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THE AIR TRAFFIC CONTROLLER'S CONTRIBUTION
TO ATC (AIR TRAFFIC CONTROL) SYSTEM CAPACITY
IN MANUAL AND AUTOMATED ENVIRONMENTS.
VOLUME I: SUMMARY REPORT

R. S. Ratner, et al

Stanford Research Institute

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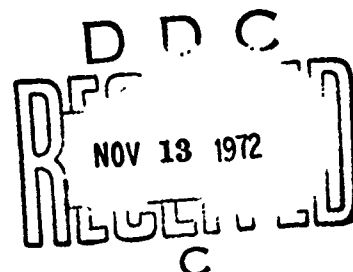
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IN MANUAL AND AUTOMATED ENVIRONMENTS**

Volume I — Summary Report

R. S. Ratner, J. O. Williams, M. B. Glaser, and S. E. Stuntz

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16. Abstract This report documents SRI's work to date on the ATC controller's contribution to system capacity in manual and automated environments. Volume I contains sufficient background material to put the work in perspective, summarizes the methodology used, and presents the study findings and implications for effective automation, as well as quantitative capacity estimates and predictions. Volume II discusses in detail the methodology, measurements and data, assumptions, and derivations behind the techniques and analysis. The methodology is based on a technique called the Relative Capacity Estimating Process (RECEP), developed to assess the implications of controller judgmental factors and decision processes for attainable capacity at several levels of automation. RECEP incorporates a technique of sector operational measurement that includes video recording and structured controller interviews. The technique has been applied to various types of transition, terminal interface, and en route sector operations in several FAA facilities. Results obtained include capacity estimates, for each of the airspace sectors studied, as operated at present and at several future levels of automation. Findings are presented concerning operational separation minima and their bearing on capacity, controller perceptions of system adequacy and reliability, intersector controller negotiations for coordination, and relative significance for automation of the several parts of ATC decision-making processes. The impact of these findings for effective automation is discussed. Functional automation applications with high and with low potentials for improving capacity are indicated.					
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GLOSSARY

ATC	Air Traffic Control
ARTCC	Air Route Traffic Control Center
ARTS	Automated Radar Terminal System
ATCRBS	ATC Radar Beacon System
ATP	Air Traffic Procedures
CAS	(Airborne) Collision Avoidance System
CFCF	Center Flow Control Facility
NAS	National Airspace System
DMT	Decision Making Time
IFR	Instrument Flight Rules
INS	Inertial Navigation System
VORTAC	Collocated VHF Omnidirectional Range (VOR) and Tactical Navigation System (TACAN)
OJT	On-the-Job Training
Transponder	Airborne Component of ATCRBS
Handoff	Intersector Transfer of Control
Pointout	A Form of Intersector Coordination
Ident	Request for Identifying Response via Transponder
Silent Handoff	Handoff Using Alphanumeric Display Control in Lieu of Voice Interphone
TAS	True Airspeed
IAS	Indicated Airspeed
RECEP	Relative Capacity Estimating Process
RNAV	Area Navigation

ACKNOWLEDGMENTS

In the course of this work we spent considerable time with air traffic controllers and other FAA staff in operating facilities throughout the country. Through the cooperation and assistance of these people we were led to an understanding of the actual practice of air traffic control. Special appreciation is due the control staff of the Oakland and Chicago ARTCCs; at these facilities we conducted intensive observation/interview programs. So many controllers and other facility staff gave us their time and cooperation that space considerations preclude listing them individually here.

Finally, we are pleased to acknowledge the guidance and participation throughout this work, of Mr. Simon Justman, of FAA's Systems Research and Development Service, as our project technical monitor. Our appreciation is also extended to Mr. Robert H. Orr, of FAA's Air Traffic Service, who shared with us his knowledge and experience in ATC at a number of meetings during the project, and made time for us whenever we asked.

EXECUTIVE SUMMARY

This report documents the work of the Stanford Research Institute (SRI) under Contract Year 2 of our air traffic control (ATC) system capacity study for the Federal Aviation Administration (FAA) under Contract DOT-FA70WA-2142. The results and findings presented here focus on control operations at air traffic control centers (ARTCCs), associated with aircraft transitions between terminal area and en route flight operations. Extension of the second year's effort to ATC operations in terminal facilities--TRACONS and IFR rooms--is now in progress. A supplemental report, concentrating on measurement and analysis of approach and departure operations in the terminal facilities, will be issued at the end of the extension period.

The work during this contract year has been directed to assessing the implications of controller judgmental factors and decision processes for attainable capacity at several levels of automation. In addition to the present system, three discrete automation levels were described in sufficient detail for capacity estimation. This detail included description of operating policies and control concepts appropriate for use with various types of automation. Much of this information was not readily available and was developed within the context of the project. We have developed and exercised an analytical process for estimating the potential capacity increases attainable in a control sector with each of these levels of automation, as limited by ATC controller judgment and human decision processes. The process has been given the name RECEP, for Relative Capacity Estimating Process, and it is used with a description of the traffic levels and mix, physical characteristics, and airspace procedures associated with a particular sector or group of sectors, rather than those associated with a hypothetical or simulated environment.

RECEP consists of two parts, the first of which relates quantitative statements of sector physical configuration, traffic flow and mix, and automation application as it bears on control decision-making, 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. 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 interview using a video playback of the observed sector operations.

The results obtained in a high-altitude transitioning sector in the Oakland ARTCC, and two high-altitude transition/over sectors and a low-altitude arrival sector, all in the Chicago ARTCC, indicate that the RECEP technique provides consistent and realistic estimates and that the parameters and relationships can in fact be tested and measured. Capacity estimates for the sectors measured have been developed on the basis of these data.

Our findings to date indicate that controllers operationally use separation minima greater than those specified by ATP standards documents, tend to avoid minimum-response-time situations, use intersector voice communication for coordination negotiations, seek additional information on future traffic, and divide decision-making responsibilities flexibly within control teams. One of our most important findings, based on work so far, is that the process whereby a controller generates and evaluates alternative control actions and selects one action to be implemented is accomplished in only a small fraction of the total controller decision-making time for each ATC situation. This finding has direct implication for selection of functions to be automated; we emphasize the limited (four sectors) basis of observation for these findings at present.

Our current findings lead us to conclusions, relative to the environment studied, concerning implications of controller judgment and decision processes for effective automation. First, the automation of those decision-making functions concerned with recognizing prospective deviations from planned or desirable behavior and assessing the particulars of prospective ATC situations, has a high potential for improving sector capacity. On the other hand, little improvement in sector capacity is likely to result from automating the decision-making functions associated with generation, evaluation, and selection of control actions for a controller-in-the-loop control concept. This is because controllers spend a relatively small portion of their total decision-making time in this decision process. Since there may be other reasons for automating a function than merely to improve capacity through reduction of decision-making time, this conclusion does not by itself dictate against automation of action selection functions. Rather, it implies that justification must come from other considerations.

Except where traffic is or can be highly structured, we believe that intersector voice communication will need to be retained because handoffs and other coordination functions will continue to constitute negotiations rather than one-way information exchange. This need for intersector negotiations for traffic planning, workload management, and transfer of partial control of aircraft will constrain the potential capacity benefit of the "silent" or automated handoff in en route and transition environments. A number of other implications for automation derived from our observations and interviews to date are also presented in the report.

The RECEP technique has been demonstrated as an evaluator of automation capacity potential in en route and transition environments, and measurements in terminal airspace are underway to extend its use. Because of the structure of the RECEP process and because it relates to an actual sector or group of sectors, we believe that it may prove useful for assessment of alternative control concepts, route and sector structures, and sector operational procedures. Also because controller productivity is directly affected by changes in the capacity of a sector or other control jurisdiction, the RECEP technique appears to have utility in predicting controller productivity increases and the relationships among future traffic demand, automation environment, and controller force level. In addition, we suggest that an assessment of RECEP be made to determine its value as a quantitative measurer of control degree-of-difficulty.

I INTRODUCTION

A. Background

This report documents SRI's work for FAA under Contract DOT-FA70WA-2142 during Contract Year 2, during which effort was focused on analysis of the controller's contribution to capacity in manual and automated environments, and implications for effective automation derived from considerations of controller judgmental factors and decision processes. The results presented here are based on our findings concerning en route and transition operations within an ARTCC. A forthcoming supplement to this report will present our findings concerning arrival/departure operations at terminal facilities.

Work under the first year of this multiyear study to develop methodologies for evaluating the capacity of air traffic control systems dealt with definitions of capacity, the relationships of capacity to functional and geographical system elements, and candidate measures of system capacity. Capacity was defined in terms of aircraft movement numbers and rates as limited by a number of factors including safety and performance. A family of conceptual capacity evaluation models was defined. A decomposition concept was applied to achieve a balance between modeling fidelity and model complexity. The concept design of members of the family of models included some preliminary algorithm development. The models were structured to measure each of the potential capacity limitations associated with

- (1) System operating strategies.
- (2) Scheduling and routing.
- (3) Delays resulting from congestion.
- (4) Separation minima and control and operating procedures.
- (5) Other safety aspects as they affect aircraft movements.
- (6) Limitations on aircraft movements and induced delays associated with control operation under heavy workload conditions.

Our work in this second contract year has focused on Items (4) and (6), with emphasis on quantitative analysis of the capacity constraint associated with the human controller's judgmental factors and decision processes.

B. Scope

The effort of Contract Year 2 has centered on assessment of the potential capacity increases associated with automating particular controller functions, and on assessing the controller's contribution to and limitations on attainable operational capacity. This effort has included analysis of controller judgmental considerations and decision processes, including a limited program of measurement of controller operations and structured data-gathering interviews.

It must be emphasized that capacity limitations associated with controller judgmental factors and decision processes are only one of the several classes of human performance limitations and man/machine operational limitations that determine capacity levels. However, this class is the focus of the present work because of its central importance in making and evaluating hardware, software, and operational decisions associated with implementation of automation technology, e.g., the advanced ARTS and NAS Stage A systems. Study of the operational characteristics of these and upgraded-third- and fourth-generation system concepts has been a part of the work. In particular, the work was oriented to provide needed information on

- What parts and functions of the control process are most susceptible to automation efforts?
- Which parts of the control process will not easily yield capacity improvements as a result of automation?
- What constraints inherent in a controller's functioning are basic limitations on the movement of air traffic?

While control operations, observations, measurements, and interviews have been a part of this year's work, a large-scale program of measurements to establish statistical significance and confidence limits has not been within the scope of this year's effort.

C. Objective

The objective of this year's contract effort has been to assess the implications of controller judgmental factors and decision processes on attainable capacity at several levels of automation. In particular, we have directed our efforts to estimating the potential capacity increases realizable in a control sector with various kinds of automation, as limited by observed and measured controller judgmental factors and decision processes.

D. Organization of this Report

This report consists of two volumes, of which this is Volume I--Summary Report. The remainder of this volume is devoted to a discussion of our approach to the study, including present and prospective uses of the RECEP methodology and techniques (Section II--Basis of Findings); the quantitative and qualitative results that we have obtained to date, including capacity increase estimates for the particular sectors we have measured (Section III--Summary of Findings); and preliminary conclusions on the implications of our findings for effective automation (Section IV).

