithm selectively delays aircraft in order to resolve the traffic congestion conditions. In essence, the congestion-relief algorithm distributes workload to upstream sectors to prevent a downstream sector team work overload. ATF traces the propoagation of traffic congestion and delays through the network over time and calculates aircraft average delay statistics. In addition, the number of aircraft and the individual sector workload values are also recorded.

ATF has been used to estimate the average aircraft delay experienced during some time interval of interest (e.g., 2-hour, 3-hour, or 8-hour intervals as may be chosen by the analysts) in a selected multisector environment for a range of traffic-loading projections. The multisector environment is defined by specifying the route network structure and control operation, baseline or proposed. The control operation is represented by the RECEP-based workload-capacity relationships determined for each feasible combination of baseline or proposed system, sector manning strategy, and sectorization configuration. For the purpose of productivity analysis, we determine and compare the average aircraft delays corresponding to the various control operations while holding the route structure fixed.

The types of input data may be classified into the following groups:

- Network composition (sectors, routes, and arcs)
- Traffic flow parameters
- Sector workload maximum
- Sector workload coefficients
- Congestion-relief strategy.

Output from the model is printed as often as each time increment or at any other frequency desired. The amount of information displayed at each print cycle can also be controlled.

The three parameters that could be used for analysis of an ATC airspace are average delay per aircraft, traffic capacity, and controller workload. These three elements are dependent upon each other. Given two of the elements, the third can be calculated.

Model Applications

RECEP and ATF are designed to allow modification and flexibility to their design structure, and thereby enable their application to various areas of study. The RECEP event task times and frequencies may be used to represent various operational requirements and strategies; ATF parameters may be used to represent alternative sectorization and routing structures. The possible areas of application for RECEP/ATF include, but are not restricted necessarily to:

- Evaluation of automation packages
- Evaluation of operations and procedures
- Evaluation of ATC manpower allocation
- Testing of productivity measures
- Energy-consumption evaluation.

To date, RECEP/ATF has been applied explicitly to the first area of study listed--evaluation of automation packages. However, this application has used techniques that could be extended to the other areas of study. The last section (Section VI) of this report gives an example of RECEP/ATF application in Productivity Analysis. A hypothetical automation package that includes Handoff Augmentation and Sector Conflict Probe automation items is used to exemplify the RECEP analyses technique and to illustrate the means by which ATF is used to develop productivity measures.

Other Related Measures and Models

Three other related measures and models are surveyed to develop a comparison with the RECEP/ATF methods. They are: (1) Workpace and Work Activity Measures, WP/WA; (2) Voice Channel Utilization, VCU; and (3) Index of Orderliness, I.O.

The major differences between RECEP and WP/WA (the WP/WA is not a multisector network model; therefore a comparison cannot be made with ATF) are: (1) the treatment of potential-conflict workload; (2) standard time vs. actual time; and (3) data resolution. The correspondence elements of WP/WA and RECEP can only be done on an aggregative basis.

The VCU simulation could be compared with ATF only on a sector-by-sector basis. The most reasonable output available for direct comparison would be aircraft load using time-series representations. Another method that may be investigated is to assume that VCU constituted all of the workload at each sector. This method would require a comparison of VCU average time and frequency products against total RECEP workload estimates. However, because VCU is an indirect measure of workload and may not reflect all controller activity, such a comparison may at best only indicate proportionality between the results.

The index of orderliness might be a useful tool to provide an estimate of potential-conflict events as modeled in RECEP. This would have two benefits. The first is that it would provide substantiating evidence regarding the validity of RECEP conflict count, and the second is that it might provide a less complex method for estimating potential conflict frequencies. One can hypothesize that there may be a correlation between the Index and the number of occurrences of aircraft pairs within a cylindrical volume of radius and height, centered on one of the aircraft. If this is assumed to be true, then the Conflict Alert option in the DART printout provides a means for a rough equivalence between the two techniques.

1. INTRODUCTION

1.1 SIMULATION MODEL IN GENERAL

1.1.1 Definition of Simulation Models

The technique of simulation has long been an important tool to engineers, scientists, and operational analysts. In a broad sense, simulation includes physical replication of real operational objects in scale models, for example, to simulate airplane flight with scale models of airplanes in a wind tunnel, to simulate space vehicle control with a ground-based trainer. With the advent of electronic digital computers, simulation has taken on a new dimension which encompasses a broad spectrum of applications including econometric models, military war games, corporate-planning models, freeway simulation, hospital simulation, etc. The types of users range from engineers and scientists to business planners, operational managers, psychologists, and administrators. In the context of this report, simulation models connote digital computer simulation. A definition can be stated as follows:

> A computer-simulation model is a procedural-logical-mathematical representation of a real-world system programmed for digital computers within which experiments can be conducted over specific periods of time.

1.1.2 Utility of Simulation Models

The basic motivation for using simulation in air traffic control (ATC) productivity analysis is the search for more knowledge about current systems and to predict the behavior of future systems. It may be either impossible, unsafe, or impractical, or too costly to observe a proposed process in a real-world environment. For example, it would be impossible to perform field experiments on a future automation system when the system is not even installed and no substitution can be made. It would also be impractical and very costly to test a set of resectorization plans at a center which would involve procedural and manpower changes.

Simulation may be used when the complexity of the system in question is beyond analytical or mathematical approaches. A typical example is a traffic network where there are sequential queues and multiple servers. The air traffic operation of an Air Traffic Control terminal or center generally is in this category.

The utility of a simulation model in air traffic control can be generally summarized as follows:

- To use simulation as a preliminary test to try out new procedures, operating priorities, etc., before actual field experimentation.
- To use simulation as an evaluation tool for comparing the merits of several competing system proposals under constrained resources.
- Simulation can be regarded as a "drafting board" for systems design. The rapid response from a computer simulation can lead to design improvements within a short period.
- Simulation studies often enable the practitioner to understand and gain insight of the current system, for example, the interrelationship among system parameters or the sensitivity of variable values.
- Simulation can be used as a training tool for operational managers, planners, and policy makers to utilize quantitative and dynamic analysis as a tool for decision making.

1.1.3 Types of Simulation Models

Although there are many ways to classify simulation models, for the purpose of this report we choose to group models by the technique with which the simulation "clock time" is being advanced. Clock time is a computer software-maintained timing mechanism which "drives" the simulation from one time point to the next. The clock time simulates the real-world time units (e.g., seconds, minutes, hours, days) as may be defined by the user. Each time the simulation is advanced by an increment of time the computer would update the "state" of the system by performing the necessary logical, computational, and housekeeping functions called for by the model software. There are two general types of methods for simulation-time progression: (1) fixed-time increment, and (2) variable-time increment.

The fixed-time increment method is also referred to as "uniform-time-step" or "synchronous" method. As the names imply, the state of the simulation system is examined and updated at every Δt which is a fixed-time interval predefined by the simulation user. The variable-time increment method is also known as "event step," or "asynchronous" method which suggests that the advancement of simulation clock time is determined by the amount of time necessary to cause the next most imminent event to occur. After the event and its related system components have been updated, the clock time is again advanced by another variable time increment (if the simulation continues). The determination of which method to use in the design of a simulation model would depend on the nature of the system. Generally speaking, the synchronous method is advantageous for a system where there are a large number of state variables to update, and the asynchronous method is favored where the average event length is great (p. 126, 127, Ref. 1). The Stanford Research Institute (SRI) Air Traffic Flow (ATF) model is a synchronous model in which the simulation progresses in uniform time steps.

The ATF model is also a "flow rate" model instead of an "aircraft-following" model. There are three primary reasons for the selection of a "rate" model:

- The potential size of the geographical area (in terms of centers, sectors, and routes) that the model was designed to serve, and the potential quantity of aircraft that could be present in the network at one time would render an aircraft-following model uneconomical and infeasible to operate.
- The main purpose of the ATF simulation is the analysis of ATC productivity and capacity. The input parameters governing these measures are flow-rate oriented (e.g., RECEP, Workpace and Work Activity, Voice Channel Utilization).
- A "rate" model has the advantage of mapping multivariate entities (aircraft identification, velocity, itinerary, times, etc.) into a single parameter: flow rate. From an analyst point of view, the manipulation of the model control variables is made easy by only having to scale the flow rate or its associated variables rather than developing aircraft inventory lists.

The selection of the synchronous-time progression for the ATF model is based mainly on the aircraft flow behavior. The air traffic flow rate tends to form a high-density stream rather than sparcely placed events, therefore, it is more aligned with a synchronous model than an event-step model.

1.2 THE NEED FOR MODELING IN AIR TRAFFIC CONTROL PRODUCTIVITY ANALYSIS

1.2.1 Advantages of Using Models Vs. Actual System Experiments

It is a commonly held belief that actual system experiments are superior to computer modeling because the former method is more realistic, therefore, more reliable. This belief may be true to a certain extent, i.e., actual system experiments are desirable as long as they are economically and operationally feasible. There are situations in which an assumed ATC system cannot be satisfactorily reproduced in a current operational environment.* Examples are: (1) The system to be modeled has a much higher traffic volume than the current operation; (2) The safety of a new operation has not been verified; (3) A different sector organization is to be tested; or (4) A future automation package that yet has to be produced must be evaluated. In these cases it is desirable to model a (future) system in question with computer simulation. Although these systems can be simulated in real time it is often much less expensive and quicker to perform them in fast time provided that the controller's role can be adequately modeled. The Air Traffic Flow model is designed with this purpose in mind. The advantage of using the ATF model rather than real-world system experiments is summarized in the following two situations:

- To project from one current system to another--Examples of this would be the modeling of increased (or decreased) traffic demand on an existing system (to scale up or down); the testing of a modified sector organization; or the evaluation of a new congestion-relief strategy that has yet to be proven prior to actual field implementation.
- To project from current system to future system--This situation mainly applies to the evaluation of future automation proposals, for example, automatic data handling, conflict probe, and control-by-exception, etc. These studies would require some changes in sector workload weighting computations as well as traffic-demand parameters. The SRI studies performed at Los Angeles and Atlanta Centers 2, 3 are primarily of this type.

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*Real-time simulation with active participation by air traffic controllers can sometimes be used to model ATC functions that are not currently installed. They are usually performed in the FAA by the National Aviation Facility Experimental Center (NAFEC) at the Digital Simulation Facility (DSF) or the Terminal Automation Test Facility (TATF).

1.2.2 History and Background

The work described here addresses the methodologies to analyze enroute air traffic control operations. Although alternative models of control operations are described, the majority of this work is based on models of sector control team workload requirements. The models include the Relative Capacity Estimating Process (RECEP), which relates controller workload to sector traffic capacities, and the Air Traffic Flow network-simulation model, which assess traffic capacity and delay in a multisector environment. Both models were developed previously by SRI for the FAA.[2-7]

RECEP was initially developed as part of an SRI effort directed to assessing the capacity implications of controller judgmental factors and decision processes for several levels of automation.[4,5,6] This initial RECEP formulation consisted of two parts. The first part relates quantitative statements of sector physical configurations, traffic flows and mixes, to an automation application as it bears on control decision-making and to the frequencies of occurrence of various types of ATC events (e.g., crossing conflicts, overtakes, altitude conflicts, priority decisions). The second part of RECEP attaches a "decision-making time" to each such ATC event, based on the minimum values measured for these times. The advantages of using minimum performance times are: (1) to avoid the necessity of a detailed and extremely difficult accounting of overlapping task situations, and (2) that the minimum performance time is more likely to be invariant over time and location, therefore, is a much more reliable measure than average or actual times. RECEP then compares aggregate decision-making time requirements to a threshold representing time available to generate relative capacity estimates for alternative automation specifications. The values and parameters that define the frequency-of-occurrence relationships and decision-making times were determined using a measurement technique developed by SRI that includes observation of sector operations, followed by structured controller interviews using a video playback of the observed sector operations.

Subsequent SRI study efforts addressed specific automation elements of the FAA's Upgraded Third Generation (UG3RD) ATC program, which required a finer description of controller activities than that of the initial RECEP formulation.[2,3,7] Therefore, a revised RECEP model was developed that differentiated individual task activities so that the impact of each automation proposal on controller operations could be assessed. The revised RECEP model is described in detail in Section IV of this report.

The ATF model was developed in parallel with the RECEP revision and was designed to assess the impact of automation on a multisector environment. ATF is a computerized device to translate the RECEP capacity estimates for individual sectors into multisector traffic constraints. The model assesses the degree to which sector traffic flow rates are constrained by individual sector capacities and estimates aircraft delay for the multisector environment.

The initial RECEP technique was applied to some 16 sectors in enroute and terminal facilities. Four enroute sectors--first one at the Oakland Air Route Traffic Control Center (ARTCC), and then three at the Chicago ARTCC--were modeled prior to implementation of the National Aviation System (NAS) Stage A system. Twelve terminal sectors--four each at the Oakland Bay, Washington National, and Boston Logan Terminal Radar Approach Control (TRACON)--were modeled subsequently as Automated Radar Terminal System (ARTS) III operatives. The revised RECEP model was developed and applied to four enroute sectors at the Los Angeles ARTCC, and later applied to seven enroute sectors at the Atlanta ARTCC.[2,7]

In all cases, the resulting RECEP sector capacity estimates were consistent with those made by the facility personnel as well as with the Busy Day Reports. Although these results may not be considered a formal validation of the RECEP model, they do indicate it to be a reasonable representation of control operations.

The ATF model was applied to two selected multisector regions, one at the Los Angeles ARTCC and the other at the Atlanta ARTCC. Both model applications used the RECEP-analyzed sectors as a basis for study although additional sectors were included. The ATF network model, which is relatively new and not previously used as extensively as RECEP, has not been subject to formal validation.

Since these applications of the Air Traffic Flow model, the model has been modified in some minor respects. These changes have been primarily for convenience. Newer output has not significantly changed from the older model. Throughout the remainder of this discussion we will describe the newer ATF model and the revised RECEP.

1.2.3 Application Areas

RECEP and ATF were developed specifically as tools to evaluate the impact of automation on ATC operations. SRI's past use of the models was to measure the traffic-handling capabilities of various automation alternatives and to compare manning requirements at various traffic projections. This technique enabled the quantification of the productivity of alternative ATC systems.

Although ATF/RECEP was designed to evaluate postulated future operations, the models may be used to analyze more near-term aspects of ATC system planning. Such applications include the analyses of operational and procedural options for the current system and resectorization alternatives. These areas of interest relate to the adjustments being made by facility personnel to keep their operations consistent with changes in traffic demand. The emphasis here is on the use of RECEP to describe changes to control procedures; it does not relate to the hardware/software alternations associated with automation.

2. SUMMARY DESCRIPTION OF RECEP AND THE AIR TRAFFIC FLOW MODEL

2.1 THE RELATIVE CAPACITY ESTIMATING PROCESS (RECEP) SUMMARY

The RECEP modeling approach estimates the traffic handling capabilities of an individual sector by encoding the controller work associated with the sector's operational requirements. RECEP models are mathematical representations of the routine, surveillance, and conflict processing workload requirements of a sector team. Routine work tasks include air/ground (A/G) voice communications, flight data processing (FDP) and radar data processing (RDP) manual data entry/display operations, flight-strip data processing, intersector interphone voice communications, and intrasector direct (face-to-face) voice communications. Surveillance work is 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 A/G voice communications.

A sector RECEP model is an additive reconstruction of the workload requirements, measured in time-based units (e.g., man-minutes of work which include minimum task performance and are associated with the sector's control operations. The routine, surveillance, and conflict processing workload requirements are formulated as functions of traffic flow rate and sector transit time. The aggregate work times (e.g., man-min of work per hour) resulting from various rates of traffic flow (e.g., aircraft per hour) through a sector are compared with a prespecified workload limit to obtain sector team traffic flow capacity estimates.

RECEP is used to estimate the traffic capacities of individual sectors under alternative operating modes. The capacity estimates correspond to baseline and enhanced system operations, as well as feasible sector manning strategies (i.e, one-man, two-man, or three-man sector teams). RECEP is also used as the basis for first-order estimation of the capacity effects of sector splitting. The capability to model alternative sector manning strategies and sectorization designs (based on sector splitting) enables us to quantify staffing alternatives for each system and is important for productivity analysis.

2.1.1 Baseline System Modeling

The RECEP models of baseline system sector team operations are constructed using field observations and related data collections. These models represent the current controller workload requirements (i.e., routine, surveillance, and conflict processing) associated with the current manning characteristics of each sector under analysis; therefore, these models describe sector team traffic capacities under current operating conditions.

To allow for baseline system staffing increases in response to future traffic increases, we adjust the workload structure of the current baseline system RECEP models to represent realistic sector team manning alternatives (e.g., expand from two-man to three-man teams) and resectorizations (e.g., split one sector into two sectors and provide additional controllers). The procedure enables restructuring in detail of the controller tasks described in the baseline RECEP models.

Modeling sector splits is less refined because route restructuring effects on sector workload requirements are not known and must be judgmentally determined. Therefore, a rough approximation is obtained of the workload and capacity relationships associated with the distribution of workload among the sectors formed by splitting. A first-order sector splitting model developed by SRI[7] takes into consideration the reallocation of conflict processing work and the additional routine work introduced by new sector boundaries. This model was used to study

Los Angeles Center sector splits. In subsequent productivity analysis work for the Atlanta Center, we have used the Los Angeles Center results as analogies from which we estimated the percentage increase in traffic capacities resulting from splitting sectors. A more detailed description is given in Section VI-A.

The RECEP models of current operations, alternative sector manning strategies, and resectorizations obtain traffic capacity estimates for each baseline sector for each operating configuration. This set of RECEP models therefore describes the sector capacity effects resulting from sector staffing changes for the baseline system.

2.1.2 Enhancement Systems Modeling

We follow the same procedure as that for the baseline system to define RECEP models for enhanced sector operations postulated under alternative manning and sectorization options. We first construct RECEP workload requirements for each sector using a sector manning strategy analogous to the current one. We construct the workload requirements by adjusting the baseline system's routine and conflict processing tasks to conform to an enhancement of automation's operating characteristics. (Surveillance adjustments could also be made if appropriate although we have found that the measured values have not changed from those in past analysis work). These adjustments encode the assumptions we make as to how an enhancement item would be implemented in an operational control environment. We then proceed, as described for the baseline case, to model realistic sector manning strategies and resectorization alternatives. The resulting RECEP models obtain sector capacities corresponding to the alternative sector staffing levels for each enhanced system under evaluation.

2.2 THE AIR TRAFFIC FLOW MODEL (ATF)

ATF is a computerized network simulation of multisector air traffic route flows in which the route network is partitioned into control sectors. That is, the route network is represented by a connected series of route segments (arcs), where each segment represents a directed flow of aircraft through one sector. Each sector contains a set of route segments each of which is connected at eigher end to route segments of adjacent sectors; the first and last route segments connect to sector boundaries. In the event that two or more separate route segments are merged into or demerged from a single route within a sector, for the purpose of proper accounting, these route segments are defined as separate routes. The connected route segments enables ATF to trace, over time, aggregate traffic flows from sector to sector, and thereby represent multisector traffic activity without actually tracking individual aircraft trajectories (an attribute that reduces calculation requirements and computer run costs).

Because the route segments are partitioned into sectors, the number of aircraft on each route segment during some small time increment (e.g, one-minute) provides a convenient means to calculate readily the number of aircraft through each sector. These data, together with RECEP-based sector workload capacity relationships, are used on ATF to determine the degree of traffic saturation of each sector team. The ATF model operation loads traffic onto the multisector network, moves traffic from sector to sector at successive time increments, and searches for sector team traffic saturation conditions. When imminent saturation situations are found, an ATF load-balancing algorithm selectively delays aircraft to resolve the traffic congestion conditions. In essence, the load-balancing algorithm distributes workload to upstream sectors to prevent a downstream sector team work overload. ATF traces the propagation of traffic congestion and delays through the network overtime and calculates aircraft average delay statistics. In addition, the number of aircraft and the workload values are also recorded.

We use ATF to estimate the average aircraft delay experienced during some time interval of interest (e.g., 2-hour, 3-hour, or 8-hour intervals as may be chosen by the analysts) in a selected multisector environment for a range of traffic-loading projections. The multisector environment is defined by specifying the route network structure and control operation, baseline or enhanced. The control operation is represented by the RECEP-based workload-capacity relationships determined for each feasibile combination of baseline or enhanced system, sector manning strategy, and sectorization configuration. For the purpose of productivity analysis, we determine and compare the average aircraft delays corresponding to the various control operations while holding the route structure fixed. The procedure isolates the delay effects of automation implementation from those effects relating to route structure.

2.3 RELATIONSHIP BETWEEN RECEP AND ATF

Although RECEP and ATF are two separate systems, their joint use has often given the impression that they must go together, or that RECEP is an integral part of ATF. It can be viewed that RECEP is an external input process to ATF when they are used jointly in a multisector ATC productivity analysis. However, RECEP can also be used as a stand-alone system when single-sector workload and capacity are of primary interest. Also, the ATF model may be used independently of RECEP if other means are available to generate workload coefficients and sector-capacity inputs.

In general, the input parameters that RECEP supplies to the ATF model are the workload coefficients that are results of routine-events, surveillance, and potential conflict-events workload estimates, and surveillance, and potential conflict-events workload estimates, and the sector capacity estimates. The rest of the ATF input parameters, such as aircraft flow rates along routes, route structure, and congestion-relief schemes, are not parts of RECEP.

3. OTHER RELATED MEASURES AND MODELS

3.1 WORKPACE AND WORK ACTIVITY MEASURES

3.1.1 Description of Workpace and Work Activity

Work activity (WA) measurement is a technique used by the FAA to perform on-site observation of controllers manual workload as it is divided into over 25 basic indicators (see Table 1 for more details). The observation is usually recorded at 5-minute intervals at selected sectors and centers over a specified period (e.g., one or two hours). In addition to the controller's basic workload activities, the sampling also includes the following traffic-loading parameters:

- Peak Aircraft--The highest number of aircraft under the sector's jurisdiction at any one time within the observation interval.
- Sector Flight Time--The average time (in minutes) that an aircraft would be under the jurisdiction of a sector.
- Aircraft Handled--The equivalent number of aircraft handled during the observation interval obtained by dividing the aircraft minutes by Sector Flight Time.

Independent of WA measurement is a rating function--Work pace (WP)--that is an interger function ranging in seven values from "very light" to "very heavy" (see Table 2 for more details). A single-digit rating is given by a peer observer for each 5-minute observation interval to describe the intensity of the workload imposed upon the controller as a result of traffic volume and complexity.

The result of these observations (both WA and WP) are kept on computer magnetic tapes; therefore, historical data can be accessed

TABLE 1

ENROUTE/TERMINAL WORK ACTIVITY CODES

Enroute Code	Terminal Code	Workload Indicator	Activity
AC	130	Altitude Control	Radio
AV	131	Altitude Verification	Radio
SC	140	Speed Control	Radio
SV	141	Speed Verification	Radio
VC	100	Vector for Control	Radio
OC	100	Other Control	Radio
AD	400	Advisory	Radio
B	--	Beacon	Radio
HO	GHF&RHF	Handoff Outside ARTCC	Interphone
HI	GHS&RHS	Handoff Inside ARTCC	Interphone
CO	CF	Coordination Outside ARTCC	Interphone
CI	CS, CCI, INT	Coordination Inside ARTCC	Interphone
IC	INT	Issue Clearances	Interphone
VH	GHM&RHM	Verbal Handoff	Verbal
VO	CC, CSM	Verbal Coordination Outside Sector	Verbal
VR	CR	Verbal Coordination With "R" Man	Verbal
VL	CH	Verbal Coordination With "H" Man (Manual Only)	Verbal
VD	CFD	Verbal Coordination With "D" Man	Verbal
Q	QL, RGH, KRH, DU, KG	C.U.E. Entries	Manual
FS	FS	Flight Strip Activity	Manual
SB	--	Shrimp Boat Activity (manual system only)	Manual
AE	AE	Adjust Equipment	Manual
DL	LC	Data Lookup, Charts, Maps, etc.	Manual
HS	--	Hand Signal	Visual
SY	S	Standby	Standby

TABLE 2

WORKPACE DEFINITIONS

- Very Light Workload (VL). A "VL" rating should be assigned when the Workpace level is so low that relatively little attention has to be paid to the position of operation. Minimal exertion is required.

- Light Workload (L). An "L" rating should be assigned when the Workpace is such that more than minimal exertion is required, but the complexity of situations is such to only engage the controller's complete attention periodically. There are no complex control situations.

- Average Workload (A). An "A" should be assigned when the situation complexity requires almost full-time attention of the controller. The workload is evenly distributed and places no unusual demand upon the controller. This pace could be maintained up to an 8-hour period with normal relief.

  - Gradient. A- should be assigned when significantly less than full attentiveness is required at the position; the demands placed upon the controller are slightly less than one could expect at average. Infrequent periods of inactivity occur.

  + Gradient. A+ should be assigned when the demands are slightly greater than A. Rare periods of inactivity, full attentiveness to the position is required. A controller could be expected to work at this pace up to six hours with normal relief.

- Heavy Workload (H). An "H" rating should be assigned when the complexity and exertion required to cope with the situation necessitate rapid decisions; there is constant operational activity. Demands placed upon the controller exceed those of a normal pace. A controller could be expected to securely deal with this level of work for up to 3 hours.

- Very Heavy (VH). A "VH" should be assigned when there is continuous, laborious activity; superior exertion is required and the rapidity of response and thinking processes are critical. There are delays in acknowledging demands placed upon the position. A controller would be "pushed" to maintain this pace for 1 hour.

to perform "before-and-after" comparisons of parameter changes. The format of the tape record is given in Appendix A. An automatic maximum hourly WP search program has been developed by the Transportation Systems Center that can rapidly search and identify from the WA/WP tapes those time periods and sectors that have experienced maximum workload. Detailed printout is also given by this program for analysis purposes. See Appendix B for more details.

3.1.2 Comparison of Data Elements Between RECEP and Work Activity

Because the development of RECEP and WP/WP techniques were independent of each other, their data elements, data classification schemes, data resolutions, and field test techniques are understandably different. However, there are enough similarities between the two techniques that would warrant a closer examination for constructing an approximating function. Each technique involves a two-dimensional classification scheme:

	WA	RECEP
Row Elements:	Workload Indicator	Control Events
Column Elements:	Activities	Control Tasks

The RECEP classification matrix contains approximately 90 nonzero entries, whereas, WA matrix contains approximately 33 nonzero entries. Because of the difference in their methods of classification and aggregation, the memberships of the two systems do not have a one-to-one match. In fact, because the number of nonzero entries has a three-to-one ratio, the mapping function is essentially many-to-one (from RECEP to WA). Although a precise mapping function may be difficult to establish because the definitions and resolutions of the data elements are not always compatible between the two systems, an attempt is made in Appendix C to show some equivalence relationships. To understand the full implications of Appendix C, the reader is advised to also read Section IV. Description of the Relative Capacity Estimating Process.

