MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

INTERIM REPORT

CONCEPT FORMULATION STUDIES OF THE CONTROL ASPECTS OF THE FOURTH GENERATION AIR TRAFFIC CONTROL SYSTEM

J. U. BEUSCH
E. J. DENLINGER

Group 41

J. W. ANDREWS
W. D. LANNING

Group 96

PROJECT REPORT ATC-2
(Air Traffic Control)

2 JULY 1971
(Manuscript closed as of 6 April 1971)

LEXINGTON MASSACHUSETTS

The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology. The work was sponsored by the Transportation Systems Center of the Department of Transportation under Contract DOT/TSC-140.

TABLE OF CONTENTS

I. INTRODUCTION

A. Relation of the Fourth Generation Concept Formulation Studies to Other ATC Programs

To develop plans for a viable ATC system over the next 25 years a whole spectrum of studies can be conducted, each concerned with a different time frame. The spectrum, when laid out over time, is bracketed by two extreme cases.

1. One extreme is analysis of the present ATC system to identify its shortcomings, followed by synthesis studies to identify evolutionary ways of overcoming these shortcomings.

2. At the other extreme one can study the ATC system sufficiently far into the future that decisions need not be constrained by existing equipment, airspace utilization and procedures.

Between these two extremes are other studies concerned with developing plans for intermediate time frames. To be effective, study (1) must be done immediately. Study (2) should precede many of the studies for intermediate time frames since the results of study (2) should be available to influence what is done in intervening periods.

In this report we view the Fourth Generation Concept Formulation Study as study (2). Thus the results are not strongly influenced by present day equipment and are influenced by present airspace utilization and procedures only where they appear to be as good or better than other ways of operating the system.

B. Relation of Studies in the Control Area to Other Fourth Generation Studies

The ATC system is designed to fulfill certain needs of the nation. To satisfy those needs the ATC system must achieve specific objectives. The major objective of the system is to provide safe, expeditious flow of air traffic at reasonable cost. It is generally accepted that to achieve this objective certain functions in the area of surveillance, navigation, and communication must be performed and that considerable data processing in the ATC system is required. The examination of ways of achieving various performance levels of these functions is the subject of concept formulation in the areas of surveillance, navigation, communication and data processing.

Given that the surveillance, communication, and navigation functions are performed, there are other functions which are required in order to achieve the objectives of the ATC system. These functions, which include flow control, metering, sequencing, spacing, conformance and hazard monitoring, and conflict and hazard resolution make up the control aspects of the ATC system. In terms of the operation of the ATC system the surveillance, communication and navigation functions must be performed if the control functions are to be performed. In terms of the design of the system, however, the surveillance, communication, and navigation functions cannot be specified in detail until the required control functions are determined in detail. Thus, studies in the control area must be performed in a timely manner in order to insure that studies in the other areas will be conducted at a high level of efficiency. Control studies seek to determine the detailed characteristics of the functions which will be performed to achieve the objectives of the ATC system.

II. METHODOLOGY FOR ATC SYSTEM DESIGN

Any control system has the task of providing instructions, signals, or other inputs to certain people and/or equipment which accomplish some task or tasks in a particular way. For example, in a servomechanism which points a large steerable antenna, its control system must provide the proper signals to the motors which drive the antenna. A designer is given the problem of specifying a control system for the antenna system. As far as the designer is concerned the antenna and its drive are fixed elements. He has no control over many of their characteristics, but does control their inputs. More complex systems which must be controlled also have fixed elements; for example, an industrial engineer designing a production control system must work with fixed elements such as machine tools, transportation media and production workers. Here they are much more complex than for the case of the antenna system encountered by the servomechanism designer. An air traffic control system also has fixed elements which include certain characteristics of the pilots, aircraft, airspace, and runways. The system designer must have a working knowledge of these characteristics.

Except for simple cases, any control system also has the task of coping with undesirable external inputs which tend to disrupt the system or to make it more difficult for the system to accomplish its primary task. We call these external inputs <u>disturbances.</u> In general, a control system has some disturbances that it copes with as a matter of course and other disturbances which either prevent it from achieving its objective or cause a breakdown. In the servomechanism example cited earlier, a wind gust incident on the antenna may cause a temporary pointing error and an overheated bearing in the motor may cause a breakdown. Both are disturbance inputs. The designer of the servomechanism must have a working knowledge of the characteristics of at least some of the disturbances.

An operating plant manager who manages by exception, i.e., one who operates a management system in which his subordinates run the plant except when some kind of variance from the desired performance occurs, is operating a control system. Using our terminology the items and events which cause the variance or exceptions would be called disturbances. The management system designer, who may be the manager himself, must have a working knowledge of the characteristics of the important disturbances. An air traffic control system also has disturbances, which include bad weather, equipment failures, pilot errors, and other factors. An air traffic control system designer must have a working knowledge of the characteristics of these disturbances. Because the ATC system must be designed to deal with all possible disturbances without a complete breakdown, an understanding of disturbances is especially important.

As was stated earlier, any control system must accomplish some task or tasks in a particular way. For example, a production control system is responsible for achieving, at reasonable cost, a particular level of output of a product which falls within a certain range of quality or performance. To the industrial engineer who designs the system this responsibility represents the demand which the production control system must satisfy. The air traffic control system must also be designed to satisfy certain demands. The statistics of expected future desires of ATC system users to make flights from each origination airport to each destination airport as well as the actual flight trajectory that the users will consider to be most favorable are all part of the traffic demand. The need to handle, at reasonable cost, a variety of levels of traffic and mixes of different kinds of flights and aircraft under various conditions is important. Another aspect of the demand placed upon the ATC system is the need to achieve an acceptable level of safety while providing for an expeditious flow of traffic at reasonable cost. The ATC system must be designed to respond effectively to the various elements of the demand which may be encountered.

The next three sections of this report discuss the fixed elements, disturbances, and traffic demand which are the basic inputs to our study on air traffic control. The following section discusses airspace organization in terms of the services provided, and both geographic distribution and kinds of flight trajectories permissible in each type of airspace. The next section discusses the control philosophy that is applicable to the various types of airspace and the final section briefly discusses the fundamental issues in the control area which must be resolved in the conceptual design of the fourth generation ATC system. Fig. 1 illustrates the interactions between the parts of the study. The two major parts of the control area interact in the following manner. The best way of performing the control functions depends on how the airspace is structured and the best way of structuring the airspace is influenced by the relative difficulty of the various ways of performing the control functions.

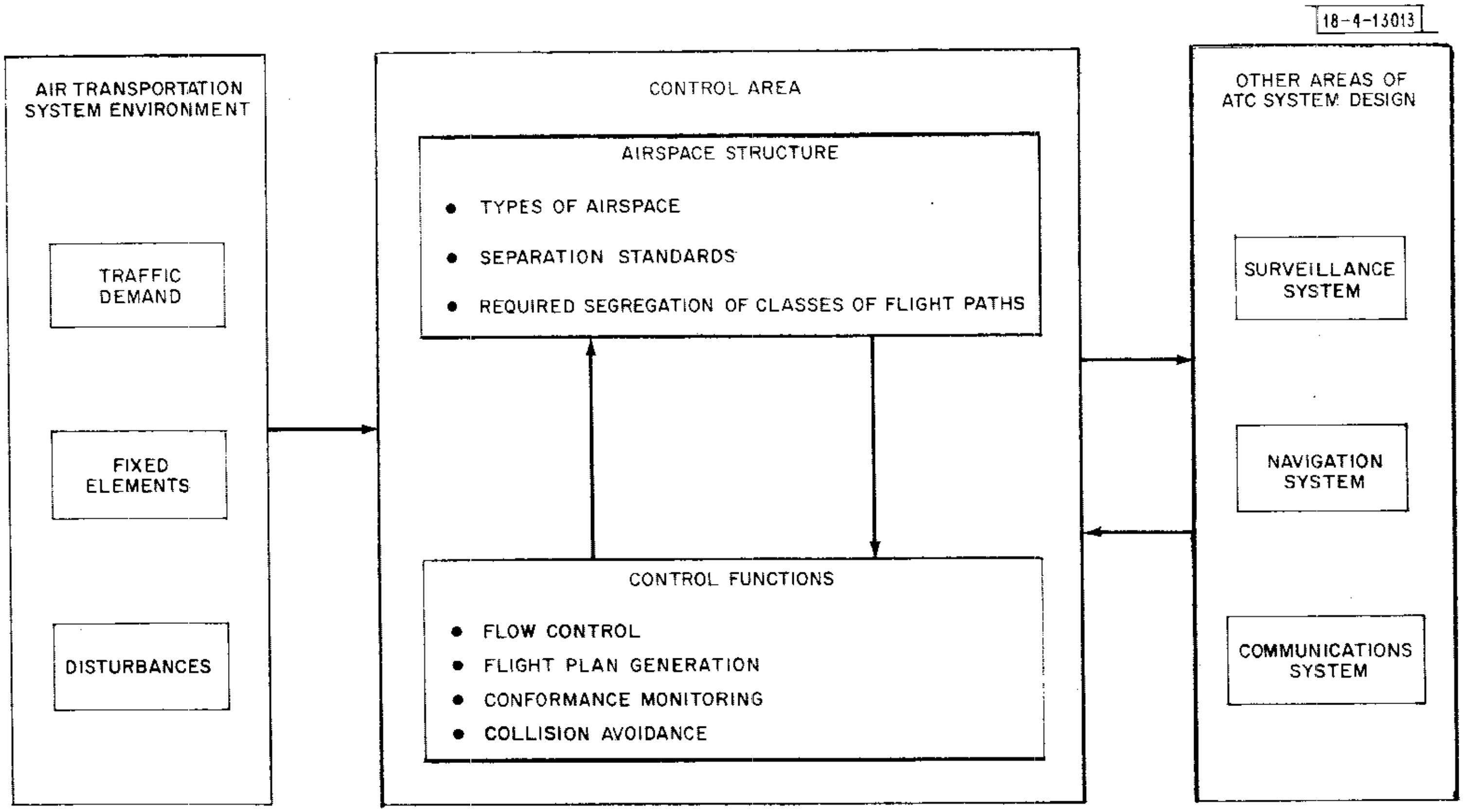


Fig. 1. Interacting parts of the ATC system design.

In summary, the methodology being used to begin this study is to characterize the fixed elements, the disturbances and the traffic demand. From the above characterization, as well as from considering cost and technological capability, the fundamental issues that have been identified can be resolved. The next step will then be to precisely determine in detail the functions that the ATC system should perform and to select the best way of performing them.

III. FIXED ELEMENTS IN THE ATC SYSTEM

As far as the ATC system designer is concerned, the pilots, aircraft, airspace, and runways have certain characteristics which cannot be changed. Pilots have certain reaction times, can only absorb a limited amount of information, and occasionally make mistakes. There are limits to the amount of acceleration, climb and descent rate, turn rate, and speed range that an airplane is capable of achieving. These and other aircraft constraints and capabilities are examined in Appendix A.

The characteristics of the airspace that are important to the ATC system designer are well known. They include the fact that aircraft cause turbulence and vortices and that air pressure decreases with increasing altitude, which places a maximum altitude limitation on many aircraft. For example, an aircraft must have a pressurized cabin in order to fly above an altitude of 12,000 to 14,000 feet. A rationale for structuring the airspace is presented in Section VI.

