

Version 6.1 4/7/03

Air Transportation Systems Engineering

**Progress in Astronautics and Aeronautics
Volume 193**

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Published by AIAA Press 2001

4/7/03

Preface

This book represents a selection of research papers that were presented at two closed forum research meetings held in 1998 and 2000. The United States Federal Aviation Administration and the European EUROCONTROL sponsored these meetings. In December of 1995, Dr. Jack Fearnside, Director and General Manager of the Center for Advanced Aviation Systems Development of the MITRE Corp. and Jean-Marc Garot, Director of the EUROCONTROL Experimental Center proposed the formation of a joint research seminar to be held approximately every 18 months. These research Seminars are designed to share the latest and best of research findings on the complex and emerging field of Air Traffic Management. These seminars produced formal papers presented in 1997 (Saclay, France), 1998 (Orlando, Florida) and 2000 (Napoli, Italy). The proceedings of these seminars are available on the Eurocontrol maintained web site <http://atm-seminar-2000.eurocontrol.fr/>. The interested student of air traffic management technology development can find the complete proceedings on this web site.

The purpose of this book is to select a subset of the papers presented in 1998 and 2000 (Orlando, Florida December 1-4, 1998 and Napoli, Italy June 13-16, 2000) and organizes them in a logical sequence. The editors' selections do not necessarily represent our view that these are the only good papers presented in these forums but represent a collection that best explains a growing understanding of the technical nature of a very complex international air transportation system. To date, there has been no comprehensive collection of system performance data and analysis of this data to identify critical system metrics. A system that is showing the signs of being so successful that it's growth is

approaching the physical infrastructure capacity limits. Unlike the highway traffic engineering sub-discipline of civil engineering, there is no engineering discipline that deals with the more complex air transportation system. Although there are textbooks on how the current air traffic control system works, there are no books devoted to the underlying theory of the air transportation system. This book is the first that attempts to address the breadth of technical details and the complex factors that drive and limit the air transportation system.

The editors of this book bring a comprehensive knowledge of the field and the international literature. The principle editor, Dr. George L. Donohue, was the Associate Administrator of the US Federal Aviation Administration for Research, Engineering and Acquisition from 1994 to 1998. In addition to developing the NAS Architecture 4.0, he encouraged Dr. Jack Fearnside and Dr. Andres Zellweger (Director of FAA Aviation Research at the time) to initiate the US and European research forums which has produced the papers in this book. Dr. Herman Rediess is currently the FAA Director of Aviation Research and was the US co-sponsor of the Seminars in 1998 and 2000. Mr. Christian Pusch was in charge of organizing and sponsoring the 2000 seminar and is currently Head of Research and Development Coordination at the EUROCONTROL Experimental Center, outside of Paris, France.

In order to keep these research seminars to a workable size that facilitate a maximum of technical exchange, they have been by invitation only and therefore provided a limited exposure of the work to a larger audience. In 1997, there were only 60 participants

discussing 40 invited papers. In 1998 an international call for papers was issued and the seminar grew to 110 participants discussing 50 papers selected from a field of 108 papers submitted. In 2000 there were approximately 150 participants discussing 64 papers selected from a field of 127 papers submitted.

The collection of research papers in this book are an initial attempt by the editors to make a comprehensive description of the current state of knowledge available to the interested student of this new emerging sub-field of transportation engineering. The chapters are organized into ten Sections:

- I. Introduction
- II. US and European ATM Systems: Similarities and Differences
- III. Economics of Congestion
- IV. Collaborative Decision Making
- V. Airport Operations and Constraints
- VI. Airspace Operations and Constraints
- VII. Safety and Free Flight
- VIII. The Changing Role of air Traffic Controllers: Cognitive Work Load
- IX. Emerging Issues in Aircraft Self-Separation
- X. Summary Observations.

Overall, this book includes 48 chapters written by over 90 authors and co-authors.

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4/7/03

Section I. Introduction

Chapter 1. Introduction

Air transportation refers to the movement of people and material through the third dimension, usually in heavier than air vehicles. These vehicles range from 400 pound (182 kilogram) powered parachutes transporting one person 25 miles (46 kilometers) to 800,000 pound (364,000 kg) jumbo jet aircraft transporting 350 passengers 9,000 miles (16,700 kilometers). In fact, jet aircraft have now been designed to the point that they can connect virtually any two points on earth non-stop in much less than a day.