It would appear from Appendix C that the correspondence between elements of RECEP and WA are aggregated and with much overlapping. The only possible agreement between the two systems would seem to be in the column totals and grand totals. The following is a list of column titles of the two systems that roughly correspond to each other:

RECEP	WA
1. A/G Communication	1. Air/Ground/Air
2. FDP/RDP Operation	2. Manual-Keypack
3. Interphone Communication	3. Interphone
4. Flight Strip Processing	4. Manual-Flight Strip Activity
5. Direct Voice Communication	5. Verbal (or Oral)

3.1.3 Major Differences Between RECEP and Work Activity Measures

This section gives a description of the differences between RECEP and work activity measures in three major categories--the development of the conflict measures; standard times vs. actual times; and data resolution.

3.1.3.1 The Development of Conflict Event Workload Measures

Although the radio transmission activities relating to conflict resolution, sequencing, and in-trail spacing (VC) are monitored by the WA technique, there are no procedures in the WA/WP technique with which to measure decision-making times imposed by potential conflict and overtake events.* It is to be noted, however, that conflict and overtake resolution workload of a sector is implied in the WP rating even though the independent variables (i.e., conflict routing parameters) are not explicitly measured.

*The portion of air/ground communication attributed to potential conflict workload is relatively small; therefore, in a first-order approximation the lack of conflict procedures in WA/WP will not significantly affect the gross agreement on the two measures in routine workloads.

A procedure based on a RECEP-WA/WP combination may be feasible in which the routine-event workload would be measured with WA technique but RECEP would still be required to compute conflict-event workload weightings.

3.1.3.2 Standard Times Vs. Actual Times

Perhaps one of the major differences in the RECEP and WA techniques is the concept of "standard time" (used by RECEP) vs. "actual time" (used by WA). The primary design purpose of RECEP is for predicting controllers' future productivity due to assumed changes rather than evaluating current performance; therefore, the minimum times developed for RECEP are intended to be invariant over time and location. It has been recognized that human performance time on a given task usually varies between individuals and even within the same individual. Unless this variance is minimized, task performance time is not an effective tool for comparing different existing systems or predicting the effect of future automation. For this reason, the basic RECEP workload measures (task times) are defined as "minimum times" which imply that the ATC tasks are described by a set of irreducible numbers and that the only time these numbers may be modified is when the operational characteristics of the tasks are changed.

On the other hand, the WA/WP technique is designed for comparing "before-and-after" effects of system changes pertinent to controllers' productivity. The task time measures are based on actual times as recorded during field observation over a sampled period. This method is especially effective when the before-and-after study is conducted for the same center with the same group of controllers. Because ATF/RECEP has been used in the past mainly for forecasting future productivity changes due to automation and the WA technique has been primarily used for measuring the actual productivity increase (or decrease) after the automation is installed, WA/WP can be effectively employed as a tool to verify the predictability of the ATF/RECEP model. This verification would be most effective if minimum rather than average task times were used in the computation of aggregate WA time-frequency task totals. These totals could then be compared on a column-by-column basis with the RECEP routine workload values.

3.1.3.3 Data Resolution of Event/Task Elements

Because the design purpose of RECEP is the ability to compare various configurations of enhancement packages under the NAS Stage A environment, the control-event and control-task categories are designed to reflect the most elementary building blocks to describe controllers' actions. Consequently, the elements in a RECEP minimum-time data matrix can be considered as workload "primitives" which are sensitive to the effect of enhancements to controllers tasks. These primitives are then used to construct sets of controllers' measures peculiar to a given automation operation. It is for this reason that the RECEP data base has been used for a wide range of enhancement packages with practically no change to its basic matrix structure from one site to another.

3.2 VOICE CHANNEL UTILIZATION (VCU)

3.2.1 Introduction

This work is described as a simulation model for ATC communications based upon voice-recording data gathered over the New York Center. The research was conducted by Princeton University and is reported in four volumes:

Volume 1: Contains extensive dictionaries and catalogs of the air/ground communication message elements.[8]

Volume 2: Describes initial statistical analyses and early simulations of single sectors.[9]

Volume 3: Describes the construction, validation, and initial exercises of the General Purpose System Simulation (GPSS) model of controller workload which is based on air/ground communications channel loading.[10]

Volume 4: Reports the simulation model for the New York air traffic control communications, the validation of the model, and the extension of the model to other air/ground communications at the Houston ARTCC.[11]

3.2.2 General Model Description

In general, the Princeton Model is structured as given in Figure 1. It has been shown by the designers to be an adequate simulation of VCU and aircraft loading operations for specific New York sectors which were modeled. In addition, preliminary findings reported in Volume 4 indicate that the model is valid for communications simulation of generalized sector types.

The model requires the following input parameters:

ρ, the aircraft arrival rate.

p and k, the parameters of the number of intercommunication gaps per aircraft distribution.

α and λ, the parameters of the transmission length distribution.

a_o and a_1, the parameters relating the CT length with the number of CT per aircraft.

The output of the model can be categorized as follows:

- Aircraft loading, n_t;
- Channel utilization, C_t;
- Number of aircraft in queue waiting to communicate, Q_t.

Each of the above sector responses can be represented by a time series:

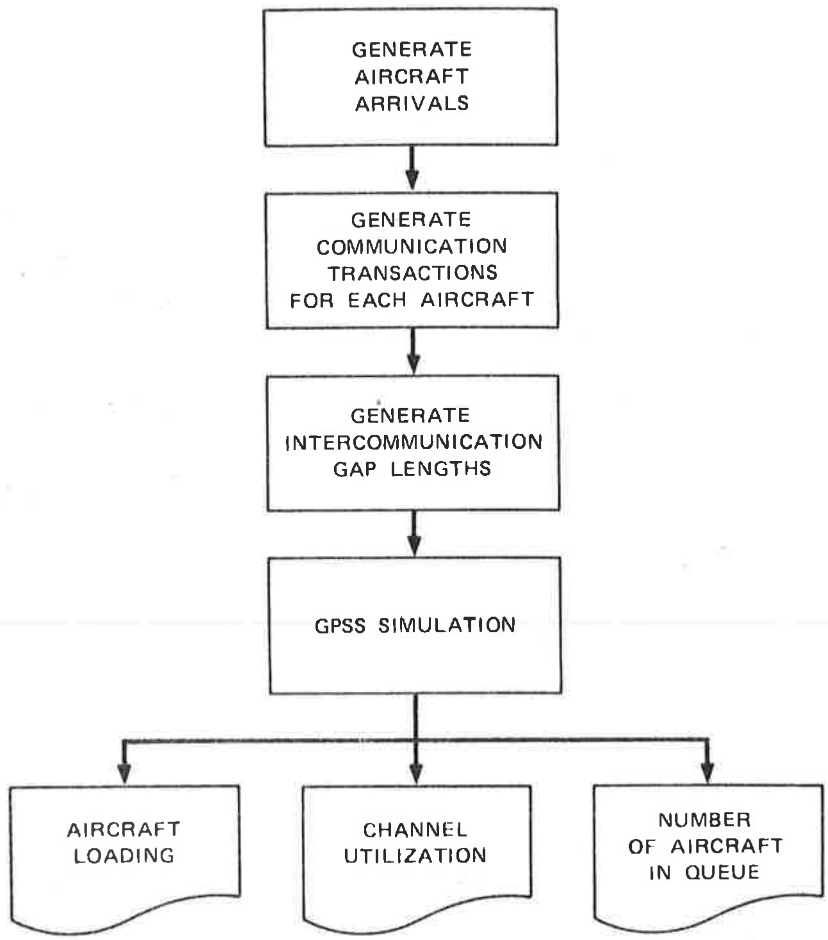

FIGURE 1 A GPSS MODEL FOR VOICE CHANNEL UTILIZATION

- For n_t, the second-order autoregressive model#

$$n_t = \mu + \phi_1(n_{t-1} - \mu) + \phi_2(n_{t-2} - \mu) + a_t$$

where ϕ_1 and ϕ_2 are parameters, $a_t \sim N(0, \sigma^2)$ and μ is the expected value of n_t.

- For CU (denoted by C_t), the first-order autoregressive model#

#The symbols ϕ and ϕ_2, ϕ_1^{**} and ϕ_2^{**} denote amplitudes of a Box-Jenkins second order autoregressive model; the symbol ϕ_1^* also denotes the amplitude of the first-order autoregressive model.[11] The notation $a_t \sim N(0, \sigma^2)$ is a standard expression in statistics which means the random variable a_t is normally distributed with mean 0 and variance σ^2.

$$C_t = \theta + \phi_1^*(C_{t-1} - \theta) + b_t$$

where ϕ_1^* is a parameter, $b_t \sim N(0, \sigma_*^2)$ and θ is the expected level of C_t.

- For Q_t (after a negative exponential transformation, denoted by a_t), the second-order autoregressive model#

$$q_t = \omega + \phi_1^{**}(q_{t-1} - \omega) + \phi_2^{**}(q_{t-2} - \omega) + e_t$$

where ϕ_1^{**} and ϕ_2^{**} are parameters, $e_t \sim N(0, \sigma_{**}^2)$ and ω is the mean level of q_t.

3.2.3 Comparison Between VCU and ATF/RECEP

The following list shows the general comparison between the two simulation models by giving descriptions of how each model handles a common set of identified model elements:

Model Elements	ATF/RECEP	VCU
Network representation	Approximated using geographic sector, route, and arc representation.	Proposed but not presently implemented or documented
Traffic flow representation	Aircraft arrival rate.	Aircraft arrival rate.
Capacity/workload measure	Minimum time and event frequency measurements for individual sectors and capacity estimates for each sector based upon field measurements.	VCU provides a linear "workload" function up to 85% utilization, which is defined as capacity.

The symbols ϕ and ϕ_2, ϕ_1^{**} and ϕ_2^{**} denote amplitudes of a Box-Jenkins second order autoregressive model; the symbol ϕ_1^* also denotes the amplitude of the first-order autoregressive model.[11] The notation $a_t \sim N(0, \sigma^2)$ is a standard expression in statistics which means the random variable a_t is normally distributed with mean 0 and variance σ^2.

Model Elements	ATF/RECEP	VCU
Multisector measures	Cumulative aircraft delay. Aircraft load. Controller workload.	No system measure. Sector measure of: Aircraft load; Voice Channel Utilization; Queue delays.
Flow control schemes	Two possible schemes presently in use.	Not applicable.
Sensitivity to automation configuration	Reflected through RECEP event frequency and time calculation adjustment.	Any automation which affected voice communications in some way could probably be reflected in VCU through the message-content dictionary.

It can be seen from the above comparison that the VCU simulation could be compared with ATF output only on a sector-by-sector basis. The most reasonable output available for direct comparison would be aircraft load. A comparison of these two system measures would require the ATF to provide sector-by-sector time series output. It would be most convenient to have the model calculate the parameters required to construct an autoregressive approximation of the ATF output.[12] These could then be compared with the VCU output for the same time period. Another method that may be investigated would be to assume that VCU constituted all of the workload at each sector. This method would require a comparison of VCU average time and frequency products with total RECEP workload estimates. However, because VCU is an indirect measure of workload and may not reflect all controller activity, such a comparison may, at best, only indicate proportionality between the results.

3.3 INDEX OF ORDERLINESS

The Index of Orderliness is a system performance measure originally developed as a supplement to more standard performance measures during cost/benefit studies conducted at the National Aviation Facilities Experimental Center.[13] The index was designed to have the following attributes:

- "Derived from objective results of the test ...
- Correlates with other factors which independently reflect safety, capacity, and workload.
- Statistically manageable ...
- Have operational meaning ...
- Free of manipulation by test subjects."

The remainder of this section contains a brief definition of the Index of Orderliness, a description of the filtering and formulations for the Index as given by Halverson, and finally a proposal for comparing the measure to RECEP conflict-modeling results.

3.3.1 A Brief Definition

The calculation of an Index of Orderliness for any airspace involves the representation of the closest point of approach of all aircraft pairs under control (a conflict prediction) in an aggregate measurement (a threat-weighting formula). The closest point of approach for a pair of aircraft is defined as the expected miss distance (in the horizontal plane) of the pair at some future time. The miss distance depends upon several factors including the relative velocity of the pair, altitude separation, accelerations (including turn rates) and the intent of each pilot. For computational ease, acceleration is handled through approximations of the accelerating aircraft's true airspeed and heading. Altitude separation is accounted for through filtering and is also included in some of the threat-weighting formulas. Pilot intent is not included.

3.3.2 Filtering and Weighting Formulas

The number of calculations of closest point of approach for all aircraft in an airspace at frequent intervals can be large. Thus, three coarse filters are applied prior to calculation of closest point of approach and another filter is applied to all computed closest points of approach prior to inclusion in weighting formulas.

The first three filters inhibit computation: (1) if the difference in altitude is greater than a specific minimum; (2) if the altitude separation is opening; (3) if the distance between aircraft is greater than a minimum; and (4) if the time to closest point of approach (at maximum possible closing rate) is greater than a minimum.

The final filter operates on the distance, altitude, and times to closest point of approach and excludes those not meeting minimum standards. The special circumstances presented by airports are also taken into account by this filter.

Several weighting formulas for the index have been proposed. The Transportation Systems Center (TSC) Cambridge, Massachusetts, explored the following six formulations:

$$\mu_1 = \sum \frac{e^{-T_M/60}}{M^2 + 0.01}$$

$$\mu_2 = \sum \frac{1.}{\frac{(T_M + 5)}{60}\,(M^2 + 0.01)}$$

$$\mu_3 = \sum \frac{1.}{\frac{(T_M + 5)}{60}\,(M^2 + 0.01)\,\frac{(Dz + 50)}{100}}$$

$$\mu_4 = \sum \frac{e^{-\Delta T}}{T_M \left[M^2 + \frac{T_M}{30}\right]}$$

$$\mu_5 = \sum \frac{\left[e^{-\Delta T} \mu_1\right]}{T_M}$$

$$\mu_6 = \sum \frac{e^{-\Delta T}}{T_M \left[\left(\frac{M}{3}\right)^2 + \left(\frac{Dz}{900}\right)^2 + \frac{T_M}{60}\right]}$$

where

M = predicted closest point of approach in the horizontal plane (miles).

Dz = predicted altitude separation (feet).

T_M = time to closest point of approach (seconds).

ΔT = problem time--matrix entry time.

The results of the analysis by TSC of these formulations are summarized in the Halverson paper.[13]

3.3.3 A Possible Comparison

It has been proposed that the Index of Orderliness might be a useful tool to provide an estimate of potential conflict events as modeled in RECEP. This would have two benefits. The first is that it would provide substantiating evidence regarding the validity of RECEP conflict counts, and the second is that it might provide a less-complex method for estimating potential conflict frequencies.

The first step in making the comparison is to obtain an approximation of the closest point of approach calculations. If one inspects the formulations for the index given previously it can be seen that all contain a term $\frac{1}{M^2}$. Thus the formulations are inversely proportional to the area of a circle with radius M. This can be (as suggested by Halverson) envisioned as a hazard area of radius M about an aircraft. Altitude separation terms are implied through filtering but are only included in some of the formulations. One can, thus, hypothesize that there may be a correlation between the Index and the number of occurrences of aircraft pairs being within a cylindrical volume of radius M and height D_z, centered on one of the aircraft. If this is assumed to be true, then the Conflict Alert option in the data analyses and reduction tool (DART) printout provides a means for a rough comparison.

This Conflict Alert option can provide a count of all occurrences of aircraft approaching within a cylindrical volume of specific size about each aircraft. Although this approach does not account for the difference in heading and speed between the pair of aircraft, it appears to be the most viable in terms of using existing tools to estimate potential conflict frequency without the rigor of RECEP conflict modeling, or calculating closest points of approach.

The procedure for experimenting with this tool would be as follows: Select four to six sectors in a test airspace for RECEP modeling. For the same time period collect SAR tape information. Make several runs with different Conflict Alert sizes. The frequencies resulting from these runs would then be compared on a one-to-one basis with the RECEP predictions to determine which distance and altitude limits best approximated the RECEP formulation. Ideally, the Conflict Alert distance and altitudes would be the same for all sectors studied.

Some of the assumptions made to conduct the experiment may cause problems. The first pitfall is that although RECEP accounts for the pilot's intent during the conflict modeling, the Index of

Orderliness and the Conflict Alert counts do not. To further complicate the problem, the Conflict Alert proximity count does not account for heading or speed of the pair in proximity. The result is that two sectors with very different RECEP conflict workloads could have exactly the same Index of Orderliness and conflict frequencies. The use of Conflict Alert to estimate conflict workload will require considerable care and attention to the operational characteristics of the sector. It is possible that procedures to handle different types of sectors can be developed.

4. DESCRIPITON OF THE RELATIVE CAPACITY ESTIMATING PROCESS

A RECEP model describes the workload requirements of a sector team based on observed controller activities and is, therefore, calibrated according to the operational characteristics of the observed or baseline ATC system. In this section we discuss the calibration of RECEP for baseline NAS Stage A enroute operations, although, except for tower activities, the calibration would also apply to terminal (TRACON) operations.

4.1 BACKGROUND

RECEP models of selected sectors were constructed using Los Angeles Center and Atlanta Center observations. The basic model structure was developed as part of the Los Angeles Center study effort, which found that a sector's traffic handling capability could be constrained by various members of the control team depending on which controller reached his workload threshold first. To account for the situation, a team workload and a radar (R) controller workload model formulation was developed for each sector to represent two-man team operations. This team includes an R controller and a data (D) controller, and was the standard manning strategy used to operate a sector during the observation sessions.

The team model was based on empirical data obtained from the observations and calibrated against each sector's capacity as reported by controllers. The team model represents the combined work requirement of the R and D controllers. Although this team model was useful for analyzing observed sector operations at the Los Angeles Center, the mode by itself was found to be deficient in its capability to model alternative operations (i.e., three-man teams, sector splitting, and enhancement systems) where the R controller, instead of the D controller, performs the dominant portion of the team work. Therefore, the R-controller model was developed as a check of the team model to assure that the R controller alone would not first be overloaded with work. The models were constructed such that the team model determined sector capacity if the D controller is work saturated and cannot accept more work from the R controller; the R controller model determined sector capacity if this controller is work overloaded. Therefore, both models would be needed to evaluate the capacity of a single sector, although only one may be critical.

The team and R-controller sector modeling approach was used also as part of the Atlanta Center study and proved to be an appropriate means to evaluate sector operations.

4.2 DESCRIPTION

The team model developed during the Los Angeles case study is based on data measurements of observed routine and conflict processing activities, and is used to estimate sector team workload time devoted to these activities as a function of traffic flow rate. Sector team workload time, W_T, measured in man-min/hr, is calculated using an additive model of work components:

$$W_T = [k_1 N + (k_2 + k_3)\ N^2]/60 \quad ,$$

where

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

k_1 is the team 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 overtaking 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.

The corresponding R controller model is constructed by allocating portions of the team's routine work and all the conflict processing work to the R controller and introducing R controller surveillance work. The surveillance work could not be measured adequately by means of direct observation, and, therefore, is not included in the team workload model. However, because PVD surveillance is an important R controller responsibility, assumptions regarding surveillance work were developed from controller interviews. R controller workload time, W_R, measured in man-min/hr, is calculated using the additive model of work components:

$$W_R = [k_1' N + c t_s N + (k_2 + k_3) N^2]/60 \quad ,$$

where

N, k_2, and k_3 are described as above for the team model.

k_1' is the R controller routine workload weighting measured in man-sec/aircraft.

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

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

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*k_2 is the sum of workload weightings from three equations representing three categories of crossing conflict: level/level, level/transitional, and transitional/transitional.

The importance of the workload component structure of the team and R controller models is the capability to distinguish 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 or $k_1'N$) 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 or k_1') for an arrival sector (where vectoring instructions are frequent) would differ from that of a high enroute sector (where vectoring 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 because the same surveillance workload constant (c) applies to each sector. The product, ct_s, is considered to be the surveillance workload weighting measured in man-sec/aircraft.

Relative to processing of potential crossing and overtaking conflicts, workload times (k_2N^2 and k_3N^2) increase with the square of the traffic flow rate. The conflict workload weightings (k_2 and k_3) 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 (e.g., level/level, level/climb, climb/climb, level/descent).

Workload is used to define the traffic capacity of a sector under the assumption that the number of aircraft that can be handled through a sector during any given time is limited by controller or control team capability to perform required communication, data maintenance, and decision making. Observations of sector operations indicate that there is a maximum total time that a controller or control team can spend performing control tasks. During the Los Angeles Center case study, calibration of the two-man sector team workload model using interviewed controllers' estimates of sector capacities found that 66 man-min/hr of team routine and conflict work corresponded to reported capacities measured in aircraft/hr. Using the calibrated Los Angeles Center sector capacities, the R controller workload threshold was determined to be 48 man-min/hr. These workload thresholds--66 man-min/hr for the two-man sector team and 48 man-min/hr for the R controller--were used subsequently to estimate sector capacities for the Atlanta Center.

We note that the calibrated team model is "descriptive" in nature and, the same as regression analysis, empirically relates observed data (controller activities) to an outcome (sector capacity). The R controller model is an attempt to develop a "causative" model of controller behavior by accounting for all the work associated with this position. It was, therefore, necessary to include inferentially derived (from controller interviews) surveillance workload, which is not based on observed data. A similar attempt to derive a causative model for the D controller was not successful because we could not determine with certainty his surveillance requirements which were complicated by D controller requirements to respond to R controller, PVD, computer readout device (CRD), and FDP activities).

In the following paragraphs, the derivation of the team and R-controller workload weightings and capacity calibration are reviewed.

4.2.1 Routine Work

The routine workload time (k_1N or $k_1'N$) represents the ordinarily occurring control events required to clear aircraft through the sector; it is generated in some form by every flight. Field data collected at the Los Angeles Center for each sector were used to identify the team routine control events, specify the set of tasks required to effect each event, determine task performance times (minimum times), and measure the frequency of occurrence of each event by sector.

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

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

The 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 procedural-based, decision-making process of guiding aircraft through a sector. Pilot requests result in real-time flight modifications, adding work. Pointouts are actions required by a sector team to retain control of aircraft briefly in or near another's airspace. General intersector coordination includes those informational transfers that are performed to keep cognizant of multi-sector 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 equipment operation and flight data maintenance.

These routine events provided an adequate basis for a first-order calibration of sector team workload limitations on traffic capacity, but they lacked sufficient operational detail to support subsequent productivity evaluations of potential design modifications to ATC system equipment. For this purpose, routine events were described on the basis of identifiable controller tasks. Each routine event was defined to consist of a single task or a sequence of tasks that must be performed to complete the event. The tasks that were identified are:

- A/G radio communication
- FDP/RDP operation
- Flight strip processing
- Interphone communication
- Direct (face-to-face) voice communication.

A routine control event represents the operational consequence of a specific task or tasks set. For example, one control event routinely required for control jurisdiction transfer is handoff acceptance. This event requires the controller to perform manual FDP/RDP 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 entail only the A/G communication task.

Results of field experiments enabled the specification of individual task times and the frequency of occurrence of each event by sector for the observed team operation. These data were used to calculate* the routine workload weighting, k_1, for the team model:

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

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*The summation process requires that the minimum performance times of all the "control tasks" (interphone communications, FDP/RDP operations, flight strip processing, etc., indexed by j) be first summed under each "control event type" (indexed by i); then the total event minimum performance time is multiplied by the frequency of the event.

where

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

t_{ij} is the minimum performance time required for all type j team tasks included in the routine event i, measured in man-sec/event.

A subset of the team routine tasks was allocated to the R controller to model his routine work during intense traffic activities. The allocations were based on observations of R-controller actions and interviews with controllers, and obtained the routine workload weighting, k_1', for the R controller model by sector:

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

where

r_i, i, and j are as defined for the team model.

t_{ij}' is the minimum performance time required for all type j R-controller tasks included in routine event i, measured in man-sec/event.

4.2.2 Surveillance Work

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

To maintain a mental picture of traffic movement, the R controller is likely to look at an aircraft's data display once every minute, 1 to 1.5 sec/look being sufficient time to identify aircraft and to recognize or recall situations. The 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.

4.2.3 Conflict Processing Work

For potential crossing and overtaking conflict processing, the workload times (k_2N^2 and k_3N^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 perceive potential conflict--to mentally project flight trajectories. The R controller activities are detection, assessment, and resolution of potential conflicts.

To estimate the conflict processing workload weightings (k_2 and k_3), we use the duration of each conflict processing event and its frequency of occurrence:

$$k_2 = t_c \, e_c$$

$$k_3 = t_o \, e_o$$

where

t_c and t_o are the minimum performance times required for crossing and overtaking conflict processing, measured in man-sec/conflict.

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

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

The hourly conflict-frequency factors (e_c, e_o) determine the number of conflicts/hr ($e_c N^2$ and $e_o N^2$) 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 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 relationships are formulated as the summation of the probability of pairwise conflicts between aircraft. The models and their use for calculating frequency factors are described in Appendix D.

4.2.4 Workload and Capacity Calibration

The observed work activity data (i.e., exclusive of the inferentially derived surveillance workload) and reported sector capacity data were used to calibrate a workload threshold for the two-man team model for four sectors of the Los Angeles Center. A workload threshold for the R-controller model was then identified using the workload and traffic capacity relationships of the team model.

4.2.4.1 Team Model Calibration

To establish empirically the relationship between sector team workload and traffic capacity, extensive interviews with controllers addressed the maximum sustainable traffic flow rates in each sector. The controller estimates (which take into consideration historical peak activity levels) of the four sector traffic capacities were:

- 40-45 aircraft/hr for sectors 19/20
- 45-50 aircraft/hr for sector 18
- 45-50 aircraft/hr for sector 7
- 50-55 aircraft/hr for sector 36.

The sector capacity estimates were compared against sector workload calculated using the team model as shown in Figure 2. The midpoint of each capacity range (indicated by parentheses) corresponds closely to 66 man-min/hr of calculated team workload; this value--66 man-mm/hr--was defined to be the two-man team workload threshold. The hourly traffic rates corresponding directly to this threshold (indicated by the dotted lines) were used as point estimates of each sector's capacity. These model-estimated capacities are 43, 48, 46, and 52 aircraft/hour for sectors 19/20, 18, 7, and 36, respectively; all fall within the capacity range estimated by controllers.