Volume II contains description and documentation of our work at a rather detailed level. The six appendices in that volume are:

Appendix A--Decision-Making and Judgment

Appendix B--Automation Levels: Control and Operating Concepts

Appendix C--Relative Capacity Estimating Process (RECEP)

Appendix D--Data Collection and Measurement Technique

Appendix E--Data Reduction and RECEP Parameter Determination

Appendix F--Analogous Systems.

II BASIS OF FINDINGS

The findings, results, and conclusions of this report are based on a series of ATC operational measurements made at the Oakland and Chicago ARTCCs. As an extension to this year's effort, these results are now being augmented and modified where necessary through a series of ATC operational measurements in terminal areas. Sectors analyzed will include representative feeder sectors, final approach sectors, and departure control sectors. Both ARTS III and conventional facilities, and operations based on extensive use of SID/STARS and radar vectoring, are planned to be studied. The results of this measurements program are to be presented in a forthcoming supplement to this report. Thus, the findings in this report are based exclusively on ARTCC operations, i.e., on control in transition and en route airspace. It should be pointed out however, that a substantial amount of the sequencing and metering activities associated with terminal control of arriving traffic is actually done in the ARTCC surrounding the terminal area; hence these activities have been objects of study.

A. Brief Description of RECEP

SRI developed an analytical process to enable a quantitative assessment of the capacity constraints associated with the human controller's judgmental and decision processes, both in manual environments and with several levels of automation. The decision-making and judgement process is considered in Appendix A; the RECEP (Relative Capacity Estimating Process) is described in detail in Appendix C.

In brief, the process uses a set of analytical models that relate, quantitatively, statements of sector physical configurations, traffic flow and mix, and automation type and extent of automation (as it bears on control decision-making functions) to frequencies of occurrence of various types of ATC events (e.g., crossing conflict, overtake, and altitude conflict). The parameters that influence frequency of occurrence that are modeled, are basic system design factors (e.g., angle between intersecting air routes, number of intersecting air routes, aircraft speeds on the air routes, and the length of the air routes). Consequently, most of the factors that are typically regarded as part of system and procedures design are used in our process and are available for manipulation and evaluation.

A second set of analytical models attaches a decision-making time (DMT) required of the controller to each ATC event. Any delay to aircraft associated with the decision is noted. The process then aggregates the DMTs required and compares this total to a threshold value to generate relative capacity estimates for each candidate ATC system automation concept.

The values for the models and validity of the relationships and the RECEP method were determined using a measurement technique that includes observations of sector operations, followed by structured controller interviews using video playback of the sector operation.

The results obtained at the Oakland and Chicago ARTCCs indicate that the technique gives consistent and realistic decision-making capacity values, and that the parameters and relationships can, in fact, be tested and measured.

In this study, we have used the RECEP technique to evaluate automation capacity potential. Because the technique requires relatively detailed specification of control and operating concepts associated with automation, it can also be used to evaluate proposed new control concepts. We believe that the RECEP technique has potential value as a quantitative and objective measurer of control degree-of-difficulty in a particular sector operating with a particular level and mix of traffic. Because controller productivity is directly affected by increases in the capacity of a sector or other control jurisdiction, the RECEP technique has utility in the context of predicting controller productivity increases. Because RECEP applies itself to a particular real sector or other control jurisdiction, rather than a hypothetical or simulated environment, we believe the technique has value for purposes of sector capacity prediction in its own right. We believe the process can be useful as well as an aid in sectorization, in route structure design (especially RNAV design), and in evaluating sector operational procedures. Finally, because the RECEP technique relates capacity, automation level, and sector manning, it can be used to evaluate the trade-offs among predicted future traffic demand level, predicted available automation level, and controller force level required or available.

B. Automation Levels

For purposes of the present study, we have identified four discrete levels of automation. These levels are described in detail in Appendix B; a synopsis of each level is presented in Table 1. We include here only a brief summary description.

Table 1

AIR TRAFFIC CONTROL AUTOMATION LEVELS

Automation Level	General Description	System Functions	System Hardware
1	Second-generation ATC Nonautomated radar control	• Unsided human decision-making • Voice communication (A/G/A and intrasystem) • Manual radar tracking • Manual update and revision of flight strips • Computer generation and distribution of flight strips	• Remote radar/beacon sensors • Broadband radar display(s) • Flight strip tabular display • Sector strip printer • VHF/UHF voice radio • Telephone, intercom (intrasystem communication) • Central computer complex (flight strip processing)
2	Third-generation ATC Mechanized tracking and flight data handling	• Beacon/radar tracking • Automated handoff • Automatic altitude report • Alphanumeric data tag • Computer-processed flight plan updates and revisions • Computer-generated display of flight data and system status	• Beacon/radar tracking • Data filter group • Alphanumeric group • Central computer (configured for automatic track, alphanumeric tag, flight plan correlation) • Plan view display • Computer readout device • Controller/computer interface: Slew ball, display filter keys, category/function selection, alphanumeric keyboard, quick-action keys
3	Upgraded third-generation ATC - Phase 1 Computer-aided decision processes	• Computer-aided metering, sequencing, spacing • Computer-generated hazard alert (e.g., conflict, deviation) • Computer-generated action recommendations • Computer-formatted control instructions • Human review of computer-recommended actions • Controller-initiated G/A communication (voice or data) • Computer-assisted intrasystem communication	• Level II hardware, end computer configured for - Metering, sequencing, spacing - Conflict detection resolution - Path surveillance • Two-way A/G/A data link • Discrete address beacon or • VHF data link • Airborne RNAV capabilities • Automatic airborne flight management • Airborne separation assurance • Airborne stationkeeping
4	Upgraded third-generation ATC - Phase II Computer-generated control actions	• Computer-generated control actions • Computer-generated clearances • Automated A/G/A information transfer • Automated conformance check • Human monitoring of automated processes, human override	• Similar to Level 3

For our purposes it is insufficient to have merely a functional description of each automation level: we must determine in some detail how each automation level will impact on the controller's decision making and judgmental processes. To do this we have had to develop and generate descriptions of the control and operating concepts and procedures appropriate to each automation level. The great bulk of this information had not been developed and compiled previously; we have developed it using a combination of discussions with FAA headquarters and field personnel, discussions with other personnel in Government and industry who have worked in particular areas of automation, and analyses based upon our own judgments and experience.

The control and operating concepts and procedures are extremely important in assessing the impact of automation on the controller, and such assessments are inherently sensitive to the assumptions made concerning how the automation functions will be used and applied in practice. Because of this sensitivity we have included extensive documentation on this part of the work (in Appendix B) so that assessment of other automation functions than those that have been considered here, or assessment of different operational concepts and procedures, can be made using the RECEP technique.

Automation Level 1 is the existing manual system with human decision making, and voice communications. Computer utilization is restricted to the preparation of flight strips.

Automation Level 2 augments the present system by the inclusion of mechanized tracking and handoff, and additional computerized flight data processing and display, but retains human decision-making and voice communications. One can make a rough equivalency of our Level 2 and the ARTS III and NAS enroute Stage A programs (when fully implemented, and when controllers have developed appropriate confidence in their use). (Note, however, that our measurements reported so far do not yet include ARTS III environments.)

Automation Level 3 consists of computer-aided decision formulation for each ATC situation, but with human review and approval or disapproval for each decision. A combination of voice and data communication are used for air/ground/air purposes. Automation Level 3 is divided into two sublevels. In Level 3a, traffic is considered to remain relatively unstructured as it occurs today, with no deliberate attempts to regularize the flow of traffic beyond flow-control measures associated with sector saturation. Handoffs would still be made in a relatively flexible way, sometimes in groups with varying physical relationships between the aircraft and over a broad sector boundary, rather than at a specific gate

point. Hence handoffs would remain a negotiated process, as they are today. Level 3b assumes the measures necessary to structure and partially regularize the flow of air traffic, in particular to obviate the need for intersector negotiations associated with handoff. Clearly there may be penalties of an economical and operational nature associated with this traffic structuring; these have not been investigated to date. With these traffic structuring measures it appears that the negotiation aspects of handoff can be eliminated and the so-called "silent" or "automated" handoff can be realized. Level 3 corresponds with the initial and later phases of the proposed upgraded third-generation system. At the time of our definition of Level 3, the description of the upgraded third-generation system was not complete, in operational terms, and hence the correspondence is approximate.

Automation Level 4 is the beginning of truly automated ATC systems. Functions include computer-generated control instructions and automatic ground-air data transmission, with the human controller operating in a "supervisory" mode with the potential capability of overriding the computer when necessary. Again we divide Level 4 into two classes. Level 4a denotes the mode of operation wherein the controller retains responsibility for aircraft separation. In this mode of operation, the movement of air traffic is still tied, or paced, to the controller's decision-making capabilities--he is still at least monitoring events having to do with individual aircraft.* Level 4b denotes a mode of operation wherein the controller is responsible for system supervision and the hypothetical handling of any special situations requiring override in this mode of operation. The flow of air traffic is no longer tied directly to the controller's decision-making processes and hence capacity estimation based on decision-making limitations is not possible. Furthermore, there are substantial uncertainties that the hypothetical override capability could be realized operationally, in view of the controller's removal from a position of "in-the-loop" control. We have not yet developed a sufficient set of operational assumptions to permit any but the most tentative sort of capacity estimation for Level 4b.

* A variety of differing views are held within the ATC community-of-interest as to what will be the eventual job of the human "controller." If he is a monitor, will he monitor aircraft? Flows on routes? System condition? How will "strategic" traffic planning functions be divided between man and machine?

C. Description of ARTCC Sectors

1. Oakland ARTCC Sector 42 (H5)

Figure 1 depicts the major air routes and principal altitudes used on each air route for the Oakland Sector 42. The major jet airways used in the sector are:

- J84 for eastward outbounds.
- The vicinity of J80 for inbounds to the San Francisco Bay area. (several STARs are built around J80 and vicinity)
- J5 for crossing traffic from Reno to Los Angeles and vice versa.
- J65 between Sacramento and Fresno.