A runway also has certain constraints and capabilities. It is generally accepted that two transport aircraft should not occupy a runway simultaneously. Thus the employment of high speed turn-outs or turn-ons to reduce runway occupancy time on landing or takeoff is attractive provided that the occupancy time becomes the tightest constraint on capacity. Another constraint, which is presently the tightest one, is the legal separation, e.g. the required longitudinal separation of three miles between two landing aircraft. If legal separations are reduced, which may be possible despite the presence of trailing vortices, runway occupancy time may become the dominant constraint. In any case, constraints presented by runways must be understood and considered by an ATC system designer.

IV. DISTURBANCE INPUTS TO THE ATC SYSTEM

A. Importance of Disturbances

Efficient air traffic control requires that future aircraft positions, traffic patterns, and airport operational parameters be predicted in some sense for time periods ranging from a few minutes to several hours. On the basis of these predictions, delays and congestion can be anticipated and minimized through flow control and alteration of specific flight plans. If all parameters of the system were subject to prediction and/or control, a purely strategic approach to decision making [i.e., one that is completely preplanned over all flight regimes] would guarantee optimal performance. However, the parameters of an air traffic control system are subject to various "disturbances" which introduce elements of uncertainty into strategic planning. The nominal control strategy must be "optimized in the presence of noise" and the total system must be able to deal with rare but significant operational anomalies.

Disturbances are also of particular concern in determining the type and extent of automation that is feasible. Most automated control algorithms are designed to deal with only a limited range of situations and traffic configurations. Certain anomalies and perturbations which cannot be handled effectively by the normal control algorithms require special intervention by the air traffic controller. Under these conditions the judgment of the pilot and controller must be smoothly integrated with the greater strategic comprehension of the computer.

In discussing the significance of disturbances it is helpful to categorize the nature of their effects on the air traffic system. Thus we may identify the following classes of effects:

CLASS A - in which only a single aircraft or only one aircraft at a time is directly affected.

CLASS B - which involves flight plan changes for a number of aircraft.

CLASS C - which concerns alterations in airport capacity (i.e., in operations per hour).

CLASS D - which includes failure or shutdown of some ATC subsystem.

A list of possible disturbances is provided in Appendix B along with an indication of their probable effects. Many phenomena have effects in several classes and the configuration of the ATC system often determines the extent of the perturbation.

B. A Control Problem

As an example of the way in which disturbance inputs can become crucial in system design, consider the problem of controlling the arrival rate in the terminal area. The desire to feed arriving aircraft smoothly and efficiently to high capacity runways leads to consideration of a queuing problem.

When the traffic intensity* is near unity, the average delay is insensitive to the statistics of the interarrival time periods. The delay can be very large if arrival times are completely random but can become small if they are regularly spaced. A flow control system which controls the release time of departures to a given terminal can regulate the long-term number of arrivals at that terminal, but the time-of-flight of each aircraft is subject to various perturbations which tend to randomize the number of arrivals in smaller time periods. It is, of course, possible to "derandomize" the arrival time by implementing a control law that requires each aircraft to correct for the effect of all unanticipated influences. However, even if such a control law is feasible, it would generate increased operational costs for the aircraft. Assigning time slots very early in the flight leads to non-optimum cruise

* In queuing theory traffic intensity is defined as the ratio of the arrival rate to the service rate.

speeds and may prevent utilization of the most economical flight level. The above aircraft operational costs must be balanced against the penalty of assigning slots too late, in which case holding patterns or radical speed changes are required whenever "clumping" of arrivals occurs.

C. Weather Effects

The most persistent and severe effects on air traffic operations are associated with weather. Sizeable investments have been made in equipment which seeks to provide all-weather landing capability and all-weather facility availability. Progress along these lines will certainly continue, but additional attention to weather is important for future ATC systems. In some areas the level of traffic approaches the limits of system capability, thus a greater sensitivity to disturbances is induced even as the techniques for dealing with those disturbances become more sophisticated.

As an example of the complex control problems which arise, consider the effect of a line of thunderstorms located near a terminal area. In the current system the information available to the pilot from the airborne weather radar is usually superior to information available to the controller. Therefore, the pilot is given the privilege of choosing his own flight path between or around the centers of storm activity. Consequently, the detours due to weather are not chosen very far in advance. Thus, radar limitations as well as inadequate capability of weather forecasting hinder strategic planning. Traffic congestion arises when many pilots request similar flight paths or altitudes in order to avoid areas of turbulence. In effect, the presence of storm centers reduces the available airspace and thus aggrevates all of the normal traffic control problems.

D. Disturbance Inputs to ATC Planning

The proper inclusion of disturbances in ATC planning requires studies that accomplish the following:

1. Listing of all disturbances,

2. Defining their characteristics statistically as to:

   a. frequence of occurrence,

   b. duration,

   c. spatial extent,

   d. predictability or forecasting capability,

3. Determining effects on various aircraft, airports, etc.,

4. Investigating detection and data gathering techniques,

5. Investigating elimination or avoidance techniques.

Finally, it should be emphasized that an investigation of disturbances as isolated phenomena is useful only as a preliminary step to the essential tasks of fully evaluating their effect on the air traffic system and of determining the type of equipment and control strategies that are needed to alleviate disturbance-related problems.

V. AIR TRAFFIC DEMAND

The forecast of air traffic activity is an important consideration for developing the fourth generation control system. Distribution of aircraft has a direct effect on the airspace structure as well as on surveillance techniques, control processes, and hardware requirements which are necessary to cohesively develop the control system. Therefore, much care should be exercised to ensure that demand forecasts are statistically accurate and are presented in the most useful form to the control system designer.

Air traffic activity has been studied in some detail by various groups and forecasts have been made through 1995. The most often quoted forecast numbers are those contained in the ATCAC Report [Ref. 1], which considers overall (domestic) air traffic activity for three broad classes of aircraft usages; air carrier, general aviation, and the military.

The bases for forecasts in air carrier activity are more easily derived, since schedules and passenger movements are accurately recorded. Growth characteristics may be postulated by correlation of the existing data base with economic trends, saturation effects, and stability considerations within the overall transportation system. However, in addition to these factors there are areas of potential future activity which should be further examined. These may be summarized as follows:

1. the effect of V/STOL in the already congested hubs,
2. the growth of the air cargo industry and its projected route structure,
3. the impact of international air traffic, the wide body jets, and the SST on major international hubs, such as JFK and LAX,
4. the regional breakdown of traffic patterns to identify high density areas.

The forecasts for general aviation are not as well defined primarily because knowledge of the current use of the airspace by general aviation is limited. It is difficult to correlate flight patterns with aircraft type and usage for this generic class of aircraft. The growth of the general aviation industry has had a supplementary effect on air carrier service, but more often has provided a service that would not otherwise exist. This conclusion implies that greater numbers of general aviation aircraft will be flying into and out of the airspace surrounding major and medium sized hubs. Very little has been done, however, to quantify the potential impact of this effect on segments of the airspace, some of which are already operating near capacity. Therefore, it is important that statistics on current general aviation flying patterns be developed especially in the vicinity of major hubs.

The forecast of military aircraft activity and the resulting demand on the system is not beset with a great number of unknowns. The activity forecast data as presented in the ATCAC Report have sufficient reliability. The

FAA does not forecast numbers of aircraft in the military inventory. For purposes of performing a study it is reasonable to make the same assumptions as the ATCAC made to reflect joint use of airspace by both military and civil users. The major area of consideration for fourth generation studies is one of compatibility and mutual satisfaction of needs.

Although traffic forecasts are an important input to the overall control mechanisms, the development of the control system should not be impeded by a lack of useful data. In spite of the inherent limitations associated with available estimates, sufficient conservatism may be introduced to permit the design of a control system that has maximum capacity within the constraints presented by disturbances and fixed elements. In conclusion, we have pointed out the deficiencies in air traffic forecasts but emphasize that although additional work is required before a detailed system evaluation can be attained, the conceptual design of the control system is not limited by these deficiencies.

VI. AIRSPACE ORGANIZATION

The design of the air traffic control system requires a working knowledge of the characteristics of the fixed elements of the system. As previously defined, the fixed elements are certain characteristics of the pilots, aircraft, runways, and the airspace. In this section we present a rationale for structuring the airspace. It is usually necessary to subdivide or structure the airspace in order to guarantee safe, expeditious flow of air traffic in various geographic regions, altitudes, and stages of flight. The present airspace structure has evolved from "see and be seen" and "see and avoid" considerations within the constraints of the two types of flights: IFR flights where separations of controlled aircraft is guaranteed by the control process, and VFR flights where separation is maintained by the "see and avoid" capability. Modifications to the airspace structure have been made in accordance with public opinion, the demands of the air transport industry, and the increasing density of aircraft in certain segments of the airspace. These modifications tend to be in the direction of further structure and/or control which is required to provide safe, expeditious flow of traffic. This trend toward further structure and control is evident in the use of climb and descent corridors and "inverse wedding cakes" for dense terminal regions of the airspace and by the continuing trend to lower the minimum altitude for positive control.

The structure of the airspace for the fourth generation control system should not necessarily be developed according to this evolutionary process. There may be better ways to subdivide the airspace, which will depend on the demand forecasts for fourth generation air traffic, the operation of the control system, and the disturbances which can have a vital effect on the system. Thus, a rationale for structuring the airspace should be developed to coincide with the control philosophy while taking into account demand forecasts and potential disturbances to the system. Many of the same concepts that have already evolved and are presently evolving will likely result from this rationale.

The rationale begins by dividing aircraft into two classes. The first class consists of aircraft in which the pilot is willing to file a flight plan and be constrained to conform to that plan, or an updated version thereof, in order to ensure safe and expeditious flow of traffic. We call this class controlled aircraft. The second class consists of aircraft in which the pilot would prefer not to relinquish flexibility and/or achieve the level of proficiency required to conform to a flight plan. In the discussion that follows we conclude that this class must be further subdivided in order to provide for safe air travel.

With these two classes of aircraft there are at most three types of airspace which must be considered: airspace containing only controlled aircraft, called positive control airspace; airspace containing both classes of aircraft, called mixed airspace; and airspace containing only the second class of airspace, called uncontrolled airspace. Consideration of the diverse needs of all of the users of the airspace leads to the conclusion that all three types of airspace are needed in the fourth generation ATC system.

The concept of mixed airspace, in which a portion of the aircraft are allowed to fly randomly with no control except for a few "rules of the road" to provide altitude separation for aircraft traveling in opposite directions, must depend on a "see and avoid" capability of the pilot. "See and avoid" philosophy is of limited value in present day technology where airspeeds of two potentially interacting aircraft are of such a magnitude that the warning time for either pilot is too small to avoid a collision in many situations. Hence, it is concluded that some minimum control should be placed on all aircraft that fly in mixed airspace. No control need be placed on aircraft that fly only in uncontrolled airspace. Thus the second class of aircraft must be subdivided into two sub-classes. We refer to aircraft in which the pilot would prefer not to conform to a flight plan and desires only to fly in uncontrolled airspace as <u>uncontrolled aircraft</u>. We designate as <u>cooperative aircraft</u> those in which the pilot would prefer not to conform to a flight plan but is willing to cooperate with the ATC system to the extent of being subject to some minimum control. To be subject to this minimum control a cooperative aircraft must be capable of receiving and conforming to Intermittent Positive Control (IPC) commands when a potentially hazardous situation exists, as was recommended by ATCAC, as well as conforming to a simple flight plan in certain localities where there is a high density of aircraft. We also refer to mixed airspace, in which there are both controlled and cooperative aircraft, as <u>controlled airspace</u>. The ATCAC Report also uses the terms mixed and controlled airspace interchangeably.