The invention and development of the jet aircraft in World War II has led to the use of aircraft as a major mode of both domestic and international transportation. Since 1960, the year that the US Department of Transportation began collecting statistics, the air mode of transportation has grown over six times faster than any other mode of transportation in the United States (that also happens to be over six times faster than the rate of Gross Domestic Product growth). The International Civil Aviation Organization states that more than one third of all international cargo by value was shipped by air in 1998. It should come as little surprise that the technical and physical infrastructure is feeling the strain of this sustained growth rate.

In the United States, there are over 7,500 aircraft (over 4,500 in Europe) in commercial service at the turn of the century. Roughly 67% of these aircraft are powered by high

bypass ratio fanjets, the rest are powered by either gas turbine or piston driven propellers. The fanjet aircraft prefer to fly above 30,000 feet in altitude, whereas the propeller aircraft prefer to fly below 20,000 feet. Aircraft flying above 10,000 feet are usually pressurized do to the lack of adequate oxygen required for passenger comfort and/or survival. The US operates approximately 40% of the world's commercial air transportation. In addition, the US has a considerable use of aircraft for private transportation. In contrast, private aircraft play a much less important role in Europe.

There are over 190,000 registered private aircraft in the US (over 10,000 turboprop or turbojet) with over 600,000 registered pilots. On any given day, there are over 5,000 aircraft in the air (between the hours of 10:00 and 22:00) under positive separation control by the Federal Aviation Administration (FAA) Air Traffic Control (ATC) system. Of this amount, approximately one third are involved in private transportation. There are also approximately three times this amount of private aircraft in the air that are not under FAA positive control. Europe operates an air transportation system that is approximately 65% the size of the US system, but with very little private air transportation activity. Africa, South America and Australia operate a considerable amount of private air transportation in addition to commercial air transportation because of the large intercity distances and lack of substantial ground transportation infrastructure.

At the end of World War II, international travel by air became increasingly popular. In 1944, the International Civil Aviation Organization was formed as part of the United Nations to regulate international civil aviation. There are approximately 180 member

countries at the beginning of the 21st century. Each member country must have a Civil Aviation Authority (CAA) to provide Communications, Navigation, Surveillance and Air Traffic Management (CNS/ATM) services to internationally accepted standards. For the United States, this agency is the FAA. In addition to the provision of CNS/ATM services, each country must provide aircraft safety oversight for the certification of aircraft airworthiness and aircraft operation. Until recently, these two functions (CNS/ATM and safety oversight) have been supplied by the same government agency. Since 1990, there has been a trend to privatize (through different means ranging from wholly owned government organizations to complete privatization) the provision of CNS/ATM services and retain government safety oversight.

The CNS/ATM function has evolved from the 1920's provision of primitive navigation and communications services to a highly computerized ATM system with Central Flow Control Management (CFCM) utilizing space-based communications and navigation equipment. With the advent of radar in World War II, the surveillance function was added to the CAA's provision of services in the late 1950's. The physical limitations of radar at that time set the aircraft separation standards that are still in use today. These separation standards (in conjunction with the number of runways that are available) set the maximum operational capacity that the air transportation system can support. These separation standard are typically 5 nautical miles in high altitude airspace (i.e. above 18,000 feet) and 3 nautical miles within 60 nautical miles of an airport (typically in low altitude airspace). Airspace that does not have radar surveillance must maintain procedural separation using aircraft onboard navigation position fixes and ATC

communications. These separation standards range from 60 to 100 nautical miles and are used in oceanic airspace, non-radar airspace and in undeveloped countries that lack radar services.

The radar physical properties that dictate these standards are beam width and sweep rate. Primary radars have narrow beam widths in azimuth (e.g. 1.4 degrees typical) but wide beam widths in the vertical (e.g. in excess of 30 degrees). Secondary radars were added to the ATC system in order to provide cooperative altitude reporting from the aircraft being interrogated using an onboard pressure altimeter and a radar transponder. Over time, this data link added aircraft identification. The aircraft identification allows the ATC computers to correlate each aircraft with its pre-flight plan and, therefore, display aircraft ID, origin, departure time, destination, estimated time of arrival, altitude and speed. Today, this information is provided to both the CAA operated Air Traffic Control centers and also to the airline Air Operations Centers (AOC). This shared information and situational awareness forms the basis for the developing operational procedures known as Collaborative Decision Making (CDM).

In practice, aircraft are routinely maintained at 7 to 30 miles separation (i.e. in excess of radar limitations) do to air traffic controller cognitive workload limitations. A typical controller can maintain situational awareness on from 4 to 7 aircraft at a time. When airspace sector loading exceeds this amount, controller teams work to maintain aircraft separation. These teams can be as high as three controllers per sector. In the US, there are over 730 sectors and in Europe there are over 460 sectors. The number of sectors that

are available to high-density airspace in the US and Europe is limited by the number of communication channels that are available to the CAA. The number of communications channels available is dictated by the technical efficiency in which the allocated radio spectrum is utilized.