4.2.4.2 R-Controller Workload Calibration

To ascertain the R-controller total workload corresponding to the sector traffic capacities, the R-controller model was used to calculate workload at the capacity flow rates as summarized in Table 3.

Although the team workload corresponding to the sector traffic capacities is 66 man-min/hr, the R-controller total workload varies from 45 to 51 man-min/hr. These data imply that R controllers

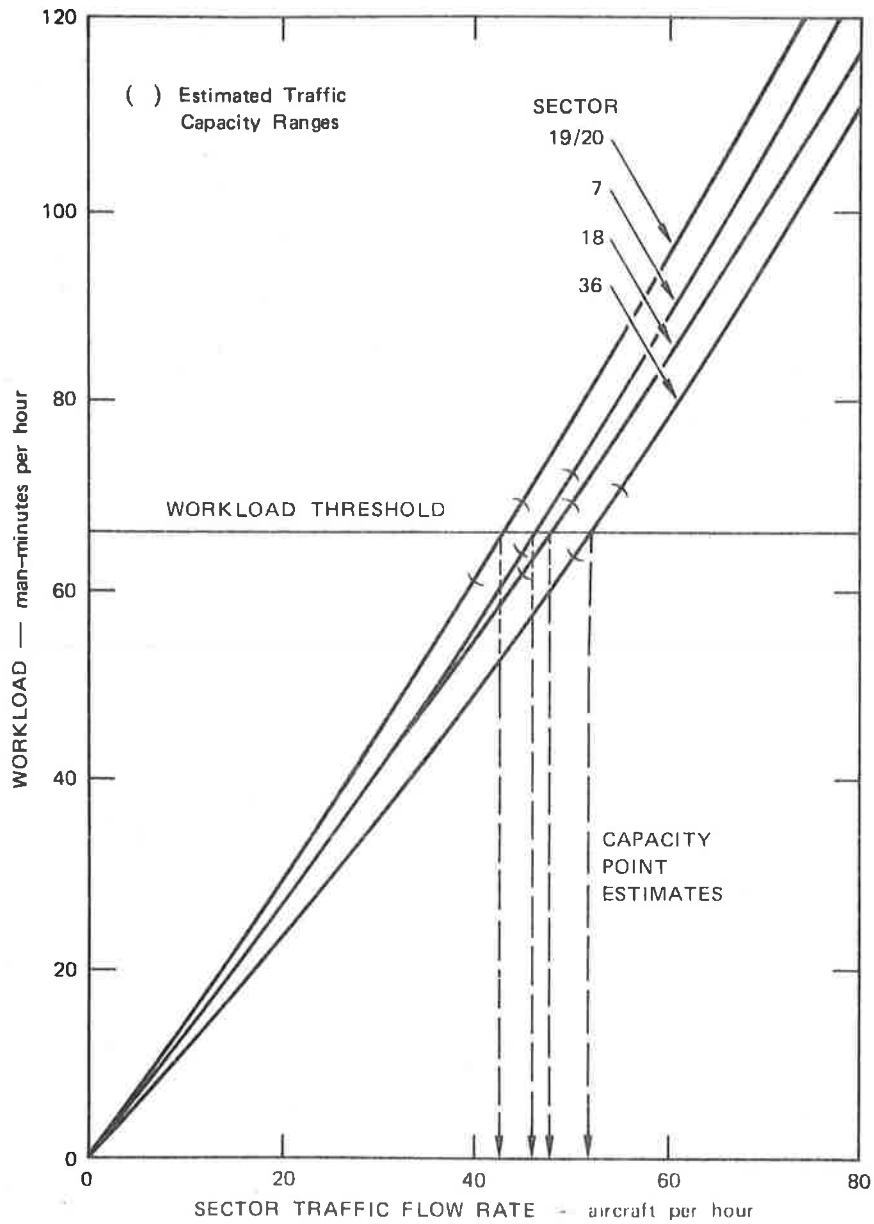

FIGURE 2 SECTOR TEAM WORKLOAD CALIBRATION

of different sectors are not working at equal levels of effort under traffic capacity conditions. Assuming each R controller is responsible for the same types of duties, regardless of sector, and that these duties are as defined by the workload allocation formulations, one finds the Sector 36 R controller is devoting more man-minutes of effort to his capacity traffic than are the others. Los Angeles Center personnel indicated that Sector 36 is the "hardest" sector to work.

interviewer uses video tape playback during examination and discussion of the operational strategies, procedures, and techniques employed by the controllers.

As part of the data-reduction process, data measurements are assembled into a format that facilitates cross-reference of the observed activities and permits a reconstruction, in part, of the routine control events. The information on operational procedures obtained during the controller interviews, along with the data observations, is essential to identify the control requirements that are in the logical reconstruction of routine events.

4.3.1 Team Routine Work Measurement

We used this procedure to collect data from four sectors at the Los Angeles Center[7] during the 5-day period 24-28 June 1974. The center was then using the NAS Stage A3d.2 system, including FDP and RDP capabilities. Because the data collection sessions at the Los Angeles Center were conducted during moderate-to-heavy traffic activity, we assume that these routine events are representative of control requirements during capacity conditions (during which nonessential activities are minimized).

Also, as part of the Los Angeles Center effort, we made stopwatch measurements of observed controller manual activities (FDP/RDP operations, flight-strip processing) and recorded and observed oral communications (A/G radio and interphone communications and direct-voice communication). For each identified task, we selected a "reasonable" minimum task performance time from the data measurements to represent task work requirements during capacity conditions. In determining minimum performance times, we considered only those observed or recorded activities that we judged to be performed completely (satisfied information transaction or message-content requirements) and with efficiency (without delay, interruption, or extraneous information).

Each DART record collected at the Atlanta Center corresponded to about a 1.25-hour period overlapping the 1-hour data collection. The DART transcriptions were manually scanned and searched, and a record was prepared of the FDP/RDP operations (e.g., handoff acceptance, altitude amendment, and data block/leader line offset) performed for each aircraft identified. An operation could be identified from the DART printout by the quick-action key and data format. This process resulted in the tabulation of the FDP/RDP operations shown by sector in Table 6. Again, cross-referencing with the A/G or interphone data was sometimes required to identify events. (For example, reference to A/G transcriptions for a particular aircraft would determine whether a flight data altitude amendment was a traffic structuring or a pilot request event.)

These three tables were then mutually cross-referenced to construct the routine control event tabulation shown by sector in Table 7. This construction required us to make logical interpretations of event characteristics based on judgment and the average hourly flow rate; the latter is the average of a sector's aircraft exits and entries, as calculated in Table 4. For example, the number of handoff acceptance, initial pilot call-in, and frequency change instruction events is assumed to be equal to the hourly traffic flow rate; the number of automatic handoff initiations is equal to the algebraic difference between the numbers of handoff acceptance and manual handoff initiation events. The entries in Table 7 were divided by the average hourly flow rate to obtain the team routine event frequencies shown in Table 8.

Because of an audio tape malfunction, no interphone data were obtained for Sector 37. In Table 8, we substituted the interphone frequencies of Sector 42 for those of Sector 37 because both are transition sectors. Because manual task activity observations were not recorded, no data were obtained for flight strip sequencing/removal and

TABLE 3

RADAR-CONTROLLER WORKLOAD CALIBRATION

Sector	Estimated Capacity* (aircraft/hr)	Workload (man-min/hr)				Workload Intensity Factor†
		Surveillance	Routine	Conflict	Total	
Low arrival (19/20)	43	8	34	6	48	0.80
Low departure (18)	48	9	30	6	45	0.75
Low enroute (7)	46	11	28	9	48	0.80
Low transition (36)	52	13	27	11	51	0.85

*Estimated capacity corresponds to a workload threshold of 66 man-min/hr.

†Workload intensity factor is based on a maximum R-controller availability of 60 man-min/hr.

The average R-controller workload at capacity for the four sectors is 48 man-min/hr. The significance of this value to the R controller can be examined using the concept of workload intensity. The total time available to the R controller to perform work is 60 man-min/hr, and the proportion of this hour actually consumed in measurable work is called the workload intensity factor; these are listed in Table 3. If the arrival pattern of control events for the R controller over a long period of time (e.g., one hour) is suitably random, an analogy to the traffic intensity factor of standard single-server queueing modeling can be made. It has been shown that, as the intensity factor approaches a magnitude of the order of 0.80, the queueing system nears instability. This implies that, if over a long time period the R controller is working under too high a workload intensity factor, he is in danger of suddenly receiving a surge of traffic over a short time period (e.g., 5-10 min) that he cannot handle. In controller terminology, such a surge would cause the R controller to "go under."

At capacity, the R controllers of Sectors 19/20, 7, and 36 are working under workload intensity factors equal to or greater than 0.80 (48 man-min/hr); in Sector 18 the factor is 0.75. Although the Sector 18 R controller may be able to accept additional work over the long term, the additional work could not be accepted by the sector team as a whole. The sector is already operating at its traffic capacity rate. Therefore, the sector team workload threshold of 66 man-min is constraining the capacity of Sector 18.

At capacity, Sectors 19/20 and 7 are experiencing R-controller workloads of 48 man-min (the maximum team workload allowable), but the Sector 36 controller experiences a 51 man-min (0.85 intensity) workload. Despite the anomaly of Sector 36, it appears that 48 man-min is a reasonable estimate of R-controller workload threshold. Therefore, this threshold value was used as a check to ensure that overall sector teamwork does not overload the R position.

4.3 DATA COLLECTION AND REDUCTION

As a result of various ATC-related data collection exercises,[4-7] SRI has developed a data collection/reduction procedure for NAS Stage A equipped enroute facilities that is based on the following data sources:

- Video tape recordings of PVDs.
- Audio (including video tape sound track) recordings of A/G and interphone communications.
- Manual recordings of observed controller physical actions.
- NAS Stage A data analysis and reduction tool computer print-out records of R and D position FDP/RDP operations.
- Flight strips, used and marked-on by controller.

These data are collected during a one-hour observation of a selected sector's control activities. Each observation session is followed by a one-hour structured interview of the sector's controllers. The

TABLE 6

OBSERVED NUMBER OF FDP/RDP OPERATIONS, CURRENT NAS STAGE A, ATLANTA CENTER

FDP/RDP Operation	Quick Action Key	Event Occurrence Per Sector: High Enroute (36) Allatoona	Departure Transition (37) Crossville	Departure (38) North Departure	Arrival (41) Norcross	Arrival Transition (42) Lanier	Low Arrival (46) Commerce	Low Enroute (52) Hinch Mountain
Control jurisdiction transfer								
Handoff acceptance	QN,QZ,QT	24	23	16	17	20	12	11
Flight data update	DM	0	0	0	0	0	0	10
Handoff initiation, manual (silent)	QN,QZ,QX	18	19	16	12	12	9	9
Traffic structuring								
Initial pilot call-in, flight data altitude insert	QR,RA	0	0	0	0	0	2	1
Altitude instruction, flight data, altitude amendment	QZ,QQ,AM	0	2	0	15	2	0	2
Heading instruction, flight data route amendment	QU,AM	4	3	0	0	0	1	1
Pilot altitude report, flight data altitude insert	QR,RA	0	0	0	0	0	0	0
Transponder code assignment, flight data code update	QB,DQ	0	0	0	0	0	0	2
Pilot request								
Altitude revision, flight data altitude amendment	QZ,AM	1	3	0	3	1	0	0
Route/heading revision, flight data route amendment	QU,AM	1	0	0	0	0	0	0
Clearance delivery, flight data update	DM	0	0	0	0	0	0	1
Pointout								
Pointout acceptance, data block suppression	QP	0	3	0	0	1	0	0
Pointout initiation	QP	1	2	7	3	3	0	2
General intersector coordination								
Clearance delivery, flight data update	DM	0	0	0	0	0	0	2
General system operation								
Flight data estimate update	*	7	11	16	9	14	6	13
Data block/leader line offset	QN,QZ	21	26	0	14	31	0	6
Data block forcing/removal	QN,QZ	39	25	16	25	50	12	6
Miscellaneous data service								
Wind request	UR	6	1	0	2	2	0	0
Altitude limits modification	QD	0	0	0	0	1	0	0
Strip request	SR	0	0	0	0	0	1	2
Flight plan/track removal	RS	0	0	0	0	0	0	2
Other								
Flight plan readout request†	QF,FR	5	0	0	0	0	2	4
Track/route display‡	QU	6	0	0	5	1	0	0

*Computer readout device (CRD) data update message.

†Concurrent with interphone communication.

‡Concurrent with conflict detection/assessment.

equipment adjustment. Also, the number of events observed at some sectors for data block/leader line offset and data block forcing/removal appeared too large to be representative of capacity or heavy traffic conditions. This conclusion is based on a small sample of observations at Atlanta in that the frequency of such event diminishes during short traffic surges. For each of these four events we assigned event frequencies (Table 8) that were adjusted in accordance with the Los Angeles Center data.

The audio tapes of A/G and interphone communications and the DART transcription obtained during the field experiment will provide sufficient data to estimate the frequencies of the great majority of the routine control events. However, for completeness, some additional data should be collected. For example, the number of hand-written flight strips (i.e., those not printed by the FDP printer) obtains the number of new flight strip events performed for pop-ups. These data could also be obtained by on-site observations of control team activities, as could the number of flight-strip sequencing/removal and equipment adjustment events.

4.3.1.2 Team Routine-Event Minimum Performance Time Measurements

Stopwatch measurements of observed and recorded minimum task performance times are summarized in Table 9. The set of routine control events shown are actually identified or finalized upon completion of the off-site reduction effort, which includes determining event frequencies. Note that this set is based on field experiments conducted at the Atlanta and Los Angeles Centers and essentially is a description of those events performed during our data collection sessions. Therefore, it is possible that "new" events might be observed if the experiments were to be repeated at some other site, necessitating estimation

TABLE 9

ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
TWO-MAN SECTOR OPERATION
SYSTEM 1A--NAS STAGE A BASE

Routine Control Event Description		Minimum Task Performance Time* (man-sec/task)					Minimum Event Performance Time (man-sec/event)
Event Function	Basic Event and Supplemental Event	A/G Communication	FDP/RDP Operation	Flight Strip Processing	Interphone Communication	Direct Voice Communication†	
Control jurisdiction transfer	Handoff acceptance		2	1			3
	Flight data update		3				3
	Intersector coordination				7	6	13
	New flight strip preparation			10			10
	Handoff initiation-automatic			1			1
	Manual initiation-silent		3				3
	Intersector coordination				7	6	13
Traffic structuring	Initial pilot call-in	4		1			5
	Flight data altitude insert		3	1			4
	Altitude instruction	4		2			6
	Flight data altitude amendment		3				3
	Intersector coordination				5	6	11
	Heading instruction	5		2			7
	Flight data amendment		10				10
	Intersector coordination				5	6	11
	Speed instruction	5		2			7
	Intersector coordination				5	6	11
	Altimeter setting instruction	3		1			4
	Runway assignment instruction	3					3
	Pilot altitude report	5		2			7
	Flight data altitude insert		3				3
	Pilot heading report	5		2			7
	Pilot speed report	5		2			7
	Traffic advisory	4					4
	Transponder code assignment	4					4
	Flight data code amendment		3	2			5
	Miscellaneous A/G coordination	5					5
	Frequency change instruction	4		1			5
	Intersector coordination				4	6	10
Pilot request	Altitude revision	6		2			8
	Flight data altitude amendment		3				3
	Intersector coordination				5	6	11
	Route/heading revision	8		2			10
	Flight data route amendment		10				10
	Intersector coordination				6	8	14
	Speed revision	6		2			8
	Clearance delivery	20	3	2			25
	Miscellaneous pilot request	8					8
Pointout	Pointout acceptance				7	8	15
	Data block suppression		3				3
	Pointout initiation		3	2	7	8	20
General intersector coordination	Control instruction approval				5	6	11
	Planning advisory				5	6	11
	Aircraft status advisory				5	6	11
	Control jurisdiction advisory				6	6	12
	Clearance delivery			2	20	6	28
	Flight data update		3				3
General system operation	Flight data estimate update		1	3			4
	Data block/leader line offset		2				2
	Data block forcing/removal		3				3
	Miscellaneous data service		3				3
	Flight strip sequencing/removal			2			2
	Equipment adjustment		3				3

*Task performance time estimates are based on data collected at the Los Angeles Center.

†Indicated value is double the measured direct voice communication time duration.

of their minimum performance times. For this reason, and for the sake of confirming the previously estimated event performance times, we suggest that subsequent field experiments should include at least a program to check the minimum times required by the various tasks.

On-site task performance time measurements need not be an elaborate program because many of the measurements can be made after completion of the field experiment and after all events have been identified. All A/G and interphone voice communication message times can be obtained from the audio or video tape records using a stopwatch. The remaining tasks, those that can be observed only at the facility, have been found to fall into a limited number of performance-time groups. FDP/RDP operations may take 1, 2, 3 or 10 seconds respectively when a single-key operation is required (i.e., to clear the CRD), when function-key and aircraft identification operations are required (i.e., accept handoff), when function-key, aircraft identification, and limited-data entry operations are required (e.g., flight data altitude amendment), or when function-key, ACID and extended-data entry operations are required (e.g., flight data route ammendment).

Flight-strip processing was found to require 1 second to confirm data printed on the strip (e.g., manually "check-off" an altitude entry), 2 seconds to update numeric data on an active strip (e.g., write a new altitude clearance) or sequence or remove a strip, 3 seconds to update flight data estimates on a proposal strip (e.g., copy CRD-displayed altitude revision), or 10 seconds to prepare a new strip or revise a routing.

Direct voice communications, which are face-to-face conversations between an R and a D controller, were found to take at least 3 seconds, but may take 4 seconds if discussions of routings are involved. (These task times are doubled in Table 9 to account for the time both controllers spend in a direct-voice communication with each other.)

The event performance times are obtained in Table 9 by summing the contributing task minimum performance times. Although this process is part of the off-site data reduction and not directly included in on-site field experimentation, it is advisable to develop a knowledge or "feeling" for the task composition of each event during the data observations. This knowledge will assist the analyst to comprehend and estimate the impact of postulated automations and controller task requirements.

4.3.1.3 Team Routine Control Event Summary

The following discussion provides an overview of the routine control events we associated with enroute sector operations. These events, which are listed in Table 10 and 11 were developed from our data observations and controller interviews to define control activities as logical representations of operational requirements. Table 10 includes a brief summary of the controller activities associated with each event and parallels this discussion.

Control Jurisdiction Transfer--A handoff between two sectors transfers authority over an aircraft and full access to the aircraft's computer data file from one team to the other (direct control is effected when the aircraft crew switches onto the receiving sector's A/G radio frequency). A silent handoff (i.e., a procedure not routinely requiring intersector interphone communication) is initiated either automatically by the NAS Stage A computerized operations or manually by a sector team using FDP/RDP keyboard or trackball operations, or both. Either handoff initiation mode caused a blinking "H" and the receiving sector's identity numbers (e.g., "H-36") from the aircraft's

TABLE 11

R-CONTROLLER ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES ATLANTA CENTER, TWO-MAN SECTOR OPERATION SYSTEM 1A--NAS STAGE A BASE

Routine Control Event Description		Minimum Task Performance Time (man-sec/task)					Minimum Event Performance Time (man-sec/event)
Event Function	Basic Event and Supplemental Event	A/G Communication	FDP/RDP Operation	Flight Strip Processing	Interphone Communication	Direct Voice Communication	
Control jurisdiction transfer	Handoff acceptance						
	Flight data update						
	Intersector coordination					3	3
	New flight strip preparation						
	Handoff initiation-automatic						
	Manual initiation-silent						
	Intersector coordination					3	3
Traffic structuring	Initial pilot call-in	4		1			5
	Flight data altitude insert			1			1
	Altitude instruction	4		2			6
	Flight data altitude amendment						
	Intersector coordination					3	3
	Heading instruction	5		2			7
	Flight data amendment						
	Intersector coordination					3	3
	Speed instruction	5		2			7
	Intersector coordination					3	3
	Altimeter setting instruction	3		1			4
	Runway assignment instruction	3					3
	Pilot altitude report	5		2			7
	Flight data altitude insert						
	Pilot heading report	5		2			7
	Pilot speed report	5		2			7
	Traffic advisory	4					4
	Transponder code assignment	4					4
	Flight data code amendment			2			2
	Miscellaneous A/G coordination	5					5
	Frequency change instruction	4		1			5
	Intersector coordination					3	3
Pilot request	Altitude revision	6		2			8
	Flight data altitude amendment						
	Intersector coordination					3	3
	Route/heading revision	8		2			10
	Flight data route amendment						
	Intersector coordination					4	4
	Speed revision	6		2			8
	Clearance delivery	20		2			22
	Miscellaneous pilot request	8					8
Pointout	Pointout acceptance					4	4
	Data block suppression		3				3
	Pointout initiation					4	4
General intersector coordination	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory					3	3
	Control jurisdiction advisory					3	3
	Clearance delivery					3	3
	Flight data update						
General system operation	Flight data estimate update						
	Data block/leader line offset		2				2
	Data block forcing/removal		3				3
	Miscellaneous data service						
	Flight strip sequencing/removal						
	Equipment adjustment		3				3

data block to appear on the PVDs of both the initiating and receiving sectors. Handoff acceptance is performed manually using FDP/RDP operations and causes the flashing "H" to be replaced by the letter "O", which is retained for about one minute on both PVDs. The receiving sector team manually marks the letter "R" (for radar contact) on its flight strip for that aircraft, and the initiating sector team marks a circle around its "R".

Handoffs between NAS Stage A sectors and non-NAS Stage A or non-ARTS III facilities cannot be performed silently and require interphone communications to transfer control jurisdiction. The NAS Stage A sector also performs FDP/RDP keyboard and trackball operation to initiate or drop computerized radar tracking. This activity is normally accompanied by an additional FDP operation to input flight data updating information (e.g., departure message, altitude clearance).

Intersector coordinations sometimes accompany silent handoffs when standard control procedures are not strictly followed (e.g., as a result of conflict-avoidance instructions). Intersector coordinations generate intrasector consultation between R and D controllers to confirm information transfers. In cases of an unexpected aircraft pop-up, a paper flight strip for the aircraft is manually prepared by the D controller.

Traffic Structuring--These events include the procedural-based activities routinely required to process an aircraft through a sector. The traffic structuring basic events are all initiated by A/G communications and generally include some manual data updating or recording task. Each A/G communication task entails negotiation or confirmation between pilot and controller. The first traffic structuring event for an aircraft is the pilot's initial flight identity and altitude report call-in, which is manually "checked" on the flight strip. If the

4.3.2 R-Controller Routine Work Allocation

Based on observations and controller interviews at both the Los Angeles and Atlanta Centers, we concluded that during busy periods the R controller concentrates on the traffic in his sector, primarily occupying himself with basic traffic structuring, pilot requests, and equipment operation. As a result, he performs all A/G communications as well as tasks associated with active flight strips (including all traffic structuring and pilot request flight-strip processing), various RDP-related actions, and his half of direct-voice communications.

To represent the R-controller's routine work, we allocated portions of the team routine tasks (defined in Table 5), and obtained the R-controller tasks as shown in Table 11 for the Atlanta Center. These allocations are not intended to be inflexible or firm descriptions of all the specified tasks that must be performed by the R controller, but show the work that typically may be expected to be performed by the R controller during capacity conditions. We note, for example, that task trade-offs between the R and D controllers may occur and are not accounted for in Table 11. For example, the R controller may perform some manual handoff or a few voice interphone communications tasks if time permits, and the D controller may perform some of the FDP/RDP operation and flight-strip processing tasks nominally observed to be performed by the R controller. However, in all circumstances, the R controller is expected to perform all the A/G communications tasks and the D controller performs most of the interphone communications tasks.

4.3.3 R-Controller Surveillance Work Calculation

Surveillance workload based on the assumption of 1.25 man-sec/aircraft-min for PVD scanning work is as shown in Table 12 for the Atlanta Center sectors. The average transit times were assumed to be

TABLE 12

R-CONTROLLER SURVEILLANCE WORKLOAD WEIGHTING, BY SECTOR
ATLANTA CENTER, TWO-MAN SECTOR OPERATION
SYSTEM 1A--NAS STAGE A BASE

Sector	Aircraft Average Transit Time (min)	Surveillance Workload Weighting* (man-sec/aircraft)
High enroute (36)	20	25
Departure transition (37)	21	26.25
Departure (38)	12	15
Arrival (41)	19	23.75
Arrival transition (42)	18	22.5
Low arrival (46)	21	26.25
Low enroute (52)	14	17.5

*Based on 1.25 man-sec/aircraft-min.

the average time aircraft were tuned into the sector's A/G radio frequency. Comparison of these times, as measured from the Los Angeles Center audio tapes against the average sector times reported by the facility in the Busy Day Annual Report (1973), found little difference between the data sources. The times shown in Table 12 were obtained from the Atlanta Center's Busy Day Annual Report (1975).

As an alternate, the average transit time may be based on the time between aircraft handoff acceptance and initiation and obtained from DART printout data. But, because the time a controller spends on an aircraft is closely related to the time he spends "talking" to the pilot, the average time or frequency is considered to be a more meaningful measure of the surveillance-time requirement.

4.3.4 Potential Conflict Work Measurement

As in the case of routine workload modeling, the two essential parameters pertaining to potential conflict workload modeling are: (1) conflict-event minimum performance times, and (2) conflict-event frequencies. We discuss separately data collection requirements of each as follows.

4.3.4.1 Conflict-Event Minimum Performance Times

Two basic types of potential conflict events of interest have been identified: crossing and overtaking conflicts. In both cases the component tasks are detection-and-assessment and resolution. During a field experiment conducted at the Los Angeles Center, SRI spent considerable time in controller interviews, using video tape playbacks of PVD displays, to ascertain the minimum times required for these two tasks. This required identifying a conflict event and then reviewing with the controller the actions required to recognize the possibility of a conflict and the reasons and methods by which he resolved the situation. Typically, the controller had difficulty in identifying exactly how much time he devoted to the conflict situation, but we usually were able, with sufficient video tape playback, to estimate the times at which he became first aware of the potential conflict, when he had sufficient information to determine resolution actions, and when the appropriate directives were issued (by means of A/G communication) and performed. This information enabled us to make estimates of the task times, although it involved considerable video tape review during the off-site data reduction.

Spot checks of the task times were carried out during the Atlanta Center field experiment by briefly reviewing a few potential conflict situations during controller interviews. These spot checks, in our judgment, indicated that, except for some minor modifications, the Los Angeles Center task times were applicable to the Atlanta Center operations. The minor modification reduced the detection-and-assessment task for overtaking conflicts at the Atlanta Center by 10 seconds because this facility was operating with ground-speed display while the Los Angeles Center was not during our data observations. The ground-speed display obviates the need for certain A/G speed reports. The resulting conflict-event performance times are summarized in Table 13.