According to this rationale the airspace is organized as follows:

1. <u>Positive Controlled Airspace</u>

   Controlled Aircraft

2. <u>Controlled Airspace</u>

   Controlled Aircraft
   Cooperative Aircraft

3. <u>Uncontrolled Airspace</u>

   Uncontrolled Aircraft

The above subdivision allows for maximum flexibility in developing the control system. Further analyses are necessary in order to account for dense regions of the airspace and to develop the control philosophy for handling a desired if not the maximum flow of traffic. The demand forecast, to some extent, forces further structuring of the airspace similar to the way in which the disturbances and fixed elements influence the structure of the control processes. Our rationale proceeds along these lines. First, however, it is necessary to define some quantities which will be used to determine the airspace structure and to develop the control philosophy. The notation that is used is an extension to that developed by Simpson (Ref. 2).

We define $\vec{P}_i(\rho, \theta, h)$* and $\vec{F}_i(\rho, \theta, h)$ as the <u>position</u> and <u>flight plan</u> vector quantities of aircraft, i, as a function of time. The coordinates of these quantities are range, ρ, from some reference origin; azimuth, θ, from some reference direction; and pressure height, h, above mean sea level. Next we define the difference vector quantity, $\vec{D}(\vec{F}_i, \vec{P}_i)$, which is also a function of time, as follows:

$$\vec{D}(\vec{F}_i, \vec{P}_i) = \vec{F}_i - \vec{P}_i.$$

The vector quantities $\vec{C}_i$, $\vec{H}_{ij}$, and $\vec{S}_{ij}$ which have positive components may be introduced as a measure of conformance, hazard, and separation, respectively. They are defined as follows. If the magnitude of each component of $\vec{D}(\vec{F}_i, \vec{P}_i)$ is less than the corresponding components of $\vec{C}_i$, the aircraft is said to be in conformance with the flight plan. Thus, $\vec{C}_i$ is an upper bound on the allowable deviation from the flight plan that can be tolerated by the control system. Similarly, if the magnitude of any component of $\vec{D}(\vec{P}_i, \vec{P}_j)$ is less than the corresponding component of $\vec{H}_{ij}$, aircraft i and j are said to be in hazardous proximity to each other. Hence, $\vec{H}_{ij}$ may be considered as a

---

* Other three-dimensional coordinate systems, e.g. x, y, z, can be used instead of ρ, θ, h.

hazard criterion or lower bound for measuring a potential collision. Finally, if the magnitude of all of the components of $\vec{D}(\vec{F}_i, \vec{F}_j)$ is less than the corresponding components of $\vec{S}_{ij}$, a conflict in flight plans is said to exist. Thus, $\vec{S}_{ij}$ is a separation standard or lower bound on the allowable separation between the flight plans of two aircraft.

We now define the concept of maneuver volume. First, we define τ_i as the warning time required by aircraft i in which to perform collision avoidance maneuvers in order to avoid a potential hazard. Associated with the position vector $\vec{P}_i$ and its velocity vector $\dot{\vec{P}}_i$ is a finite volume, V_i, which consists of the complete set of all points in space that can be reached by aircraft i within the time interval $(t, t + \tau_i)$ assuming aircraft i is free to perform any turn or acceleration within its capability. This volume is called the maneuver volume and is dependent on the performance characteristics of aircraft i.

In the further development of the airspace structure and control philosophy we will use these definitions and notation. The airspace structure that has been derived thus far is independent of aircraft density. Obviously, density is an important consideration in the overall control process. We now define the terms "high density airspace" and "low density airspace" in relation to the concept of maneuver volume. If the control system permits an overlap of the maneuver volumes, V_i and V_j, of two aircraft which do not have altitude separation greater than the altitude component of $\vec{S}_{ij}$, we refer to this as "high density airspace." Otherwise, it is called "low density airspace." The control processes for each density airspace are different. For example, the control for "high density airspace" must be accomplished by monitoring the conformance or the deviation from a specified flight plan. Deviation from or changes in a flight plan **must** be minimal within high density airspace. If the control system permits maximum freedom, potential hazards will exist in high density airspace. They must then be resolved by the pilot. The airspace surrounding some approach and departure control sectors are examples of high density airspace. Part of the enroute environment may necessarily reach high density in order to meet fourth generation traffic demand forecasts.

The control for low density airspace may be accomplished either by insuring conformance to a flight plan or by looking for potential hazards which allows for greater flexibility in the choice of flight plans. The issue of which approach is more attractive is discussed in a later section. These considerations lead us to a structuring of the airspace as shown below.

1. <u>Positive Controlled Airspace</u>
   - a. High Density Airspace
     - Controlled Aircraft
   - b. Low Density Airspace
     - Controlled Aircraft
2. <u>Controlled Airspace</u>
   - a. High Density Airspace
     - Controlled Aircraft
     - Cooperative Aircraft
   - b. Low Density Airspace
     - Controlled Aircraft
     - Cooperative Aircraft
3. <u>Uncontrolled Airspace</u>
     - Uncontrolled Aircraft

In summary, the general airspace structure which has been derived forms a basis from which the control system can be developed. It should be emphasized that further development of the control system may reduce or modify the airspace structure as defined above to a form which is compatible with the control processes, the surveillance techniques, and the hardware and equipment required for fourth generation air traffic control.

The fundamental issues regarding further structuring of the airspace involve specifying the types of flight trajectories such as 1D, 2D, or 3D,*

* The terms 1D, 2D, and 3D are used to classify the amount of freedom permitted in choosing a flight plan. 1D permits usage of only certain paths or airways, 2D permits considerable freedom in two dimensions and 3D permits freedom in three dimensions.

that will be permissible in the above categories of airspace as well as determining altitude and geographical locations of these categories. The location of the high density airspace depends primarily on the traffic demand but may also depend upon weather conditions and wind velocities, since the choice of optimum flight paths are affected by disturbances of this kind. Although the concept of 4D is an important area of study for fourth generation air traffic control, it is not included as a type of flight trajectory because the concept of 4D as used in this report relates chiefly to the method of control rather than to the structuring of the airspace.

VII. MAJOR CONTROL FUNCTIONS AND OBJECTIVES

A. Objectives

An air traffic control system exists to satisfy the needs of aircraft operators while honoring certain obligations to that extended part of society which air traffic affects. The first interest of government and operators alike is air safety, a quality esteemed for economic, political, and ethical reasons. But even the most reasonable safety regulations tend to have significant influences on the capacity of the air traffic system and may result in excessive cost and inconvenience to air system users. For this reason, a large number of proposals have been presented for ATC improvements which would allow more efficient air traffic operations while maintaining the excellent safety record of the current system.

In considering the benefits which might accrue from the introduction of new ATC techniques, one must be cognizant of the multitude of forces which can influence the way in which the system is operated. Safety requirements must be carefully evaluated. A single accident--no matter how unlikely the circumstances of its occurrence--may produce changes in the control procedures. It will also be necessary to show that air traffic planning has considered problems of noise reduction and has made efforts to reduce the noise levels associated with airport proximity to densely populated areas. Due thought must be given to user conflicts which occur when servicing one user at a given facility results in refusal of service to another. When this occurs, it may be necessary to establish some basis of priority other than first-come-first-served.

Ideally, an air traffic system should accommodate the widest variety and greatest numbers of users at a minimum of expense to each. In working toward this end it is necessary to devise control strategies which optimize the capacity of each proposed ATC system. Unless the control strategies are properly formulated, the prediction of capacity improvements for a given investment may err significantly.

In this section the major ATC functional areas will be briefly discussed. The goals of the ATC system in a given type of airspace may be attained by implementing only one function, for example, collision avoidance in mixed airspace. In other areas all functions may be important.

B. Collision Avoidance

One form of a collision avoidance system senses hazards between aircraft and issues warnings or instructions which serve to avert danger. A hazard has been previously defined in terms of a required separation in one or more dimensions between aircraft. The other form of a collision avoidance system monitors conformance to a conflict free flight plan. It is discussed in a later section on conformance monitoring.

In order to provide a reasonable time period for the execution of collision avoidance maneuvers it is necessary to project the motion of aircraft into the future. This projection and associated computations establish a hazard volume, U_i, defined by the locus of all points which, from the perspective of the control system, represent the aircraft position, $\vec{P}_i$, at time τ_i into the future. The system must now recognize a hazard for aircraft i and j if the shortest vector from a point in U_i to a point in U_j is less than $\vec{H}_{ij}$, the required separation distance.

The size and shape of the hazard volume depend upon the type of data and projection techniques employed in its generation. Because the volume must be conservatively defined, the use of incomplete data or crude projection techniques tends to increase its size. Conversely, greater sophistication in its generation allows its size to be decreased. Knowledge of pilot intentions would tend to make the hazard volume smaller than the previously defined maneuver volume, V_i, and lack of accurate knowledge of the aircraft velocity would tend to make it larger than V_i.

In any event, imperfections in the system lead to the issuance of a certain number of unnecessary commands (or false alarms), which can cause inconvenience to pilots. For ATC purposes the efficiency of the system can be measured by the command ratio, which is the number of commands given by the system divided by the number which are truly necessary.

Figure 2 indicates several ways in which the hazard volume may be defined. In general, the more data that is available and the more sophisticated the projection techniques, the smaller the hazard volume will be. In designing a practical system it may be necessary to employ several different techniques for defining the hazard volume. Those procedures which require less computer time may be exercised often with the more complicated techniques being applied only when a hazard is declared at a lower level. This ensures that a hazard must meet the most sophisticated criteria that the system can evaluate before a command is issued to the pilots.

The hazard volume may increase rapidly with longer warning times due to the possibility of aircraft maneuvers. For this reason it may be desirable to introduce a statement of pilot intent into the hazard evaluation process. For instance, suppose the aircraft under consideration replied to interrogation with beacon codes which served to indicate intentions to maneuver or which indicated "cruise conditions." The cruise indication could be interpreted as meaning "I intend to continue to fly at my current course and heading." The hazard volume for such an aircraft could be greatly reduced, thus providing greater freedom for those aircraft which reserve the right to maneuver.