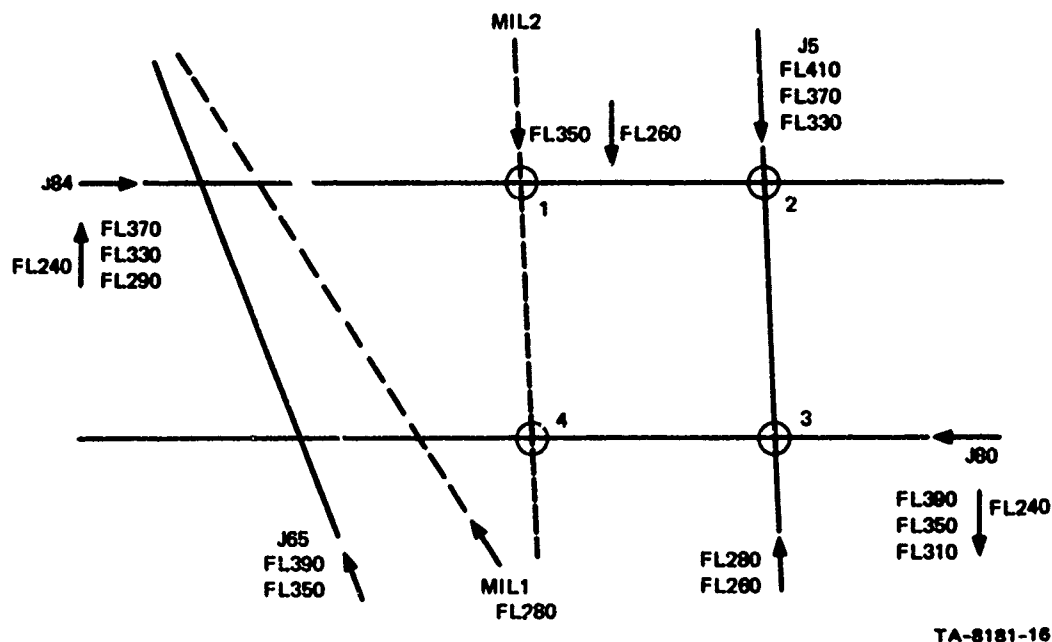


FIGURE 1 MAP OF OAKLAND ARTCC SECTOR 42 (H5): PRIMARY ROUTES, ALTITUDES, AND POTENTIAL CONFLICT POINTS

Major military air routes are indicated by the two dotted lines. The traffic on J84 enters the sector climbing to FL240 and usually continues climbing until reaching one of the three cruising altitudes of FL290,

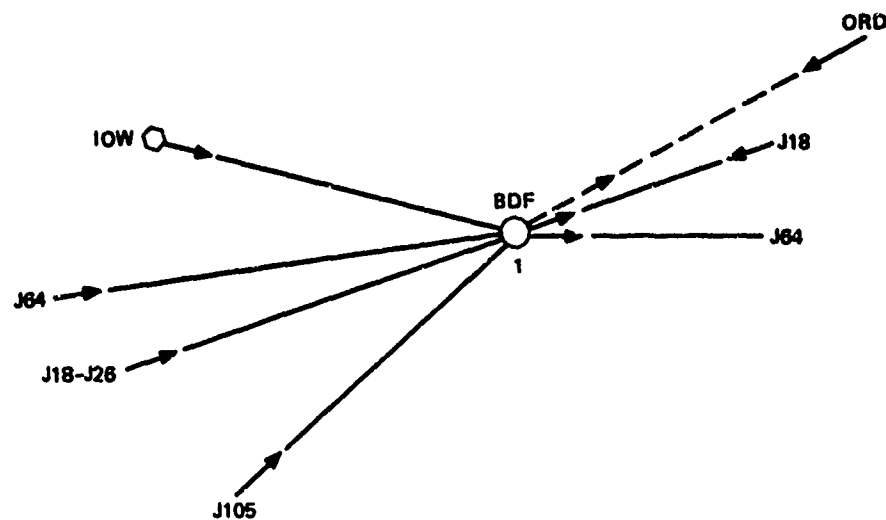
FL330, or FL 370. Since this traffic is usually below the traffic on J65 and the MIL 1 military route, there are usually no potential intersection conflicts between these routes. However, potential conflicts exist between the traffic on J84 and the military traffic on the route designated as MIL 2 as well as the traffic on J5 that is at FL330 and FL370. These potential conflict points are indicated by the circles in Figure 1. All the traffic in the vicinity of J80 going to the Bay area airports (San Francisco, Oakland, San Jose) must be descended to FL240 as well as be put in trail for final sequencing and spacing. As indicated by the circles, the J80 traffic has potential conflict points with both J5 traffic and MIL 2 traffic.

2. Chicago ARTCC Bradford High Sector

Figure 2 shows a drawing of the major air routes with the primary altitudes used on each air route for the Chicago Bradford High sector. As can be seen, the major jet airways used in the sector are:

- J64 for eastbound overs and arrivals into O'Hare.
- J18 for eastbound and westbound overs and arrivals into O'Hare.
- J105 for arrivals into O'Hare.
- IOW-BDF for eastbound overs.
- ORD-BDF for departures from O'Hare for J18.

The primary altitudes used on each of these routes are indicated in Figure 2. As can be seen, this sector has only one major potential conflict point, which is located at the Bradford (BDF) VORTAC--the point where all of the primary routes used in the sector intersect. This potential conflict point is indicated by the circle labeled 1 in Figure 2. There are potential level intersection conflicts between the traffic on J64 and J18, J64 and IOW-BDF, J18 (westbound) and the traffic merging from O'Hare, and J18 and IOW-BDF. There are potential intersection conflicts between traffic descending on J64 and travel level on J64, traffic descending on J18 and traffic level on J18, traffic climbing from O'Hare, and traffic level on J18 (westbound). There are potential conflicts between traffic descending on J64 and J18, J64 and J105, and J18 and J105. Also there are the potential overtake conflicts on nearly all the routes.



ROUTE	ALTITUDES	
	EASTBOUND	WESTBOUND
J64	FL410 FL370 FL330	
J64-BDF (ORD)	FL370 FL330	FL240
J18	FL410 FL370 FL330 FL290	FL350 FL310 FL280
J18-BDF (ORD)	FL370 FL330 FL290	FL240
J105	FL370 FL330 FL290	FL240
IOW-BDF	FL410 FL370 FL330	
ORD-BDF		FL240 FL350 FL310 FL280

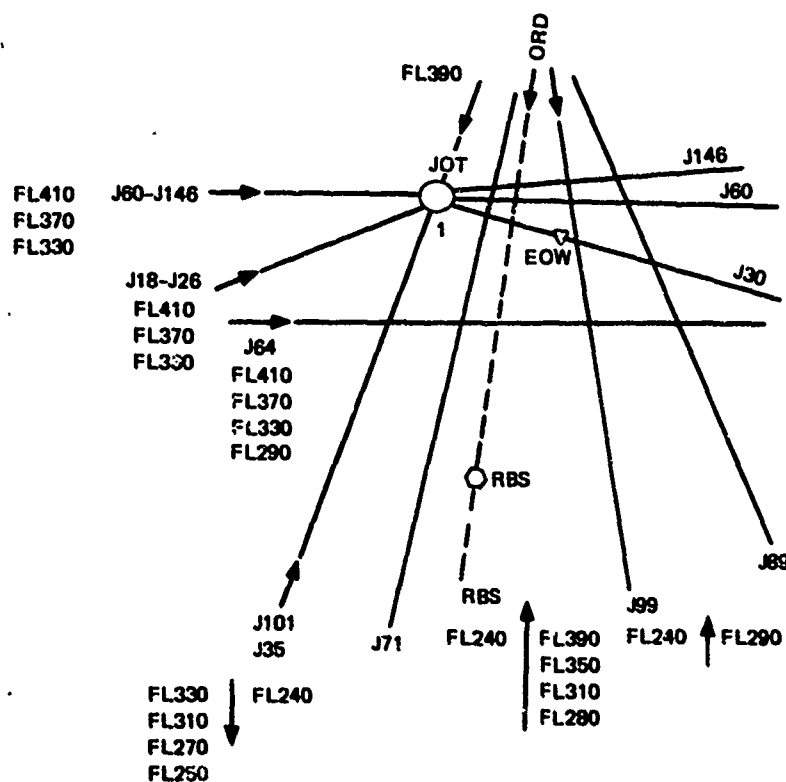
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FIGURE 2 MAP OF CHICAGO ARTCC BRADFORD HIGH SECTOR: PRIMARY ROUTES, ALTITUDES, AND POTENTIAL CONFLICT POINTS

3. Chicago ARTCC Joliet High Sector

Figure 3 shows the major air routes with the primary altitudes used on each air route for the Chicago Joliet High Sector. As can be seen, the major jet airways used in the sectors are:

- J64 for eastbounds
- J60 for eastbounds
- J18 for eastbounds
- J101 for overs and arrivals to O'Hare and Milwaukee
- ORD-RBS for departures from O'Hare (ORD)
- J99 for departures from O'Hare.



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FIGURE 3 MAP OF CHICAGO ARTCC JOLIET HIGH SECTOR: PRIMARY ROUTES, ALTITUDES, AND POTENTIAL CONFLICT POINTS

The primary altitudes used on each of these routes are shown in Figure 3. As can be seen, this sector has only one major potential conflict point. This point is located at the Joliet (JOT) fix, which is the point where J60, J18, and J101 intersect and is indicated by the circle labeled 1 in the Figure. The only potential intersection conflict at this point (1) is between the traffic at FL410, FL370, and FL330 on J60 and J18. There are potential overtake conflicts on nearly all of the routes.

4. Chicago ARTCC Papi Arrival Sector

Figure 4 shows the major air routes with the primary altitudes used on each air route for the Chicago Papi Arrival Sector. As can be seen, the major jet airway used in the sector is J94/V84 for inbound from the east into O'Hare.

The aircraft enter the sector at altitudes between FL200 and FL300 and are handed off to approach control at 10,000 ft. Since there are no major intersecting routes, there are no significant conflict points of this type. Since most sequencing for final approach has been accomplished in the preceding sector, the only type of conflicts in this section are the potential overtakes during descent.

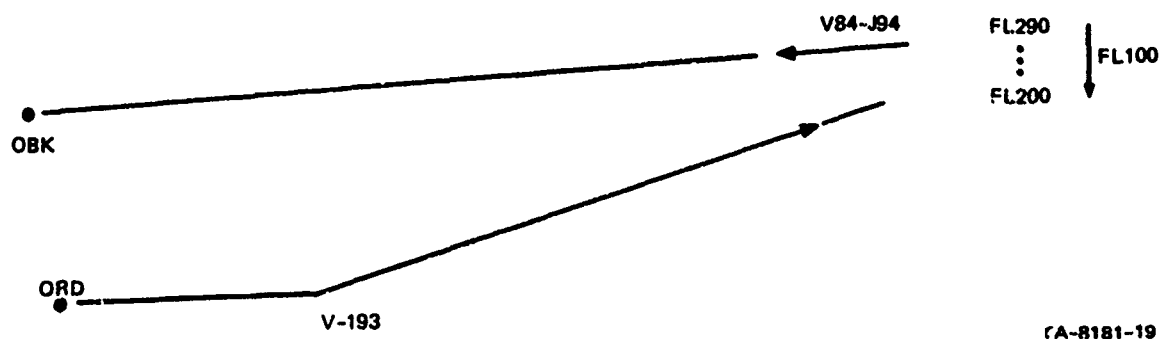


FIGURE 4 MAP OF CHICAGO ARTCC PAPI ARRIVAL SECTOR: PRIMARY ROUTES AND ALTITUDES

III SUMMARY OF FINDINGS

A. Judgmental Factors

The following paragraphs summarize our observations and measurements related to judgmental factors, as we have found them in the Oakland and Chicago ARTCCs. The operations we have examined are believed to be representative of ATC in the various transition and en route environments of the United States, with the qualification that we have not examined low-altitude en route operations in detail except in the vicinity of terminal areas.