The radio spectrum is allocated and controlled by the International Telecommunications Union (ITU), also a United Nations charter organization. Today, most ATC communications is conducted utilizing either 25 kHz or 8.33 kHz double side-band, amplitude modulated VHF frequencies between 108 MHz and 139 MHz. A shift to digital communications began over 20 years ago with ARINC Corp. providing aircraft to AOC digital communications over 25 kHz channels in the 139 MHz frequency range. This data link became known as ACARS and is a 2400-baud character oriented link. For the last 5 years, the FAA has been using this data link to provide pre-departure clearances for over 40 high capacity hub airports in the USA. After 20 years of data communication traffic growth, ARINC is migrating to a Carrier Sense Multiple Access (CSMA), fully digital (using D8PSK protocol), 31.5 kbaud data link to accommodate the increasing message traffic. Also, aircraft flying in international oceanic airspace are beginning to utilize the IMARSAT data-link for Future Air Navigation System (FANS) equipped aircraft to provide position reports, gradually replacing the old HF voice communications system.

The ATC providers are still debating within the ICAO Radio Navigation forum the exact international standard and implementation time line for a fully digital ATC

communications system. Although there are strong system inter-relationships between the CNS functions and the ATM function, this book is emphasizing only the ATM function. There are several good textbooks on the subject of wireless communications and this book will not treat this subject any further. A good book that discusses many of the CNS systems commonly used in aviation is *Avionics Navigation Systems, 2nd Edition* by Myron Kayton and Walter Fried.

Most of the world allocates air transportation routes through government agencies. In the US, prior to 1978, the Civil Aviation Board (CAB) controlled the allocation of routes that commercial air carriers could provide. In 1978, the US government deregulated the air transportation industry and allowed economic forces to shape the air transportation network. This system evolved very quickly to a hub and spoke network. At the beginning of the 21st century, there are approximately 60 hub airports in the United States with a maximum capacity of about 40 million operations per year. Decreasing aircraft separation in the final approach to a runway from an average of 4 nautical miles between aircraft (the practical limit due to +/- 1 mile variance of today's system) to 3 nautical miles could increase this capacity to over 55 million operations per year.

This increased capacity could be achieved by migrating from the use of radar surveillance to the use of aircraft broadcast Global Positioning System satellite navigation fixes over a wireless digital data link (this is referred to as Automatic dependent Surveillance – Broadcast or ADS-B). This capacity increase cannot be realized, however, without a change in the enroute and terminal separation procedures used by air traffic controllers

due to human cognitive workload limitations. Today, in both the US and Europe, approximately 2 minutes or more of delay per aircraft can be attributed to saturation of the terminal and/or enroute sectors. At individual high-density airports, these average delays can be as high as 10 minutes per aircraft at airport capacity fractions (cf) of over 0.9. Queuing theory would predict that airport delays will be proportional to $cf / (1 - cf)$. Increasingly, a central flow control function is being used to institute ground delay programs to anticipate these delays and hold aircraft on the ground at the point of origin rather than in the air at the point of destination. In the US, these delays are frequently triggered by a weather event at one or more of the hub airports. It is not clear whether or not a central flow control function can eliminate or even reduce delays at airports with $cf \geq 0.8$ due to the current First Come First Serve (FCFS) runway assignment protocol and the inherent uncertainties involved with an aircraft flying through a time varying atmosphere.

With this background in mind, one should now realize that there are five main actors that control the utilization of the air transportation system: 1) The CAA's in the provision of regulations and aircraft separation / flow control standards and services; 2) The airlines in their utilization of aircraft enplanement capacity / modern avionics and the utilization of ATM information in their Air Operations Centers; 3) The airport operators in their provision of airport infrastructure; and 4) The private aircraft operators in their provision of suitably equipped aircraft and cooperative airspace utilization and finally, 5) The flying public who will suffer the consequences of failure to modernize the systems and infrastructure. In order for the capacity and quality of service to increase in the 21st

century, each of these players (except the flying public) will have to make substantial capital investments in new equipment and/or significantly revise their operational procedures. If these changes are not done, the flying public will pay the price in loss of transportation mobility, safety and economy.