Steps which might be taken in order to reduce the number of collision avoidance commands are listed in Table I. Certain techniques would obviously

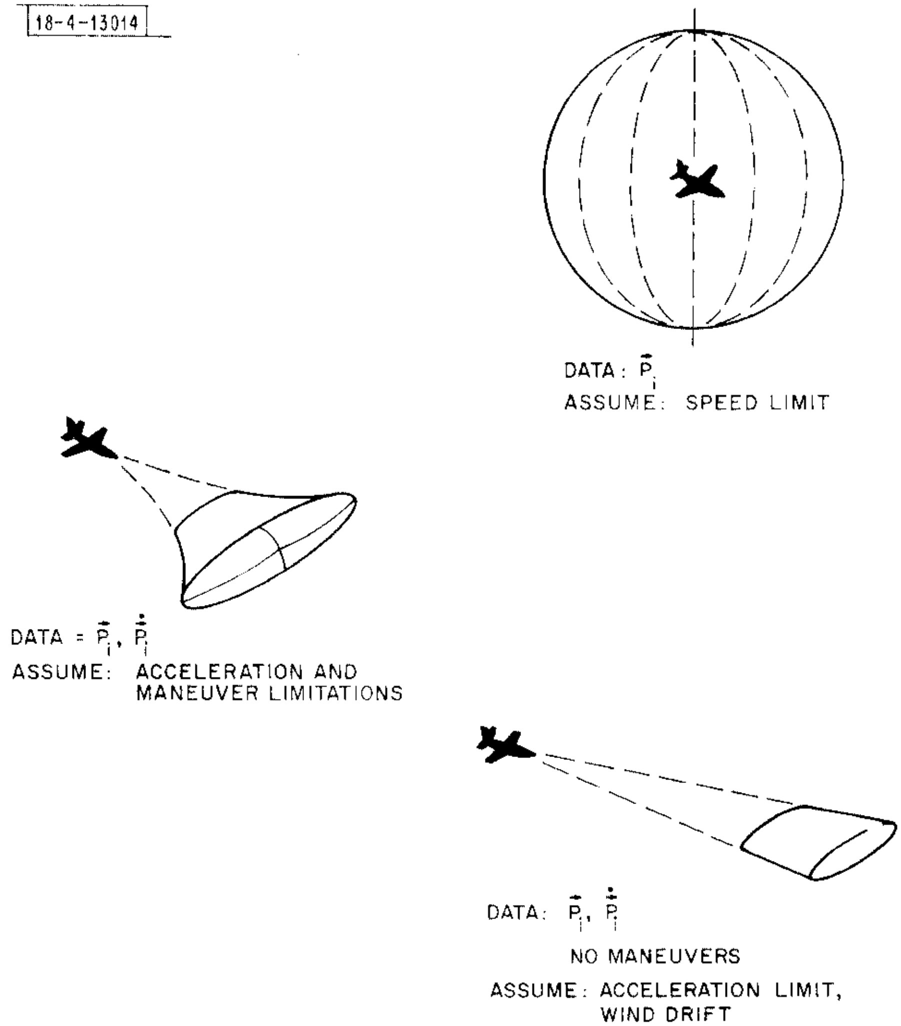


Fig. 2. Hazard volumes which can be used in monitoring hazards.

be un-acceptable except where a high frequency of commands produces serious inconvenience or hinders certain air operations.

C. Flow Control

Flow control can be defined as that ATC function which attempts to regulate the flow of traffic in various parts of the system in order to permit the highest level of usage of available facilities with a minimum of cost and inconvenience to aircraft operators. The degree of planning involved depends upon the sensitivity of the system to flow fluctuations and the levels at which the various parts of the system become saturated. Further discussions of flow control issues are presented in Section VIII. E. and in Appendix C of this report.

TABLE I

Techniques for Reducing the Frequency of Collision Avoidance Commands

TECHNIQUES	COMMENTS
Employ Additional Data	Position, $\vec{P}_i$, is minimum level of data. May also use speed or velocity, doppler, etc. Implementation depends on capability of surveillance and data processing systems.
Use more sophisticated projection techniques	May require more data, more data processing.
Minimize warning time	Response time of pilot and aircraft will determine a minimum safe warning time.
Employ pilot intention indicator	May not be used by all aircraft in the airspace.
Order airspace, regulate maneuvers, etc.	Reduces relative velocities between aircraft. Restricts pilot freedom.

D. Conformance Monitoring

A high degree of airspace organization and traffic planning can be achieved in positive control airspace due to the fact that all aircraft proceed on flight plans which are known to the ATC system. However, due to various disturbances and navigational errors aircraft will deviate to some extent from their intended flight paths. The degree to which an aircraft is able to follow its flight plan is termed conformance.

The possibility now arises that all conflicts can be eliminated simply by assigning flight paths which are separated by sufficient distances from each other. The separation required obviously depends on the ability of the aircraft to conform to the flight plan or on the capability of the ATC system to detect and correct deviations.

When aircraft deviate significantly from the flight plan due to navigational errors or disturbances, the ATC system must detect and react to this deviation. The aircraft may be sent conformance commands which serve to restore it to the original flight plan. On the other hand, the aircraft may be given a new or modified flight plan which does not require it to "chase" its former flight plan position.

Figure 3 illustrates the way in which control might be exercised for an aircraft which proceeds on a flight plan. When an aircraft deviates from its assigned path there are two options. Either the aircraft must be made to come back into conformance with the flight plan or the plan must be changed. The various parts of the system which are involved with changing the flight plan constitute the command loop. Those parts of the system which are involved with keeping the aircraft in conformance with this plan constitutes the control loop.

E. Flight Plan Generation

The generation of an acceptable flight plan for a particular aircraft involves considerations other than conflicts. The following list suggests possible inputs to the flight plan selection process:

1. conflicts,
2. cost-optimum flight profile,
3. flow control decisions,
4. weather hazards,

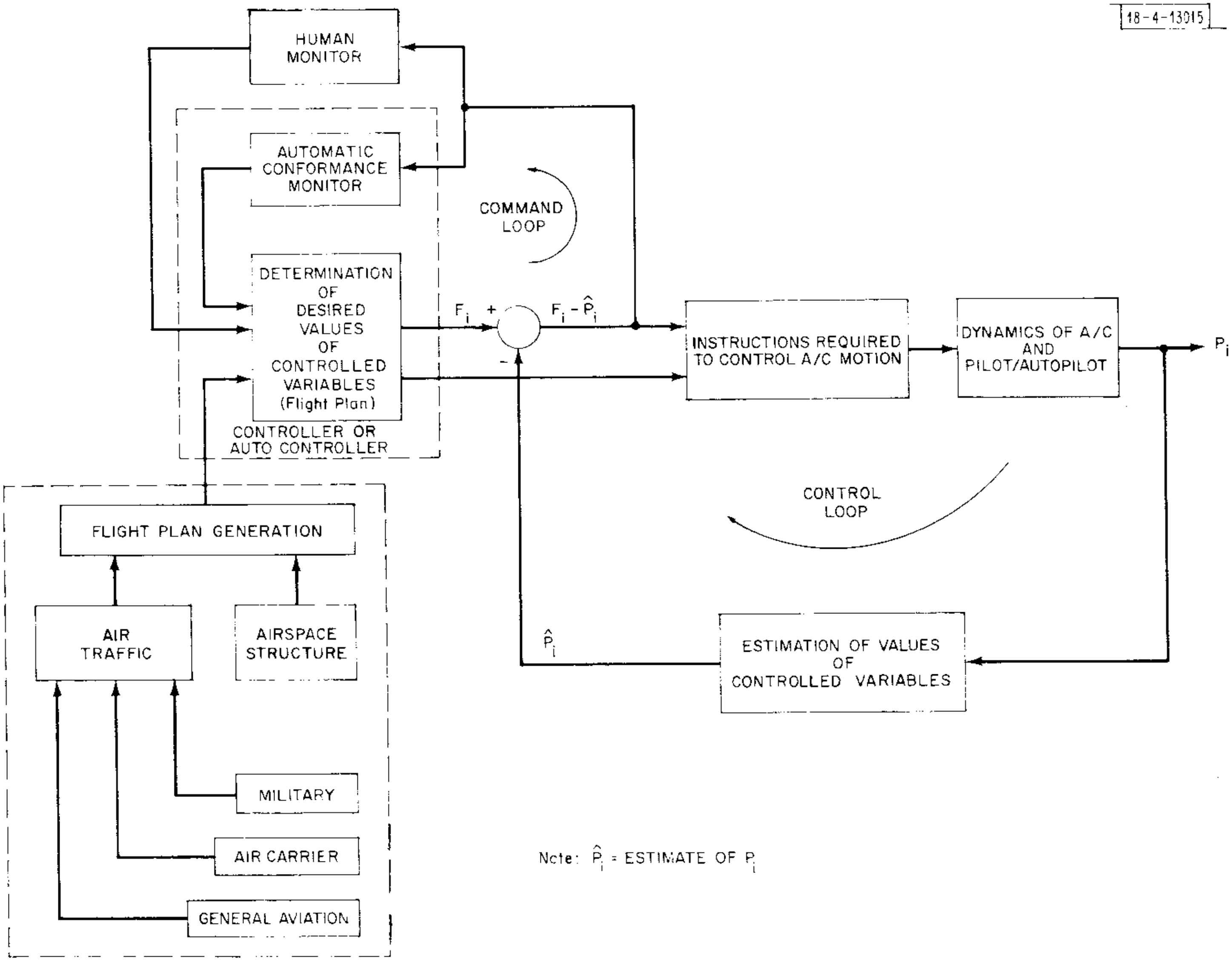


Fig. 3. Air Traffic Control system.

5. navigation and/or stationkeeping capability of the particular aircraft,

6. isolation (attempt to minimize interaction with other flight paths),

7. special user requests.

Particular attention must be given to situations in which flight plan generation may not proceed in series, i.e., one flight plan at a time. This may occur when there is an unanticipated decrease in capacity at a particular airport. The status of all aircraft which are destined to that terminal must be evaluated en toto in order to decide on a modified flow control strategy for that particular anomalous situation. The speed with which new flight plans can be generated and sent to aircraft may determine the ease with which such perturbations are handled.

F. Integration of Functions

In this section we have divided the control actions into functional categories such as collision avoidance, flow control, conformance monitoring, etc. In certain cases the goals of the ATC system may be achieved by concentrating on only one function, such as collision avoidance in mixed airspace. In other cases, all functions may be important.

The interactions between control areas require careful consideration. Resourceful implementation of one function may make another function easier or partially eliminate the need for it. Provision must also be made for the transferral in appropriate form of decisions in one area to other interacting areas. Figure 4 provides an indication of the type of integration which may be necessary.

VIII. FUNDAMENTAL ISSUES

In the control area we see six fundamental issues to be investigated. They are discussed in the following paragraphs.

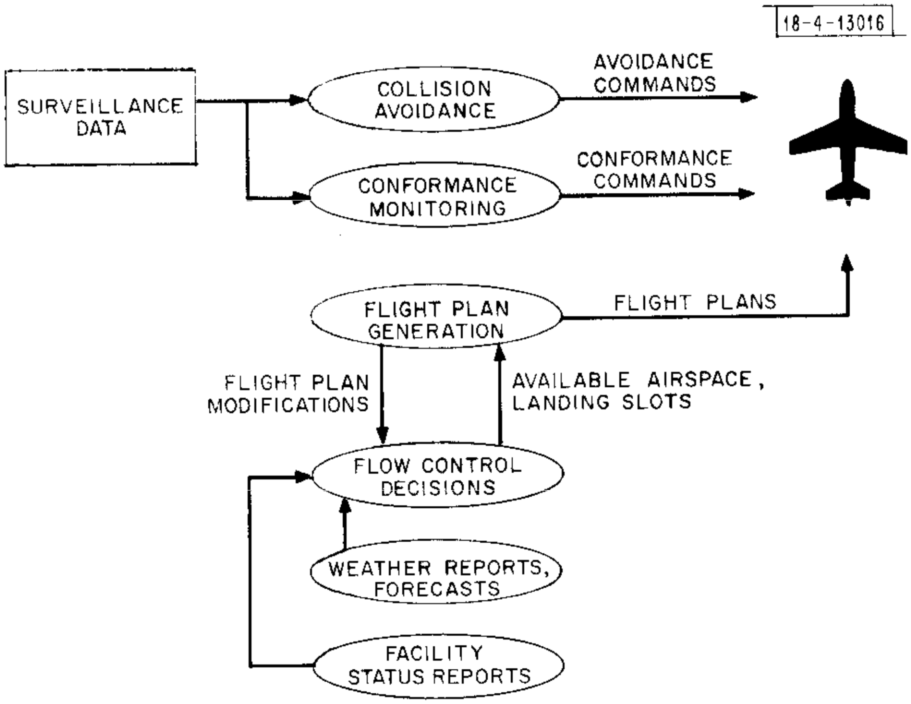


Fig. 4. Basic integration of ATC functions.