1. Aircraft Separation

In complex sectors that have several potential conflict points or areas, controllers seldom allow separations between aircraft at or near air traffic procedure minima. In particular, controllers tend to maintain or increase separations whenever it appears to them that separation may decrease below 10 to 20 miles if they take no action (operations are at the lower end of this range at Chicago). This "effective" separation minimum is obviously at variance with the ATC-specified minima of 3 or 5 miles under radar control.

If controllers in these types of sectors were persuaded to use less separation (i.e., to allow aircraft separations to approach ATP minima), fewer potential conflict situations would require intervention, because many of the situations in which controllers now intervene are well above ATP minima. There are two apparent reasons that the controller in such sectors sets greater separation minima than ATPs allow:

- The ATP minima are perceived as too small to allow effective control action in the event of an unforeseen speed or heading change.
- Controllers retain sufficient doubt of the accuracy and adequacy of the plan position information available to induce them to add their own "margin for error" to extrapolations based on this information.

It is reasonable to ask what capacity payoff would be gained by taking steps to reduce "actual" minimum separations (e.g., installing new equipment, introducing different training). Using the RECEP technique to examine the sensitivity of decision-making time requirements to actual separation minima, we find that at best only a minimal capacity benefit would result. The reasoning is as follows: Decreasing minimum separation would reduce the frequency of occurrence of conflict situations in which the controller feels compelled to intervene. However, the potential conflict-related decision-making load is only a part of the total decision-making load--a decreasing part as the level of automation increases. Hence, the reduction in total DMT is less than proportional. Typically, for a decrease in minima from 10 to 5 miles, the potential capacity increase is on the order of 5 percent. To see how insignificant this is, observe that adherence to smaller separations may have the additional effect of causing the controller to spend additional time on traffic structuring and planning. An increase of only 2 seconds or so per aircraft spent on traffic planning would cancel out the decision-time reduction associated with the reduction in potential conflicts.

The traffic observations made have so far been based on ATCRBS displays. We were able to measure separations with varying geometries of route direction with respect to radar beacon transmitter location; we were able to measure both radial and tangential orientations. The 10- to 20-mile separation quoted above refers to separation between nearest portions of adjacent beacon slashes, not between their centers. Both in-trail and crossing situations are included in this finding.

We emphasize that this finding refers to particular types of sectors and that the separation situation is entirely different in sectors without significant aircraft speed-adjusting problems or potential crossing conflicts (e.g., those that act as terminal feeders for an airport, or on final approach or departure paths). There, separations at or near ATP minima are regularly used; in the Papi low sector of Chicago ARTCC, for example, five- to six-mile separations are common.

2. Response Times

In the operational situations we have measured so far, we have observed that controllers actively avoid situations where minimum response times, either between pilot and controller or between controllers, would be required. Because of the operational techniques by which such situations are avoided, a few seconds are rarely critical in ATC operations (with the obvious exception of emergency situations).

3. Intersector Communication

The controllers we interviewed perceived benefits of using intersector voice communication, as opposed to data/display communication between sectors. The SRI team came to appreciate these perceptions and to realize that intersector communication often constitutes a process of negotiation between controllers regarding traffic management and planning. In addition controllers use intersector voice communication to sense workload levels in adjacent sectors.

4. Communication Mode

For normal operations, controllers perceive no similar benefit of air/ground/air voice communication over a data link mode of communication. In our work to date we have made no formal measurement contact with aircraft flight crews; hence, this finding refers specifically to the perceptions of the controllers. Neither has any attempt been made to evaluate the utility or desirability of retaining voice air/ground/air communication to maintain the "party line" effect wherein all aircraft operating within a sector use the same radio frequency and monitor each other's instructions and responses. Furthermore, only air carrier, military, and high-performance general aviation aircraft were present in the operations measured. This conclusion excludes emergency and other unusual situations that are so rare that they influence routine traffic control (and hence capacity) only indirectly through the controller's perceptions of such rare events, which we account for in his perceived responsibility.

5. Short-Term Traffic Planning

Information on future traffic (targets yet to be handed off) is used extensively for on-line traffic structuring. This is manifested by controllers "reaching out" for handoffs (i.e., calling adjacent sectors to request earlier-than-planned handoffs to their sectors or to request information on this future traffic). This sort of information need appears to be associated with the way controllers manage their sectors based on prospective workload. Where radar displays do not cover a large enough area around a sector, controllers develop other schemes to get at least some planning information.

6. Division of Responsibility

The division of decision-making responsibilities between radar and handoff controllers is fluid. The Oakland ARTCC uses a three-man configuration for the busier sectors. The three are the radar controller, the manual controller, and the handoff controller. In this type of team operation, the manual controller has certain data and backup functions and certain off-line and peripheral duties in support of sector operations. The handoff and radar controllers collectively make the on-line traffic decisions associated with traffic management, planning, and control. In this type of operation many of the decisions, especially those associated with traffic planning and management, can be made by either the handoff or radar controller, depending on relative proficiency, traffic load, type of situation, and opportunity.

In Chicago Center most of the sectors we observed are nominally three-man sectors, with duties roughly corresponding to those in Oakland; in practice, manning is accomplished by a two-man configuration (a radar controller and a manual controller with some handoff duties) supplemented by a shared coordinator. As in Oakland, decision-making responsibilities are shared.

This fluid sharing of decision-making responsibilities enhances the flexibility and adaptivity of the controllers to respond to extra-heavy traffic peaks.

7. Contributions to Decision-Making Time

The parts of the decision process occupying most of the decision-making time are associated with deviation recognition and situation assessment. The action selection phase is accomplished in a small fraction of the total DMT.

In our work we have considered the ATC decision processes to consist of three parts. The first part is deviation recognition, wherein the controller perceives that some situation is developing in a manner other than planned or desirable. The second part of the decision process is situation assessment, wherein the controller evaluates the extent of the prospective unplanned or undesirable behavior. A collective example of these two parts of the decision process is the conflict prediction function. The final part of an ATC decision starts as the controller defines and considers alternative actions to resolve or avoid the assessed situation. This part of the decision process continues through the evaluation of the alternatives and the selection of an appropriate action.

We term this phase action selection. The action selection phase, although it is very complex is accomplished in a small fraction of the total DMT, simply because the controller has a detailed and explicit perception of the current and prospective spacial and temporal traffic situation. Controllers call this perception "having the picture;" it appears that along with having the picture comes an ability to select an appropriate action quickly, once the traffic situation has been appropriately assessed. (This finding applies principally to journeyman controllers.)

8. Consistency Among Journeyman Controllers

There is a strong observed consistency in the essentials of control technique among journeyman controllers. One might expect to find at least several "good" ways to control traffic. Our observations indicate different controllers pursued similar courses of action in similar situations. This is not to say that these actions were all based on the same reasoning or objective, merely that actions in support of these objectives were similar. We note that all journeyman controllers operating a particular area of airspace in an FAA facility are trained and checked out by controllers who are themselves qualified for that area. Thus, consistency may be an outgrowth of the on-the-job training process.

9. Differences Between Journeyman and Developmental Controllers

There is an equally clear observable difference in control technique between developmental and journeyman controllers. Because on-the-job training is a routine and continuing part of center ATC operations, we observed many developmental controllers as well as journeyman. The simplest way to describe the difference between these groups in terms of their control technique is that developmentals generally show a "wait and see" attitude in their control. They are hesitant to intervene in a developing traffic situation until it is quite clear to them that intervention will be necessary. They appear loath to exert a heavy-handed influence on the traffic they control. The actions of the journeyman controller, on the other hand, can perhaps be viewed as a continuing attempt to guard against the future by immediate actions. The journeyman controller knows that within moments his attention may be diverted by another traffic situation, an emergency, or some other priority workload. He will invariably protect himself against future diversion of attention by taking some action in an emerging situation as soon as practicable, rather than waiting to see if that action would ultimately be required. His actions usually take the form of short or interim clearances (especially in altitude), which he fully intends to remove

before an aircraft reaches its clearance limit. However, should his attention be diverted, safety is "automatically" ensured. This difference in control technique between developmentals and journeymen is exemplified in the OJT process, where it appears that the predominant amount of instruction time is spent in converting the developmental's control technique to that of the journeyman.

It seems clear that there is an intimate relationship between the judgmental factors we have observed and the process of controller training. The judgmental factors are in some measure instilled in this process, especially the OJT part of it. The implication here is, of course, that a training program so constituted to encourage development of the desirable judgmental factors will accompany an effective automation program.

10. Reduction of Potential Crossing Conflict Points

The principal method employed to increase sector capacity to meet demand in transition and en route sectors appears to be the reduction of potential crossing conflict points. This finding derives from our observations of 25 percent greater capacity in sectors with only one such point when compared with those having three or four. Manning on the higher-capacity sectors is no greater (in fact slightly less), traffic mix is similar, and decision-making time capacity thresholds are similar. Yet, we have found that controllers move more traffic with the same level of DMT by restructuring routes and airspace procedures to remove potential conflict points. Some decrease in flexibility of the ATC system is associated with this sort of capacity increase; some penalty to users may occur. It would appear that where these measures have been employed, the benefits to users of increased capacity have outweighed possible drawbacks of decreased flexibility.

11. Balancing of Workloads

A goal of sectorization efforts, to balance workload among sectors within facilities, correlates closely with the balance of decision-making time requirements among sectors in a facility. This finding is based on our operations measurements in three Chicago ARTCC sectors. Although, among these sectors, there are substantial differences in sector physical and traffic characteristics, the operational sector capacities are nearly identical. Of more significance is the finding that DMT requirements are also essentially identical at these capacity values. One would expect that controller workloads in general would be similar

within a facility, since this is one objective of sectorization efforts. The similar capacities seem to imply that (at least in transition and en route airspace we have studied) the relationship between controller workload and capacity can be made fairly independent of route configuration and traffic characteristics by suitably optimizing these characteristics through redesign of airspace procedures. Optimization can be pursued by building into the airspace the appropriate number of conflict points, and by selecting sector boundaries to yield the appropriate number, kind, and lengths, of route segments. Again, we note that the increased capacity is obtained (assuming the same manning) in nonautomated systems, at the price of less flexibility for users and perhaps some penalties in added route length and nonoptimum vertical profiles.

Our measurement of DMT at capacity indicated that the limiting DMT was the same among the three measured sectors of Chicago ARTCC, providing evidence in support of the contention that RECEP gives a reasonable measure of degree of difficulty in control operations.

12. Differences Between ARTCCs

The sectors measured in Chicago have higher capacities than the one measured in Oakland because airspace procedures in Chicago have been designed to eliminate most potential crossing conflict points. We found that DMT values at capacity are the same among all the measured sectors. Similarly, manning was not substantially different, nor were sector flight times. The major difference appears to be that there are four potential crossing conflict points in Oakland sector 42, and at most one in any of the measured Chicago sectors.

B. Effects of Judgmental Factors on Capacity

During the course of this study we investigated the significance of a number of controller judgmental factors for present capacity. The objective of this part of the work was to identify which factors now constrain operational capacity. The impact of such constraints could well be to limit the potential payoff of automation of functions related to these factors--i.e., automating the mechanics of some ATC function is not likely to increase capacity if in fact performance of that function is limited explicitly by the controller's judgment rather than by other factors. Of the five judgmental factors we investigated, we found two of them active in current ATC operations in the Oakland and Chicago sectors that we observed. The five judgmental factors investigated are described below.