Six chapters are included in the next section to briefly describe the current and envisioned future ATM operational concepts of the USA and of Europe. This section is then followed by six chapters in a section on the economics of the airlines and their linkage to the operations of the ATM system. The next section discusses the emerging practice of Collaborative Decision Making (CDM) as a new paradigm for dynamic optimization of the distributed air transportation command and control structure. The next two sections discuss in some detail the operations in and near airports (six chapters) and enroute airspace (seven chapters) respectively. These sections not only provide details on operations and current metrics but discuss early field evaluations of computer embedded Decision Support Systems that are envisioned as improving the capacity and productivity of the future ATM system.

It is rare to see a discussion of the relationship between air transportation safety and capacity. It is intuitively obvious, however, that at some separation level, the technology will become inadequate to prevent aircraft collisions. This implies that safety and capacity are inversely related in the limit. Figure 1.1 illustrates a hypothetical inverse relationship between safety and capacity at different levels of technical capability. These curves are analogous to the interrelationship described in economics theory as Labor-

Capital Substitution Curves with constant Technology Isoquants. Over the last 30 years, the world commercial aircraft Hull Loss rate has been approximately 15 Hull Losses per year. This has allowed capacity to increase by increasing commercial aircraft safety features such as Flight Management Systems (FMS) and Traffic collision Avoidance Systems (TCAS). This continuous improvement in aircraft safety will eventually reach the ATC separation technology limit shown in Figure 1.1 and further increases in capacity will result in a decrease in overall system safety resulting in increased annual Hull Loss rates. In order to avoid this increase in aircraft hull loss rate, a new separation technology must be adopted to move to a new safety – capacity tradeoff curve.

Figure 1.1 Hypothetical Safety – Capacity Substitution Curves for the United States ATC System.

The research communities in both the United States and Europe are converging on the option of transferring aircraft separation authority and responsibility to the aircraft flight-deck. The combination of Global Positioning System (GPS) Navigation accuracy and wireless digital communication systems is allowing Automatic Dependent Surveillance – Broadcast (ADS-B) systems to provide very precise aircraft location and situational awareness directly to the aircraft flight deck and FMS. This has the potential to decrease the ATM controller workload to allow more aircraft per sector by using the controller to supervise traffic flow control while the pilots are assuring aircraft separation. A hypothetical Pilot workload – Controller workload substitution curve is illustrated in

Figure 1.2. The exact relationship between pilot and controller workload is unknown. If one assumes that it is a simple inverse relationship, even a simple transfer of separation authority could lead to a significant decrease in controller workload. An understanding of this relationship will be required to move to the enhanced technology, higher capacity iso-quant shown in Figure 1.1.

Figure 1.2 Hypothetical Pilot – Controller Workload Substitution Curves

Sections VII-IX address the safety issues associated with both the current ATM systems in the USA and Europe and the more important issue of how changes in the system may either increase or decrease the safety. Section VII presents five chapters that expressly address the analysis of ATM safety. The next section then presents six chapters on the assessment of ATC controller's cognitive workload and the necessity of changing the role of controllers in the future system. The next section presents six chapters on the emerging trend toward allowing aircraft to provide more self separation as new technology provides more timely high quality information to the aircraft flight deck and the controllers workload is approaching a limit. The final section presents the editors' view of what this all means to future design of the international air transportation system and the technical and operational changes that must occur over the next 5 to 10 years in order to keep the system from serious decline as an economical and reliable means of both domestic and international passenger and cargo transportation.

Section II. USA and European ATM Systems: Similarities and Differences

Five chapters are presented in this section that provide an introduction to the two largest air traffic management (ATM) systems in the world. The first chapter presents an operational concept for air traffic management in the United States. This chapter introduces the concept that the air transportation system can be modeled as a nested sequence of feedback control loops with different time constants and different signal quality. This is a powerful mental model of the system and the editors believe that more work needs to be done to expand on this initial work.

The second and third chapters describe the underlying characteristics of ATM systems and means for assessing and comparing operational concepts. Chapter 3 provides a good description of the European view of the evolution of the future Air Traffic Management system. Chapter 4 is a more quantitative view of the two systems and is written by a combination of knowledgeable US and European authors.

The last two chapters deal with performance and capacity assessment of the European and U.S. ATM systems. Chapter 5 is the first quantitative assessment of the growth in delay observed in the European ATM system. Chapter 6 introduces a macroscopic system capacity model that can be used to conduct gross quantitative estimates of system

maximum capacity. This equation provides good insight into the relationship between airport capacity constraints and airspace capacity constraints.