TABLE 13

CONFLICT EVENT PERFORMANCE TIME ESTIMATES
ATLANTA CENTER, TWO-MAN SECTOR OPERATION
SYSTEM 1A--NAS STAGE A BASE

Conflict Event	Minimum Task Performance Time* (man-sec/task)		Minimum Event Performance Time (man--sec/event)
	Detection and Assessment	Resolution	
Crossing	20	40	60
Overtaking	20	20	40

*Based on data collected at the Los Angeles Center and observations of Atlanta Center operations.

To determine whether conflict-event task time adjustments are necessary for subsequent RECEP modelings, we feel that future field experiments at least should spot check task times. Furthermore, given the somewhat inferential nature of conflict event task time "measurement" as described above, we believe that, for the best interest of modeling accuracy, intensive examination of conflict-event times should be carried out wherever possible. However, because controller interview-based task assessment is a very time-consuming process if carried out on a large scale, due consideration should be given to the field experiment costs involved.

4.3.4.2 Potential Conflict-Event Frequencies

We have used as part of the Los Angeles and Atlanta case studies mathematical relationships for estimating the number of potential crossing and overtaking conflicts in a sector: these are described in Appendix D. The mathematical relationships relate frequency of potential conflicts at a conflict-point-to-aircraft flow rates, the separation minima, and sector geometries. In using these relationships, we found fairly close correlation between the calculated frequencies and the number of potential conflict situations reported by interviewed controllers. For example, for a 1-hour data collection session during which three conflicts were identified, the conflict equations calculated 3.7 conflicts/hour. Although this is not a formal validation of the conflict frequency calculations, their use in subsequent field experiments may be obtained as described following.

Important information regarding potential conflict situation control procedures is obtainable during controller interviews with playback of the PVD video tapes. Controllers will identify actual conflict points that command their attention. These conflict points are those that have not been "procedurallized" out of existence (e.g., tunneling routes to ensure altitude separation) and require controller intervention to resolve pairwise conflicts between aircraft. Furthermore, the controllers could provide useful insights, based on their experience, regarding the relative intensities of crossing and overtaking conflicts at different points and reasons for conflict situations that may not be obvious to the observer (e.g., speed differentials and unique noise-abatement procedures). The controller interviews should also clarify questions regarding the in-trail separation procedures applied at various locations. For example, controllers may be observed to maintain in actual practice 10 nmi separations in enroute airspaces, but use 5 nmi at boundaries with terminal facilities.

This kind of background information is most useful for developing a perspective on the appropriate applications of the mathematical-conflict models; however, additional empirical data are needed to support the modeling approach. In accordance with past SRI practice, we recommend the use of aircraft ground-speed displays as recorded on video tape to estimate the speed classes along each route. Maps obtained from the Center are useful for measuring intersection angles and route lengths. Also, the route flow rates may be determined from the video tape recordings or or, as we have done for data-reduction convenience, by inspection of flight-strip data. Further details describing data collection are given in Appendix E. This field experiment procedure was used at the Atlanta Center to develop the potential conflict-event frequencies shown in Table 14.

4.3.5 Sector Traffic Capacity Estimation

The workload thresholds defined during the Los Angeles Center case study--66 man-min/hr for the two-man sector team and 48 man-min/hr for the R controller--were used to estimate capacities for seven sectors observed at the Atlanta Center. The team and R-controller models were simultaneously applied to each sector to determine which one (team or R controller) constrains sector capacity. The workload weightings determined for the team and R controller models are summarized in Table 15 for each sector; these weightings are based on the data presented in Tables 8, 9, and 11 through 14.

TABLE 14

ESTIMATED FREQUENCY OF CONFLICT EVENTS PER SECTOR
ATLANTA CENTER, TWO-MAN SECTOR OPERATION
SYSTEM 1A--NAS STAGE A BASE

Sector	Conflict Event Frequency Factor $[(\text{conflicts/hr})/(\text{aircraft/hr})^2]$	
	Crossing	Overtaking
High enroute (36)	4.8×10^{-3}	0.9×10^{-3}
Departure transition (37)	4.4×10^{-3}	0.5×10^{-3}
Departure (38)	0	0.7×10^{-3}
Arrival (41)	2.7×10^{-3}	6.4×10^{-3}
Arrival transition (42)	3.5×10^{-3}	5.8×10^{-3}
Low arrival (46)	6.6×10^{-3}	0.7×10^{-3}
Low enroute (52)	5.3×10^{-3}	4.3×10^{-3}

The capacity estimation procedure was to calculate the workload for successive 5-aircraft/hour increments in traffic flow and to interpolate the sector traffic capacity corresponding to the critical workload threshold. (One alternative capacity estimation procedure would be to plot workload time versus the hourly number of aircraft through the sector. The traffic capacity of the sector could then be determined by graphically finding the number of aircraft/hour corresponding to the specified upper limit on workload time. Another alternative would be to solve for the quadratic equations (listed in Section IV-B) for N.

The resulting point estimates of sector capacities obtained by both models are shown in Table 16. Sectors 36, 37, 38, 41, 42, and

TABLE 15

WORKLOAD WEIGHTINGS
ATLANTA CENTER, TWO-MAN SECTOR OPERATION
SYSTEM 1A--NAS STAGE A

Sector	Routine Workload Weighting (man-sec/aircraft)		Surveillance workload weighting, ct_s	Conflict Workload Weighting $[(\text{man-sec/hr})/(\text{aircraft/hr})^2]$	
	Two-man Team, k_1	R Controller, k_1'	(man-sec/aircraft)	Crossing, k_2	Overtaking, k_3
High enroute (36)	51	31	25	28.8×10^{-2}	3.6×10^{-2}
Departure transition (37)	64	38	26	26.4×10^{-2}	2.0×10^{-2}
Departure (38)	77	40	15	0	2.8×10^{-2}
Arrival (41)	92	58	24	16.2×10^{-2}	25.6×10^{-2}
Arrival transition (42)	66	40	23	21.0×10^{-2}	23.2×10^{-2}
Low arrival (46)	81	41	26	39.6×10^{-2}	2.8×10^{-2}
Low enroute (52)	103	47	18	31.8×10^{-2}	17.2×10^{-2}

TABLE 16

SECTOR TRAFFIC CAPACITY ESTIMATES
ATLANTA CENTER, TWO-MAN TEAM OPERATION
SYSTEM 1A--NAS STAGE A BASE

Sector	Sector Capacity (aircraft/hr)		
	Controller Estimate*	SRI Workload Model	
		R-D Team†	R Controller‡
High enroute (36)	40-45	57	42 §
Departure transition (37)	35-40	50	38 §
Departure (38)	45-50	50	50 §
Arrival (41)	30-35	38	30 §
Arrival transition (42)	35-40	46	37 §
Low arrival (46)	30-35	40	35 §
Low enroute (52)	30-35	33 §	35

*Controller estimates of sector capacities obtained during interviews at Atlanta Center.

†The two-man team capacity is that hourly traffic rate that generates 66 man-min/hr of team routine and conflict work.

‡The R controller capacity is that hourly traffic rate that generates 48 man-min/hr of R controller routine, surveillance, and conflict work.

§SRI sector capacity point estimate.

46 are constrained by the R-controller workload that results with capacity estimates of 42, 38, 50, 30, 37 and 35 aircraft/hour, respectively. Sector 52 is constrained by the team workload that results with a capacity estimate of 33 aircraft/hour.

For comparison, we also show in Table 16 the sector capacities estimated by Atlanta Center controllers. These estimates, obtained in interviews during our data collection effort, are shown to correspond to our workload modeling-based capacity point estimates. In a subsequent review of our capacity estimates, an Atlanta Center supervisory staff member evinced general agreement. However, he conjectured that our capacity point estimates for Sectors 36 and 38 may be slightly high by a few aircraft/hour, while the estimate for Sector 41 may be low by about five aircraft/hour. Because the use of these estimates was to provide a baseline for relative productivity of enhanced systems, these small capacity differences would not measurably affect subsequent comparisons.

4.3.6 Alternative Sector Manning Strategy Analysis

To demonstrate the application of the RECEP methodology to the analyses of operations that could not be observed, let us examine the modeling of three-man sector teams for the Atlanta Center sectors. The three-man team includes an R controller, D controller, and a tracker (T) controller.

Three-man sector teams were not in operation during our scheduled data collection periods; modeling of their task activities was based on controller interviews and observations without data collection of three-man operations. Controllers reported that this manning strategy requires the T controller to work closely with the R controller, and the D controller operates in a less-reactive role. The T controller performs the time-critical FDP/RDP manual operations in reaction to R-controller actions and assists in flight-strip processing. The D controller performs much of the interphone communications and the less traffic-reactive FDP/RDP manual operations (e.g., flight data estimate updating) and flight-strip processing (e.g., sequencing/removal). We note that, at the Atlanta Center, the T controller is physically situated between two adjacent sector consoles so that he can use both sectors' FDP/RDP keyboards to manually initiate and accept handoffs between the two sectors. However, in this so-called "half-man" operation, his primary function during busy periods is to directly support only one of the two R controllers, thus effectively being integrated into the control operations of one sector team.

Because the R-T control operation is similar in structure to the R-D team operation of the two-man sector manning strategy, the 66 man-min/hr workload limit was assumed to apply to the R-T team. The corresponding R-T team routine event performance times are shown in Table 17. Tasks performed by the D controller were not included in this model formulation as his workload would not constrain traffic capacity.

The 48 man-min/hr workload limit was applied to the R controller. R-controller task allocations are similar to those described for the two-man operation except for transfer of some traffic structuring flight-strip processing and FDP/RDP operations to the T controller. We assumed that the T controller will take over the flight-strip processing associated with the altitude instruction and transponder code assignment events (in conjunction with the FDP/RDP manual tasks required for these events), as well as the FDP/RDP manual operations for pointout acceptance-data block suppression and data block/leader line offset events (which parallel his handoff activities).

Conflict processing and surveillance work would be the same as those described for two-man sector operations. Routine-event frequencies would be as shown in Table 8, and workload weightings may be calculated in the same way as that for the R and D operations.

Sector traffic capacity is the traffic flow rate that generates the quantity of work corresponding to the two-man R-T controller team (66 man-min/hr) or R controller (48 man-min/hr) workload threshold, whichever is critical. Under three-man sector operations, the capacities of Sectors 36, 37, 38, 41, 42, 46, and 52 are 44, 42, 55, 32, 40, 37,

TABLE 17

R-T TEAM ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
ATLANTA CENTER, THREE-MAN SECTOR OPERATION
SYSTEM 1B--NAS STAGE A BASE

Routine Control Event Description		Minimum Task Performance Time* (man-sec/task)					Minimum Event Performance Time* (man-sec/event)
Event Function	Basic Event and Supplemental Event	A/G Communication	FDP/RDP Operation	Flight Strip Processing	Interphone Communication	Direct Voice Communication†	
Control jurisdiction transfer	Handoff acceptance		2	1			3
	Flight data update		3				3
	Intersector coordination				0(7)		6(13)
	New flight strip preparation			0(10)			0(10)
	Handoff initiation-automatic			1			1
	Manual initiation-silent		3				3
	Intersector coordination				7	6	13
Traffic structuring	Initial pilot call-in	4		1			5
	Flight data altitude insert		3	1			4
	Altitude instruction	4		2			6
	Flight data altitude amendment		3				3
	Intersector coordination				0(5)	6	6(11)
	Heading instruction	5		2			7
	Flight data amendment		10				10
	Intersector coordination				0(5)	6	6(11)
	Speed instruction	5		2			7
	Intersector coordination				0(5)	6	6(11)
	Altimeter setting instruction	3		1			4
	Runway assignment instruction	3					3
	Pilot altitude report	5		2			7
	Flight data altitude insert		3				3
	Pilot heading report	5		2			7
	Pilot speed report	5		2			7
	Traffic advisory	4					4
	Transponder code assignment	4					4
	Flight data code amendment		3	2			5
	Miscellaneous A/G coordination	5					5
	Frequency change instruction	4		1			5
	Intersector coordination				0(4)	6	6(10)
Pilot request	Altitude revision	6		2			8
	Flight data altitude amendment		3				3
	Intersector coordination				0(5)	6	6(11)
	Route/heading revision	8		2			10
	Flight data route amendment		10				10
	Intersector coordination				0(6)	8	8(14)
	Speed revision	6		2			8
	Clearance delivery	20	3	2			25
	Miscellaneous pilot request	8					8
Pointout	Pointout acceptance				0(7)	8	8(15)
	Data block suppression		3				3
	Pointout initiation		3	2	7	8	20
General intersector coordination	Control instruction approval				0(5)	6	6(11)
	Planning advisory				0(5)	6	6(11)
	Aircraft status advisory				0(5)	6	6(11)
	Control jurisdiction advisory				0(6)	6	6(12)
	Clearance delivery			0(2)	0(20)	6	6(28)
	Flight data update		0(3)				0(3)
General system operation	Flight data estimate update		0(1)	0(3)			0(4)
	Data block/leader line offset		2				2
	Data block forcing/removal		3				3
	Miscellaneous data service		3				3
	Flight strip sequencing/removal			0(2)			0(2)
	Equipment adjustment		3				3

*Revised System 1A performance times are indicated in parentheses.

†Indicated value is double the measured direct voice communication time duration.

37 aircraft/hr, respectively. In each case, the R controller (48 man-min/hr), limits capacity.

4.4 RECEP/ATF INTERFACE

RECEP estimates the traffic capacity of individual sectors, and ATF estimates aircraft delays for a multisector environment. The ATF model identifies situations in which individual sectors are about to be overloaded and delays aircraft in other sectors to prevent overloadings. The interface between RECEP and ATF is effected by transforming RECEP capacity estimates into certain ATF-modeling parameters; these parameters define overloading situations and are determined using the input data needed to begin an ATF formulation.

ATF uses three parameters (sector workload threshold and two workload coefficients), to assess sector traffic-handling capabilities. All can be obtained directly by the RECEP technique. The sector workload threshold is 66 or 48 man-min/hr depending upon which model establishes capacity. The first workload coefficient is the sum of the linear constant terms in the RECEP model being used and the second coefficient is the sum of the constants associated with the quadratic terms. Multiplying the workload coefficients respectively by the number of aircraft and number of aircraft squared in the sector during a specific time increment (e.g., 1-min) obtains the total sector workload for that time increment. ATF constrains sector (arc) entries to assure that the total sector workload during the time increment does not exceed the workload threshold. This prevents the occurrence of workload surges of magnitudes exceeding the average long-term workload limit specified by the threshold value. That is, the greatest rate at which a sector team is allowed to work is 66 man-min/hr for any 1-min increment (during which 1.1 man-min of hourly work are expended), and the R controller is limited to a work rate of 48 man-min/hr during any 1-min increment.

The workload coefficients are calculated so that an aircraft's cumulative workload contribution is distributed over its expected undelayed sector transit time. However, ATF allocates workload by delaying aircraft in upstream sectors. Additional work involved in delaying actions (e.g., vectoring, speed restrictions) is induced on the upstream sector team. This induced work has not been accounted for in the calculation of the workload coefficient. Because of the natural implementation of planning control by in-trail restrictions, it may be assumed that induced delay work corresponds to an additional amount of "normal" (i.e., routine conflict and surveillance) work. Therefore, the workload coefficient also could respresent the total workload contribution of an aircraft while it is being delayed. This approach was used to model multisector operations for the Los Angeles Center and Atlanta Center.

4.5 RECEP DATA BASE UPDATE AND MODEL VERIFICATION

The RECEP data base update and model verification are required periodically to maintain its validity as a reliable measuring and predicting tool.

4.5.1 RECEP Data Base Update

Although the RECEP data bases that have been used for the Los Angeles study[2] and the Atlanta study[3] are adequate for the two centers and it is also possible that the task minimum times of the current data bases may be equally applicable to other centers as well, it is nevertheless desirable to perform a two- or three-day field test at the same sites ("quick look") to recalibrate the routine and conflict workload estimates prior to the application of RECEP to a new center.

4.5.2 Model Verification

The purpose of this test is to compare RECEP estimates with some other field measures estimating workload and traffic capacities (e.g., peer observations of workpace, voice channel utilization, aircraft proximity weighting) to verify the realism of the RECEP technique.

The verification will probably involve two stages. The first one is an initial comparison between the RECEP workload/aircraft loading function for each sector and the workpace/aircraft loading functions (as measured in the field). In the event the two functions do not coincide, then a second stage would be necessary that involves a recalibration of the RECEP estimates to be more closely aligned with field measures. Some detailed approaches on RECEP data base update and model verification have been suggested by TSC* and are described in Appendix G. However, this procedure has not been tested; therefore, its effectiveness is not known at this time.

The update and verification procedures are primarily for repetition routine-event workloads. For conflict-event workloads a direct comparison may not be feasible; it is, however, possible to compare sectors with similar conflict complexities and volumes.

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*In connection with this requirement the Transportation Systems Center has developed a software methodology for rapid scanning the workpace and Work Activity tapes to produce the following information:

To select those sectors and time intervals that have experienced maximum traffic load as may be specified by the input search parameters.

To compute the Work Activity actual task times (e.g., for interphone communication, RDP/RDP operations, and flight strip processing) in order to compare these times with RECEP estimates. A description of this methodology is given in Appendix F.

5. DESCRIPTION OF THE AIR TRAFFIC FLOW MODEL

5.1 MODEL OVERVIEW

The ATF model is a "flow-model" in which individual aircraft are aggregated in terms of flow rates along routes. The flow rates are used to define a uniform distribution of arrival times at the route origins according to a Poisson process. The route arrival times for each aircraft (or group of aircraft) in turn define expected aircraft counts along each arc as described below.*

Real World Quantity	Variable Name (if applicable)
Network definition	
Sectors	
Arcs	ij
Routes	k
Arc transit times	τ_{ij}
Aircraft arrival rates for route k for the time period T (e.g., 20 min)	$r_k(T)$
Sector workload approximation (a function of the number of aircraft, n, sector m)	$WL_n(n)$
Sector workload maximum for each sector	$W_{max,m}$
Congestion-relief strategy	B or C

For each route (made up of arcs connecting node i to node j) the uniformly distributed arrival rate $r_k(T)$ defines an arrival distribution

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*Portions of this discussion have been abstracted from Wong, Peter J., et al., "SRI's Air Traffic Flow Model," Paper presented at the 1976 Summer Computer Simulation Conference, July 1976 (Proceedings as yet unpublished).

system time, t, the expected flows are readjusted through the mechanism of "delaying" aircraft from entering congested sectors. There are two strategies presently available for imposing this delay.

The first strategy, B, can be titled "Route Delay Priority Based on Instantaneous Loading." The rationale for the basic structure of this scheme is as follows. For each fixed-time increment, Δt, we pick the most congested sector to try to relieve congestion. We off-load aircraft to the neighboring sectors that feed the congested sector with the most net activity, beginning with the sector that feeds the most net activity. Net activity is defined as gross entries from the feeding sector minus gross departures to the feeding sector. We do this until the congested sector is relieved. If, based upon net activity, we cannot find a feeding sector where aircraft can be delayed without causing congestion, we pick a new feeder sector with the most feeding traffic (gross entries). Traffic is delayed in this sector up to the number of aircraft that are expected to feed the feeder. We repeat the process until the congested sector is relieved. Once the most congested sector is processed we repeat the operation for the next most congested sector. This algorithm tends to push congestion along the major routes to the boundary of the center.

The second strategy, C, is described as a "Present Route Priority." The rationale for this scheme is straightforward. The priority list of routes on which delays should be distributed in the event congestion occurs is set beforehand in accordance with the actual procedures used at the enroute or terminal site being modeled. In this scheme we pick the most congested sector and search the route priority list for the highest priority route passing through the sector. Delay is assigned to the sector upstream on this route. We continue the route search until congestion is relieved or there are no more routes on the priority list. The whole operation is repeated for the next most congested sector until all congestion is relieved. Priorities are assigned to imitate the procedures in actual use for flow management in the center.

Scheme C is the preferred congestion-relief strategy for present operations. However, because of the possibility of assigning route priorities wrong it should be applied with care. Problems can occur if two adjoining sectors are both congested and the preset route priorities are such that the two congested sectors delay traffic back and forth. In most cases, only one of two routes passing through adjoining sectors in opposite directions should be assigned a delay priority. In all cases thus far studied, the above situation has not been encountered.

A secondary cause of delay which is independent of the congestion-relief strategy results from an excess of aircraft on the route over a preset maximum. This type of delay is imposed at the route origin whenever an expected entry would cause the count of aircraft on the route to exceed the maximum. An example of a possible area for application of this feature is provided in the next section.

The primary functional output from the ATF model is amount of delay. Delay, for the purposes of the model, is defined as an additional wait of one time increment due to individual sector saturation or excess aircraft on the route. The number of delays multiplied by the time increment, Δt, is excess transit time. Excess transit time is time in excess of inputed arc transit times (τ_{ij}). System delay is the average of the delays for all aircraft within the system (including those delayed on the boundary) for the period of operation. The traffic load is also outputed in terms of number of aircraft in various parts of the network (i.e., entering/exiting each route, sector, and arc). A third output is instantaneous sector workload. All output is printed according to the print frequency specified at input. The frequency is expressed in time increments per print cycle.

The air traffic flow model is thus a model that provides the analyst with several estimates of the performance of a multisector environment based upon sector workload capacity and traffic loads.

The ATF model is written in FORTRAN IV language and currently contains approximately 1,000 statements. Based on recent experience, an average case (10 sectors with 500 aircraft for a 9-hour operation) takes about 20 to 30 seconds central processor time on SRI's CDC 6400 computer system. Altogether (program plus data arrays) approximately 50,000 octal core locations are required. This requirement is based on a potential network of up to 40 sectors and 60 routes along with their corresponding traffic flows at capacity.

The model is designed to run on batch-processing mode. However, a remote job-submission and termination procedure, including some limited on-line terminal input and output capabilities is available. The beginnings of some interactive design features have also been incorporated in the code.

5.2 ASSUMPTIONS AND LIMITATIONS

The basic assumption made in formulating the Air Traffic Flow Model is that average flow rates, rather than independent aircraft following calculations, are sufficient for capacity estimates. This simplifying assumption dictates much of the remainder of the model design. Individual flight paths can be aggregated into route representations because the sector entry and exit times for the aircraft (not their position within each sector) are the variables of interest. It is assumed that all aircraft in a particular sector have the same transit time. Each arc along a route is assigned a transit time at input and all aircraft transit the arc in the assigned time. The arrival rate for individual aircraft at the origin of each route is specified in terms of a flow rate. Actual arrival times for the specified period are randomly generated according to a Poisson process. Two or more aircraft which arrive in the same time increment are treated as a set for computational purposes. Thus computer run time depends relatively little upon the number of aircraft unless congestion relief is required.

Congestion relief is applied to balance traffic loads whenever a sector is congested. A secondary cause for delay can be excess aircraft in a route above a maximum (specified as a program input). The capacity of a sector is defined to be constant according to the value calculated using RECEP. There are no provisions for allowing a sector workload to exceed the constant capacity for short periods. The program will print out warnings and stop processing (depending upon the run option) whenever certain delay maxima are exceeded. These maxima, which are set at run time, are maximum delay at all route origins, maximum delay in all sectors, and maximum average aircraft delay. Individual routes and sectors are compared to the maximum one by one.

We have said that by definition one delay is counted each time an aircraft is restrained. We make the following additional definitions in terms of the program output. Cumulative Aircraft Delay count is the total delay count for all aircraft in the system, including those trying to enter and delayed at origin. Average Aircraft Delay is the cumulative delay divided by the number of aircraft which have entered. To obtain the system delay (as used to compare different automation systems) we run the ATF model to completion without using the maximum delay-stopping option. The Average Aircraft Delay figure becomes the total delays divided by the total aircraft to enter (where no additional aircraft are waiting to enter). If the time increment is one minute, the figure is in minutes. System delay is this figure minus the traffic and delays generated during an initial system loading period and final unloading period as described below.

At the start of a simulation run there is no traffic in the network. The initial traffic load results from running the system for some loading period prior to the portion of time actually used for analysis. For example, in past applications the model has been run for nine hours of simulation input. The effects of the first hour of traffic have to be factored out of the output statistics for purposes of analysis. Also the system delay figure is calculated after all input traffic has been allowed to enter.

For some applications, the above procedure may not be completely satisfactory. It might be desirable to factor out the effects of delay at origins automatically and before all origin delays have entered. To do this, the present output should be modified. The average aircraft delay figure must become the cumulative delay divided by the number of aircraft that have entered plus the number waiting to enter but delayed at the origin. When the model is run until there are no aircraft waiting to enter, the present average aircraft delay and the above figure will be equal.

The limitations in application of the Air Traffic Flow model can be considered in light of the above assumptions. First, because there is only one arc transit time, if an airspace with a large mix of aircraft velocities and trajectories is being modeled the results must be used carefully. Statistical distributions for arc transit times could be implemented rather easily, however, if this becomes important. It would be done by sampling a distribution whenever aircraft arc exit times are stored in the code. In controlled airspace, velocities of all aircraft on a route in a sector tend to be the same. This minor limitation is also overcome to some extent because RECEP conflict models are sensitive to variabilities in traffic and thus enter ATF calculations through the sector capacity estimate. A second limitation to the ATF application is the lack of re-routing capability. (That is, the congestion relief schemes do not re-route aircraft.) If extensive delays are being encountered in some part of the system it is not possible at the present time to divert aircraft to a less congested area. SRI has used the methods described here to model the enroute environment. Application to a TRACON airspace requires the definition of an interface to the tower. It is believed that the tower constraints may be represented by an adjustment of the boundary flow rates in accordance with gate schedules, runway taxi conditions, runway restrictions, etc.

5.3 MODEL COMPONENTS

This section contains a description of the conventions used in the ATF model on a designer's level. It is intended to provide a user some insight into the model logic and thus help him avoid possible pitfalls in the use of the tool.

As stated previously, the model calculates an expected flow and congestion status for each sector at each time increment. Aircraft are delayed from this expected movement if congestion exists. The system tables are updated based upon the results of the delay actions.

The remainder of this section will deal with:

- The internal table structure and its relation to the abstract network and traffic movement.
- The traffic generation logic.
- Expected traffic movement calculations.
- Conditions causing the imposition of delay and the delay strategies available.