Perceived responsibility actively limits the movement of traffic.

Based on the evidence that increased separations are used in many sectors and the judgmental considerations articulated by controllers in our structured interviews, it appears that the controller's perception of his own responsibilities in the ATC system exerts a more stringent constraining force on ATC sector capacity than the limits imposed by formal ATPs and separation minima. Because this use of increased separations appears directly associated with perceived inability to assess ATC situations precisely in their early stages of development, the limits imposed by this judgmental factor may be relaxed where situation assessment functions are automated, and where the controller grows to develop confidence in this automation.

Perceived system adequacy actively limits capacity in the present system. Based on the controllers' deliberate avoidance of short-response-time requirements, and the efforts they expend to sense the workload and responsiveness of other controllers and pilots, we conclude that controllers limit the flow of air traffic to compensate for the possibility of inadequate or delayed responses from other controllers and pilots, and from possible inaccuracy and inadequacy of control information received, both by radar display and voice communication links. The controller in today's system is quite close, in an interactive sense, to the interface with the rest of the system. He understands, compensates for, and lives with the weaknesses he perceives in that system. It should be made explicit that a similar level of interactivity, understanding, and confidence will be needed in order to realize the potential capacity increases of an automated system. This, of course, will happen over a period of time as a "learning" or "break-in" phase. This time period may well be measured in years; experience now being acquired in ARTS III operations will provide some information in this regard.

Perceived system reliability does not currently limit sector capacity.

We distinguish here between two different kinds of perceptions of reliability. First is the perceived likelihood that a momentary dysfunction or outage will occur in some piece of equipment (e.g., radio transmitter or receiver trouble, radar azimuth shift, loss of video map, or loss of beacon video). For considerations of perceived system adequacy the controller avoids requirements for short response times. This insulates him from the untoward effects of such momentary outages (by momentary we denote time periods of from a few seconds to a minute or two). It is not yet known how far one can generalize this finding made on the basis of Chicago and Oakland ARTCC sectors observed. We will address this question during our forthcoming measurements of terminal area airspace operations.

The second kind of reliability perception has to do with judgments about the long-term performance assurance of the equipment, i.e., the likelihood that radio communication, radar, or the like will be lost in a sector for a period of time that is long with respect to that sector's flight time. We found no evidence that controllers' perceptions of longer-term system outage possibilities have a bearing on the rate at which they move traffic. Rather, they deem adequate the equipment and procedural backups available to them. It is not clear to the SRI project team that this degree of confidence is warranted in all cases. Although many controllers interviewed articulated recollections of extensive system outages of substantial duration, they also recalled handling the resultant problems on an ad hoc basis. We have found no evidence that these perceptions influence control capacity in any direct way. It is possible that this judgmental factor may be "inactive" because it is perceived to be subsumed by some other factor.

The degree to which the controller expects his actions to be visible to other people in the system does not effect sector capacity. While one might expect that a controller would operate differently depending on who was watching him (e.g., team supervisors, peer controllers, pilots, other observers), we found no evidence of this. Perceptions that video and audio recordings are made and retained have a similar lack of impact. As articulated in our structured interviews, controllers have high confidence in the propriety and correctness of each of their individual actions. They appear to have no need to tailor their actions to meet the expectation of observers. One reason why observation by area supervisors does not appear to affect capacity may be that area team supervisors are themselves qualified controllers and each controller knows that his supervisor has had similar experience.

The latitude of reasonable decision objectives and control actions does not constrain capacity in the present system. One might expect to find that a wide variety of control actions could be considered in each situation and that a significant latitude exists for judgment and selection of such action. In fact this is not the case; there is a remarkable consistency in control technique and control action selection among journeyman controllers, and there appear to be very few viable alternative actions possible in each individual situation. For example, it might appear that to resolve some potential transitioning conflict between aircraft, one might resort to short altitude clearance (profile interruption), speed reduction, vectors for spacing, 360° turns to one or both of the aircraft involved, or some other action. In practice, in each particular situation one or two of these alternative actions are,

to the controller, "obviously" the only viable one(s). That the controller has an implicit understanding of those one or two actions appropriate in each situation is borne out by the facility and rapidity with which he completes the action selection phase of his decisions.

C. Potential Capacity Increases

The RECEP estimates of potential capacity increase (referenced to Level 1) are shown in Table 2. Concomitant increases in productivity

Table 2

POTENTIAL INCREASES IN CAPACITY

Sector	Potential Capacity Increase by Automation Level					
	1	2	3a	3b	4a	4b
Oakland Sector 42	1.00	1.10	1.40-1.50*	1.80-2.00*	2.00	†
Chicago Bradford	1.00	1.10	1.20-1.25	1.65-1.75	1.75	†
Chicago Joliet	1.00	1.10	1.15-1.20	1.55-1.65	1.65	†
Chicago Papi	1.00	1.10	1.20	1.60	1.60	†

* These values are somewhat higher than those stated for this sector in our preliminary report. This results from adjustments and modifications to the RECEP logic, based on additional work.

† Will be higher than for Level 4a, but cannot be estimated at this time.

will accompany increases in capacity. For Level 2, an increase in overall productivity of 10 percent (entirely due to the increase in capacity) is seen. For Level 3, the increase in productivity can be expected to be about 25 percent higher than the increase in capacity due to possibilities for somewhat reduced manning. No estimate has been made of Level 4 productivity increases.

The RECEP technique also enables the identification of the particular functions principally responsible for the capacity increases that we have predicted: For Level 2 the capacity increase predicted is associated with

the use of the alphanumeric tag and associated data, particularly the current-altitude display. The conflict alert indication and computer-aided traffic structuring, sequencing, and metering assistance to the situation assessment function are responsible for the capacity increase predicted for Level 3a. The additional capacity associated with Level 3b comes from realizing effective mechanization of handoffs, and the associated modification of airspace and traffic structure and procedures. Level 4a is essentially that of Level 3b, as it is actually operated, and as pointed out, the system operating policy of Level 4b is inherently different--the controller's function and mode of operation has been changed.

Differences between sectors in the potential capacity increases associated with each level of automation are due to differences in sector physical and traffic characteristics, and airspace procedures in use. These differences result in different proportions of the various DMT elements in each sector, and hence automation can be expected to affect different sectors differently. The implications of these differences are discussed in our findings and conclusions.

D. Sector Decision-Making Time Requirements

1. General

Based on our observations, interviews, and other project work under this contract year's effort, the various ATC events requiring decision-making on the part of the controller were defined. This information is presented in detail as part of the automation levels description given in Appendix B. For purposes of generating decision-making-time (DMT) curves, the ATC events requiring controller decision-making are classified as follows:

- Handoff events
- Pointout* events
- Coordination events
- Potential conflict events
- Pilot request events
- Traffic structuring and workload management events.

* A Pointout is a form of intersector coordination whereby one sector controls an aircraft that is briefly in or near another's airspace. Pointouts are negotiated on a case-by-case basis.

The first five event classifications are the generic types usually found throughout the ATC system. The last event type aggregates all of the other events (such as traffic planning, establishing priorities, performing surveillance, and establishing flow organization) that are performed by the controller in trying to structure and manage the traffic flow so that the workload is somewhat leveled out in time.

The expressions used to determine the expected number of each of the event types are given in Appendix C as a part of RECEP. To determine these values as well as the values for the parameters in these expressions, data were collected in four sectors of the Oakland and Chicago ARTCCs.

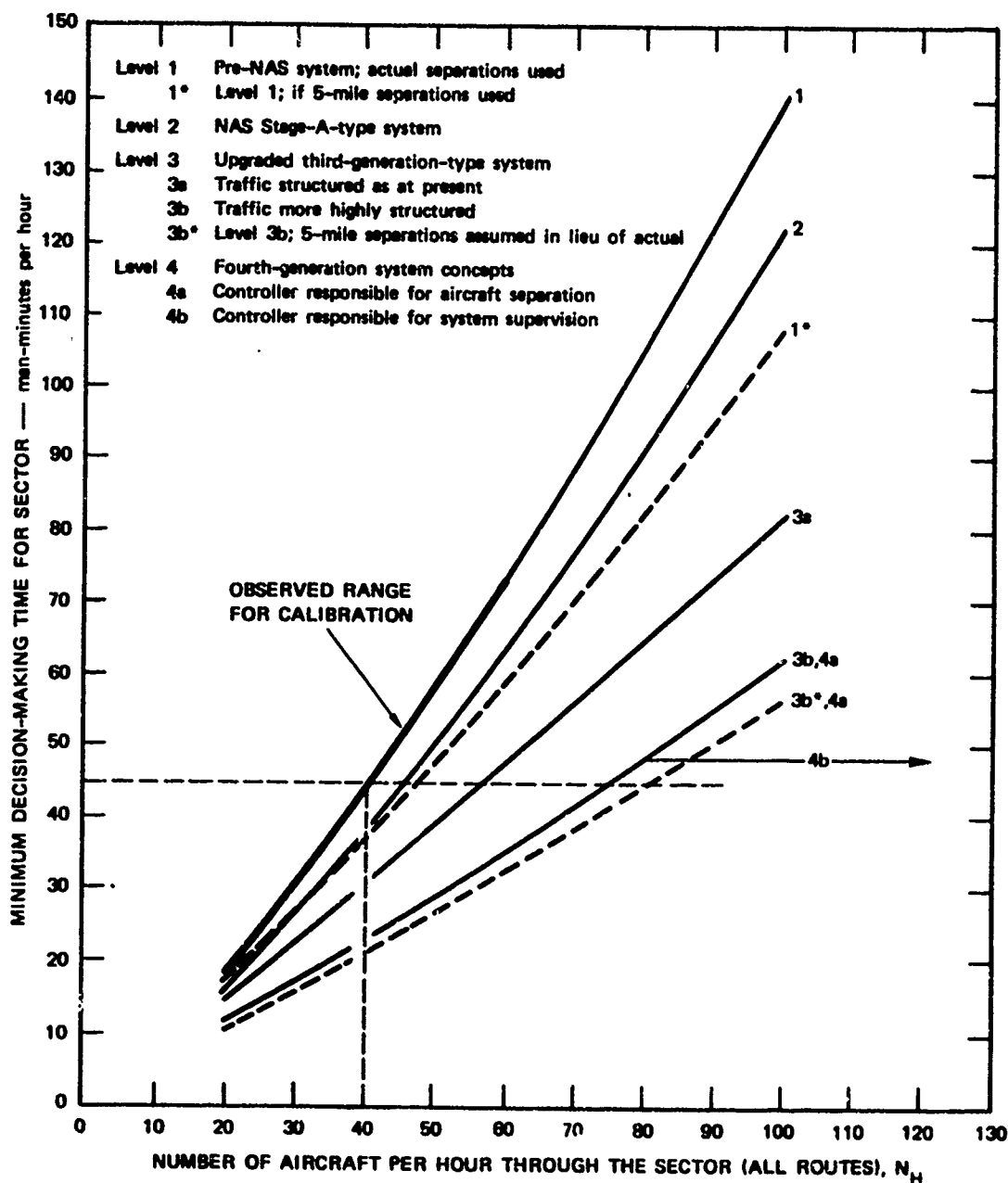
RECEP, with the parameters described in Appendix E, was used to generate the curves of total decision-making time required versus number of aircraft per hour through the sector, for each system automation level, for each of the sectors observed. A summary of how these curves were generated appears below. As noted, the sectors where observations and measurements were made are Sector 42 of the Oakland ARTCC and the Bradford High, Joliet High, and Papi arrival sectors of the Chicago ARTCC; these sectors are described in Section II-C. The various automation levels considered in generating these curves are described in detail in Appendix B and summarized in Table 1.