Chapter 2. Air Traffic Management Capacity-Driven Operational Concept Through 2015, Aslaug Haraldsdottir, Robert Schwab and Monica Alcabin, Boeing, 1998.

Chapter 3. European and USA Operational Concepts for 2000-2010: A Framework for Comparison, R.A.McCulloch, NATS, 1998.

Chapter 4. The US and European operational concepts development and validation activities – airspace and airports comparison, Diana Liang, Jonathan Green, William Marnane and Steve Bradford, FAA and EHQ, 2000.

Chapter 5. ATM Performance Review in Europe, Xavier Fron, Eurocontrol EEC, 1998.

Chapter 6. United States and European Airport Capacity Assessment using the GMU Macroscopic Capacity Model (MCM), George L. Donohue and William Laska, George Mason University, 2000.

Section III. Economics of Congestion

Six chapters are presented in this section that examine the air transportation system from an airline service provider perspective. The first two chapters are concerned with the generic approach to understanding the economic impacts of ATM system changes and of operational disruptions. Chapter 9 presents a very informative description of how schedule disruptions can propagate through the transportation system. Chapter 10 is the first description of the airline AOC. The AOC is becoming as important to the operation of the commercial public transportation system as the FAA ATC center.

Chapter 11 illustrates how all delays are not equal to the airline AOC. Delays in the morning hours can multiply many times over as they disturb all of the succeeding flights in a tightly banked hub and spoke transportation system schedule.

The final chapter in this section, chapter 12, explores the concept of using pricing of services instead of technical and operational solutions for solving the congestion problem. Economic techniques of differential pricing, slot auctions, and route or bank auctions will increasingly be examined as alternative means of dealing with the increasing levels of delay and cancellations associated with the decreasing usable capacity margins of the system.

Chapter 7. Evaluating the Economic Impacts of ATM Innovations on Commercial Air Carrier Operations, Eric M. Gaier and Peter F. Kostiuk, Logistics Management Institute, 1998. (incorporate 2000 paper into one chapter with the 1998 paper)

Chapter 8. The Impact of Air Traffic Management on Airspace User Economic Performance, William MacReynolds and Joseph Sinnot, MITRE/CAASD, 1998.

Chapter 9. The Effects of Schedule Disruptions on the Economics of Airline Operations, Zalman A. Shavell, MITRE/CAASD, 2000

Chapter 10. Modeling an Airline Operational Control Center, Nicolas Pujet and Eric Feron, MIT, 1998.

Chapter 11. Preliminary Evaluation of Flight Delay Propagation Through an Airline Schedule, Roger Beatty, Rose Hsu, Lee Berry and James Rome, American Airlines and Oak Ridge National Laboratory, 1998.

Chapter 12. Pricing Policies for Air Traffic Assignment, Jean-Loup Farges, Karine Deschinkel and Daniel Delahaye, ONERA CERT, ENSAE, LOG, 2000.

Section IV. Collaborative Decision Making

Seven chapters discuss the developing concepts and theory behind the new distributed optimization strategy of information sharing and collaborative decision-making.

Chapter 13. Martinet et al, - Investigation of Improved Information Distribution for the Realization of Collaborative Decision Making, ATM 98

Chapter 14. Quinn, et al. - ATC/Air Carrier Collaborative Arrival Planning: Data Sharing and User Preference Tools, ATM 98

Chapter 15. Data Flow Analysis and Optimization Potential from Gate to Gate, Matthias Poppe and Georg F. Bolz, DFS, LHSystems, 1998

Chapter 16. Carlson - Operational Concept for FAA Inter-facility TFM Collaborative Decision Making, ATM-98

Chapter 17. R.J. Hansman and H.J. Davison, "The Effect of Shared Information on Pilot /Controller and Controller/Controller Interactions, MIT, ATM 2000 paper 19.

Chapter 18. Modeling Distributed Human Decision-Making in Traffic Flow

Management Operations, Keith Campbel, Wayne Cooper, Daniel P. Greenbaum and

Leonard A. Wojcik, MITRE/CAASD, 2000

Chapter 19. Assessing the Benefits of Collaborative Decision Making in Air Traffic

Management, Michael O. Ball, Robert L. Hoffman, Dave Knorr, James Wetherly and

Mike Wambsganss, U. of Maryland, Metron Scientific Consulting and FAA, 2000.

Section V. Airport Operations and Constraints

Six chapters are presented in this section with an emphasis on the Airport as a limiting factor in total system capacity.

Chapter 20. Airline Arrival Prioritization in Sequencing and Scheduling, Gregory C. Carr, Heinz Erzberger and Frank Neuman, NASA Ames, 1998.