A. Strategic vs. Tactical

Before we begin discussing the problems of choosing between so-called strategic and tactical ATC systems, let us define these terms. A totally strategic system is one in which the approved flight plan is followed very closely with no issuance of commands from the ground. At the other extreme, a tactical system is one in which the flight plan has been approved in detail only over a limited geographic area and is frequently being updated from the ground both when the aircraft is traversing a single sector of airspace and when it is moving from one sector to another. These definitions imply that all aircraft under control have been given a specified flight plan. A flight plan is broadly defined to include corrections to an existing flight plan by changes in airspeed, altitude, or vector heading, thus constituting a new flight plan. In addition, aircraft under Intermittent Positive Control (IPC) are given a flight plan over short time periods during which "do" or "don't" commands apply.

In terms of the command and control loops of Fig. 3, totally strategic control implies that the command loop is never exercised by the ground controller, i.e., no revised flight plan is issued while the full burden of control is placed on the control loop. In the perfectly tactical case the command loop is exercised very often and the control loop is exercised by requiring the aircraft to rigidly follow a flight plan only under certain conditions, e.g. in the event of a potential collision or while being "vectored" in the terminal area.

There is a continuum of levels between the two extremes of strategic and tactical which really involves two issues. They are the frequency with which flight plans are changed and the geographical extent over which these plans are examined in detail for conflicts and then approved. From the continuum of levels between these extremes some optimum system must be chosen to provide a safe and expeditious flow of air traffic.

There is a question as to where 4D control, i.e., control of all three spatial dimensions of the aircraft position as a function of time, is needed, whether it be strategic or a tactical system. In the present system 4D control is essentially used in the final stages of flight in a busy terminal area. The issue of how far back along flight paths should 4D control be exercised must be resolved. There is the possibility of employing a relaxed level of control in the enroute area with 4D control being initiated at a specified distance from the terminal area. This might alleviate the problem of automatically sequencing aircraft onto a runway. Another remote possibility is 4D control throughout the entire flight. It is expected that the effect of disturbances will be a primary factor in deciding what parts of the airspace and under what conditions 4D control should be exercised.

An important issue for choosing a level between tactical and strategic is that of cost. One factor that affects this cost is the delay of the aircraft in the air. What must be considered is the amount of divergence from the flight plan that is required and the frequency of occurrence of this divergence during an average flight. As the system becomes more tactical one would expect the divergence to become greater and, therefore, the cost of delay to also become greater. However, many other factors enter into the determination of system cost and they must all be considered.

Another important issue is the degree of automation to be employed. The tradeoff between a tactical and a strategic system may be strongly influenced by how much computer workload is required. Future computer capacity limitations are available in the literature as a basis for investigating this issue.

In a system which is closer to the extreme of being totally strategic, the pilot workload might be excessive in meeting the required degree of conformance to the flight plan. Limitations of aircraft performance and/or navigation system accuracy may imply that this mode of operation is not feasible. Conversely, in the tactical extreme, the workload on the controller and/or the automated system required to frequently vector aircraft to avoid conflicts may be excessive. Therefore, an optimization of the system that considers the feelings and capabilities of both the pilot and the controller must be attained.

The degree to which disturbances may alter flight plans and also the frequency of these alterations will certainly be important factors to consider in choosing the degree to which the ultimate system is strategic. The present tactical system gives the controller great freedom in vectoring aircraft around disturbances. In a more strategic system, there is an important question as to the complexity involved in changing aircraft plans to avoid disturbances, whether it is simply a minor flight plan alteration of one or a very small number of aircraft or whether it involves changing the flight plans of a large number of aircraft.

Certain geographical areas in which there are a number of major terminals contain a high density of aircraft. Perhaps the choice of a level between a strategic and a tactical extreme will depend upon the geographical area.

When a part of the ATC system fails whether it be in the aircraft, the surveillance system, or the ground computer, it seems reasonable to believe that the strategic system has an advantage. Since the aircraft is on a predesignated flight plan that is very seldom updated and assuming the pilot can maintain conformance, the aircraft can "coast" for a fairly long time during the failure period with little danger of hazards arising. Of course, beyond a certain time period it may be necessary to employ rules and procedures which involve the use of line formations, landing at the nearest available airport, holding patterns, etc.

B. Responsibility Trade-Offs Between Pilot and Controller

Another fundamental issue relates to the relative responsibility of the controller and the pilot. Referring to the control loop in Fig. 3, it may be desirable that the controller manage this loop only by exception and that he delegate to the pilot the responsibility to conform to his flight plan. However, the controller would exercise the command loop and change flight plans according to conflict situations, hazards, and disturbances. In the event of failure of the pilot to conform to his flight plan, the controller would take corrective action either to insure conformance or to change the flight plan.

C. Degree of Automation

The degree of automation in the ATC system that is feasible and desirable will not be the same for all operating conditions. Thus, the degree of automation is not a simple level but is really a function of at least three variables. These variables are:

1. The severity of any disturbances which is present, i.e., one must determine which disturbances can be handled by automation or semi-automation and which must be handled manually.

2. The flight regime, i.e., one must determine whether the enroute area can be handled automatically and whether the terminal area must be handled in a semi-manual or manual way.

3. The density of aircraft in a particular portion of the airspace.

D. Rules and Procedures to Deal with Failures

Certain rules and procedures must be formulated to deal with the effect on air traffic of failures in the ATC system. This may involve the use of certain kinds of backup equipment either in the aircraft or on the ground. For instance, the possible failure mechanisms may necessitate the installation of stationkeepers in high density controlled airspace and the rule for aircraft to fly in line formations. Override strategies must be synthesized to permit intervention of the air traffic controller. It is necessary to design a system with a small probability of system failure. However, when failure does occur, the situation of long delays and/or the necessity of aircraft landing at airports remote from their predetermined destination may be unavoidable in order to insure safety.

E. Flow Regulation

An important issue is that of flow regulation. First, there is a question as to what part of the airspace (Positive Control, Controlled, etc.), what types of aircraft, and for what destination airports should central flow control by imposed. Then one must determine a cost effective way of regulating the flow of traffic.

The decisions involved here are necessarily complex. Questions arise as to how far into the future planning will be done. Some form of rather imprecise long range planning may be necessary for days in advance. However, the major difficulties appear to be the intermediate range planning in which the time period is long enough for disturbances to affect the system and yet short enough to require definite projections and control. Consideration must also be given to unforeseen changes in crucial parameters such as airport capacity. A general formulation of the decision process for flow regulation is presented in Appendix C of this report.

Planning ability can be increased by making the system less susceptable to disturbances. This can be achieved by proper design of airports, more sophisticated navigation equipment, by improving forecasting ability, and by implementing "hard" control rules which force aircraft to maintain their assigned schedule. The costs and inconveniences involved with creating a more predictable system must be balanced against the resulting increase in system capacity.

F. Collision Avoidance

Another fundamental issue to be addressed is the best manner in which aircraft collisions can be avoided. It is possible that the primary collision avoidance system will be ground based and that any CAS equipment that may be aboard the aircraft will serve as a backup system. There are two methods of providing ground based collision avoidance. In the first method, the control system compares the positions of all pairs of aircraft, predicts future positions with or without the aid of a flight plan, and detects and resolves the hazards resulting from close proximity of aircraft. In the second method, the control system generates conflict free flight plans for all aircraft and assures that they are controlled to conform to the flight plans, thus insuring that no collisions occur. These two methods must be examined in detail to determine their level of safety and ease of automation. Economic implications of these methods must be examined. It is likely that the first method will be used in all controlled and positive control airspace as a primary mode when the second method is not employed and as a backup mode when the second method is employed.

APPENDIX A

AIRCRAFT CONSTRAINTS AND CAPABILITIES

I. INTRODUCTION

This appendix provides a brief summary of the constraints and capabilities of existing aircraft (A/C) and, to a certain extent, future types of aircraft such as the V/STOL's and SST's. The pilot/aircraft characteristics have a direct bearing upon the design of the command and control loops of the ATC system. Realizing that the great variety of aircraft yields a large range for each of the flight parameters such as speed, maximum pitch angle, etc., we have attempted to obtain limiting values for these parameters which are in consideration of passenger's comfort and are influenced by the past experience of pilots. Much of the information was obtained from the ATCAC Report [Ref. 1], the Conference on Aircraft Operating Problems [Ref. 3], the Lecture Series sponsored by NATO's Advisory Group for Aerospace Research and Development [Ref. 4], consultants at MIT, Aviation Week Magazine [Ref. 5], and an FAA document [Ref. 6].

II. CONVENTIONAL SUBSONIC AIRCRAFT

Let us first consider the so-called Conventional Take-Off and Landing Aircraft (CTOL) which includes both General Aviation and air transport aircraft. A few characteristics of these planes vary to a large degree. One example is the variation of cruising speeds and maximum altitudes between different types of aircraft as shown in Table A.1.

TABLE A.1. Cruising Speed of CTOL A/C

Type	Cruising Speeds (mph)	Approximate Maximum Altitude (kft)
Piston A/C	90 - 315	12
Turboprop A/C	250 - 360	28
Jet A/C	400 - 580	40
Military Jet A/C	up to Mach 3	100

Note: 1 mph = 0.868 knots

The optimum altitude for a particular flight obviously depends upon the range. FAA regulations dictate a 250 knot speed limitation below an altitude of 10,000 feet. There is also a significant variation in the stall speed, which is approximately equal to the minimum speed at which the aircraft can develop lift equal to its own weight. Typical values of this parameter lie in the range of 60 to 120 knots. The runway approach speed is largely dependent upon the stall speed according to the following formula used by pilots:

$$V_{app} = 1.3\, V_{stall} + \frac{1}{2}\,(\text{surface winds}) + \text{reported gusts}.$$

Figure A.1 gives typical values for the reference speed $V_{ref} = 1.3\, V_{stall}$ for today's commercial jet transport aircraft. With regard to the airport-related characteristics of aircraft, there is a large variation in the required runway length and the minimum turning radii on the ground. Table A. 2 gives the range of these two parameters for General Aviation and air transport aircraft.