The abstract Air Traffic Flow network has been described theoretically as a series of nodes, arcs, routes, and sectors. A node is defined to be the point where an arc begins or terminates at a sector boundary. Thus, if we define an arc in terms of its origin, transit, and destination sectors we implicitly define the nodes. The ATF model employs this logic to eliminate the need to input and store a node lsit. Routes are defined as a series of arcs beginning and ending at the airspace boundaries. For example, when an enroute area is being modeled, the boundaries consist of terminal and enroute sectors outside the multisector area of interest. The arcs must be connected. That is, if arcs 1 and 2 make up a route, arc 1 must end in the sector that arc 2 transits and arc 2 must begin in the sector that arc 1 transits. Because there are no nodes internal to a sector, the logic requires that merging and diverging of routes be treated as completely separate routes within each sector. For example, if two paths 1 and 2 merge (or diverge) within a sector into (or from) path 3, it must start (or end) at the sector boundary.

A route is unidirectional to simplify the logic. If bidirectional traffic is encountered (obviously with altitude separation) then two routes must be defined. Each arc on the route is assigned a transit time in the same units as the time increment.

For each sector, workload maximum and constants assigned at input must be maintained. Finally, the traffic flow at the origin of each route is required. The flow is used to calculate specific aircraft (or group of aircraft) arrival times as described later. The expected exit times for each aircraft (or group), as described in Section V-A (Model Overview) is also calculated and stored.

The above logic defines a requirement for four kinds of tables: arc tables, route tables, sector tables, and traffic tables. These tables contain the network structure information described above and all system status information. To provide for the use of dynamic run time memory allocation, three of these tables are contained in a single internal array called LINK. They are the arc table, route table, and expected aircraft exit time table, in that order. Other arrays used as pointers are maintained along with these tables. The sector information is stored in a series of arrays because three of the variables (WL_m, K_A, K_B) are real while sector counts and delay counts are integer values.

Traffic flows are defined for specific contiguous time periods. For example, if five aircraft are to arrive on route 1 from the start of the simulation until the end of 60 time increments (say 60 minutes if time is in minutes), then the next set of arrivals might be defined for time 61 through 120.

The actual arrival times for each of these flow periods are generated according to a Poisson process. For example, if we had a flow of five aircraft within 60 time increments, a pseudorandom uniform distribution is sampled five times and actual arrival times for the five aircraft are calculated from the sample values.

To assure that arrival distributions for lower traffic level are contained (explicitly) in higher traffic distributions the random-number generator is seeded with a particular start value. For example, suppose for traffic level 1 there were four aircraft arriving on route number 11. The pseudorandom number generator would be seeded and then sampled four times for route 11. If the same route had eight arrivals for traffic level 2, we would start with the same seed. Thus, we obtain the four original arrival times plus the four new times for the total of eight aircraft.

Expected traffic movements for each arc are maintained as arc exit times for each aircraft (or group) in the traffic movement table. At each time increment all delayed and any expected undelayed aircraft are allowed to move. The movement table is not updated at this time because if it were, and delay is imposed, movements would have to be updated to reflect the delay. Instead the program logic waits until the next time increment to store movement times and counts for all aircraft that were not delayed. Any delayed aircraft are counted as part of the delay queue.

Sector loads in terms of number of expected aircraft and workload are calculated next and stored in sector tables. Sector workload and its relation to capacity are the primary cause for delay. A secondary cause can be the number of aircraft allowed on a route. These two types of delay have been discussed previously.

A secondary cause for delay, as previously described, can be an excess (over a preset maximum) of aircraft on a route. Suppose for example, that a terminal area is being modeled. The general avaiation traffic is minimum so no sector is overworked. The physical airspace and procedures along the primary arrival route, however, restricts the number of aircraft that can be handled. The program will delay aircraft at the origin to avoid allowing an unrealistic number of aircraft on the route. If this type of delay is not desired, the input maximum for each route should be set to some high number.

This section has provided a description of the logic behind the ATF model. Specifically the logic for network formulation and related program internal table structure have been discussed. Traffic generation logic, expected movement calculations, sector loading and workload calculations have been covered. Two conditions causing the imposition of delay were discussed as well as the choice of congestion relief strategies available for imposition of delay under sector-overload conditions.

5.4 INPUT AND OUTPUT SPECIFICATIONS

The input and output information for the ATF model are covered in this section. The discussion is intended to provide the analyst with an understanding of the real-world correspondence with each data element.

The types of input data may be classified into the following groups:

- Network composition (sectors, routes, and arcs)
- Traffic flow parameters
- Sector workload maximum
- Sector workload coefficients
- Congestion-relief strategy.

The following sections will give descriptions on each of the above input groups with particular mention of the relationship between the parameters and the source of field data from which the computer input is developed.

5.4.1 Input

5.4.1.1 Network Composition and Traffic Flow

In the previous section we described the logic incorporated for inputing network structure. We saw that we use implied nodes for input to the model. We also explained the unidirectional nature of each logical route and the connectivity requirements for arcs comprising the route. Here we will provide an example and details as to how a real-world airspace can be abstracted. Figure 3 shows a multisector study area for the Atlanta Enroute Air Traffic Control Center. This figure and a large portion of this section have been abstracted from an as yet unpublished study conducted by SRI in 1976.[3] They are included in full here for the reader's convenience. The fixes shown on the figure are identified as follows:

- ATL Atlanta
- AND Anderson
- BNA Nashville
- CHA Chattanooga

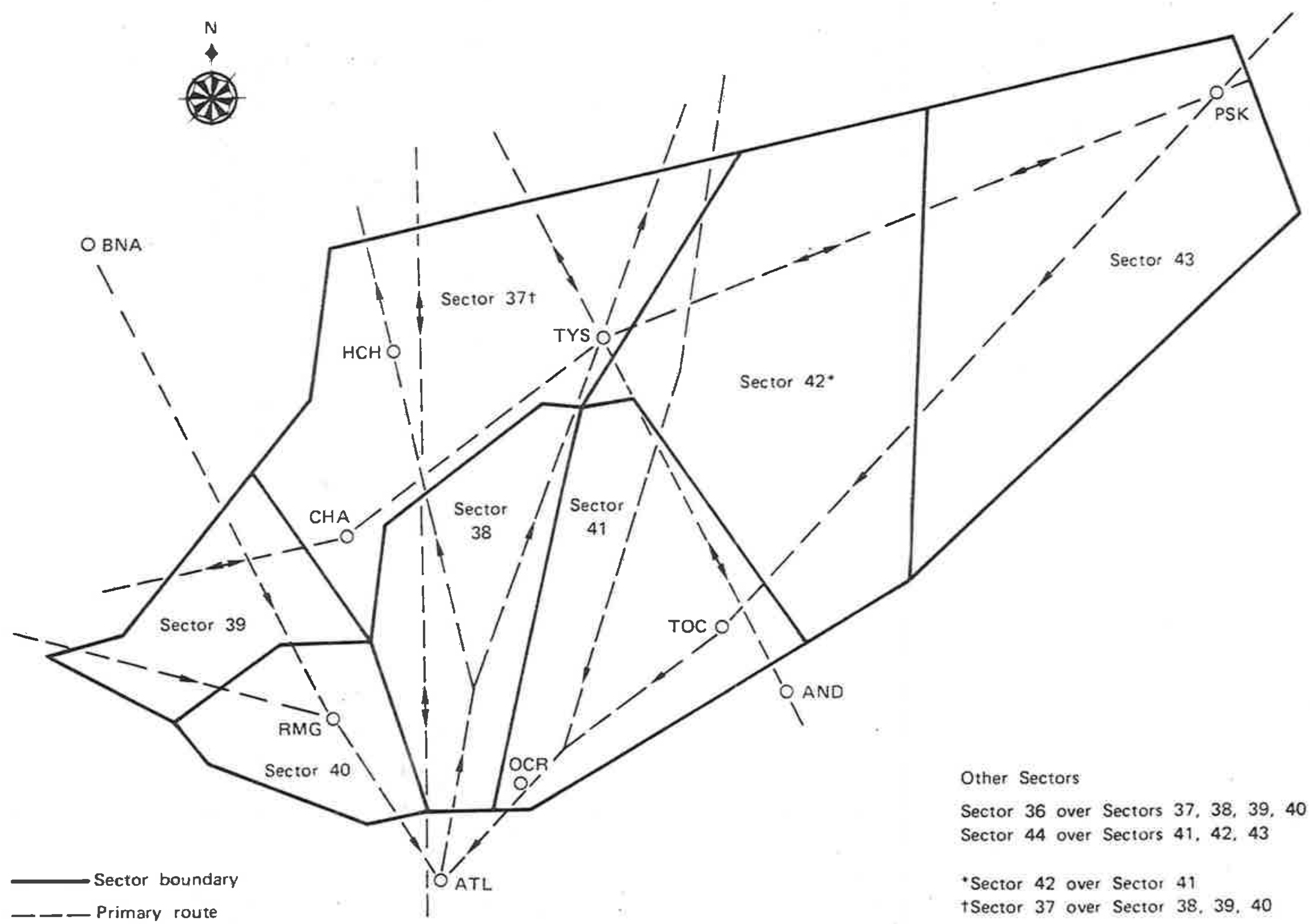

FIGURE 3 ATLANTA CENTER MULTISECTOR STUDY AREA

- HCH Hinch Mountain
- OCR Norcross
- PSK Pulaski
- RMG Rome
- TOC Toccoa
- TYS Knoxville.

The Atlanta Center is comprised of 41 sectors. Of these the nine sectors selected for study control primarily airline arrival, departure, and cruise traffic north of the Atlanta airport.

ATF Multisector Model Structure

The primary arrival and departure airline traffic routings within the Atlanta Center are configured in a radial pattern (four arrival and four departure corridors) with the Atlanta airport as the focus. The study area modeled by ATF included the two arrival corridors from the northeast and northwest and the northbound departure corridor. The nine sectors in this study area are:

- Sector 36 (Allatoona, ALU)--high enroute traffic, FL330 and above.
- Sector 37 (Crossville, CSV)--departure transition traffic, FL240-FL310.
- Sector 38 (North Departure, NDEP)--departure traffic, FL120-FL230.
- Sector 39 (Chattanooga, CHA)--arrival transition traffic, surface to FL270.
- Sector 40 (Dallas, 9DP)--arrival traffic, FL120-FL270.
- Sector 41 (Norcross, OCR)--arrival traffic, FL120-FL230.
- Sector 42 (Lanier, 2LI)--arrival transition traffic, FL240-FL310.

- Sector 43 (Pulaski, PSK)--arrival transition traffic, FL240-FL310.
- Sector 44 (Baden-Blue Ridge, BAUBU)--high enroute traffic, FL330 and above.

With reference to Figure 3, Sectors 39 and 40 are in the northwest arrival corridor; Sectors 41, 42, and 43 are in the northeast arrival corridor, and Sectors 37 and 38 are in the northbound departure corridor. The sectors overlap in each corridor to form stepwise configurations that handle climbing and descending traffic transitioning in and out of the Atlanta TRACON. Sectors 36 and 44 overlay the other sectors (as noted in Figure 4) and handle primarily cruising overflights and some transitioning aircraft.

Arrivals into Atlanta Center from directly north generally enter Sector 42 at FL310 or lower, begin descent immediately, and continue the descent in Sector 41 until they are handed off to the Atlanta TRACON near OCF at FL120. The arrivals from the east over PSK in Sector 43 or Sector 44 are somewhat higher and do not begin descent until approaching the border of Sector 42. They are merged with the arrivals from the north in Sector 41 and handed off to the Atlanta TRACON near OCR at FL120. Arrivals along the two routes from the northwest enter Sector 40 at FL270 and descend to FL120 just south of RMG, where they are handed off to the Atlanta TRACON.

Departures to the north diverge in Sector 38 and proceed over HCH and TYS in Sector 39. Departing traffic generally crosses the center boundaries between FL240 and FL310.

Three major cruise routes through the area were modeled. One is a two-directional east/west route through Sectors 37, 42, and 43 in the FL240 to FL310 range, and through the overlying Sectors 36 and 44 at FL330 and above. Primary fixes along the route are CHA, TYS, and PSK. Also in the high airspace at FL330 and above are two generally north/south routes. The first crosses Sector 36 and passes over the Atlanta airport (ATL), and the other crosses Sectors 36 and 44 and passes over TYS and AND.

A large number of small volume routes were also in the area modeled, but are not shown in Figure 3, and include the arrival and departure routes into and out of the Chattanooga airport. Military activity makes up about 10% of the total traffic and conforms reasonably well to the routes followed by civil aircraft. Had this not been the case we could have included routes or pseudo routes for this traffic. A pseudo route would be a route completely enclosed by a sector. The transit time for this route would be the average time a military flight would be in the sector. A pseudoroute is thus a route made up of a single arc which begins and ends at the area boundary and carries military traffic.

Sector and Route Network Representation

The sectorization and routing structure shown in Figure 3 is abstracted for input to the ATF network model, as shown schematically in Figure 4. ATF arc number identities are indicated. Because the high sectors overlap lower ones in a stepwise arrangement, we juxtaposed, in Figure 4, the sector schematic presentations to diagram the route network. The overlapping of sectors can be observed to some extent if the figure is folded along the dashed lines like an accordian. The lower sectors should be folded up first. The two high sectors--36 and 44 (at the top of Figure 4)--overlay Sectors 37, 39, 42, and 43; these latter four in turn overlap the low airspace sectors--38, 40, and 41. Diagrammatic connectors (circled) were included in Figure 4 to facilitate mental piecing (by superimposing connectors) of the juxtaposed sectors.

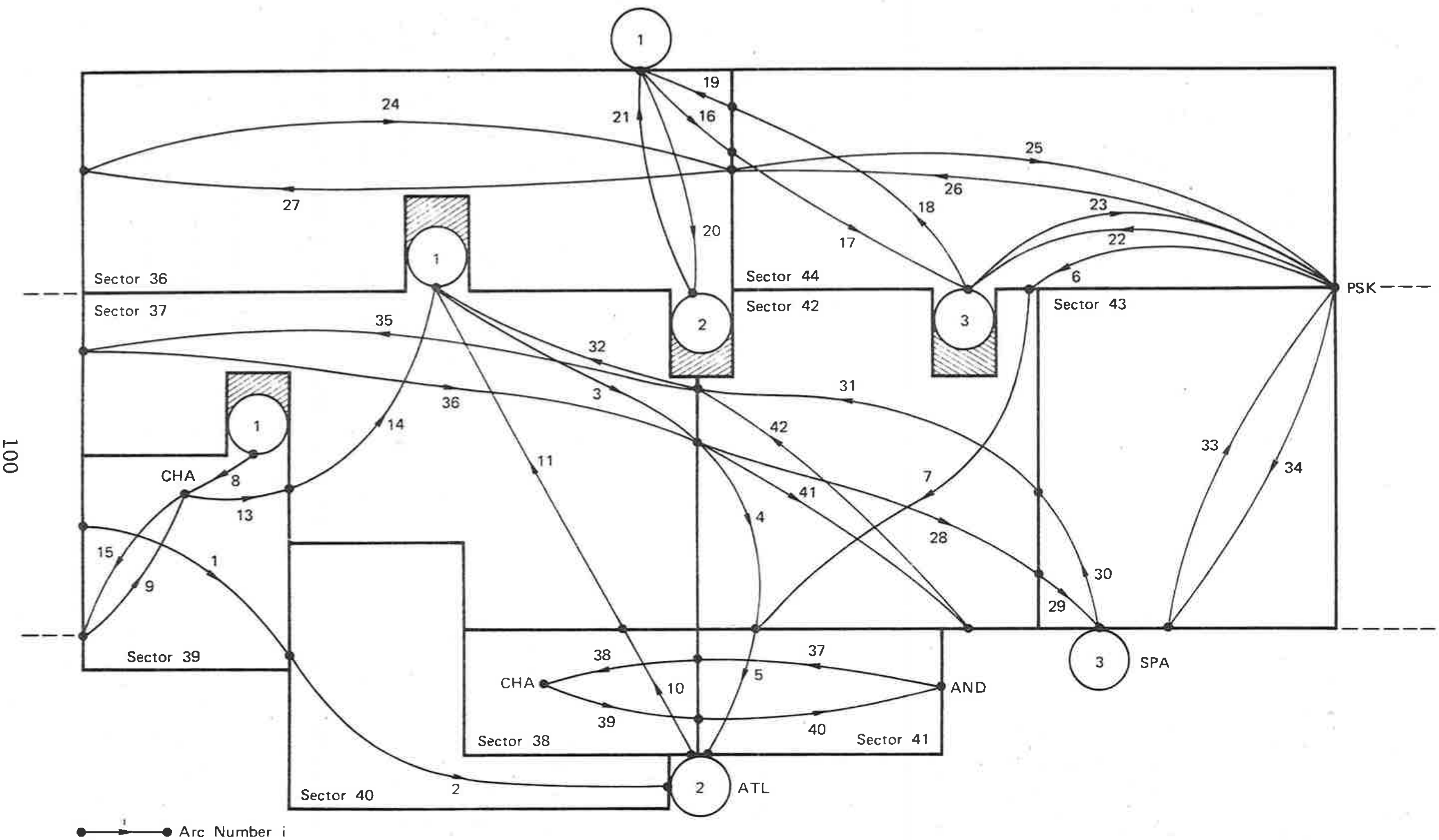

FIGURE 4 SCHEMATIC OF STUDY AREA ROUTE MODEL

In the conversion from the actual configuration to the schematic, the only important properties (for ATF modeling) of an arc are the transit time, the origin sector, the destination sector, and the sector including the arc. Therefore, if two or more arcs originate at the same sector, end at the same sector, and are included in the same sector, they may be combined into one arc whenever transit times are equal.

As mentioned earlier, some of the actual routes have two-directional traffic while others have only one-directional flow. For two-directional routes, two logical (ATF) routes were defined to represent the actual route. Consequently, in the schematic, each arc shown represents one-dimensional traffic flow. This representation results in a system of nine sectors, 26 routes (or origin-destination pairs), and 42 arcs.

It can be seen from the previous discussion that establishing routes for the Air Traffic Flow model is of primary importance in setting up the sector, route, and arc description. The following procedures were used to arrive at the description represented in Figure 4.

The first step is to gain an operational understanding of the airspace being modeled. We have found that interviews are useful in establishing the primary routes. This information is then used to help structure the routes from flight strips (collected at the center) after the visit. The procedure described here is used to obtain arrival counts at route origins as well as defining route structure. Only routes with substantial traffic over the day or shift being simulated are included as logical routes. Traffic not conforming to these routes is counted as part of traffic on a route most nearly approximating the flight plan. The number of routes is dependent upon the traffic patterns and the level of detail required by the analyst. Theoretically there could be one route for each aircraft but this would be impractical. Thus, the number of routes is determined through subjective judgment during the flight-strip reduction. The procedures for flight-strip reduction are not rigid. A suggested approach is given below to provide insight into the information that should be sought during the on-site interviews:

1. Sort strips by aircraft identification. Exclude any unmarked strips.
2. Sort by civil aviation and military flights or any other combination of traffic classes with different predicted growth characteristics.
3. Sort by time periods (20-min to 1-hr periods have been found to be reasonable).
4. List route identification based upon interviews with Center personnel.
5. Tally aircraft entries by time period and route. (Sector-to-sector progression of the flight is the most important factor in assigning aircraft to routes).
6. Establish new routes for any reasonable number of aircraft which do not fit well into the routes established in Step 4.

Another data reduction procedure sorts aircraft by route after Step 2. This procedure starts with the primary route being established as in Step 4 (eliminating Step 3). We have no preference for either procedure.

The end result of this procedure is a route-and-arc structure representing the model area and a count of arrivals at route origins.

5.4.1.2 Traffic Flow Parameters

The elements of this input type are:

arc transit times $\{\tau_{ij}\}$, for all i,j and

aircraft arrival rates $\{r_k(T)\}$, for all routes k, and time T.

The arc transit time is calculated at the average aircraft velocity for aircraft in the sector. These transit times can also be derived from information obtained from System Analysis and Recording (SAR) tracking in the field. Please see Appendix G for further information.

The other input parameter is the rate of aircraft generation at the origination node, $r_k(T)$, for each route during each time period. The general approach for obtaining the traffic count is to obtain a basic count first. The basic count is coded and used as input to the model. The ATF model is then run for at least one run without congestion adjustment to evaluate traffic loads by sector.

Hourly sector traffic can be compared to the Busy-Day Reports from the center being modeled. For example, assume the model shows the following relationship for aircraft handled:

	ATF Output	Busy Day Reports
Sector 1	20	20
Sector 2	32	30
Sector 3	35	36

The analyst should search for the routes crossing Sector 1 and reduce flows on those routes. The model can be run again and the same comparison made.

If future operations are to be evaluated, traffic must be scaled to future forecast levels. The method that has been used at SRI has been to deterministically scale the traffic load by route. This has been done manually in one case. We also have a small preprocessor program which will scale specific types of traffic. This program called

ADD is written in Fortran and is designed to take the base case traffic load by route and provide an incrementally scaled traffic file for input into the ATF model.

The overall goal of scaling traffic is to gradually increase traffic throughout the center until its capacity value is reached. It is desirable for purposes of delay comparisons to have higher volume traffic include the characteristic pattern present in the basic count. Thus, if Route 2 is loaded with a basic count of 20 aircraft per flow period (e.g., 20 minutes), it is desirable to have those 20 aircraft plus Route 2's proportion of the additional traffic.

The scaling methods used by SRI have not affected the distribution of traffic. For example, the scaled traffic levels for Atlanta contain the same relative proportion of traffic on each route that is found in the base-case traffic. It is possible that actual future traffic may be heavier on routes from the west into Atlanta. However, we had no basis for estimating changes in distribution in forecast traffic levels and so none were made.

5.4.1.3 Sector Capacity and Workload Coefficients

RECEP constants corresponding to the particular automation being evaluated should be estimated. This is done by adjusting the event times according to the estimated enhancement's design goals (see Section VI, Example of RECEP/ATF Application in Productivity Analysis). Constants may also be adjusted to reflect sector reconfiguration or other proposed changes to the airspace. The new constants are used as the input by sector for the ATF model. Each change in a sector constant is followed by a new ATF run. The results are evaluated in the manner described in Section VI.

5.4.1.4 Congestion-Relief Strategies

Two congestion-relief strategies have been used in the Air Traffic Flow model. They were described in the Section V-A (Model Overview). It is possible that as procedures change, different congestion-relief schemes will become necessary. This should become apparent to the analyst as he looks at the flow control being modeled.

5.4.2 Output

Output from the model is printed as often as each time increment or at any other frequency desired. The amount of information displayed at each print cycle can also be controlled.

The three parameters that could be used for analysis of an ATC airspace are average delay per aircraft, traffic capacity, and controller workload. These three elements are dependent upon each other. Given two of the elements, the third can then be calculated.

The remainder of this section describes the ATF output item by item. Those items which are obvious are not covered. There are four basic status displays as shown in Table 18. Items are defined as follows:

- Sector Status

  Workload = $K_1 N + K_2 N^2$ at the particular time, t.

  $$\text{Avg. Work} = \frac{\sum_{\text{over-all time steps}} WL_k}{\#\ \text{time steps}} \quad \text{for each sector, k.}$$

  Sector count = N at the particular time for each sector.

  Sector entries = number of aircraft entering sector at the particular time.

  Sector exits = number of aircraft leaving sector at the particular time.

TABLE 18
AFT OUTPUT

SECTOR STATUS

SECTOR	WORKLOAD	AVG. WORK	SECTOR COUNT	SECTOR ENTRIES	SECTOR EXITS	SECTOR DELAYS	ORIGIN DELAYS
1	7.44	6.81	3	1	1	0	0
2	8.43	4.48	3	1	1	0	0

ARC STATUS

ARC	ARC COUNT	ARC ENTRIES	ARC EXITS	CUMULATIVE ARC DELAY
1	3	1	1	31
2	3	1	1	0

ROUTE STATUS

ROUTE	CUMULATIVE ROUTE ENTRIES	CUMULATIVE ROUTE DELAY	AVERAGE ROUTE DELAY
1	9	79	8.78

AIRCRAFT STATUS

AIRCRAFT COUNT = 6 AIRCRAFT ENTRIES = 1 AIRCRAFT EXITS = 1 CUMULATIVE AIRCRAFT DELAY = 79
CUMULATIVE AIRCRAFT ENTRIES = 9 AVERAGE AIRCRAFT DELAY = 8.78

Sector delays = count of the number of aircraft delayed in the sector at the particular time.

Origin delays = count of the number of aircraft delayed at the boundary of the entire multisector sector area under consideration at the particular time.

- Arc Status

  Arc count =
  Arc entries = See above definition for sector status.
  Arc exits =

  Cumulative arc delay = Total count of the number of delays on any arc up to the particular time.

- Route Status

  Cumulative route entries = number of aircraft to enter each route not counting any delayed at the origin.

  Cumulative route delay = count of the number of delays all along the route and at the origin.

  Average route delay = cumulative route delay divided by cumulative route entries.

- Aircraft Status

  Aircraft count = number of aircraft presently in the system.

  Aircraft entries = aircraft entering at the particular time increment.

  Aircraft exists = aircraft exiting the system at the particular time increment.

  Cumulative aircraft delay = count of the number of delays in the system.

  Cumulative aircraft entries = cumulative aircraft to enter the system not counting those delayed at the origin.

  Average aircraft delay = cumulative aircraft delay divided by cumulative aircraft entries.

There are two procedures for stopping the Air Traffic Flow model. The first is to terminate the aircraft arrivals with an input card with FINI on it. The second method is the result of the optional delay termination procedure. Using this option, if one of the delay maxima is exceeded, the program will stop. In both cases the program will first zero out all undelayed aircraft scheduled to enter in the future and continue to run until all aircraft in origin delay queues have entered. The program then prints system status and hourly summaries (up to 24 hours) and stops if there is no new input.

5.5 MODEL APPLICATIONS

RECEP and ATF are designed to allow modification and flexibility to their design structure and, thereby, enable their application to various areas of study. The RECEP event task times and frequencies may be used to represent various operational requirements and strategies, and ATF parameters may be used to represent alternative sectorization and routing structures. The possible areas of application for RECEP/ATF include, but are not restricted necessarily to:

- Evaluation of automation packages,
- Evaluation of operations and procedures,
- Evaluation of ATC manpower allocation,
- Testing of productivity measures,
- Energy consumption evaluation.

To date, RECEP/ATF has been applied explicitly to the first area of study listed--evaluation of automation packages. However, this application has used techniques that could be extended to the other areas of study. In the remainder of this section, we briefly review automation package evaluation and address the broader implications for RECEP/ATF application.