Chapter 21. Capacity-Related Benefits of Proposed CNS/ATM Technologies, Tara J. Weidner, Seagull Technology, Inc. , 1998

Chapter 22. Collaborative Optimization of Airport Arrival and Departure Traffic Flow Management Strategies for CDM, Eugene Gilbo and Kenneth W. Holward, VOLPE National Transportation System Center, 2000

Chapter 23. Analysis and Modeling of Ground Operations at Hub Airports, Kari Anderson, Francis Carr, Eric Feron and William D. Hall, MIT and Draper Laboratory, 2000

Chapter 24. A conceptual Design of a Departure Planner Decision Aid, Ioannis

Anagnostakis, Husni Idris, John-Paul Clarke, Eric Feron, R. John Hansman, Amedeo

Odoni and William D. Hall, MIT, 2000

Chapter 25. Modeling of ATM Automation CD&R and Metering Conformance Benefits,

Tara Weidner and Steve Green, Seagull Technology Inc. and NASA, 2000.

Section VI. Airspace Operations and Constraints

Six chapters are presented in this section emphasizing the development of ATM metrics with a primary focus on airspace constraints and performance. The first two chapters present metrics and performance assessment methods for evaluating ATM system changes. The last four chapters are performance analyses of specific potential improvements to the ATM system.

Chapter 26. The Effect of Direct Routing on ATC Capacity, S.A.N. Magill, DERA, 1998.

Chapter 27. Performance Measures for Future Architecture, Steve Bradford, Diana Liang and David Knorr, FAA, 2000.

Chapter 28. Analytical Identification of Airport and Airspace Capacity Constraints, William Voss and Joe Hoffman, FAA and MITRE/CAASD, 2000

Chapter 29. Operational Assessment of Free Flight Phase 1 ATM Capabilities, David Knorr, Joseph Post, Jeff Biros and Michelle Blucher, FAA, TRW and MITRE/CAASD, 2000.

Chapter 30. Lessons Learnt form CENA-PHARE experiments and requirements for future evaluation of novel concepts in ATC, Didier Pavet, CENA, 2000.

Chapter 31. Restriction Relaxation Experiments Enabled by URET, a D-Side Strategic Planning Tool, Michael Burski and Joseph Celio, FAA and MITRE/CAASD, 2000.

Section VII. Safety and Free Flight

Safety has always been the overarching objective of the entire aviation system, but, until recently, there has been very little progress in a systematic methodology for ensuring that new ATM system developments are indeed safe. A great deal has been learned about how to build and operate safe systems from the nuclear industry and even from the aircraft industry and we are now beginning to see the transfer of this to ATM system development.

But, as Blom points out in the first chapter of this section, the tools that have been successful in these arenas are not well suited to the assessment of safety in a complex, dynamic, interactive environment like Air Traffic Management. Thus Blom and his co-workers developed a safety risk assessment model, TOPAZ. The methodology includes heuristic and stochastic system analysis and also takes into consideration of the "human element" in the safety formula. They apply their model to airborne separation assurance, comparing this to traditional ATC separation assurance. In the second chapter, Blom and his co-workers extend the TOPAZ methodology with a mathematical model of the cognitive performance of the air traffic controller. The model is an excellent start at factoring human performance into the equation but it does not provide a mechanism for understanding human performance risk when other system elements exhibit "failures". These are important interactions that must be analyzed because the science of safety of highly reliable systems has clearly established that accidents generally are the result of

multiple failures of different elements of the total system. In the third chapter of the section, Blom and his co-workers present the results of an extension of the TOPAZ models to probabilistic risk assessment of wake vortex induced accidents. The TOPAZ methodology used in these three chapters represents the state of the art in rigorous CNS/ATM safety analysis.

The fourth chapter in this section, by Hoekstra, Ruigrok, and Van Gent, develops a case for the need of a distributed system to permit Free Flight in high density airspace. The results of analysis and simulation are presented to make the case that it is precisely in high density airspace that the power of a distributed system (as envisioned by Free Flight airborne separation) is required. The authors argue that a distributed system for separation is inherently safer (more reliable and more robust) than a centralized, ground-based ATC system.

The fifth chapter presents a comprehensive safety assessment methodology, developed under ICAO auspices, that will help lead to certification of Airborne Separation Assurance System (ASAS) applications. The work is based on an RTCA/EUROCAE methodology for Operational Safety Assessment of CNS/ATM systems. The assessment is built around a comprehensive operational hazard analysis that takes into account the severity and likelihood of hazards.