TABLE A. 2. Runway Lengths and Minimum Turning Radii of CTOL A/C

Type	Runway Length (ft)	Minimum Turning Radii (ft)
General Aviation	525 - 2000	20 - 47
Transport A/C	3,450 - 10,500	64 - 109

The other limitations are very similar for all types of CTOL aircraft. The maximum thrust-to-weight ratio (T/W) is about 0.2 and the horizontal acceleration is less than 0.5g. A four engine subsonic jet has a longitudinal acceleration of 0.1g during takeoff. In maneuvering, the plane is subjected to a lift acceleration of less than 2g. Mild turbulence produces a force of about 0.1g on the aircraft while severe clear air turbulence and thunderstorms may cause the lift acceleration to vary as much as 2g peak to peak. An aerodynamic limitation associated with an airfoil is the maximum angle of attack (angle between the velocity vector and the attitude of the aircraft) or "stall angle" beyond which the wings no longer produce a lift force. This angle is about

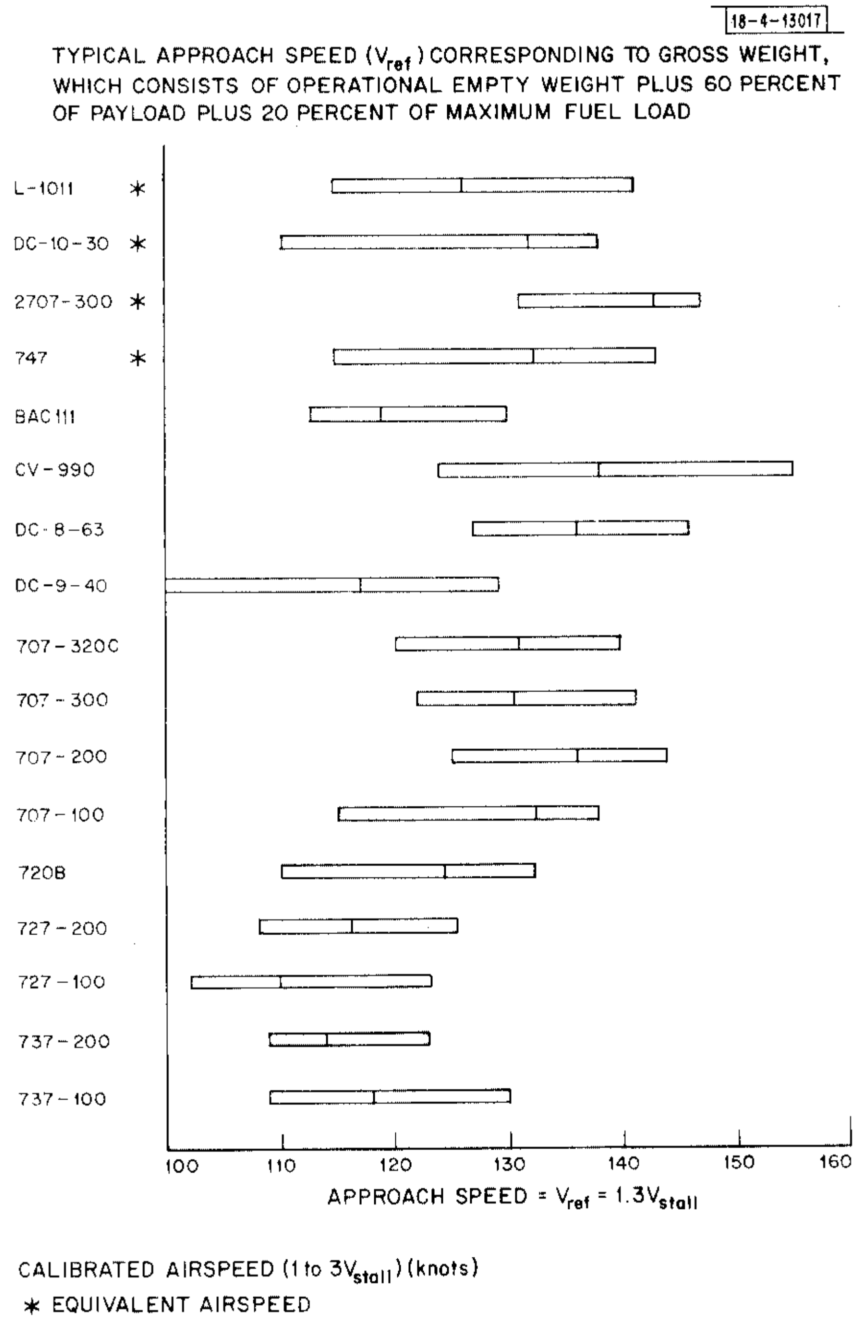


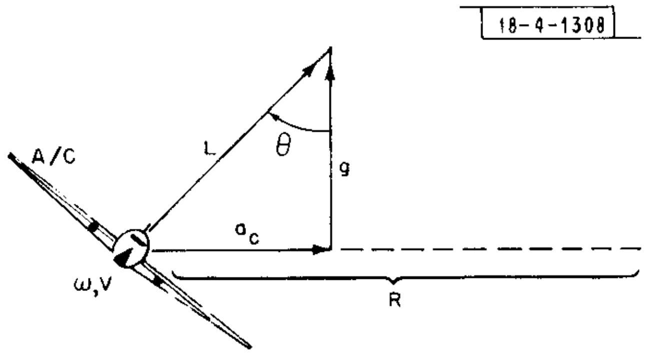
Fig. A-1. Typical approach speed (V_{ref}) for various commercial jet transport aircraft [Ref. 1].

20°. During takeoff and in normal flight conditions, the plane's pitch attitude (angle between the horizontal and the attitude of the aircraft) is held to less than 15°.

Three important aircraft parameters needed in the design of a collision avoidance system (CAS) are the maximum vertical rates, the maximum turn rate and bank angle, and the required minimum warning time which includes the total delay time in getting a maneuver initiated and the actual maneuver time. The normal sustained rate of climb depends largely upon altitude; below 20,000 ft. it is between 1500 and 2000 ft./min. while at greater altitudes it may become as low as 600 ft./min. Idle power clean descent is approximately 300 ft./mile with the descent angle being about 3 degrees; these numbers are about doubled with either gear or airbrakes extended. The maximum rate of climb or descent over a short time period can be as high as 5,000 ft./min. with a vertical acceleration of about 1/4g. Therefore, in an ATC system there should be protection against relative values of these parameters between aircraft of 10,000 ft./min. and 1/2g, respectively. The maximum turning rate is approximately 3°/second with the banking angle held to less than 30° primarily for the passengers' comfort. The relationships between the various parameters associated with a turning maneuver is shown in Fig. A.2. The total warning time needed for an aircraft to make a maneuver in order to avoid a collision is about 30 seconds and can be broken up into its constituent parts as shown in Table A.3.

TABLE A.3. Breakdown of Warning Time Ref. 1

	Time (seconds)
Data Interval	4
Pilot Reaction	3
Aircraft Reaction	1
Rollout	2
Computation	2
Total Delay	12
Maneuver Time	19
Total Warning Time	31



$$a_c = \frac{V^2}{R} = \omega^2 R$$

$$\omega = \frac{g \tan \theta}{V}$$

$$R = \frac{V^2}{g \tan \theta}$$

θ = bank angle; ω = turning rate;

L = lift accel.; R = radius of turn;

a_c = centripetal accel.; V = velocity of A/C;

g = accel. of gravity = component needed in order for condition in which wings support weight of aircraft (no loss in altitude)

Fig. A.2. A/C parameters in turning maneuver.

The ability to control speed is very important for air terminal sequencing and approach control as well as for a working collision avoidance system. Contemporary A/C air speed indicator systems have an instrument accuracy of approximately 5 knots (1σ) at 240 knots indicated. This produces a position error (single airplane loss in separation) of 3.1 seconds (1σ) per 10 n.m. of flight. Thus the instrument error alone (not including pilotage or wind effects) for a 30 mile approach would contribute a loss in separation of 13.4 seconds (1σ) between adjacent aircraft. Since the spacing error increases with flight time and there is difficulty in causing an aircraft to arrive at a given point at a predetermined time, it is recommended that air speed not be used for control purposes. A better technique is the use of ground speed which can be controlled by doppler radar navigation, DME, area navigation, or precise navigation. Measurement accuracies for these various methods are given in Table A.4.

TABLE A.4. Performance of Aircraft Velocity Instrumentation Ref. 1.

Technique	Accuracy (1σ)	Error after 30 n.m. flight[1]
Doppler ground speed	1.22 kts	2.29 sec.
Inertial ground speed	4.0 kts	7.5 sec.
DME ground speed	2.25 kts	4.22 sec.
DME (Time to waypoint)	0.2 n.m.	3.0 sec.[2]
Precision Nav. (Time to waypoint)	0.05 n.m.	0.75 sec.[2]

[1]Error in arrival time after 30 n.m. flight at 240 knots due to errors in distance or velocity sensor measurement.

[2]Independent of distance flown.

In a controlled approach, it may be necessary for the speed to be changed using autothrottle on the aircraft. Typical responses to speed change commands based on simulator operations of two types of contemporary aircraft are shown in Table A.5.

TABLE A.5. Response to Speed Change Commands Ref. 1

Speed change (knots)	Time to achieve 90 percent of speed change (seconds)	
	Airplane A	Airplane B
+5	12	10
+10	15	13
+15	19	17
+20	25	20
-5	19	24
-10	33	35
-15	50	48
-20	54	64

The altitude coordinate is currently supplied only from the aircraft via radio or transponder. There are three separate errors associated with the measurement of this quantity: the instrument error; the installation error; and the flight technical error. The installation error is largely dependent upon the location of the static pressure sensor on the body of the aircraft. This error may be considerably reduced by the use of externally mounted pitot - static tubes which are compensated for errors associated with a particular location. Associated with random deviation from the intended altitude is the flight technical error, which increases with increasing turbulence and is nearly twice as large when the plane is flown manually as when the auto-pilot is used. Present day and possible altitude errors are given in Table A.6.

TABLE A.6. Altitude Error (3σ in feet) Ref. 1

At sea level

Error	General Aviation[1]	Transport[2,3]		Possible[4]
Instrument	20	20	20	20
Installation	150[5]	250	90	75
Flight technical	600	250	250	250
Total	620	355	265	260

At 40,000 feet for transport, 10,000 feet for general aviation

Instrument	80	230	230	80
Installation	250[5]	750	250	115
Flight technical	600	250	250	250
Total	655	800	420	285

[1]Based on use of minimum required IFR altimeter, no correction for static system error, and no autopilot, these conditions are representative of majority of general aviation aircraft.

[2]Based on use of minimum required IFR altimeter, no correction for static system error, and autopilot with altitude hold; these conditions are representative of older types of transport aircraft.

[3]Based on use of minimum required IFR altimeter, correction for static system error based on manufacturer data and autopilot with altitude hold, these conditions are representative of newer types of transport aircraft.

[4]Based on use of best currently available equipment, calibration techniques, and autopilot with altitude hold.

[5]These are assumed values since little significant test data are available for this category of aircraft.

III. V/STOL AND STOL AIRCRAFT LIMITATIONS

Before discussing the limitations of these aircraft, some definitions of the terms VTOL, STOL, and V/STOL should be given. VTOL means vertical take-off and landing. STOL means short take-off and landing and refers to an A/C which requires some take-off and landing run. The term V/STOL refers to an A/C that can perform either vertical or short take-offs and landings. Although VTOL and V/STOL are sometimes used interchangedly in the literature, the above definitions are adopted here.