5.5.1 Evaluation of Automation Packages

Various UG3RD enroute ATC automation concepts currently are under examination. RECEP/ATF has been used by SRI to postulate the operational impact of these automation alternatives and to assess their productivity implications relative to facility staffing requirements. These analyses are in various stages of preparation and are under review by the Office of Aviation Policy of the FAA; analyses documentation will be forthcoming upon final approval of the results. However, a brief review of the methodology used will provide some insight into the applications of RECEP/ATF as a tool for examining the feasibility of postulated automation concepts.

The systems were examined in sequence under the assumption that each automation feature is added to the previous system. The automation features, added consecutively to the NAS Stage A Base (System 1) are:

- Automated data handling (System 2).
- Automated local flow control (System 3).
- Sector conflict probe (System 4).
- Area navigation, RNAV (System 5).
- Discrete Address Beacon System (DABS) data link (System 6).
- DABS intermittent positive control, IPC.

5.5.1.1 Automated Data Handling (System 2)

This first add-on to System 1 includes the implementation at sector positions of an electronic tabular flight data display, and RDP/FDP refinements. The tabular display is an electronic flight data presentation designed to replace paper flight strips and attendant manual activities and would effectively automate some controller manual and verbal tasks associated with intersector control procedures and flight data distribution. The RDP/FDP refinements are minor system modifications that would facilitate equipment operation.

5.5.1.2 Automated Local Flow Control (System 3)

This feature, which we assume is added on to System 2, is designed to maximize sector capacity utilization by smoothing out traffic peaking situations.[3] It would control traffic flow on routes by means of an on-line computerized traffic planning process that regulates workload surges in accordance with the traffic-handling capabilities of a multisector environment. It impacts on enroute operations by redistributing traffic peaks and workload surges on the air traffic route network.

5.5.1.3 Sector Conflict Probe (System 4)

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

5.5.1.4 RNAV (System 5)

This feature, which we assume is added on to System 4, incorporates navigation avionics that could be used in enroute operations to achieve closely spaced, multilane traffic routes. Overtaking conflict processing would be eliminated by placing successive aircraft on closely spaced parallel routes.

5.5.1.5 DABS Data Link (System 6)

This feature, which we assume is added on to System 5, transmits to pilots digital data including routine clearance 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 minute-by-minute tactical decision making. He would have to maintain cognizance of the computerized sector control operation and intervene when necessary to adjust procedural rules, respond to pilot requests, and resolve nonstandard situations.

5.5.1.6 DABS IPC

IPC provides traffic advisories and threat-avoidance commands to pilots, as needed. Because this service could operate in the enroute environment on imminent conflict situations that might be "missed" by controllers, we assume IPC to be a safety-enhancement device that would not directly impact routine staffing requirements. IPC may be necessary to provide fault tolerance in the event of failures in the other enhancement system operations.

These systems were analyzed using the RECEP/ATF formulations developed for the Los Angeles Center and Atlanta Center. In each case, the RECEP and ATF descriptions of current NAS Stage A operations were revised to represent ATC operations under the proposed automation systems; sector capacity and delay results were obtained for each system (exclusive of IPC which was assumed not to affect sector capacity). The RECEP/ATF models were structured to represent the capacity/delay relationships associated with various manning strategies. This technique enabled the estimation of the staffing required to maintain current delay for increasing levels of forecast traffic and to compare the corresponding productivity implications of the alternative systems.

We note that RECEP descriptions of automation packages require postulation of their modes of operation in terms of the work activities of controllers. Therefore, a subset of automative evaluation is the use of RECEP to describe automation operating requirements, which could be used to define automation design specifications.

5.5.2 Evaluation of Operations and Procedures

As part of the analyses of manning strategies for automation alternatives, RECEP was used to estimate to the first-order the capacity effects of sector splitting. As described in Appendix H, the methodology used RECEP to approximate the redistribution of work among newly created sectors and to account for the additional sector workload induced by introducing new sector boundaries (controllers must carry-out control jurisdiction transfer, traffic structuring, and related activities each time an aircraft crosses a sector boundary). Although the sector-splitting model was designed for the purpose of theoretical analysis, the concept of using RECEP/ATF to analytically compare alternatives could be extended to the evaluation of current operations and procedures.

RECEP conceivably could be refined to differentiate not only the operational impacts of inserting sector boundaries, but also those impacts of adjusting procedural requirements or operational rules-of-thumb. For example, changes to standard altitude or speed restriction procedures would impact routine work activities, and decisions to procedurally segregate aircraft routings would impact potential conflict activities. These procedural decisions could be modeled within the RECEP formulations by adjusting event task times and frequencies, and assessments concerning the effects on sector capacities could be made. Clearly, the accuracy of such assessments would depend on the precision with which operational requirements are translated into work task requirements; these requirements are understood best by those personnel knowledgeable in day-to-day control operations.

ATF in conjunction with RECEP, could be extended as a tool to assess and plan current multisector operations. In particular, ATF might be refined to examine the means by which adjacent facilities interact with each other. This approach would address the interface between facilities by examining the formal procedural agreements regarding routings, in-trail separation, speed and altitude restrictions, and the like, and could be used to assess the integration of tower/TRACON/ center procedures.

5.5.3 Evaluation of ATC Manpower Allocations

Resectorization based on sector splitting is one way of increasing manning to handle increases in traffic flow. An alternative is to expand the manning of existing sectors by adding controllers to sector teams (e.g., expand from 2-man to 3-man teams). Also, a combination of both approaches may be used to match manpower capabilities with traffic-handling requirements. The evaluation of which manpower allocation technique--sector splitting or sector team manning adjustment--to use to solve current operational problems could be modeled on RECEP/ ATF.

RECEP/ATF has been used to compare multisector manpower allocations for automation alternatives. This application used RECEP to estimate the sector capacity impacts of sector splits and team manning adjustments, and used ATF to identify the manning force needed to maintain the current level of delay for various traffic projections. Again, although these models were used for the theoretical analysis of postulated automation systems, the modeling approach may be used to meet the near-term planning needs of facility personnel to make trade-off comparisons between sector splittings and sector team manning adjustments. The use of the model would be similar to those applications for automation analysis described above; however, the uses in this case would be for the facility operational functions.

5.6 DATA BASE UPDATE AND MODEL VERIFICATION

Similar to the purpose of RECEP data base update (Section IV-E), the ATF data base for a center should also be recalibrated periodically to reflect the most current operational features. These features include sector configuration, route structure, traffic flow rates, and congestion relief schemes. The current operation of a center often serves as the base-line for an ATF simulation for future productivity predictions; therefore, the reliability of this base-line input is important to the simulation results.

The ATF data base update (or ATF "quick look" field test) can be performed in conjunction with the RECEP data base update because some of the common data elements are shared by both models (e.g., route structure). RECEP uses it for potential-conflict frequency calculations, and ATF uses it for route and arc definitions.

The ATF model verification requires the comparison of ATF output (e.g., sectors at capacity) with some other known data such as center Busy Day Report, Workpace/Work Activity records, etc. One of the methods would require a series of straight simulation runs each for a sufficient period of simulated time, say three hours. The traffic parameters are scaled for capacity throughput (using the Busy Day Report as one of the data sources). A midhour period of each simulation output will then be compared with actual field data collected from selected sectors which have experienced high traffic loadings. An agreement in sector workload or traffic loading statistics between the simulation and the actual field data would constitute a verification.

Another method, which takes into consideration the random variations of a dynamic system, would be to perform time series analysis on ATF simulation output (e.g., aircraft loading or workload values at each time increment) by expressing them in autoregressive and autocorrelation functions (pp. 23-45, Ref. 12). Likewise, the real-world counterparts of ATF simulation responses would also be measured (e.g., WA/WP aircraft loading and workpace values covering the same time period as in simulation) and converted into autoregressive and autocorrelation functions. The comparison of the time-series functions between ATF output and field measures would constitute a verification.

6. EXAMPLE OF RECEP/ATF APPLICATION IN PRODUCTIVITY ANALYSIS

The methodology previously used to evaluate automation packages analyzed the relative productivity of automation alternatives and compared their productivity against that of the baseline NAS Stage A operation. The productivity comparisons were made using RECEP/ATF to estimate manning requirements corresponding to traffic projections for selected multisector environments. RECEP was used to estimate sector capacities associated with alternative manpower allocations for each automation package; ATF was used to estimate the multisector manning needed to maintain current delay at selected traffic projections.

In this section, we demonstrate the productivity analysis application of RECEP/ATF. We use a hypothetical automation package to exemplify the RECEP analyses technique and illustrate the means by which ATF is used to develop productivity measures.

6.1 RECEP DEMONSTRATION

We describe in this section the structuring of RECEP models for a hypothetical automation package. The package includes Handoff Augmentation and Sector Conflict Probe automation items, for which we will develop workload relationships using previously established RECEP models of current NAS Stage A baseline operations at the Atlanta Center. The relevant elements, for this discussion, of the baseline system RECEP models are the routine event and conflict processing task times previously presented in Tables 9 and 13. In the remainder of this section, we describe the impact of Handoff Augmentation on routine event task times and the impact of a sector conflict probe on conflict event task times.

6.1.1. Handoff Augmentation

We hypothesize Handoff Augmentation as a limited version of the electronic tabular flight data system (ETABS) where Handoff Augmentation would simplify some of the control jurisdiction transfer task requirements (as defined in Table 9); it would not affect traffic structuring and other functions nor would it eliminate the need for flight-strip processing (as would ETABS).

We visualize our fictional Handoff Augmentation system as a small, electronic, alphanumeric-display/keyboard unit built into the sector team's current operating console. The display lists aircraft identity (ACID) data; special purpose, quick-action keys are located adjacent to each ACID. Manual "punching" of one such key would activate handoff acceptance for the corresponding ACID; another key would effect manual handoff initiation. We assume two such keys per ACID are needed to enable retraction of handoff initiation; otherwise, a single key would be sufficient to facilitate both acceptance or initiation depending on the current control status of the aircraft. "Flashing" or "blinking" ACID displays would accompany the handoff operations in parallel to PVD data block flashing.

We develop a RECEP workload model of the Handoff Augmentation operation by making the adjustments to control jurisdiction transfer task performing times as summarized in Table 19. The parentheses enclose the baseline system's task time originally presented in Table 9, and the remaining data entries in Table 19 correspond to the Handoff Augmentation enhanced operation.

With reference to Table 19, we assume that the Handoff Augmentation will reduce the time required in FDP/RDP operation for handoff acceptance will be reduced from 2 man-sec (baseline system) to 1 man-sec. In this case, we assume a 1 man-sec augmented keypunch operation (which

TABLE 19

R-D TEAM ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
TWO-MAN SECTOR OPERATION
SYSTEM 2--AUTOMATED DATA HANDLING

Routine Control Event Description		Minimum Task Performance Time* (man-sec/task)					Minimum Event Performance Time* (man-sec event)
Event Function	Basic Event and Supplemental Event	A/G Communication	FDP/RDP Operation	Flight Strip Processing	Interphone Communication	Direct Voice Communication†	
Control jurisdiction transfer	Handoff acceptance		1(2)	1			2(3)
	Flight data update		3				3
	Intersector coordination				7	6	13
	New flight-strip preparation		3(0)	10			13(10)
	Handoff initiation-automatic			1			1
	Manual initiation-silent		1(3)				1(3)
	Intersector coordination				7	6	13

*Revised System 1A performance times are indicated in parentheses.

†Indicated value is double the measured direct voice communication time duration.

is associated with a single ACID display) will automatically identify the aircraft being handed off, and no further manual keyboard/slew ball operations are needed.

We assume the manual (silent) handoff initiation FDP/RDP operation will be reduced from 3 man-sec to 1 man-sec. In this case, the baseline system's manual operations needed to identify both the aircraft and receiving sector are performed automatically when the augmented handoff is initiated by a 1 man-sec keypunch. The augmented display could flash the ACID as well as the receiving sector's identity (determined by computer from FDP flight plan data files) when appropriate, and the controller need only "authorize" handoff initiation by keypunch.

Some modeling dexterity is needed to represent more detailed aspects of the control operations. For example, the term handoff acceptance as used in the Table 9 RECEP formulation includes track initiations for FDP/RDP operations to establish computerized radar tracking of a target, and manual preparation (writing) of a new flight strip because no FDEP printed flight strip would be available. These FDP/RDP operations would also be required to establish tracking with the Handoff Augmentation automation, and are represented in Table 19 by the addition of 3 man-sec of FDP/RDP operations associated with original 10 man-sec for new flight strip preparation. (The baseline system FDP/RDP operations requires 3 man-sec to "capture" the target by slew ball and identify the aircraft by keyboard data entry. For modeling convenience, the 3 man-sec operation is represented in Table 9 as 2 man-sec for FDP/RDP operation and 1 man-sec for flight strip processing. These task activities are required for a normal handoff acceptance, and are used in Table 9 as a surrogate measure for pop-up tracking because no handoff from another sector is actually performed.)

6.1.2. Sector Conflict Probe

The Sector Conflict Probe would use computer-calculated projections of flight trajectories to identify potential conflict situations, assess the situation, and recommend resolution actions to controllers. We assume this device would be integrated with the Handoff Augmentation operations; conflict probes could be activated automatically each time a handoff acceptance key is activated or could be activated manually by another key (i.e., third key set) adjacent to an ACID display on the Handoff Augmentation. The latter capability enables early and selected probe scanning.

The sector conflict probe's potential effects on controller task performance times are estimated as shown in Table 20. Again, baseline system task times obtained from Table 13 are indicated in parentheses. Detection and assessment tasks are performed by the computerized probe, and resolution directives/suggestions are displayed to

TABLE 20

CONFLICT EVENT PERFORMANCE TIME ESTIMATES
ATLANTA CENTER, TWO-MAN SECTOR OPERATION
SYSTEM 4--SECTOR CONFLICT PROBE

Conflict Event	Minimum Task Performance Time* (man-sec/task)		Minimum Event Performance Time* (man-sec/event)
	Detection and Assessment	Resolution	
Crossing	5(20)	40	45(60)
Overtaking	5(20)	20	25(40)

*Revised System 2 performance times are indicated in parentheses.

formulation. This attribute of ATF--the sensitivity of delay to sector capacity--makes the model a useful tool for differentiating the operational efficiencies of the baseline and automated systems.

For example, consider a comparison between a baseline system and a single automated one. Let us assume that the automated system will reduce considerably the control workload requirements per aircraft, and increase the sector traffic capacities relative to the baseline system. Therefore, an ATF run for the automated system should obtain a lower average delay (e.g., over an 8-hour interval) than one for the baseline system under conditions of fixed-route structure and traffic loading. Similar results would be obtained at different traffic loadings. We demonstrate the ATF analysis using the hypothetical situation shown in Figure 5 where the current traffic loading during an 8-hour shift on some current 10-sector configuration is 500 aircraft. At this traffic level, let us assume the ATF average delay estimate for the baseline operation (with current sector manning strategies) is 1 min/aircraft, while the corresponding automation system delay is 0.5 min/aircraft. Similar pairwise comparisons between each system's delay characteristics can be made at projected traffic levels. Figure 5 demonstrates successive runs of the ATF in which traffic increases in 20% increments; all other ATF model parameters (i.e., route structure and sector capacity limits) are held constant. Interpolations between each delay point obtains the curves shown. We note that Figure 5 exemplifies the capability of ATF to translate the sector capacity advantages of the automated system into delay reductions as traffic loading increases.

If one were to look at the two systems under a different sectorization design in which one of the baseline sectors are split, the RECEP analysis would show an increase in the capacity of the airspace of the original sector. Therefore, rather than restructure the ATF route network to model the two new sectors, the effects of the sector

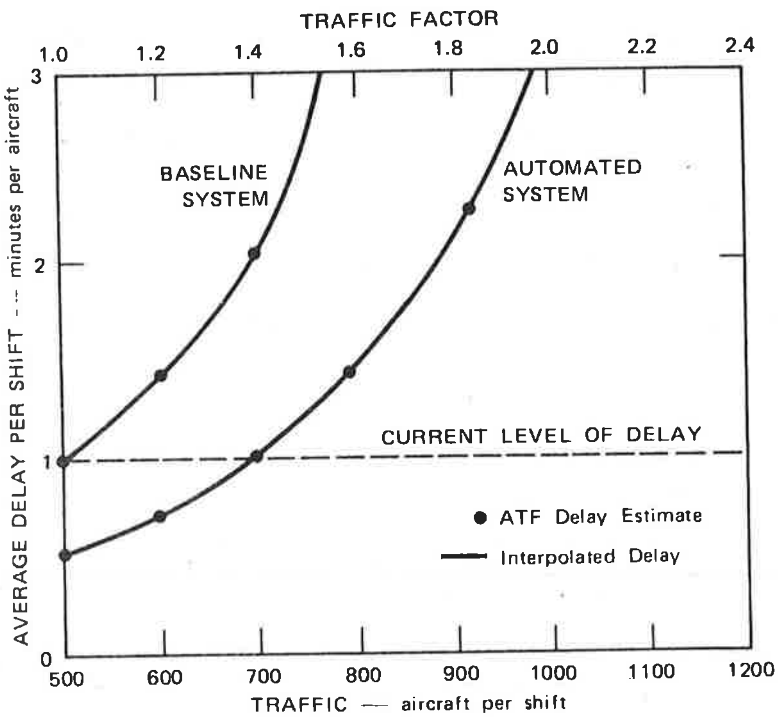

FIGURE 5 10-SECTOR DELAY

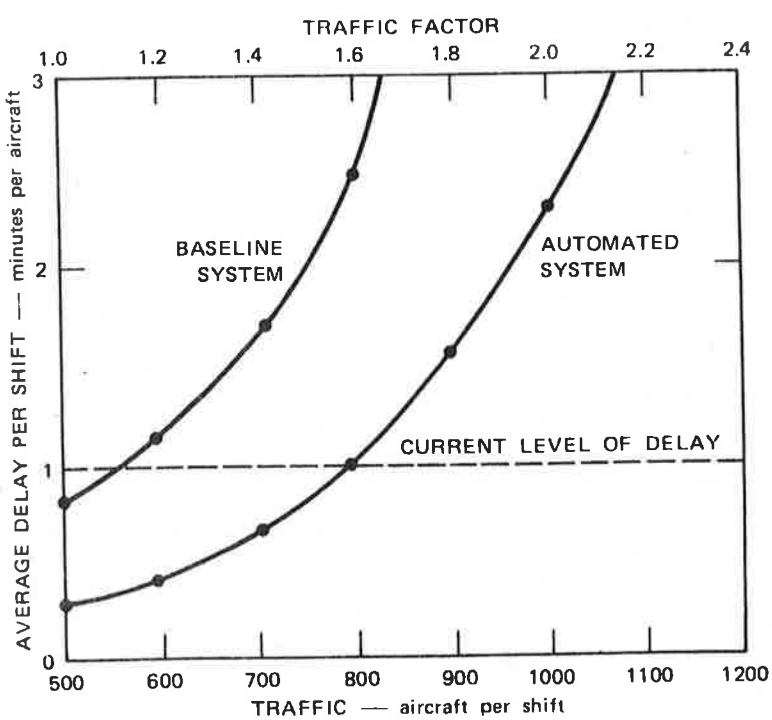

FIGURE 6 11-SECTOR DELAY

splitting are conveniently represented by increasing the capacity of the original sector in the ATF model. The resulting delay estimates, relative to traffic loading, could be as shown in Figure 6 for the two systems.

This procedure for incorporating control operation changes into ATF by means of RECEP-based capacity adjustments may be continued for selected automations and sectorizations, and of course, applied to manning strategy alternatives.

6.2.2. Productivity Comparisions

We wish to compare the manning and traffic handling capabilities of baseline and automation systems at some common level of service. Such a comparison enables us to determine the efficiency of each system's ability to provide an identical service quality. For this purpose, we use the current level of delay as determined by ATF for the baseline system, and compare each system's operations at this reference point. We need to estimate the manning required by each system to maintain current delay and quantify the corresponding traffic-handling capability.

To demonstrate this approach, we use the examples introduced in Figures 4 and 5. Let us assume that the baseline system operation requires 2.5 men per sector (i.e., one R controller, and one D controller, and the shared services of an A controller), and the manning strategy of the automated operation calls for 2 men per sector (i.e., eliminate the A-controller). Therefore, the baseline system requires 25 controllers to man the 10-sector configuration and 27.5 controllers to man the 11-sector configuration. The automated system requires 20 and 22 controllers, respectively, for the 10- and 11-sector configurations.

Traffic-handling capabilities at the current delay level corresponding to the above manning levels are obtained by inspection from

Figures 4 and 5. The current 10-sector baseline system is shown to have 25 controllers handling 500 aircraft/shift with 1 min/aircraft delay; with the 27.5 manning level of the 11-sector configuration, the baseline system handles 550 aircraft at the same delay level. The automated system with 20 men handle 700 aircraft, and with 22 men, the automated system handles 800 aircraft at the current delay level. Using the current 25 controllers and 500 aircraft/shift as the base for comparison, the productivity factor is defined as the ratio of traffic factor to manning factor fur current level of delay operations:

System Operation	Traffic Factor	Manning Factor	Productivity Factor
10-sector Baseline	1.0	1.0	1.75
11-sector Baseline	1.1	1.1	1.0
10-sector Automated	1.4	0.8	1.75
11-sector Automated	1.6	0.88	1.81

where:

Traffic factor = Traffic handling capability/500 aircraft/shift

Manning factor = Multisector manning/25 men

Productivity factor = Traffic factor/staffing factor

The statistics shown above are a sample subset of the productivity estimates that need to be made. For example, we see that the manning increase associated with the automated system's single sector split increases the productivity factor from 1.75 to 1.81. Clearly, we would like to know the productivity implication of further manning increases and the limits of the traffic handling capabilities associated with such manning increases. Therefore, the SRI productivity evaluation methodology requires the RECEP/ATF modeling of the range of feasible manning alternatives associated with feasible resectorization and sector manning options. This procedure parametrically encodes manning, traffic handling, and productivity relationships.

For demonstration purposes, let us assume that judgmentally based analyses (including consultations with field facility personnel) concludes that the original 10-sectors could each be split, but air-space limitations would preclude further resectorization. Therefore, the maximum number of sectors eventually obtainable is 20, which results in a manning upper bound equal to twice the 10-sector manning levels for baseline and automated operations. RECEP/ATF models of the 10-sector, 20-sector and selected intermediate configurations would obtain traffic and delay relationships for each operation. (Alternative sector team manning strategies would also be modeled, but to simplify this discussion we do not do so here.) These relationships would be used, as described in the preceding paragraphs, to determine a series of traffic and staffing factor pairs representing current level of delay.

Each traffic and manning factor pair could be graphically plotted as shown in Figure 7 to obtain productivity curves for each system. Figure 7 presents the staffing increase needed by each system to maintain current delay as traffic grows. The point at which a system's productivity curve reaches its manning upper bound indicates the maximum traffic capable of being handled at current delay. For our purposes, we refer to each of these maximum traffic levels as the "capacity" of the system, although additional traffic may be handled with increased delay. Specifically, the "delay constrained capacity" of each system is the traffic handled at the current delay level by the system's maximum practical manning.

We may compare system productivity ratios at any traffic factor or manning factor ratio we wish, and correlate the results with yearly traffic forecasts if desired. However, for general productivity analysis purposes, we will compare productivity ratios corresponding to the delay-constrained capacity of each system.

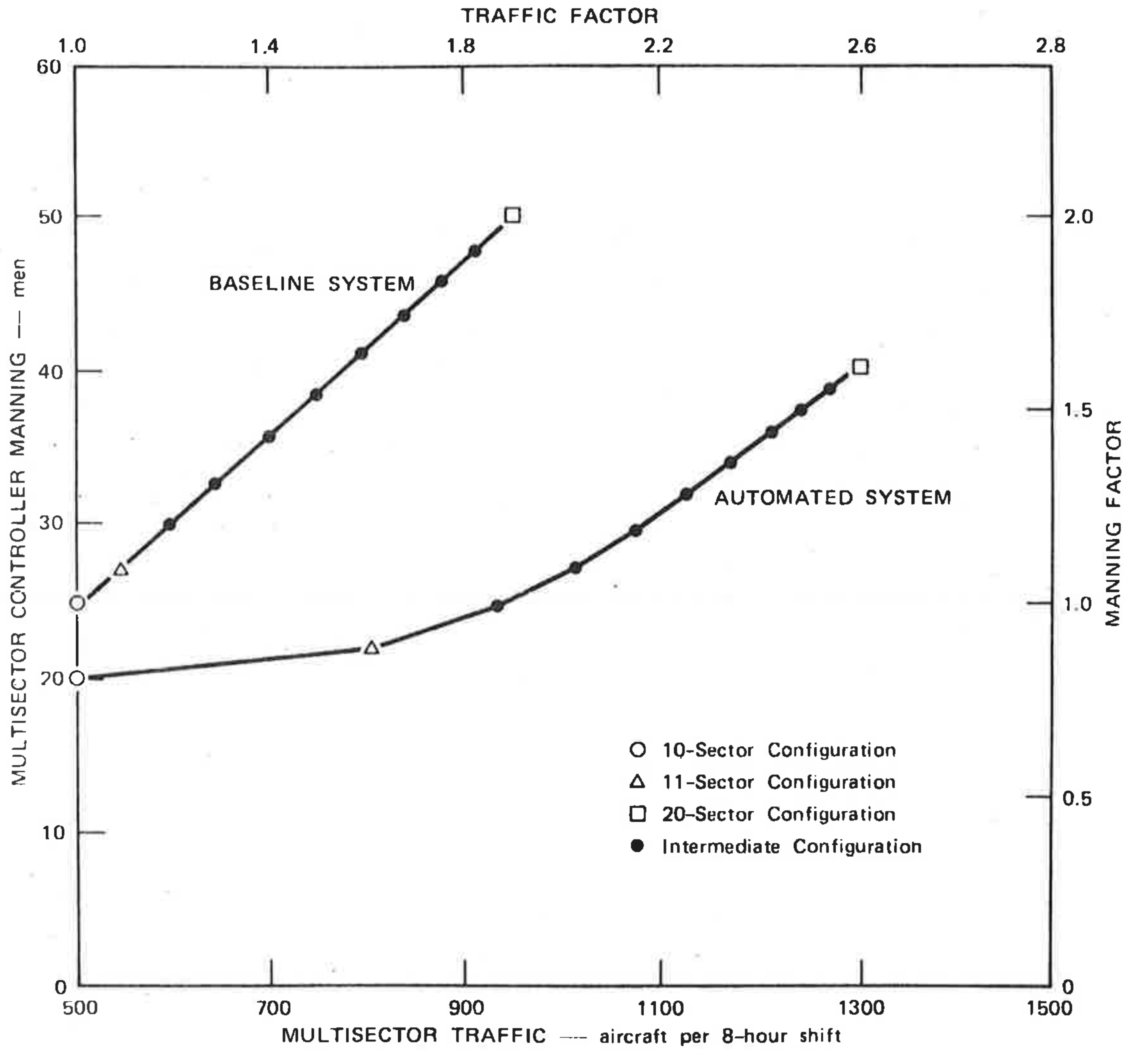

FIGURE 7 PRODUCTIVITY RELATIONSHIPS

Recall that the multisector manning here is 25 men (1.0 manning factor) and the traffic loading base is 500 aircraft/shift (1.0 traffic factor) with reference to Figure 7, the 20-sector upper-bound manning factor for the baseline system is 2.0 (i.e., 50 controllers), and its corresponding traffic factor is 1.9 (950 aircraft/shift). The upper-bound manning factor for the automated system is 1.6 (i.e., 40 controllers), which corresponds to a traffic factor equal to 2.6 (1300 aircraft/shift). The relative efficiency of the two systems operating with maximum manning can be determined by comparing productivity factors:

System Operation	Traffic Factor	Manning Factor	Productivity Factor
20-sector Baseline	1.9	2.0	0.95
20-sector Automated	2.6	2.0	1.3

Recall that current 10-sector baseline operation is assigned a productivity factor equal to 1.0, and the productivity factor of the alternative system operations are determined relative to this base case. Therefore, the baseline system operating at maximum staffing shows a "loss" in productivity relative to current operations (i.e., 0.95 versus 1.0), and the automated system counterpart shows a productivity "gain" (i.e., 1.3 versus 1.0).