2. Oakland ARTCC Sector 42

In generating the curves for each of the sectors,^{*} the following assumptions are made. For Level 2 and Level 3 systems, it is assumed that the same intimate man/machine relationships exist as in the existing Level 1 system. This means that the Level 2 and Level 3 systems are operating in the "steady-state" condition; that the transitional learning periods are over, and the system and man are well integrated. Also, it is assumed that the controller's perceptions regarding the five postulated judgmental factors presented in Section II-C are basically the same.

Figure 5 shows the minimum decision-making-time curves for the Oakland ARTCC Sector 42. The Level 1 curve was calibrated with observed data collected at the center.

* This technique is described here in the context of Oakland Sector 42 and applied to the other sectors in the subsequent subsections.



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FIGURE 5 DECISION-MAKING TIME REQUIREMENTS FOR OAKLAND ARTCC SECTOR 42

The data collected on Sector 42 were reduced and are presented in Tables E-1 through E-15 in Appendix E. Table E-1 gives the breakdown of the percentage of each aircraft type (e.g., military, air carrier, high-performance general aviation) observed during the data collection effort. Table E-2 shows the observed distribution of aircraft on the different sector routes, and Tables E-3 through E-6 show the primary altitude distribution of the aircraft that were observed on J84, J80, J5, and J65 respectively. The values from these tables, Tables E-3 through E-6 were used to distribute traffic for various assumed values of aggregate sector flow in aircraft/hour, denoted N_H .

The traffic distributed along the routes in the sector for each assumed value of N_H was used to determine the expected number of potential conflicts for each of the trouble spots indicated in Figure 1. Point 2, as mentioned above, is the potential intersection of the traffic on J84 and J5 at FL330 and FL370. The traffic flow information for each N_H obtained as outlined above, along with the speed distribution on the routes taken from observed data (see Tables E-7 and E-9) was used with the expression for the expected number of conflicts at an intersection of two air routes (E_{CA}), given in Eq. (C-1) of Appendix C, to determine the number of potential conflicts expected at the intersection of J84 and J5. Point 3 is the potential intersection of the traffic in the vicinity of J80 descending to FL240 through the traffic that is level on J5. The number of potential conflicts per hour for Point 3 was determined from the traffic flow information for each N_H , the speed distribution on these routes (see Tables E-8 and E-9) and the expression for the expected number of conflicts at an intersection of a transitioning route and a level route (E_{CB}), given in Eq. (C-2) of Appendix C. Points 1 and 4 are similar in that they both involve the potential conflict of two transitioning routes: Point 1 is the result of the intersection of the climbing traffic on J84 and the descending traffic on MIL 2, Point 4 is the intersection of traffic descending on MIL 2 and traffic descending on J80. Similarly, the number of potential conflicts expected at these two points was determined from the traffic flow information for each N_H , the observed speed distribution on these routes (see Tables E-7 through E-8) and the expression for the expected number of conflicts at an intersection of two transitioning routes (E_{CC}), given in Eq. (C-3) of Appendix C. Typical climb/descent profiles for the aircraft types in this sector were obtained from Ref. 1.

The potential number of overtakes involving aircraft climbing on J84 was determined using the traffic flows for each N_H and the speed distribution information, from this route, in the expected number of potential overtakes (E_O) given in Eq. (C-4) of Appendix C. Similarly the number of potential overtakes were determined for traffic descending on J80.

A value for the separation minimum is required in using the expressions for the expected number of conflicts per type of intersection and the expected number of overtakes. From our observations, the typical minimum separation used at Point 2 was 20 miles; the typical minimum separation was observed to be 10 miles for the other three points and the overtakes.

These minimum separation values were used in calculating the Level 1 curve. The values obtained for E_{CA} , E_{CB} , E_{CC} , and E_O for Level 1 in Oakland Sector 42 were verified as reasonable by comparing them with actual counts from the observed data. By using composite techniques (i.e., using actual data where traffic on a particular route was comparable to that distributed in the manner outlined above) verification was obtained for N_H up to 60. It should be emphasized that this verification was not performed with a statistical confidence, because there was no obvious way to control most of the parameters being measured in the limited live-data collection effort.

As discussed in Appendix C, the expected number of pointout (E_{NS}), coordination (E_{SC}), handoff (E_{HO}), and traffic structuring and workload management (E_{TS}) events are expressed as a function of the number of aircraft through the sector during the time period of interest. The expressions used for these events are given in Eqs. (C-6) through (C-9) in Appendix C. The values for the parameters used in the expressions were obtained from the data collected at the Oakland ARTCC and are given in Table E-10 of Appendix E. Using these expressions along with the N_H values assumed for the sector, resulted in the values for E_{NS} , E_{SC} , E_{HO} and E_{TS} . (Note that because the number of pilots' requests were small compared to the other events, they were not included in the generation of these curves.)

Hence, these values, along with those previously determined for the potential conflict situations, constituted the events requiring a decision on the part of the controller. The minimum DMTs for each of these event types for the Level 1 system were obtained from the data collection and the controller interviews and are presented in Table 3 at the end of this section. Discussions of how these values were determined are presented in Appendices D and E.

From these event values and the event decision-making times, the total DMT for each of the N_H values was determined for the Level 1 system and provided the data for the Level 1 curve in Figure 5.

Curve 1^{*} in Figure 5 was generated in the same manner as the Level 1 curve except that the 5-mile minimum separation was used in the

calculation of all expected potential conflict events. In other words, this curve represents what could be expected if the controllers used 5-mile minimum separation instead of the 10 to 20 miles actually used without suffering an increase in any of the other type of events. Use of reduced separations would probably result in some increased traffic structuring work, quite possibly negating the small potential capacity increase.

Level 2 curve in Figure 5 was generated for Oakland Sector 42 using the following rationale. The Level 2 system as described in Appendix B is similar to Level 1 in terms of the decisions required of the controller: The human controller still has full responsibility for making and implementing ATC decision; the computer provides assistance in the organization and presentation of information. The important information with regard to decision making provided by the computer is the alphanumeric (A/N) tag with the associated altitude information and the availability of aircraft speed information. From our observation of controllers in action, extensive controller interviews, and the tables in Appendix B that describe in detail how the assumed system functions and operational policies will affect controller decisions, we were able to predict how these factors will affect the decision time associated with the Level 1 system, as follows:

For a potential overtake or crossing conflict, because of the lack of up-to-date altitude or speed information on the aircraft, the controller often must wait during the decision-making period for one or more scans of the display strobe for information update (situation assessment as to whether an actual-three-dimensional conflict is imminent) before completing his decision-making. Hence, with the availability of the up-to-date aircraft altitude information and with the immediate accessibility of accurate speed information, the decision associated with accurate situation assessment time will be reduced by at least one strobe scan, i.e., a potential conflict (in three dimensions) will be predictable sooner. Since there are 6 scans per minute in en route radar/beacon systems, the reduction for these types of events was assumed to be a minimum of 10 seconds.

Also, on the average, one of the traffic structuring and workload management events was an altitude request from the controller. With the availability of the accurate altitude information with the A/N tag, the average number of these type of events per aircraft can be reduced from 6 to 5. Hence, Table 3 shows the events and decision times used to generate the curve for the Level 2 system.

The Level 3 curves in Figure 5 were generated using the following rationale: Although the Level 3 system as described in Appendix B will be significantly more automated than the previous two systems, the controller will still be in control of each aircraft, directly, and will be pacing the flow of the traffic. The changes in the controller's decision time and function will result mostly from the conflict alert indication and the computer assisted spacing, metering, and sequencing. These will affect the decision times in the following manner.

Because of the lack of precise information on aircraft, the inaccuracy of unaided human prediction capability, and the like, the major portion of the decision time for potential crossing or overtake conflicts was taken up by the controller trying to assess if these potential conflicts would really occur if no action was taken. In terms of the decision model presented in Appendix A, these steps coincide with the deviation recognition and situation assessment phases of the decision process. When these two phases of the decision process had been completed, the action selection part was accomplished very quickly. (These controller factors are discussed in more detail in Section III-B.) Hence, with the assistance of the computer in conflict alert indication, the majority of the decision time for this type of event will no longer be required of the controller. Most of the controller's time then will be spent in reviewing the computer-generated recommended actions to determine if they are "reasonable." Since this (action selection) phase of the decision process takes a short time and since there are not many alternative solutions for the various potential conflicts, this should be possible within about ten seconds, based on our measurements.

Although much of the traffic structuring and workload management functions will be performed by the computer (see Appendix B), the controller must spend some time reviewing the recommended actions. This means that he must continue to function much as he now does to determine the adequacy of the recommended actions. Hence, it can be argued that there will be no significant reduction in the time required for these types of decisions. As a first approach, we assume this. For the other types of events, we assume that there are two Level 3 systems, 3a and 3b. Level 3a is as described in Appendix B except that the traffic in some areas is still sufficiently unstructured such that intersector voice communication is still required between controllers for coordination. Hence, pointouts, coordination, and handoffs will be handled basically as in Level 2. Level 3b then would be the system where the traffic is sufficiently structured such that no voice coordination would be required between controllers. Hence, the complete automated handoff would also be operable and the only time required would be the amount of time associated with the controller's decision concerning acknowledgement of each handoff and other required duties for this function.

Table 3 shows the events and decision times related to Level 3a and 3b systems respectively that were used to generate the curves in Figure 5.

Table 3

DECISION-MAKING-TIME REQUIREMENTS
WITH VARIOUS AUTOMATION LEVELS

Event	Minimum Decision Time per Event			
	1	2	3a	3 b/4a
Potential conflict*	1 min	50 s	10 s	10 s
Handoff	6 s	6 s	6 s	3 s
Pointout	12 s	12 s	12 s	--
Coordination [†]	6 s	6 s	6 s	--
Pilot request	5 s	5 s	5 s	--
Traffic structuring, workload management	5 s	5 s	5 s	5 s

* Intersection of level/level, transition/level, transitioning/transitioning.

[†] Exchange of information.

Curve 3b* in Figure 5 was generated in the same manner as the Level 3b curve, except that the 5-mile minimum separation was used in the calculation of all expected potential conflict events.