The fundamental operational differences between conventional aircraft and V/STOL aircraft can be derived from Figure A.3, which illustrates how the lift and power of the A/C depend upon the airspeed. For the conventional A/C operating above the stall speed, the airplane is supported entirely by aerodynamic lift

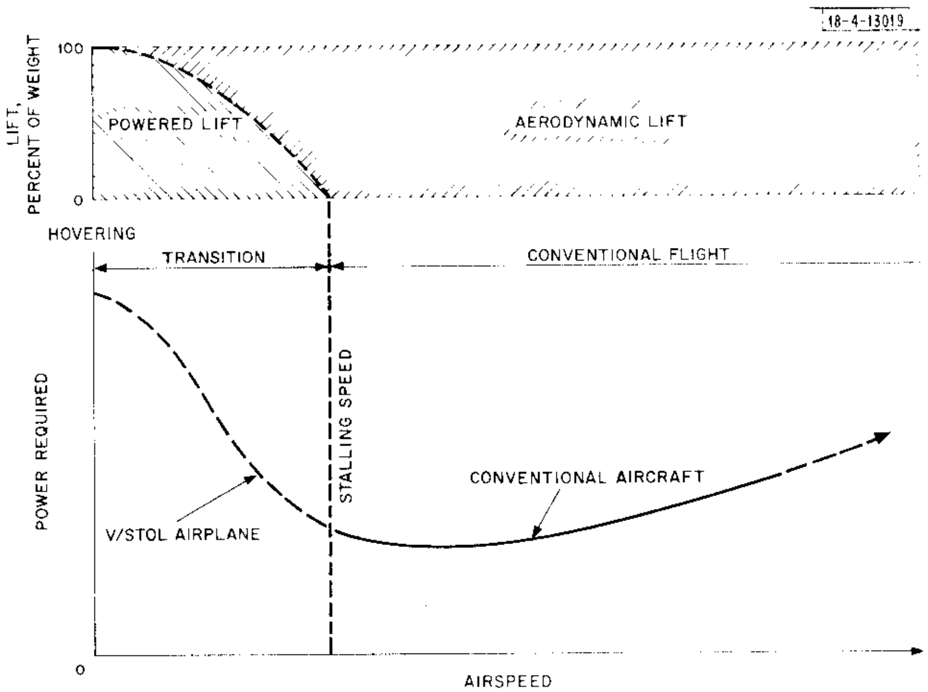


Fig. A.3. Lift and power vs airspeed [Ref. 3].

provided by the wing. However, for the V/STOL aircraft which can operate below conventional wing stalling speeds on down to hovering flight, the aerodynamic lift is gradually replaced by powered lift as the velocity is decreased and, at the same time, the required power rises rapidly to a maximum in the hovering condition. STOL aircraft only go part of the way up the power-required curve to obtain a modest reduction in stalling speed from a modest increase in power. A typical stall speed for such an A/C is about 50 knots. Final approach speeds and take-off speeds are on the order of 60-65 knots. For V/STOL's the final approach speed is usually about 45 knots. The maximum speeds of the most popular VTOL's, namely the helicoptors, range between 86 mph and 168 mph. Cruise speeds of other types of V/STOL's and STOL's are in the range 150 - 500 mph.

The higher power required by V/STOL aircraft in hovering flight results in very high fuel consumption. Therefore, especially for the higher performance V/STOL types, such as the turbojet configurations, the hovering times should be kept to a minimum and long periods of vertical climb or descent during take-off and landing operations should be avoided. Typical take-off and landing profiles for both V/STOL and conventional aircraft are shown in Figure A.4. The maximum landing approach angle for V/STOL's is about 15° and the maximum climb-out angle is 20°. The runway length required by V/STOL's is about 500 feet and that required by STOL's is between 1000 and 2000 feet.

Maximum rates of turn, bank angles, and speed change rates for passengers' comfort have not yet been specified since most of the V/STOL's and STOL'S have not yet

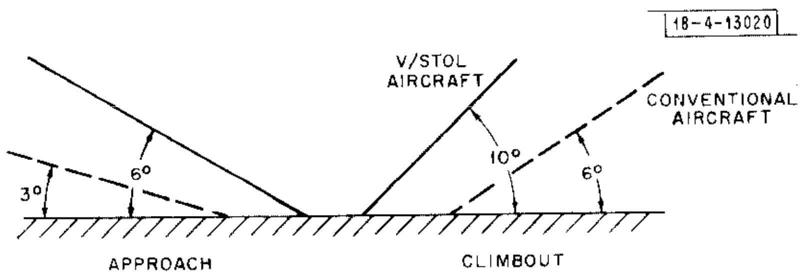


Fig. A.4. Take-off and landing profiles [Ref. 3].

reached operational status. However, it is expected that these parameters will not be much different from those of conventional aircraft.

IV. SUPERSONIC TRANSPORT (SST)

The Concorde SST built jointly by England and France is a Mach 2 aircraft which is currently being flight tested. It remains to be seen whether the American SST, which is proposed to be a Mach 3 aircraft, will ever be built. In comparison with the subsonic jet on take-offs, the SST has a higher longitudinal acceleration and a greater pitch attitude as shown in Figure A.5. The maximum thrust to weight ratio T/W is about 0.44, which is about twice the ratio for a subsonic jet. Take-off speeds are 180-200 knots with the cabin floor angle being 16° - 18° for the first minute and leveling to 8° - 9° on climbout. The maximum angle of attack during normal flight operations is about 18° and the maximum rate of climb is about 8,000 ft./min. Cruise altitude will be between 50,000 and 70,000 feet with the maximum range being

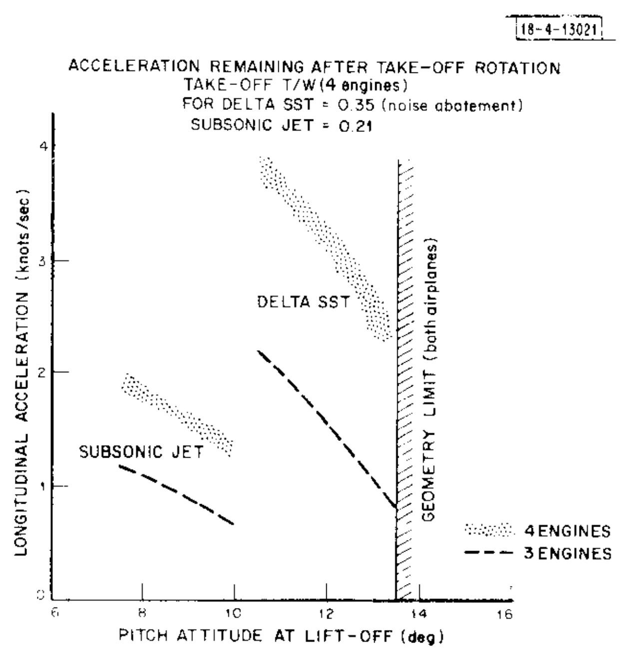


Fig. A.5. Longitudinal acceleration and pitch attitude of SST's and subsonic jets [Ref. 3].

3,500 n.mi. In the terminal area the fuel consumption will be high at speeds currently set for subsonic jets. During the Concorde test flights, the approach speeds have been about 160 knots at 230,000 lb. landing weight. Because of vortices, a 1 minute separation standard for arrivals and departures is required.

APPENDIX B

POTENTIAL DISTURBANCES

Disturbance	Effects (By Likely Classes)
Atmospheric Conditions	
Thunderstorms	B
Weather Fronts	B
Fog	C
Icing	B
Wind Changes	A, B, C
Snow/Ice on Runways	C
Clear Air Turbulence	A, B
Gusts and Turbulence in Approach Zone	A, C
Special Operations	
Presidential Flights	A, B
AEC Flights	A, B
Search and Rescue	B
Flight Test Operations	B
Pilot Training	B
Military Operations	B
Airborne Emergencies	
Propulsion Failure	A
Navigation/Communication Problems	A
Fuel Jettisoning	A, B
Aircraft Fire	A
Depressurization	A

Medical Emergency	A
Aircraft Seizure	A
Bomb Threats	A
Loss of Visibility by VFR Pilot	A, B
Bird Collision	A

<u>Difficulties on Ground</u>

Disabled Aircraft on Ground	C
A/C Equipment Malfunctions on Ground	A
Bomb Threats	C
Ramp Congestion	C

<u>Operational Anomalies</u>

Collision Avoidance Maneuvers	A
Intruder Aircraft, Balloons	A, B
Radio Frequency Interference	A
Missed Approach	A, B
Wake Turbulence Encounters	A
Human Errors	A, B, C, D
Noise Abatement Programs	B, C
Maintenance Shutdowns	C, D
Labor Strikes and Slowdowns	A, B, C, D
Power Blackouts	D
Subsystem Failures	C, D

APPENDIX C

FLOW REGULATION

For an aircraft at various stages in its flight, the Flow Regulation System has the following alternatives:

1. Permit the aircraft to proceed at normal speed.
2. Direct the aircraft to change its speed. The new speed must be selected.
3. Direct the aircraft to hold.

The flow regulation system should choose from among these alternatives on a rational basis. It should select the alternative which minimizes a cost function.

Ideally, the ATC system is perfectly safe so that safety does not explicitly appear in the cost function (safety does place certain constraints on system operation). It appears that the cost function will simply be a function of delay* experienced by all aircraft in the system, $\underline{D}$, which results from the outcome of the flow regulation decision O, which in turn is based upon the information available to the flow regulation system, $\underline{I}$. $\underline{I}$ may be a vector with a large number of components. Thus,

$$C = f(\underline{D}, O, \underline{I}).$$

The flow regulation problem, at least conceptually, is simply the problem of deciding which alternative minimizes C based upon the information available (i. e., choosing the value of O which minimizes C). In practice $\underline{I}$, the information available, will not be a complete description of the true state of nature. Two approaches are possible:

A. Categorize unknown effects as random variables and choose O to minimize the expected value of C, E [C.]

B. Ignore unknown effects.

---

*The cost is also a function of the fuel consumed;but the fuel is a function of the flight trajectory and the velocity, all of which are related to delay. In this formulation fuel costs are indicated in the delay. Mathematically, delay can be positive or negative since it is a deviation from an expected flight time.

Approach B yields a very simple "solution". All aircraft destined for a busy runway are scheduled such that if they arrive on time, no aircraft will be delayed at all. If all aircraft do arrive on time the value of the cost function will be zero. In practice the unknown effects are not zero, the aircraft will not arrive on time, and the cost will not be zero.

Approach A yields a decision making feedback control system which, if the unknown effects are modeled correctly in a probabalistic sense, will yield a smaller E [C]than approach B.

This discussion raises a number of questions:

1. What is the exact form of the cost function?
2. How does one model the unknown effects?
3. How much more difficult is it to implement approach A than approach B?
4. How much better is the actual performance, E [C], of approach A than approach B?
5. If the modelling of the unknown effects is done poorly, will approach A actually yield poorer performance than approach B?