Analyzed from another point of view, the baseline system may be maintained with current level of service by increasing staffing until traffic grows by 90%. Thereafter, the baseline system may be kept in operation, but only with increased traffic delay or by constraining traffic demand, or both. Let us suppose that traffic is forecast to increase by 90% in the year 1985. Our analysis suggests that some alternative system should be in operation by this time to maintain the current level of service. Clearly, our hypothetical enhanced system could provide such service beyond 1985 and should be maintained at the latest until the traffic grows by 160%.

We wish to point out that controller manning requirements can be expanded into annual staffing requirements by making allowances for standard or authorized controller relief and annual leave and support and supervisory personnel needs.

APPENDIX A

RECORD FORMAT FOR ENROUTE WORK ACTIVITY MEASURES*

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*This appendix is developed from the FAA "before-and-after" data file formats by Mr. Robert Wiseman and Dr. John Royal of the Transportation Systems Center.

ENROUTE WORK ACTIVITY MEASURES

CHAR. NO.	IDENTIFICATION	FORMAT	EQUIV. CODE	COMMENT
1,2	Sector Number	XX	-	ARTCC, Sector numbers, and dates of experiment are known beforehand. Select from sectors tested.
3,4	Data	XX	-	Select from days of tests
5,8	Greenwich Mean-Time	XX(hrs), XX(min)		Start time. Every 5 min. for test duration.
9,10	Staffing Level	X, Blank	-	Number controllers at sector
11,12	Workpace	0,X	-	Seven levels 0 thru 6, first character is zero
13	Flag	X	-	1 if OC&VC (See chars. 23-26) monitored together. 2 if monitored separately.
14	Flag	X	-	1 if D-controller monitored. 2 not.
15,16	Altitude Control	XX	AC	Number of radio transmissions in 5 minute time interval starting at 5-8 GMT. R-controller
17,18	Altitude Verification	XX	AV	" " " " "
19,20	Speed Control	XX	SC	" " " " "
21,22	Speed Verification	XX	SV	" " " " "
23,24	Vector for Control	XX	VC	Radio. R-controller. Vector related to other traffic: (1) conflict resolution; (2) sequencing; and (3) in-trail spacing

(Cont'd)

CHAR. NO.	IDENTIFICATION	FORMAT	EQUIV. CODE	COMMENTS
25,26	Other Control	XX	OC	Radio. R-controller frequency changes, clearance issuances, shorten flight path, all other radio transmissions that do not fit into above catagories.
27,28	Advisory	XX	AD	Radio. R-controller.
29,30	Beacon	XX	B	" "
31,32	Handoff Outside ARTCC	xx	HO	Interphone. R-controller.
33,34	Handoff Inside ARTCC	XX	HI	" "
35,36	Coordination Outside ARTCC	XX	CO	" "
37,38	Coordination Inside ARTCC	XX	CI	" "
39,40	Issue Clearances	XX	IC	" "
41,42	Verbal Handoff	XX	VH	Verbal. R-controller.
43,44	Verbal Coordination Outside Sector	XX	VO	" "
45,46	Verbal Coordination with "R" Man	XX	VR	" "
47,48	Verbal Coordination with "H" Man	XX	VL	" " Manual systems only. Zero for NAS Stage A Model 3.d.2.
49,50	Verbal Coordination with "D" Man	XX	VD	Verbal. R-Controller.

(Cont'd)

CHAR. NO.	IDENTIFICATION	FORMAT	EQUIV. CODE	COMMENTS
51,52	C.U.E. Entries	XX	Q	Manual. R-controller. Includes mode, off-centering, CRD category/function, Quick-Action, ANK, and Track-ball enter keys.
53,54	Flight Strip Activity	XX	FS	Manual. R-controller.
55,56	Shrimp Boat Activity	XX	SB	Manual system only. R-controller. Zero for NAS Stage A Model 3.d.2.
57,58	Adjust Equipment	XX	AE	Manual. R-controller. Systems Status Keys and Display Control. (e.g. filter, field select, and mode keys; range, off-centering, radar history, leader and vector controls).
59,60	Data Lookup, Charts, Maps, etc.	XX	DL	Manual. R-controller.
61,62	Hand Signal	XX	HS	Visual. R-controller. Infrequently used.
63,64	Standby	XX	SY	Standby. R-controller. Infrequently used.
65,66	Coordinator Handoff	XX	-	Coordinator. Number of coordinator handoffs (rare). Counted by peer observer each five minutes.
67,68	Total Number of Radio Transmissions	XX	-	All R-controller radio activities (AC thru B. See characters 15 thru 30) within 5 min. interval
69,71	Total Radio Transmission Time	XXX	-	Total seconds within 5 min. interval for above activities.
72,73	Total (number of) Handoffs Outside ARTCC	XX	-	Interphone. R-controller. Total handoffs outside ARTCC within 5 min. interval.

(Cont'd)

CHAR. NO.	IDENTIFICATION	FORMAT	EQUIV. CODE	COMMENTS
74,76	Total Time For Handoffs Outside ARTCC	XXX	-	Seconds time within 5 min. interval for above handoffs.
77,78	Total Handoffs Inside ARTCC	XX	-	Interphone. R-controller. Total handoffs ~~out~~ IN side ARTCC within 5 min interval.
79,81	Total Time For Handoffs Inside ARTCC	XXX	-	Seconds time within 5 min. interval for above handoffs.
82,83	Total Coordinations Outside ARTCC	XX	-	Interphone. R-controller. Total coordinations outside ARTCC within 5 min. interval
84,86	Total Time For Coordinations Outside ARTCC	XXX	-	Seconds time within 5 min. interval for above coordinations.
87,88	Total Coordinations Inside ARTCC	XX	-	Interphone. R-controller. Total coordinations inside ARTCC within 5 min. interval
89,91	Total Time For Coordinations Inside ARTCC	XXX	-	Seconds time within 5 min. interval for above coordinations.
92,93	Total Issue Clearances	XX	-	Interphone. R-controller. Total issue clearances.
94,96	Total Time For Issue Clearance	XXX	-	Seconds time within 5 min. interval for above clearances.
97,98	Handoff Outside ARTCC	XX	HO	Interphone. D-controller
99,100	Handoff Inside ARTCC	XX	HI	" "
101,102	Coordination Outside ARTCC	XX	CO	" "

(Cont'd)

CHAR. NO.	IDENTIFICATION	FORMAT	EQUIV. CODE	COMMENT
103,104	Coordination Inside ARTCC	XX	CI	Interphone. D-controller
105,106	Issue Clearances	XX	IC	" "
107,108	Verbal Handoff	XX	VH	Verbal. D-controller
109,110	Verbal Coordination Outside Sector	XX	VO	" "
111,112	Verbal Coordination With "R" Man	XX	VR	" "
113,114	Verbal Coordination With "H" Man	XX	VL	" "
115,116	Verbal Coordination With "D" Man	XX	VD	" "
117,118	C.U.E. Entries	XX	Q	Manual. D-controller. Data entry action. (e.g. A/N, keyboard and quick action keypack)
119.120	Flight Strip Activity	XX	FS	Manual. D-controller.
121,122	Shrimp Boat Activity	XX	SB	Manual system only. D-controller. Zero for NAS Stage A Model 3.d.2.
123,124	Adjust Equipment	XX	AE	Manual. D-Controller.
125,126	Data Lookup, Charts, Maps, etc.	XX	DL	Manual. D-controller.
127,128	Hand Signal	XX	HS	Visual. D-controller. Infrequently used.

(Cont'd)

CHAR. NO.	IDENTIFICATION	FORMAT	EQUIV. CODE	COMMENTS
129,130	Standby	XX	SY	Standby. D-controller. Infrequently used.
131,134	Equivalent Aircraft	XXXX	-	For each five minute interval, the number of aircraft obtained by dividing the Aircraft Minutes by Sector Flight Time.
135,138	Aircraft Minutes	XXXX	-	For each five minute interval, the total time in minutes that all aircraft are under the sector's jurisdiction. Obtained by computation of sector in and out times for each aircraft, recorded by peer observer every five minutes. Includes aircraft minutes less than five minutes.
139,140	Peak Aircraft	XX	-	For each five minute interval, the computed maximum number of aircraft that are simultaneously under the sector's jurisdiction.
141,144	Sector Flight Time	XXXX	-	The average time in minutes per aircraft that aircraft take between entering and exiting the sector.

APPENDIX B*

SECTOR BUSY HOUR IDENTIFICATION WITH A WORKPACE SEARCH PROGRAM

This appendix briefly describes† a software program that identifies the busiest sector hours in a multisector terminal or enroute area. The program is entitled Workpace Search and is based on the peer evaluations of controller workpace taken in the field experiments. The main purpose of this program is to select data for further processing when the total of observed workpace values is greater than totals obtained during other days of a controlled experiment under the following conditions:

1. A multisector area (say, 10 to 12 sectors) has been selected as a configuration for evaluation over a two-week test period (10 days).
2. Controller workpace is observed at a maximum of four sectors in the configuration and during the same time each day.
3. Workpace observations will be taken for one and one-half hours at each sector at test times that are coincident with RECEP and other measures taken simultaneously.
4. The start times of Workpace observations at each sector may differ from those taken at other sectors by as much as 15 minutes.
5. Workpace will be observed at one or two selected sectors for all ten days of the experiment while observations taken at other sectors may vary from day to day.

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*By Mr. Robert Wiseman of the Transportation Systems Center.

†A more detailed description of this program is contained in "Workpace Search Program," Draft Report, Dr. John Royal, Kentron, Hawaii LTD, September 30, 1976.

Given the test conditions, the Workpace Search program uses a five-minute moving window to find the hour over which each sector's workpace is maximum. The program then totals these maximums for all observed sectors for that day to select three one-hour median time intervals when the observed Workpaces are maximum. Although this selection may be performed manually as a rough data screening in the field, three other features have dictated the use of a computer program. These are:

1. The program quickly searches past workpace data on the CDC 6400 data files.
2. The program then obtains aircraft counts and controller work activities from the same data files. It is also constructed to track the corresponding minimum task times* for man-second comparisons with the column totals in the RECEP routine workload measures.
3. Time series of Workpace and aircraft load, sampled every five minutes,† are directly formulated for coarse comparisons with the ATF model traffic samples and sector workload outputs.

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*This feature will require the collection of individual (rather than aggregate) task times for the work activities listed in Appendix C.

†Finer grain comparisons over one-minute intervals are made from the DART aircraft track history data described in Appendix G.

APPENDIX C

EQUIVALENCE RELATIONSHIPS BETWEEN RECEP AND WORK ACTIVITY

C.1 ONE-TO-ONE EQUIVALENCE

The following are those measures of the systems that closely approximate each other:

RECEP	WA
A/G:	RADIO:
• Initial Pilot Call-in	• AV*--Altitude Verification (131)*
• Pilot Speed Report	• SV--Speed Verification (141)
• Traffic Advisory	• AD-Advisory (400)
FDP/RDP:	MANUAL--KEYPACK:
• Equipment Adjustment	• AE--Adjust Equipment
• Handoff Acceptance	• Q--Handoff Accept (KRH)
• Handoff Initiation	• Q--Handoff Initiation (RGH)
INTERPHONE:	INTERPHONE:
• Planning Advisory	• CI--Coordination with Coordinator (CCI)
DIRECT VOICE:	VERBAL:
• Handoff Acceptance--Intersection Coordination	• VH--Handoff Received Verbally (RHM)

*Prefix to WA indicator is the enroute code. Code in parenthesis indicates terminal code.

C.2 MANY-TO-ONE EQUIVALENCE

The following equivalence relationship involves the collapsing of a number of measuring parameters under one system to a single aggregated parameter under the other system:

RECEP	WA
A/G:	RADIO:
• Altitude Instruction • Pilot Altitude Report • Altitude Revision	• AC--Altitude Control (130)
• Heading Instruction • Altimeter Setting Instruction • Runway Assignment Instruction • Pilot Heading Report • Transponder Code Correction • Misc. A/G Coordinate • Frequency Change Instruction • Route/Heading Revision • Misc. Pilot Request	• VC--Vector for Control (100)
• Speed Instruction • Speed Revision	• SC--Speed Control (140)
FDP/RDP:	KEYPACK:
• Pilot Altitude Report--Flight Data Update • Initial Pilot Call in--Flight Data Altitude--Insert • Altitude Instruction--Flight Data Altitude Amendment • Transponder Code Correction	• Q--Update/Change/Cancel (DU)

• Altitude Revision--Flight Data Altitude Amendment • Route/Heading Revision--Flight Data Route Amendment • Flight Data Estimate Update	
• Handoff Acceptance--New Flight Strip Preparation • Pointout Acceptance--Data Block Suppression • Pointout Initiation • Data Block/Leader Line Offset • Data Block Forcing/Removal • Miscellaneous Data Service	• Q--Keyboard (Action Unknown) (KG)
FLIGHT STRIP PROCESSING: • All Flight Strip Tasks--22 nonzero entries (see Table 9 for details)	MANUAL: • FS--All Flight Strip Activities (FS)
INTERPHONE: • Handoff Acceptance--Intersector Coordination	INTERPHONE: • HO--Handoff Received from another Facility (RHF) • HI--Handoff Received from Complex in Facility (RHS)
DIRECT VOICE: • Handoff Initiation--Intersector Coordination • Frequency Change Instruction--Intersector Coordination	VERBAL: • VH--Handoff Given Verbally (GHM)

C.3 MANY-TO-MANY EQUIVALENCE

The following equivalence relationship is on a group-to-group basis. All of the data elements are in the Interphone Communication and Direct Voice Communication areas:

RECEP	WA
INTERPHONE:	INTERPHONE:
• Handoff Initiation--Intersector Coordination • Frequency Change Instruction--Intersector Coordination	• HO--Handoff given to another Facility (GHF) • HO--Handoff Received from another Facility (RHF)
• Altitude Instruction--Intersector Coordination • Heading Instruction--Intersector Coordination • Speed Instruction--Intersector Coordination • Pointout Acceptance • Pointout Initiation • Aircraft Status Advisory • Control Jurisdiction Advisory • Clearance Delivery	• CO--Coordination with another Facility (CF) • CI--Coordination within Facility (CS)
• Altitude Revision--Intersector Coordination • Route/Heading Revision--Intersector Coordination	• CI--Coordination with Coordinator (CCI) • CO--Coordination with Coordinator, Another Facility (CCF)

DIRECT VOICE:

- Altitude Instruction--Intersector Coordination
- Heading Instruction--Intersector Coordination
- Speed Instruction--Intersector Coordination
- Altitude Revision--Intersector Coordination
- Route/Heading Revision--Intersector Coordination
- Pointout Acceptance
- Pointout Initiation
- Control Instruction Approval
- Aircraft Status Advisory
- Control Jurisdiction Advisory
- Clearance Delivery

VERBAL:

- VR--Coordination with R Position (CR)
- VL--Coordination with Handoff Position (CH)
- VD--Coordination with D Position (CFD)
- CO--Coordination with another Facility (CF)

APPENDIX D

POTENTIAL CONFLICT MODELS*

D.1 POTENTIAL CONFLICT FREQUENCY MODEL

This appendix describes mathematical models for estimating the expected frequency of potential conflicts. Potential conflicts are projected violations of separation minima perceived by controllers. Because this project was concerned with the radar environment, the ATC radar separation minima are the criteria to be maintained. These criteria, based on our observations of the actual separations exercised by controllers, are as follows:

- Aircraft are separated by less than 1000 feet in altitude (2000 feet above FL290).
- Aircraft on arrival routes about to enter terminal airspace are separated by at least five nautical miles.
- All other aircraft are separated by at least ten nautical miles.

The two primary means by which these separation minimums can be violated are by (1) intersecting of two aircraft flights paths or (2) one aircraft overtaking another. The possible events resulting from these two violations are listed in Table 21.

SRI has developed a number of simple mathematical models for predicting the expected number of events. Data acquired in our measurement phase were compared with estimates generated by these models as verification.

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*This appendix is extracted from Appendix B, Reference 7.

TABLE 21

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 altitude. Aircraft transitioning on the same track.

The development of the model used to predict the expected number of conflicts at two air routes is described in detail by Siddiqee.[14] Only the resulting expressions are presented here.

Assume the following statements are true about intersections at the same altitude: (1) a conflict event occurs any time an aircraft along route 1 is closer than X miles to an aircraft along route 2; (2) the arrival of aircraft at the sector entry point, along the air route, is uniformly distributed with random variations; (3) the variation in aircraft speed along the air route is negligible. Then, the relationship for the expected number of conflicts can be expressed as

$$C_A = \sum_i \frac{2\, f_{i1} f_{i2} X \sqrt{V_{i1}^2 + V_{i2}^2 - 2V_{i1}V_{i2} \cos\alpha}}{V_{i1}V_{i2} \sin\alpha} \qquad (1)$$

where

C_A is the expected number of conflicts per hour.

f_{i1} is the flow of aircraft at altitude i along route 1 (aircraft per hour).

f_{i2} is the flow of aircraft at altitude i along route 2 (aircraft per hour).

X is the separation minimum (miles).

v_{i1} is the average speed of aircraft at altitude i along route 1 (miles per hour).

v_{i2} is the average speed of aircraft at altitude i along route 2 (miles per hour).

α is the angle of intersection between the routes.

i is the different altitude levels used along this air route.

The expected number of conflicts at an intersection of a transitioning aircraft track and a level aircraft route can be expressed as

$$C_B = \sum_j \sum_k \frac{2f_j f_k X \sqrt{V_j^2 + V_k^2 - 2V_j V_k \cos\left[\sin^{-1}\frac{V_t}{V_j}\right]}}{V_j V_k \left[\frac{V_t}{V_j}\right]} \qquad (2)$$

where

C_B is the expected number of conflicts per hour.

f_j is the flow of aircraft along the j^{th} transitioning track (aircraft per hour).

f_k is the flow of aircraft along the route at the k^{th} altitude (aircraft per hour).

X is the separation minimum (miles).

V_j is the average speed of aircraft along the j^{th} transitioning track (miles per hour).

V_k is the average speed of the aircraft along the route at the k^{th} altitude (miles per hour).

V_t is the transitioning rate for the transitioning aircraft (miles per hour) (i.e., climb or descent rate for the transitioning aircraft).

j is each transitioning track used in the sector.

k is each altitude level used for air traffic that intersects j.

It can also be shown that the expected number of conflicts at an intersection of two transitioning aircraft routes can be expressed as

$$C_c = \sum_{\ell}\sum_{m} \frac{2f_{\ell}f_m X\sqrt{V_{\ell}^2 + V_m^2 - 2V_{\ell}V_m \cos\left[\sin^{-1}\frac{V_{t\ell}}{V_{\ell}} + \sin^{-1}\frac{V_{tm}}{V_m}\right]}}{V_{\ell}V_m\left[\frac{V_{t\ell}}{V_{\ell}} + \frac{V_{tm}}{V_m}\right]} \qquad (3)$$

where

C_c is the expected number of conflicts per hour.

f_{ℓ} is the flow of aircraft along the ℓ^{th} transitioning route (aircraft per hour).

f_m is flow of aircraft along the m^{th} transitioning route (aircraft per hour).

X is the separation minimum (miles).

V_{ℓ} is the average speed of aircraft along the ℓ^{th} transitioning route (miles per hour).

V_m is the average speed of aircraft along the m^{th} transitioning route (miles per hour).

$V_{t\ell}$ is the transitioning rate for the aircraft along route ℓ (miles per hour).

ℓ is each transitioning route used in the sector.

m is each transitioning route used in sector that intersects ℓ.

Equations (2) and (3) are used only if the situations under consideration pertain to transitioning aircraft and/or level aircraft that coincide along the same ground track. If the situation involves aircraft along different ground tracks, then the expression in Equation (1) is also used to determine the expected number of conflicts of transitioning aircraft and level aircraft whose ground tracks do not coincide, as well as to determine the expected number of conflicts between two different transitioning aircraft whose ground tracks do not coincide. Hence, the expressions in Equations (1), (2), and (3) give estimates of the expected number of conflicts for each of the intersecting situations listed in Table 21.

SRI has also developed a simple mathematical model for predicting the expected number of overtakes. Assume the following:

- An overtake event occurs anytime a faster moving aircraft comes within X miles (separation minimums) of a slower moving aircraft, both at the same altitude and along the same air route, or both transitioning along the same route, during the period of time the aircraft are within the sector boundaries.
- The arrival of aircraft at the sector entry point, along the air route, are uniformly distributed with random variations.
- The variations of aircraft speeds along the route are distributed in discrete speed classes.

Then, the relationship for the expected number of overtakes along an air route (including transitioning aircraft) can be expressed as

$$O_1 = \sum_{i=1}^{n-1} \frac{(\ell + 2X)\ f_i}{V_i} \sum_{k=i+1}^{n} \frac{f_k}{V_k} \left[\left(\frac{V_i + V_i'}{2} \right) - \left(\frac{V_k + V_k'}{2} \right) \right] \qquad (4)$$

where

O_1 is the expected number of overtakes per hour.

n is the number of discrete speed classes along the route.

ℓ is the length of air route (miles).

f_i is the flow of aircraft travelling at the i^{th} speed (aircraft per hour).

V_i is the beginning speed of aircraft in the i^{th} speed (miles per hour).

f_k is the flow of aircraft travelling at the k^{th} speed (aircraft per hour).

V_k is the beginning speed of aircraft in the k^{th} speed class (miles per hour).

V_i' is the ending speed of aircraft in the i^{th} speed class (miles per hour).

V_k' is the ending speed of aircraft in the k^{th} speed class (miles per hour).

X is the separation minumum (miles).

As stated above, this expression also includes expected overtakes for transitioning aircraft. Hence, Equation (4) gives the expected number of overtakes for two overtake situations listed in Table 21.

Adding the expected conflict events and expected overtake events together yields a total of four possible expected conflict events. The frequencies of crossing and overtaking conflicts obtained by the applications of these models will be used as functions of total sector traffic flow in the RECEP workload calculation.

D.2 SECTOR CONFLICT FREQUENCY FACTORS

Equations (1), (2), and (3) estimate the expected number of potential conflict occurrences for a single confliction point or route for a given rate of flow for 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:

$$\text{Number of crossing conflicts/hour} = e_c N^2$$

$$\text{Number of overtaking conflicts/hour} = e_o N^2$$

where

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

e_c and e_o respectively are frequency factors that measure the rates of occurrence of crossing and overtaking conflicts for the sector measured in (conflicts/hr)/(aircraft/hr)^2.

The frequency factors e_c and e_o are calculated (as discussed below) using Equations (1), (2), (3), and (4) 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 we summed over all conflict points and routes to obtain the expected number of potential crossing, E_c, and overtaking, E_o, conflicts/hr for the entire sector:

$$E_c = \sum_x (C_A + C_B + C_C) \text{ for all intersections points } x = 1, 2, \ldots$$

$$E_o = \sum_z O_1 \text{ for all routes } z = 1, 2, \ldots$$

Recall that C_A, C_B, and C_C 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:

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

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

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 $e_c N^2$ and $e_o N^2$ estimate the number of conflicts per hour corresponding to any value of N aircraft/hour through the sector. Because it is reasonable to assume that the traffic distribution remains unchanged, we need not calculate individual values of C_A, C_B, C_C, and O_1 for each intersection and route for each value of N.

APPENDIX E

DATA COLLECTION AND REDUCTION TECHNIQUES FOR POTENTIAL CONFLICT-EVENT FREQUENCY

The primary sources of data for the potential-crossing and overtake-conflict events are the flight progress strips, the PVD video recording, and controller-supplied information. The controller-supplied information is obtained through informal meetings and interviews and is essentially the following:

- Identification of potential conflict routes and potential conflict situations in sector.
- The procedures for resolving potential conflict situations in sector.
- The selection of one or two particular examples for discussion. The discussions are assisted by video tape play-backs.
- The minimum separation criterion used in sector (which may be more stringent than the standard minimum separation requirement).