As discussed in Appendix B, the Level 4 system would evolve from a Level 3b system. The only postulated difference between the Level 4 and Level 3b would be the operating policy of the system. Although the computer is used to perform many of the functions in the Level 3 system, it still assists, enhances, or augments the man. The man still "paces" the system, i.e., the system operates only as fast as the man can perform his required decision functions in support of traffic movements. In the fully operative Level 4 system, the man would have obtained sufficient confidence in the adequacy and the reliability of the system so that he would primarily supervise and perform any functions that are rarely

required and that cannot be performed by the system. Since we see this role of the controller evolving from the Level 3b system, we postulate two Level 4 systems: Level 4a and Level 4b. The Level 4a curve is the same as for Level 3b. The Level 4b curve cannot be generated by this particular procedure since (by the system operating policy) the man's decision-making limitations are no longer the determinants of system capacity.

3. Chicago ARTCC Bradford High Sector

Figure 6 shows the minimum DMT curves for the Chicago Bradford High Sector. The first curve in the Figure is for the Level 1 system and was generated from data collected at the sector. These data were reduced and are presented in Tables E-16 through E-22 in Appendix E.

Using the same approach as previously presented for the Oakland ARTCC Sector 42, the total DMT requirements curves for each system level were generated. From our observations the typical minimum separations used at the one potential conflict point and for the potential overtake events was 10 miles. These minimum separation values were used in the calculations for the Level 1 curve.

The starred curves were also generated in the same manner as for the Oakland Sector using the 5-mile minimum for all potential conflict event calculations.

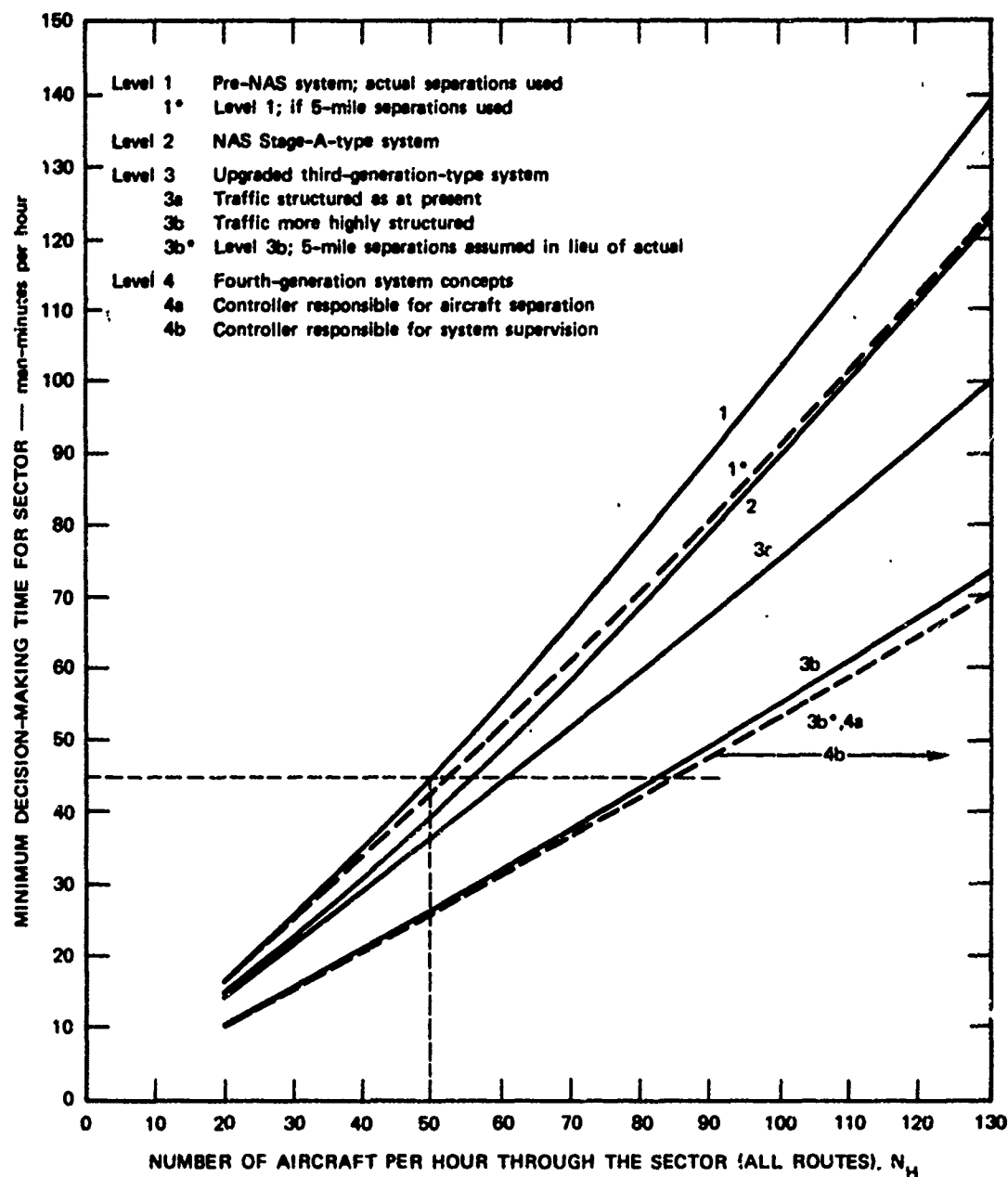
4. Chicago ARTCC Joliet High Sector

Figure 7 shows the minimum DMT curves for the Chicago Joliet High Sector. The Level 1 system curve was generated from data collected at the sector. The data were reduced and are presented in Tables E-23 through E-34 in Appendix E.

The curves for the Joliet High sector were generated in the same manner (with the same 10 mile-minimum separation and data collection constraint) as for the Chicago Bradford High.

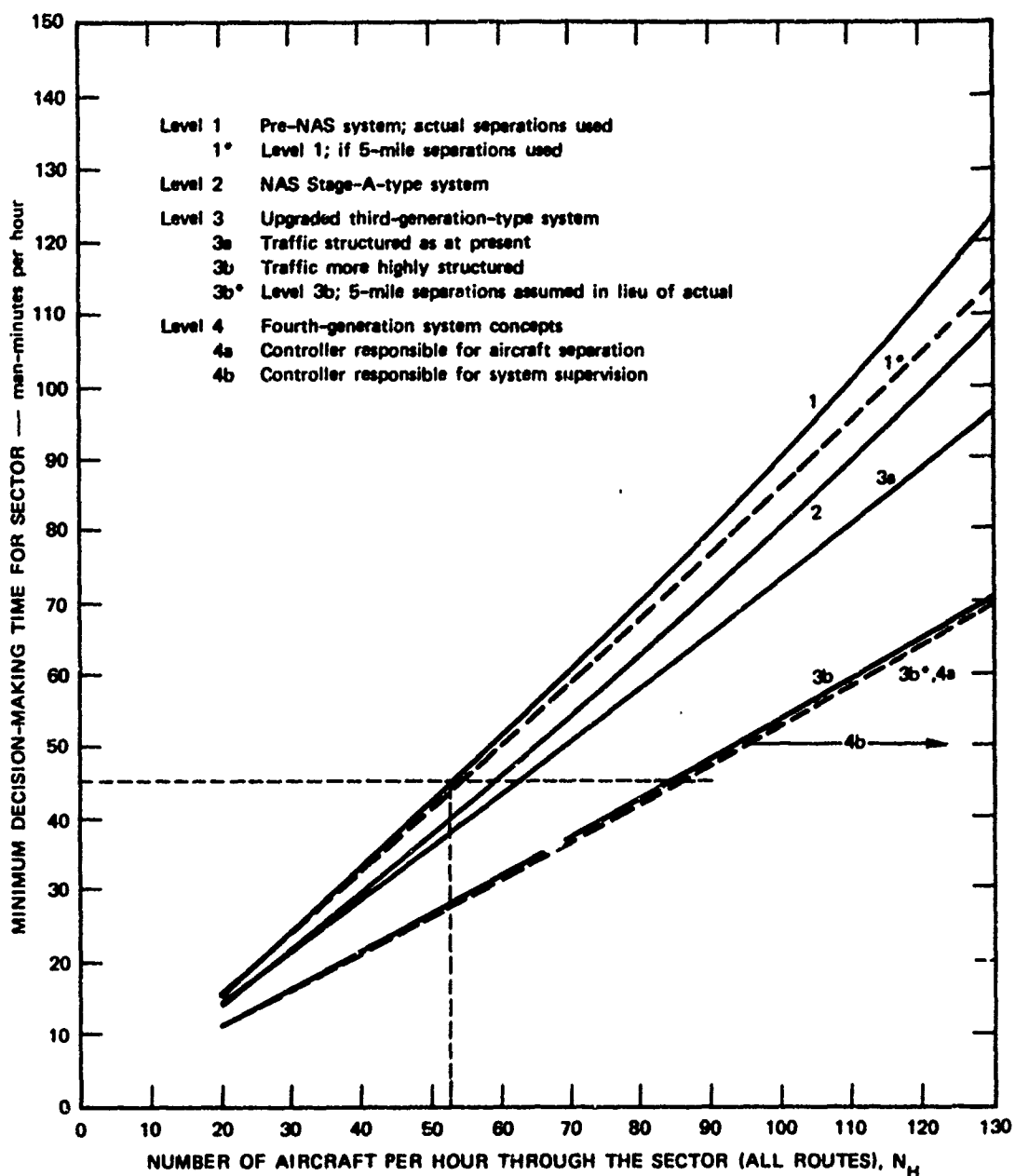
5. Chicago ARTCC Papi Arrival Sector

Figure 8 shows the minimum decision making time curves for the Chicago Papi arrival sector. As with the other sector curves, data were



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**FIGURE 6 DECISION-MAKING TIME REQUIREMENTS FOR CHICAGO ARTCC
BRADFORD HIGH SECTOR**



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FIGURE 7 DECISION-MAKING TIME REQUIREMENTS FOR CHICAGO ARTCC JOLIET HIGH SECTOR