Question 1 is addressed in this paragraph. Consider an Air Transport System composed of a very large number, N, of aircraft. We focus on the flow control decision for aircraft i. Assume it costs G_i dollars to delay aircraft i on the ground for one second. Assume it costs A_j dollars to delay aircraft j in the air for one second, $j = 1, 2, \ldots, N$. Let g_i be the time aircraft i is to be intentionally delayed on the ground, a_i be the amount of time aircraft i is to be intentionally delayed in the air, and d_j be the amount of time all aircraft will be unintentionally delayed, $j = 1, 2, \ldots, N$. Then the cost function associated with flow control decisions regarding aircraft i is

$$C_i = G_i g_i + A_i a_i + \sum_{j=1}^{N} A_j d_j . \tag{1}$$

At any given time the outcome of the flow control decision is a choice of g_i or a_i which minimizes $E[C_i]$. Each d_j has three components: a random component d_j^r, a component which depends on present and expected future positions of all aircraft in the system d_j^I, and a component which depends on a_i and/or g_i, d_j^O. Thus

$$E[C_i] = G_i g_i + A_i a_i + E\left[\sum_{j=1}^{N} A_j(d_j^I + d_j^0)\right] + E\left[\sum_{j=1}^{N} A_j d_j^r\right]. \quad (2)$$

The last bracketed term in Eq. 2 is independent of the choice of g_i and a_i so it does not affect the outcome of the decision.

Questions 2 through 5 have not been addressed in detail at the present time. To address them one must understand the type and extent of disturbances experienced by air traffic and must be able to predict future delays that will be caused by other aircraft. In today's system these delays occur in a holding pattern and the problem of predicting the number of aircraft that will be in a holding pattern at some time in the future is of interest.

Perhaps the following example will illustrate some of these ideas more clearly. Consider the decision as to whether to permit aircraft i to depart for a high traffic density airport. The part of the cost function which depends on g_i is

$$E[C_i] = G_i g_i + E\left[\sum_{j=1}^{N} A_j (d_j^I + d_j^0)\right]. \quad (3)$$

The best decision to make depends on the amount of information you have. If you have no information about the positions of any other aircraft, your model of the second term in Eq. 3 will be that it is not a function of g_i. Thus $g_i = 0$ minimizes $E[C_i]$ and aircraft i should depart immediately. But a flow control system will have a great deal of information about the positions of other aircraft.

If at the expected time of arrival of aircraft i at its destination the congestion is expected to be increasing, the second term in Eq. (3) might have the form shown in Fig. C.1.

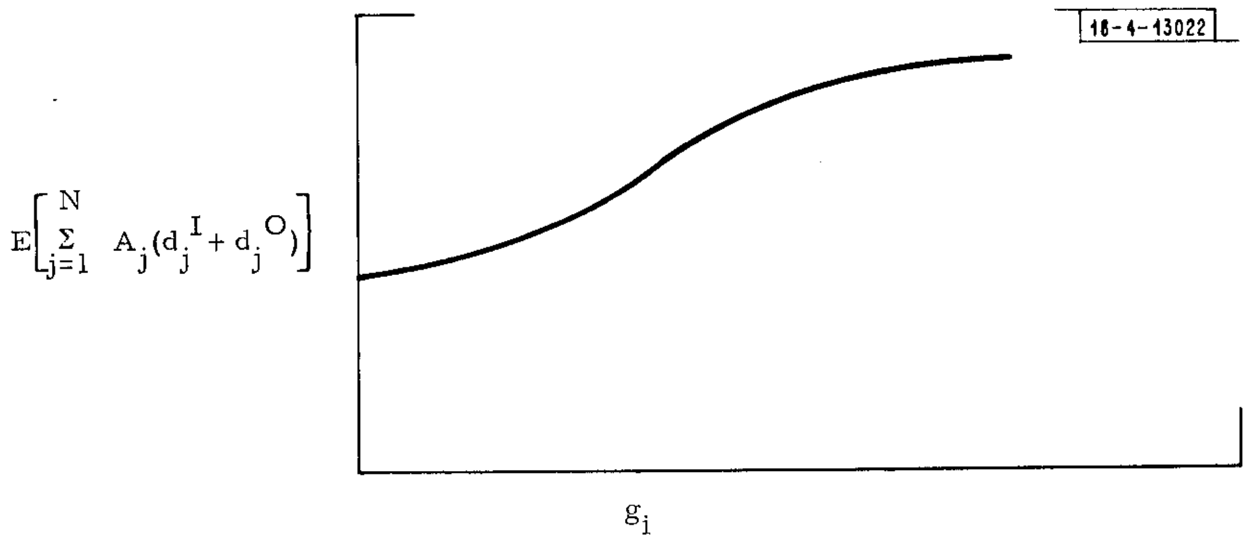


Fig. C. 1.

Then $g_i = 0$ would minimize $E\,[C_i]$.

If at the expected time of arrival of aircraft i at its destination the congestion is expected to be decreasing, the second term in Eq. (3) might have the form shown in Fig. C.2.

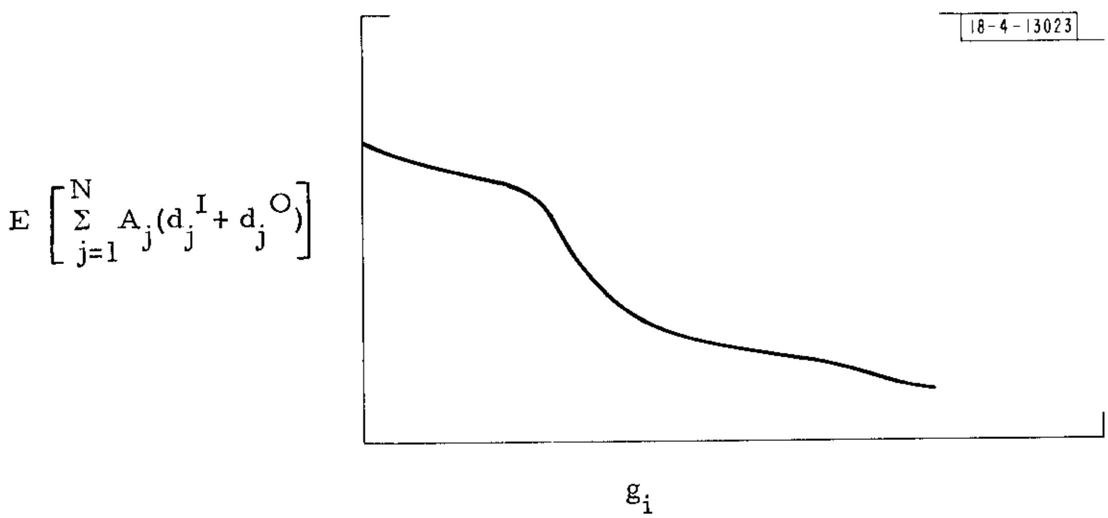


Fig. C. 2.

In this case, depending on the value of G_i relative to the A_j's, $E[C_i]$ might take the form of Fig. C.3 or Fig. C.4. In Fig. C.3, $g_i = 0$ minimizes $E[C_i]$ but in Fig. C.4 a non-zero value of g_i minimizes $E[C_i]$. In the case of Fig. C.4, aircraft i should be held on the ground rather than be permitted to depart. In a well-designed system this should not happen very often.

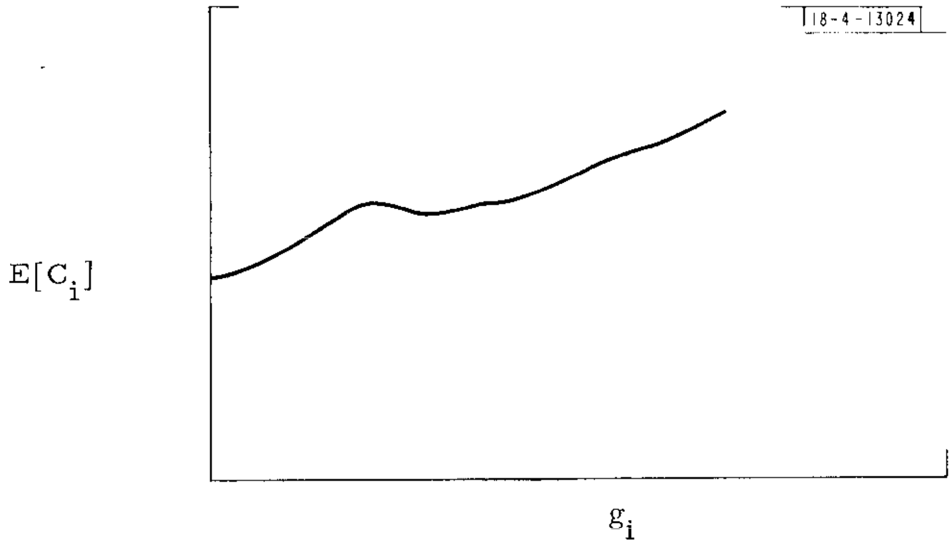


Fig. C. 3.

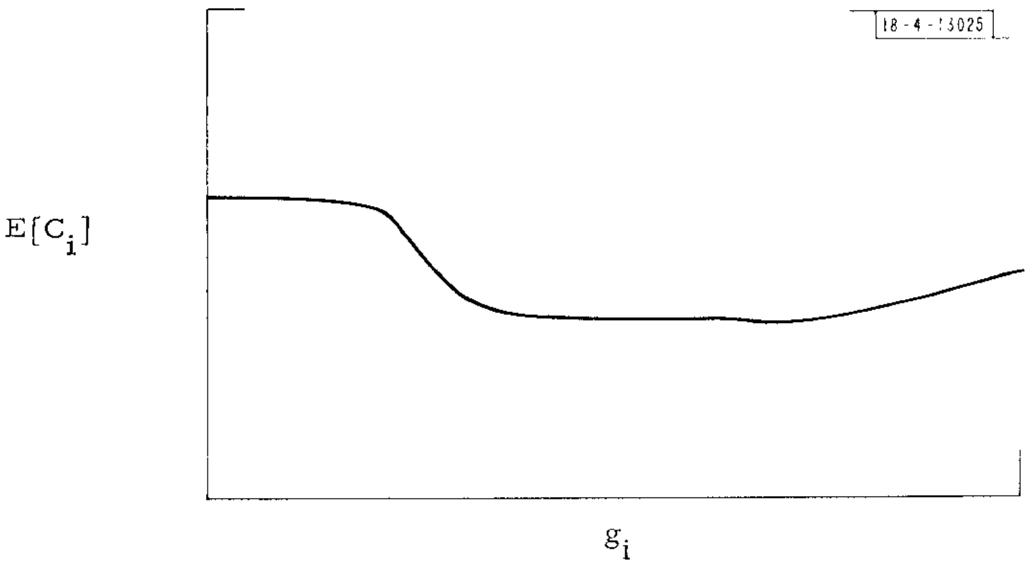


Fig. C. 4.

REFERENCES

1. Report of Dept. of Transportation Air Traffic Control Advisory Committee, Vol. 2, December 1969.

2. R. W. Simpson, Private Communication

3. Conference on Aircraft Operating Problems, NASA-SP-83, Langley Research Center, May 10-12, 1965.

4. The Aerodynamics of V/STOL Aircraft, AGARDograph 126, May 1968.

5. Aviation Week and Space Technology, February 8, 1971.

6. Design for the National Airspace Utilization System, 1st. edition, FAA Systems Research & Development Service, June 30, 1962.