For clarity, a flow diagram* depicting the major steps involved in RECEP potential conflict event data collection and reduction is given in Figure 8. The process begins with identification and classification of sector and route characteristics. Next, the potential crossing-conflict routes and overtake-conflict routes are segregated for separate processes. Each cross-conflict situation would result in using one of the three crossing-conflict equations given in Appendix D and the overtake-conflict situations would use the fourth equation given in the same appendix. A

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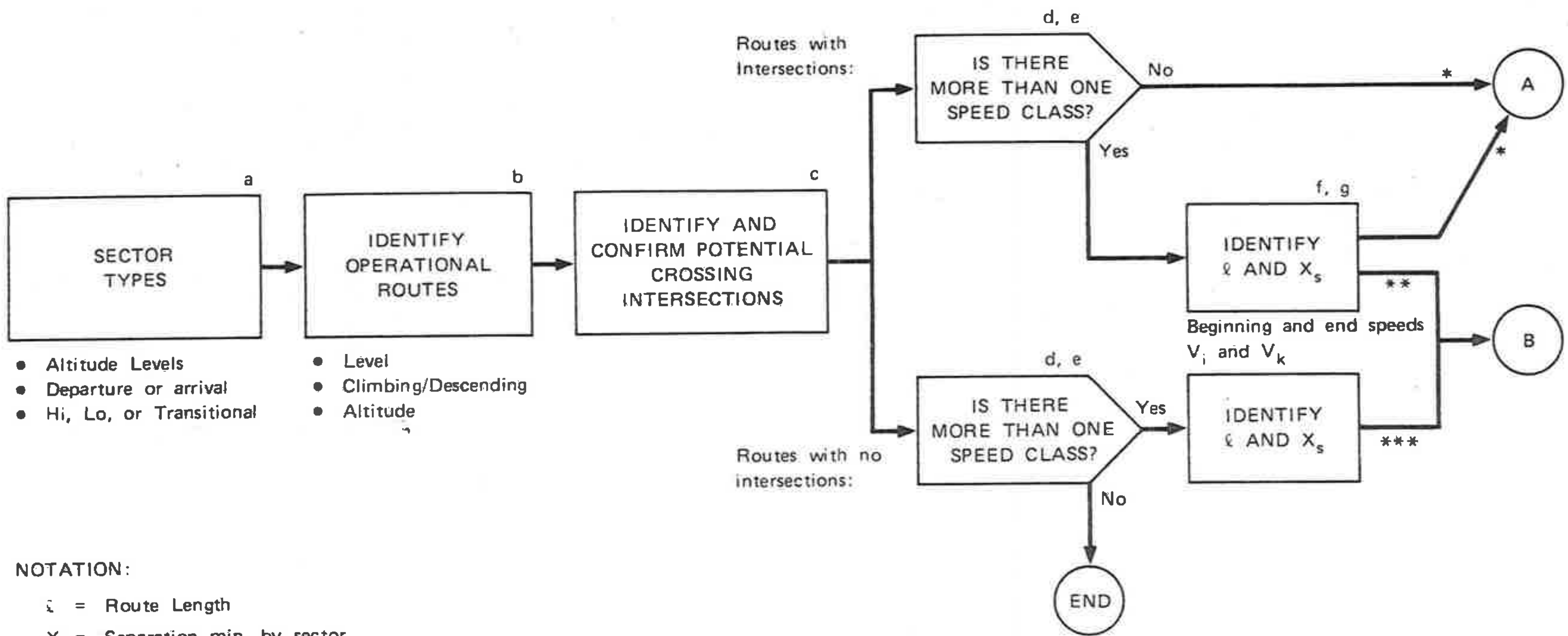
*This flow diagram was originally contributed by Mr. Robert Wiseman of TSC.



NOTATION:

ℓ = Route Length

X_s = Separation min. by sector

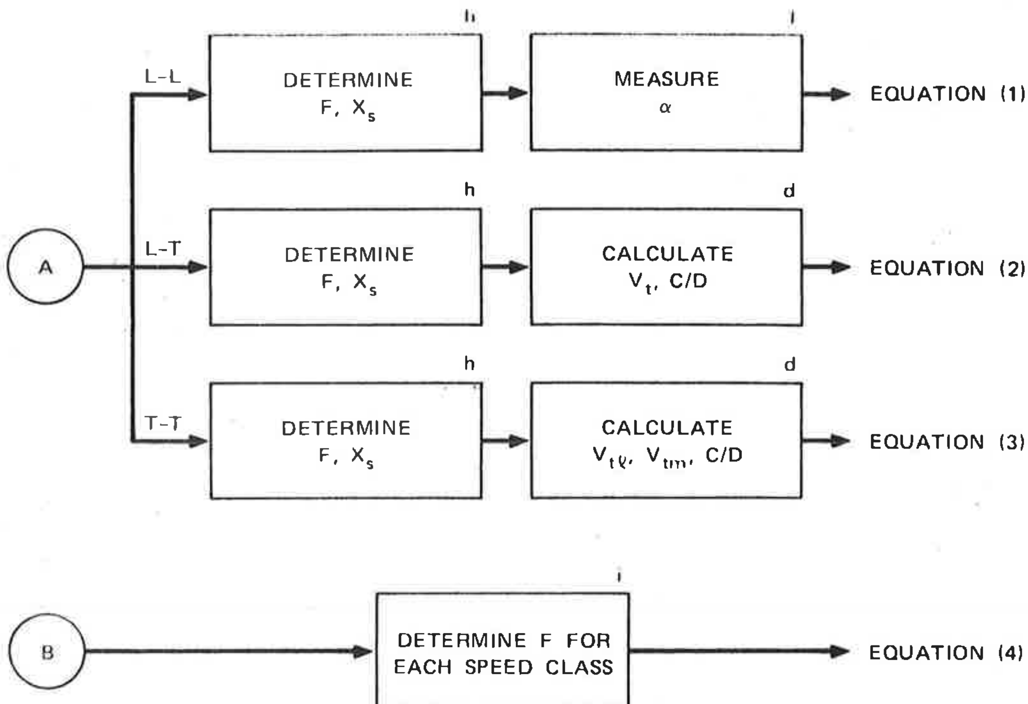
a Small alpha character refers to source document data element in Table 22.

*The identification of level-level (L-L), level-transitional (L-T), or transitional-transitional (T-T) for each route has been made on the basis of information obtained in the first two boxes of this flow diagram.

**Intersecting routes in which speed classes were identified.

***Overtakes on route segments.

FIGURE 8 RECEP DATA COLLECTION AND REDUCTION ON POTENTIAL CONFLICT EVENTS – MAJOR STEPS



NOTATION:

L = Level
T = Transitional
F = Average Flow Rate for Each Route Within a Sector
α = Angle Between Routes
C/D = Climb/Descend Rates

V_t, $V_{t\ell}$, V_{tm} defined in Appendix D
Conflict equations defined in Appendix D

FIGURE 8 RECEP DATA COLLECTION AND REDUCTION ON POTENTIAL CONFLICT EVENTS — MAJOR STEPS **(Concluded)**

number of data sources are used to develop variable values for the conflict equations. For example, average aircraft velocity (V) and aircraft flow rates (F) are obtained from flight strips and video tape recordings. The major data sources may be classified as follows (the alphabetic item numbers are keyed to the flow diagram boxes shown in Figure 8):

a. Sector identification and characteristics.

b. Operational routes and flight profiles.

c. Potential crossing-conflict intersections.

d. Average speed along route and climbing/descending rate for transitional route.

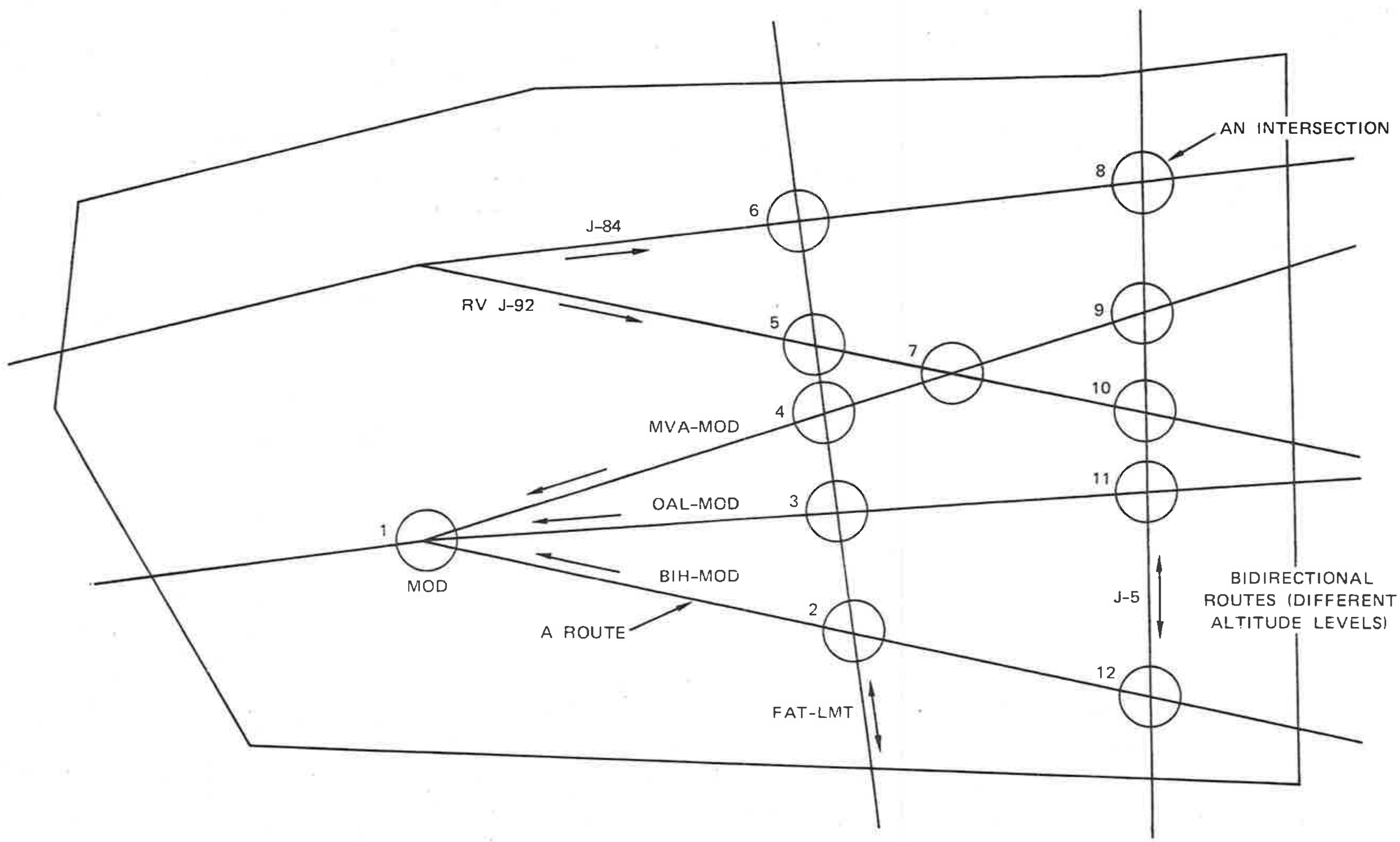


FIGURE 9 AN EXAMPLE OF A SECTOR'S OPERATIONAL ROUTES AND INTERSECTIONS

TABLE 23

TYPICAL TRAFFIC DISTRIBUTION EXAMPLE
(N_H = 30 Aircraft/Hour)

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

*The arrows indicate whether routes are descending or ascending.

TABLE 24

POTENTIAL INTERSECTION CONFLICTS
(N_H = 30 Aircraft/Hour)

Inter-Section	Route 1	Route 2	Angle of Inter-Section	Flow 1	Flow 2	Velocity 1	Velocity 2	Average Number of Conflicts
1	MVA	BIH	30°	2	2	450	460	0.2
	MVA	OAL	15°	2	9	450	440	1.0
	BIH	OAL	15°	2	9	460	440	1.0
2	FAT-LMT	BIH-MOD	110°	1	1	450	460	0.1
3	FAT-LMT	OAL-MOD	90°	1	3	450	440	0.2
				1	6	450	440	0.5
4	FAT-LMT	MVA-MOD	100°	1	2	450	450	0.2
				1	2	450	450	0.2
5	FAT-LMT	RV J92	110°	1	2	450	465	0.2
6	FAT-LMT	J84	90°	1	5	450	435	0.4
7	RV J92	MVA-MOD	150°	1	2	465	450	0.3
8	J5	J84	90°	2	6	435	435	0.9
				1	2	435	435	0.1
9	J5	MVA-MOD	75°	1	1	435	450	0.1
10	J5	RV J92	75°	2	1	435	465	0.2
				1	1	435	465	0.1
11	J5	OAL-MOD	90°	1	5	435	440	0.3
				1	3	435	440	0.2
12	J5	BIH-MOD	75°	1	1	435	460	0.1
							Total	6.3

TABLE 25

OVERTAKE CONFLICTS (OAL-MOD ROUTE)
(Route Length = 75 Nautical Miles)

Speed Class (Knots)		Number of Aircraft		Average Number of Overtakes
1	2	1	2	
425	460	1	5	0.09
425	475	1	3	0.11
460	475	5	3	0.13
			Total =	0.33

speed class are essential to the computation. The flight strips' role in this (besides giving aircraft identification information, route, sector, times, etc.) is to supply ground-speed information. This information is currently also provided by the PVD display but not in all cases. The ground-speed information from both data media is then used to develop aircraft flow distributions at various speed classes along each route.

APPENDIX F*

USE OF DART FOR QUICK ESTIMATION OF RECEP FDP/RDP AND AIRCRAFT LOAD COUNTS

This appendix briefly describes[†] two methods, developed by TSC, for the semiautomatic estimation of enroute RECEP FDP/RFP operations frequencies and sector aircraft loads. The methods employ the Data Analysis and Reduction Tool (DART) program on the IBM 9020 computer to obtain these data for specified sectors and over selected intervals of time. The DART program is available to perform flexible, off-line, batch analysis of System Analysis Recording (SAR) data that are always gathered automatically for all sectors at each enroute center. The intent is to eventually obtain a rapid and fully automatic count of sector aircraft load and FDP/RDP keyboard/display operational counts in a form suitable for direct use in the RECEP routine workload estimates. Although a complete, fully enumerated routine workload data base requires more information than SAR data alone can provide, it should be remembered that RECEP events, in man-minutes per aircraft, already contain judgmental estimates of minimum times and often require other data sources (such as communications and video tape replays) for their identification. The method developed in this appendix carries the RECEP approximations a step further toward automation in two ways: (1) some basic FDP/RDP

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*By Dr. Mitch Grossberg and Mr. Robert Wiseman of Transportation Systems Center (TSC).

†A more complete description of this method is described in, "The Use of DART for the Quick Estimation of RECEP FDP/RDP Workload Operations and Aircraft Load Counts," Draft Interim Report, Dr. M. Grossberg and R. Wiseman, DOT/TSC, September 30, 1976.

events are combined into a single event; and (2) Sector Control jurisdiction of aircraft is estimated to occur when the manual or automatic handoff action is sensed by the NAS computer. These approximations eliminate cross-referencing to other RECEP measures and, when coupled with similar approximations in controller verbal communications and flight-strip activities, allow a rapid processing of data into the RECEP matrix. However, it should be noted that the overall purpose of these methods is to assess the accuracy of RECEP for current operations and not for future ATC automation enhancements. In the latter case, it may be necessary to examine individual RECEP events and aircraft loads using the slower, but more accurate, original methods developed by SRI. These considerations are discussed in the descriptions of the two methods which follow.

F.1 ESTIMATION OF FDP/RDP WORKLOAD

This method focuses on the FDP/RDP operations event counts under the assumption that the corresponding minimum times for each event are invariant with the time, controller, and site location of any current enroute ATC situation. Given the invariance, it is then sufficient to identify only the number of each FDP/RDP event to obtain an individual man-minute product. The DART program concerns messages that are entered into a center's computer by the R and D controllers from their respective data-entry devices. The controller's computer entries define the occurrence of events that may, in the real situation, also involve air/ground communications, flight-strip processing, etc. If the individual FDP/RDP component of the multiple activity events is identified, then it is not necessary to count any other component (for example, the flight-strip processing component). That is, the eventual automation of FDP/RDP counts will also partly reduce the requirement to count events in other columns of the RECEP matrix. The first step in automating the FDP/RDP operations counts starts with working back from the computer-entered messages to RECEP events. This requires a message-to-event translation table, one designed to facilitate look-ups by an analyst. The analyst finds a match between the format of each message in a DART printout and the format that corresponds to a RECEP event. A match may involve either the message type alone, when all possible message contents apply, or both the message type and the message contents. Having identified the corresponding RECEP events, the analyst later counts the number of messages that corresponded to a particular event and multiplies this frequency by the minimum performance time that is tabled as a constant for this event.

To obtain the FDP/RDP man-minute estimates, several simplifications are made. One is to ignore the nature of the controller's interaction with the pilot and just focus on actions that the controller takes by himself--the messages input to the computer. For example, a DART printout can indicate that a controller made a quick-action keyboard entry to insert an altitude value into a flight plan, but the printout does not indicate whether the altitude insert was prompted by an initial pilot call-in or by a pilot's altitude report. If SAR data are to be used independently of other sources of concurrent data especially taped air/ground voice communications, then the analysis cannot deal with this distinction. In the DART-based analysis of SAR data, all occurrences of altitude insert actions are thus represented by only one instead of two frequency counts. If the minimum performance time for each of these actions is the same, then this simplification does not introduce an error into the estimate of total workload. In this instance, the time is three seconds whether the altitude insert follows a pilot call-in or a report. Fortunately, this is usually the case when events are combined. If not, the times for each event must be approximated by an average of both.

Because message content as well as message type are both needed to translate messages to RECEP events, the Log option is used in the DART procedure to select and arrange the SAR data which has been formed on an edited tape. Control card statements are used to limit the DART outputs to preselected sectors and specified time intervals with the FDP/RDP messages types listed in the RECEP format shown in Table 26. The table indicates those message types that have been combined or eliminated from consideration. It also applies to both R and D controller activities which can either be combined or separated as DART outputs.

Control cards are also used to arrange the printout data in a way that facilitates message matching. This is obtained through a sorting hierarchy--DEVID, CID, MESSAGE, and TIME--causing the messages to be arranged with all messages grouped by sector, then by aircraft, then by message types, and finally by time, so that all messages of the same type are in the order of their occurrence. The resulting printout shows, for example, the QN messages for a given aircraft arranged so that the handoff acceptance, altitude amendment, data block offset, and handoff initiation messages are listed one after the other in order of entry. To identify the corresponding RECEP event, the analyst can quickly look up QN messages and compares message contents with prescribed formats. An efficient computer program can presumably be written to compare these messages with the tabled formats that correspond to RECEP events.

F.2 ESTIMATION OF A SECTOR'S TRAFFIC FLOW RATE

This method is based on the following assumption: until a tracked aircraft crosses the boundary between a sector and the adjacent sector or facility to which control of the aircraft has already been transferred, the radar controller in the sending sector is required to maintain surveillance over the aircraft on his Plan View Display (PVD). Transfer of control jurisdiction thus does not end all of the sending controller's

TABLE 26

ROUTINE FDP/RDP CONTROL EVENTS

ATLANTA CENTER - TWO-MAN SECTOR

Event Function	Basic Event: Supplemental Event	Time (sec)	Type of Input Message	Quick-Estimate Simplifications Combined*	Delete
Control jurisdiction transfer	(1) Handoff acceptance	2	QN,QT,QZ		
	Flight data update	3	DM	4	
	(2) Handoff initiation: manual-silent	3	QN,QZ		
Traffic structuring	(3) Initial pilot call-in: flight data altitude insert	3	QR,RA	1	
	(4) Altitude instruction: flight data altitude amendment	3	QN,QQ,QZ,AM	2	
	(5) Heading instruction: flight data route amendment	10	AM,QU	3	
	(6) Pilot altitude report: flight data altitude insert	3	QR,RA	1	
	(7) Transponder code assignment: flight data code amendment	3	DQ,QB		
Pilot request	(8) Altitude revision: flight data altitude amendment	3	AM,QN,QQ,QZ	2	
	(9) Route/heading revision: flight data route amendment	10	AM,QU	3	
	(10) Clearance delivery: flight data update	3	DM	4	
Pointout	(11) Pointout acceptance: data block suppression	3	QP		
	(12) Pointout inition:	3	QP		
General intersection coordination	(13) Clearance delivery: flight data update	3	DM	4	
General system operation	(14) Flight data estimate update	1	None		Yes
	(15) Data block/leader line offset	2	QN,QZ		
	(16) Data block forcing/removal	3	QN,QZ		
	(17) Wind/weather request	3	UR,WR		
	(18) Altitude limits modification	3	QD		
	(19) Flight strip request	3	SR		
	(20) Flight plan readout request	3	FR,QF		
	(21) Flight plan/track removal	3	QX,RS		
	(22) Equipment adjustment	3	None		Yes
	(23) Track/route display	3	QU		

*The same number indicates events that are represented later as one event.

activities with respect to an aircraft; nor did the earlier absence of formal control acceptance by the receiving sector mean that its controllers were not already maintaining surveillance over an expected flight. Control transfer, viewed in terms of controller behavior, is a gradual process. However, viewed in terms of the enroute flight-plan-aided automatic tracker, it is the point in time when the receiving sector handoff acceptance is entered. The present method for estimating the number of aircraft controlled by a sector relies on this latter definition and is considered sufficiently accurate for sector traffic flow rate estimates made for both RECEP and the ATF model.

Because control jurisdiction confers eligibility to make certain changes in an aircraft's flight data, the NAS computer keeps a continuously updated record, the Track Control/Display Table (also known as Table HO) which identifies the sector that has jurisdiction over each aircraft. Table HO is included in SAR data, and is accessed by one of the DART options, Track, whose primary application is the detailed analysis of aircraft position as a function of time. The point here is that use of Table HO for the present purpose does not require this interpretation of control events. The use of Table HO eliminates using other DART programs which consider transfer of a fairly complex series of control events, both manual and automatic, in two sectors and, in the NAS computer.

A Track printout contains three lines of time-tagged information for every six-second period in each aircraft's track history, or 10 three-line samples of information per minute--a substantial amount of potentially useful information. However, only the fact that the aircraft was controlled by a particular sector at a specified time is needed to count the number of aircraft in a sector. Using data control statements, the amount of printed information can be limited, and this later facilitates aircraft counting by either manual or automatic means; at present, automatic means are not available.

Control statements are used to reduce the three lines of information to the first line, and the 10 samples per minute to one sample. The number of lines is reduced by setting the LINE control statement to 1. The sample rate is reduced to one time-tagged sample per minute by explicit TIME control statements, such as 163000,163006. Expressed in hours, minutes, and seconds, these times are the start and end of a six second interval, and produce a record for 163001.5. The record for the next minute, that is, 163101.5, is requested using the interval 163100,163106, and so on. Although this method of explicit time interval specification is tedious to express when entering control statements, and is a use for which the software was not originally intended, it greatly reduces the amount of data in the printout, making the printout manageable for manual work.

A Track printout that is obtained for a specified time period (using the "PARM" control statement), say a half hour and with one line of tracking information per minute, will give one printed page per aircraft for all aircraft that are tracked by the NAS during the half hour. As shown in Table 27, which illustrates a sample DART printout. The analyst scans the printed column of sector control numbers, asking whether a selected sector or sectors controlled that aircraft, and the answer is tabulated. This task is clearly one that a computer can accomplish quite efficiently.

Whether an analysis requires a count of the number of aircraft controlled by a sector every minute, every five minutes, or every hour, the method described here can provide the needed information with a constant level of accuracy.

TABLE 27

SAMPLE OF DART TRACK PRINTOUT TO IDENTIFY CONTROLLING SECTOR

TRACK SORT=AID,TIME NAS ID=A149016 NAS DATE=30/01/75 COMPCOL=X3024150 12/19/75 PAGE 0017
75 350

AIRCRAFT ID = C0430 COMPUTER ID = 920 TRACK ID = 028

TIME / CPT	:MRI :ASI :	FMI TOC	ND	TC	M	TMS SID	CN RS	HDI AHI	AALT AHDT TSB	RALT BETA REPA	ABC DDR	RBC : DOT : PVB :	PREDX TPF CLUTR-	PREDY TNF CONTR	SPD PFX	HDG EXS	PVX DELSP	PVY DELHG	ES CLI	A T	J	V	R S	DEVX DLAT	DEVY DLCNG
163001.5	:FLT	FLT	00	D8	P	ENR	37	NUL	00250	00107	3412	3412:	0543.0	0452.8	00275	100	000271	-00045	E3	S	M	1	1	000.25	000.25
163101.5	:FLT	FLT	01	D8	P	ENR	37	CEN	00250	00115	3412	3412:	0548.6	0452.6	00310	095	000309	-00029	E3	S	M	1		000.62	000.00
163201.5	:FLT	FLT	01	D8	P	ENR	68	NUL	00250	00132	3412	3412:	0554.6	0453.0	00339	090	000338	-00002	E3	S	M	1		000.12	000.25
163301.5	:FLT	FLT	01	D8	P	ENR	68	NUL	00250	00153	3412	3412:	0560.1	0455.5	00331	064	000298	000144	E3	L	M	1	2	-00.50	001.12
163401.5	:FLT	FLT	01	D5	P	ENR	68	NUL	00250	00165	3412	3412:	0567.3	0455.5	00376	080	000370	000065	E3	S	M	1		000.25	-00.25
163501.5	:FLT	FLT	01	D8	P	ENR	68	NUL	00250	00178	3412	3412:	0574.3	0456.1	00402	083	000399	000049	E3	S	M	1		000.25	000.00
163601.5	:FLT	FLT	00	D8	P	ENR	68	NUL	00250	00195	3412	3412:	0581.3	0457.2	00413	082	000409	000056	E3	S	M	1	1	000.00	000.12
163701.5	:FLT	FLT	00	D8	P	ENR	68	NUL	00250	00211	3412	3412:	0588.5	0458.2	00419	083	000416	000048	E3	S	M	1	1	000.00	000.00
163801.5	:FLT	FLT	00	D8	P	ENR	68	NUL	00250	00225	3412	3412:	0595.5	0458.7	00420	085	000418	000037	E3	S	M	1	1	000.00	-00.25
163901.5	:FLT	FLT	00	D8	P	ENR	68	NUL	00250	00236	3412	3412:	0602.6	0458.6	00417	088	000417	000013	E3	S	M	1	1	000.12	-00.37

AID SUMMARY FOR AIRCRAFT C0430 TRACK LIFE = 9 MINUTES

	TRACK MODE	TRACK MERIT	CODE EST	SEARCH	COR PRF	VAL	MEAN DEV	STANDARD	TMD-CHG	FLT MAT
ENROUTE	100 FLAT	100 RELPR	100	10 LSA	100-1	0-6	0.113(X)	0.269	0	100 MATCH
	0 FLATC	0 RELSP		90 SSA	0-2	0-7	0.085(Y)	0.398		0 UNMAT
	0 FREE	0 UNREL			0-3	0-8	0.396(Z)	0.324		
	0 FREEC				0-4	0-9				
	0 TURN				0-5	0-10				
L/S TURN	0 FLAT	0 RELPR	0	0 LSA	0-1	0-6	0.000(X)	0.000	0	0 MATCH
	0 FLATC	0 RELSP		0 SSA	0-2	0-7	0.000(Y)	0.000		0 UNMAT
	0 FREE	0 UNREL			0-3	0-8	0.000(Z)	0.000		
	0 FREEC				0-4	0-9				
	0 TURN				0-5	0-10				

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