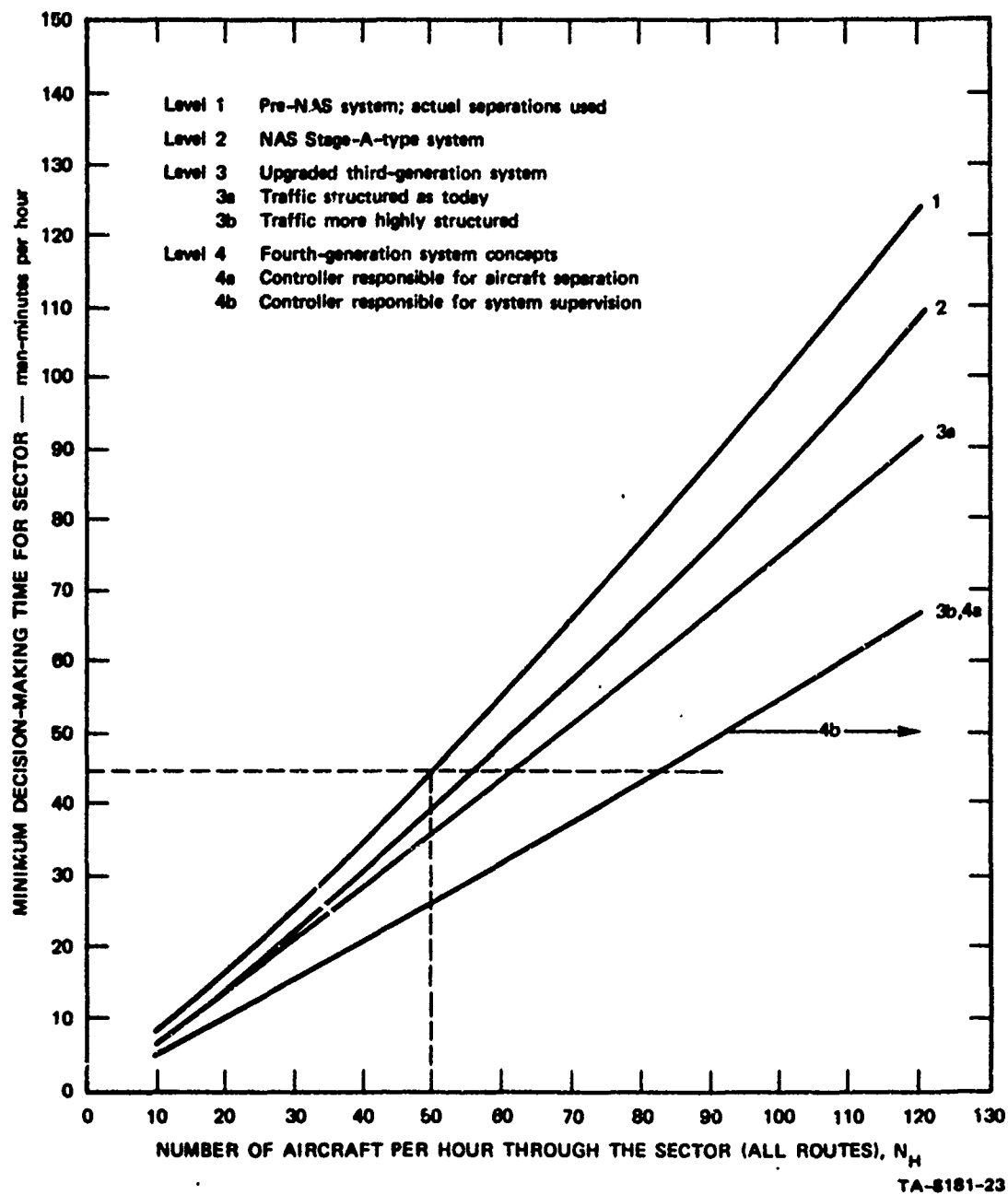


FIGURE 8 DECISION-MAKING TIME REQUIREMENTS FOR CHICAGO PAPI APPROACH SECTOR

collected at the sector. These data were reduced and are presented in Tables E-36 through E-38 in Appendix E.

The curves were generated in the same manner as previously outlined for the other sectors except that the minimum separation observed during the observation period was the 5-mile standard. This was used in the generation of the curves, and explains why there are no starred curves in Figure 8.

E. Operational Level Where Human Decision-Making is Limiting

During our data-collection effort at the Oakland Center, we observed traffic at Sector 42 during morning and afternoon peak periods. The maximum flow of traffic through the sector during these periods was around 30 aircraft per hour. From the DMT curves for this sector (shown in Figure 5), 30 aircraft per hour require about 30 minutes of decision-making time on the part of the controllers. The breakdown of how this time is distributed is shown in Table 4.

Table 4

DISTRIBUTION OF DECISION-MAKING TIME FOR $N_H = 30$ AIRCRAFT PER HOUR

Event	Minimum Decision-Making Time Required (minutes)
Potential conflicts	6
Handoffs	6
Pointouts/coordination	3
Traffic structuring and workload management	<u>15</u>
Total	30

From our sessions at the Oakland center we could see that of the events listed in the table above, the radar controller was usually primarily concerned with the potential conflict events and the traffic

structuring and workload management, while the handoff man usually made the handoffs and took care of the pointouts and other coordination events. This was not true in all cases because the controller team was usually very adaptive in getting the particular job done as dictated by the workload. However, for the most part, this distinction in functions can be made. Using this as a rudimentary guide, the functions classified here as radar controller functions take up about 20 minutes of his time per hour. From our observations at the sector, we felt (and this was confirmed by comments from the controllers during the interviews) that from the standpoint of required decision-making time, the controllers at Sector 42 could handle a larger amount of traffic than the 30 aircraft per hour.

Using the information obtained from our observations along with a thorough analysis of the sector structure and traffic flows, as well as from our 24 hours of interviews with controllers who control traffic in this sector, we concluded that decision-making time would become limiting about where the R-controller was spending half of his time in decision-making. This would really be a very busy pace for the R-controller. From Table 5, this corresponded to about 40 aircraft/hour and about 44 man-minutes per hour of total decision-making time required of the controller team with the Level 1 system. This capacity value was confirmed by Oakland Sector 42 controllers and by the values used in Central Flow Control Facility operations.

Table 5

DISTRIBUTION OF DECISION-MAKING TIME
FOR $N_H = 40$ AIRCRAFT PER HOUR

Event	Minimum Decision Making Time Required (minutes)
Potential conflicts	12
Handoffs	8
Pointouts/coordination	4
Traffic structuring and workload management	<u>20</u>
Total	44

In order to draw the horizontal line in Figure 5 at 44 man-minutes, the assumption was made that this value of DMT would also be limiting in the Level 2 and Level 3 systems. This assumption seems reasonable to us for the Level 2 system because that system is highly similar operationally to the Level 1 system. However, for Level 3 and beyond, the capacity limiting line, due to decision-making, could go up or down; convincing arguments for both possibilities can be presented. For want of more definitive information, the line was drawn horizontally to indicate the level of capacity, assuming the controller's judgmental factors are as specified, and that DMT is the limiting constraint.

As a first approach, we assumed that for sectors in ARTCC operations, 44 man-minutes of total decision making time was the threshold or limiting value for the Level 1 system. This value for decision-making time was then used in each of the figures drawn for the Chicago Center sectors where data was collected. The resulting capacity values (N_H) were compared with expected values obtained from our observations and judgments of the workloads associated with the various capacity levels that we saw, as well as our analysis of the sector structures and traffic flows. Not only did the values of N_H for Level 1 obtained from the 44 man-minute threshold correspond very well with controller judgments and our expectations, they also corresponded very well to the sector capacity values as used by the CFCF. This appears to verify that the DMT limits we are using are controller centered and not sector-specific.

The same rationale as presented above for Oakland Sector 42 was used for the sectors in the Chicago Center in extending the 44 man-minutes of total decision-making time limitation to the future level systems.

IV CONCLUSIONS ON IMPLICATIONS FOR EFFECTIVE AUTOMATION

We reiterate in stating the implications for effective automation that our measurements to date have been associated with the operations of the Oakland and Chicago Centers. In the Oakland Center, the high-altitude transition sector studied is the most complex in the facility. It handles climbing and descending military and civil traffic on both crossing and conflict-free routes, level civil traffic crossing the climbing and descending routes, and the sequencing and merging activities associated with descent into a major hub.

Three sectors in the Chicago center were studied. The Bradford Sector is a high-altitude sector with route structure and sector boundaries such that it has the aspect of a high-altitude en route sector as well as a high-altitude transitioning sector. It handles overflying traffic on merging routes from western to eastern cities (Detroit, Cleveland, and New York), climbing and descending traffic on both crossing and conflict-free routes, and the sequencing and merging activities associated with descent into Chicago O'Hare.

The Joliet sector is a high-altitude transitioning sector that handles overflights on merging routes from the West to the New York area, climbing traffic from O'Hare, descending traffic that is going to Detroit and Cleveland, and the sequencing and merging actions associated with the descent.

The Papi sector is a low-altitude sector that is responsible for control of arrival traffic into O'Hare from the east and northeast. Most of the traffic is along one route and descending from flight levels between 200 and 300, to 10,000 ft, and reducing speed from 300K IAS to 250K IAS before this sector hands off to O'Hare's IFR room.

Although our measurement experience so far has been limited to four sectors in two ARTCCs, we are aware at present of certain differences in operations within terminal areas in the airspace close to an airport. We are presently in the process of taking measurements at several terminal type facilities (e.g., TRACON, IFR room) as a step toward generalizing and verifying our conclusions to include these types of areas. However, our observation and measurement experience is such that we feel that our conclusions are representative of en route, transitioning, and terminal interface operations that are performed at the centers with the possible

reservation that we have not studied low-altitude en route operations except in the vicinity of terminal areas. Within the context of these qualifications, we can state the following conclusions:

1. Automation of the decision-making functions that we denote as deviation recognition and situation assessment has a high potential for improving sector capacity. The conflict prediction function falls in this class.

2. Automation of the decision-making functions associated with action selection has a low potential for improving sector capacity through reduced decision-making time, for a controller-in-the-loop control concept, because controllers in the present system spend a relatively small proportion of their total DMT in the action-selection process. Conflict resolution is a function in this class. (Of course, there may be other reasons to automate these functions. In particular, such automation would be necessary in order to achieve a mode of operation where controllers function as system supervisors.)

3. Except where traffic is or can be highly structured, intersector voice communications should be retained because handoff and other coordination functions will continue to constitute negotiations rather than one-way information exchanges.

4. Equipment outages of up to a minute or two are generally tolerable on an occasional basis, because of the control techniques used at present to avoid minimal-response-time requirements. Equipment outages of longer durations must continue to be backed up at least to the point where the controller will not consider the possibility of such outages in his control techniques.

5. Except where traffic is highly structured and relatively uniform, plan position displays used for surveillance should cover an area considerably larger than one's own control jurisdiction, or other suitable means of providing a controller with planning information on future traffic must be used. The information on flight strips as they are made today is often not sufficiently accurate or up-to-date to be suitable for future traffic planning.

6. Except where traffic is highly structured, the need for intersector negotiations for traffic planning, workload management, and transfer of partial control of aircraft will constrain the potential capacity benefit of the silent or automated handoff.

7. Automation of the deviation recognition and situation assessment functions may have a positive bearing on controller training, especially on-the-job training as it appears to us that a substantial amount of training time is expended in controller OJT concerning these functions.

8. Automation of conflict handling functions (especially Level 3) will in general have a smaller relative impact, in terms of capacity increase, in sectors with more highly developed and structured airspace procedures than in sectors with more flexible organization. This conclusion follows from the fact that most of the payoff for capacity predicted for Level 3 automation comes from reducing the time spent in handling potential conflicts. However, through structuring of airspace procedures, many of these potential conflicts are "procedurized" out of existence. Hence, there are proportionately less conflict-handling decisions to be made, even before automation. To the extent that this procedurization entails penalties to users, however, such automation could serve to relieve them.

9. Efforts aimed at automating traffic planning and structuring activities would have a substantial payoff in terms of capacity. As most of the capacity increases predicted from automation Level 3 accrue through direct reduction of conflict handling time, the relative proportion of the remaining DMT requirement associated with traffic structuring and planning increases, making even more attractive reduction of this portion of the DMT requirement.