The final chapter proposes a methodology for evaluating changes to separation standards. To ensure safety in a Free Flight environment it will be necessary to develop the

appropriate separation standards and a methodology such as the one proposed in this chapter might be used for this.

The chapters in this section represent the state of the art in addressing the safety considerations that must be taken into account as we move toward a Free Flight paradigm, but much more work is required in this area. The challenge becomes even greater than in the past as we see an increase in the complex interaction between humans and machines in the cockpit with the ground based elements (human and machine) of the CNS/ATM system.

Safety experts agree that systems with the complexity and component interaction of the CNS/ATM system elements will fail. The challenge is to design a system that minimizes interactions and builds in "defenses" to guard against and to mitigate the effects of failures. A broad-based pragmatic approach to safety that considers all aspects of the system, including the human operator, is required. There must be a focus on safety from early conceptual development through system design, development, test and ultimately operation. Techniques such as the ones presented in this section must be augmented with analysis and fast and real time simulation to ensure a thorough understanding of system behavior under a range of normal and abnormal conditions.

Chapter 32. A Probabilistic Risk Assessment based methodology to assess advanced ATM on Safety, Henk Blom, Bert Bakker, Peter Blanker, Jasper Daams and Mariken Everdij, NLR, 1998.

Chapter 33. Human Cognition Modeling in ATM Safety Assessment, Henk Blom, Jasper Daams, and Herman Nijhuis, NLR, 2000.

Chapter 34. Probabilistic Wake Vortex Induced Accident Risk Assessment, J. Kos, H.A.P.Blom, L.J.P.Speijker, M.B.Klompstra and G.J.Bakker, NLR, 2000.

Chapter 35. Free Flight in a Crowded Airspace?, Jacco Hoekstra, NLR, 2000.

Chapter 36. Managing Criticality of ASAS Applications, Beatrice Bonnemaïson and Andrew D. Zeitlin, CENA and MITRE/CAASD, 2000.

Chapter 37 Analysis of Separation Minima using a surveillance State Vector Approach, Tom G. Reynolds and R. J. Hansman, MIT, 2000

Section VIII. Cognitive Workload Analysis and The Changing Role of the Air Traffic Controller

Five Chapters are presented in this section with an emphasis on measuring the cognitive work load and of evaluating potential future roles of the air traffic controller and the pilots that operate the air transportation system. The first chapter provides a comprehensive discussion of measuring controller workload. The second and third chapters explore the shifting role of the air traffic controller. The fourth chapter reports on the research evaluation of specific possible future controller working methods. The last two chapters discuss the human factors evaluation of two specific controller decision support tools that will change the role of the controller. The first is being considered for and the second is in the process of being implemented.

Chapter 38. The Passive Final Approach Spacing Tool (pFAST) Human Factors Operational Assessment, Katharine K. Lee and Beverly D. Sanford, NASA Ames and Sterling Software, Inc. 1998.

Chapter 39. Investigating the Validity of Performance and Objective Workload Evaluation Research (POWER), Carol Manning, Scott Mills, Cynthia Fox, ..., FAA, 2000.

Chapter 40. Controller Roles – Time to change, Bob Graham, Isabelle Pichancourt, Alan Marsden and Frank Dowling, EEC, 2000.

Chapter 41. Trajectory Orientation: A Technology-Enabled Concept Requiring a Shift in Controller Roles and Responsibilities, Ken Leiden and Steve Green, Micro Analysis and Design and NASA, 2000.

Chapter 42. Advanced Decision Aids for Air Traffic Controllers: Understanding Different Working Methods from a Cognitive Point of View, M.C.Bressolle, R. Benhacene, N. Boudes and R. Parise, CENA, Protectic and SOFREAVIA, 2000.

Section IX. Emerging Issues in Aircraft Self-Separation

Five chapters are presented in this section dealing with the emerging issue of aircraft pilots assuming a larger role in assuring aircraft separation under all weather conditions. The first three chapters focus on algorithmic and mathematical issues related aircraft self-separation. The last two chapters report on an operational evaluation of ADS-B, the leading candidate technology for self-separation.

Chapter 43. Co-operative Optimal Conflict Avoidance in Free Flight Airspace, Miguel Viilaplana, Colin Goodchild and Stefano Elefante, University of Glasgow, 2000.

Chapter 44. Operational Efficiency of Maneuver Coordination Rules for an Airborne Separation Assurance System, Raoul Schild, J.K.Kuchar, MIT, 2000.

Chapter 45. Geometric and Probabilistic Approaches toward Conflict Prediction in Free Flight, Bert Baker, Harmen Kremer and H.A.P.Blom, NLR, 2000.

Chapter 46. The Computerized Analysis of ATC Tracking Data for an Operational Evaluation of CDTI/ADS-B Technology, Scott Mills, FAA Civil Aeromedical Institute, 2000.

Chapter 47. Safe Flight 21: the 1999 Operational Evaluation of ADS-B, Jim Cieplak,
Edward Hahn and Baltazar O. Olmos, MITRE/CAASD, 2000.

Figure 1.1 Hypothetical Safety – Capacity Substitution Curves for the United States ATC System.

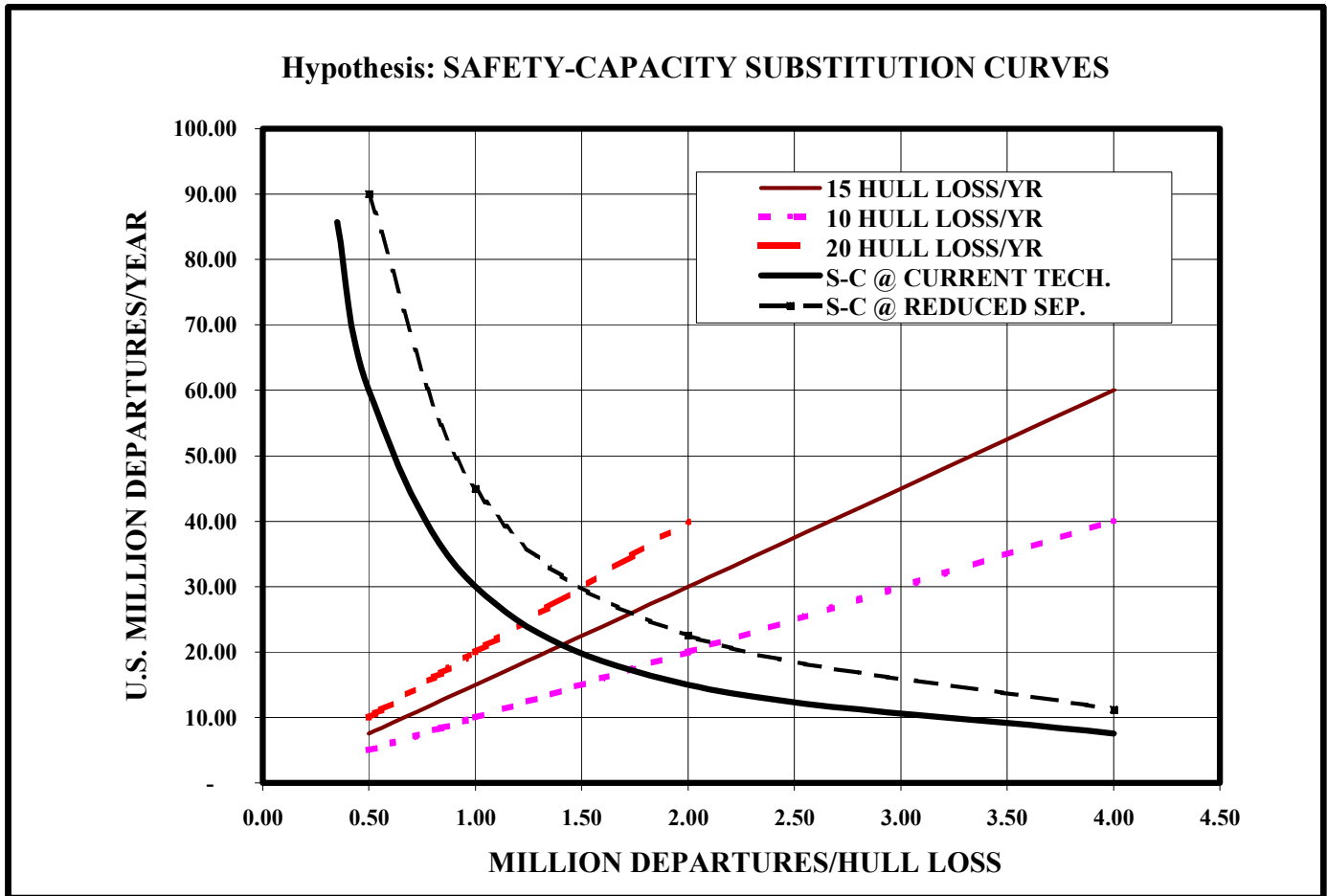


Figure 1.2 Hypothetical Pilot – Controller Workload Substitution Curves

