Project Report
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FINAL REPORT

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

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ABSTRACT

A concept formulation study of the control aspects of the fourth generation air traffic control system is presented. The results of this study are not strongly influenced by present-day equipment. They are influenced by certain aspects of present airspace utilization and procedures which appear necessary for the design of an effective system. The inputs to the control system design include the fourth generation air traffic demand, characteristics of fixed elements (types of aircraft, etc.), and disturbances such as weather effects. The control system which has been formulated includes flight plan generation, flow control, conformance monitoring, and collision avoidance as control functions.

A baseline control system is given as a first iteration of the fourth generation system. The baseline system is defined by classifying types of airspace, conformance requirements, and required segregation of classes of flight paths. The airspace is divided into three categories: positive control airspace containing only controlled aircraft, controlled (mixed) airspace containing both controlled and cooperative aircraft, and uncontrolled airspace containing uncontrolled aircraft. Cooperative aircraft must be able to accept IPC commands as well as simplified flight plans when flying in high density mixed airspace. The surveillance, navigation, and communications systems complete the interacting parts of the control system.

Candidate fourth generation system concepts ranging from the completely tactical to the highly strategic have been described both in this report and elsewhere. In order to characterize a proposed concept we have drawn up a list of decisions which we find must be made in the course of a flight. We then consider where these decisions are made and thereby characterize the system.

The feasibility of generating conflict free flight plans is investigated with the aid of analytical models. A consideration of the factors which influence the flight planning process is presented. Use is made of a generally accepted traffic density model for the 1995 time period. The expected number of conflicts for selected routes and the distances required to resolve conflicts are evaluated. The use of aircraft performance characteristics in evaluating the effectiveness of conflict resolution maneuvers is discussed. The level of conformance necessary for conflict free flight plans is determined for each maneuver. For cases in which the required conformance was unrealistically high, it was determined that providing velocity structure in high density airspace permitted a decrease in conformance requirements. Factors which directly influence the capability of aircraft to conform to flight plans in a strategic system as well as the relevant technology areas peculiar to the implementation of conflict free flight plans are considered. The conclusions reached during this study are followed by recommendations for future work in specific areas.

CONTENTS

LIST OF SYMBOLS

a	acceleration or deceleration of aircraft
a'	effective vertical dimension of aircraft
a_o	vertical separation standard
a_c	centripetal acceleration
a_L	lift acceleration
a_i	time aircraft i is to be intentionally delayed in air
A	area
A_j	cost in dollars to delay aircraft j in air for one second, $j = 1, 2, \ldots, N$
AC	number of air carrier flights over the peak hour in the year 1995
b	separation of aircraft that is required, which includes both the minimum separation standards and the conformance errors expected of both aircraft
c	number of conflicts
c'	effective lateral dimension of aircraft
c_I	number of conflicts encountered by one aircraft
c_{II}	number of conflicts per airway intersection
c_{max}	practical maximum number of conflicts expected
c'_{max}	maximum number of resolvable conflicts using model based on equally spaced conflicts
C	cost

C_D	coefficient of drag
C_L	coefficient of lift
$\vec{C}_i$	allowable deviation from flight plan
C_o	speed of sound at sea level
d	separation (in feet) between flight levels
d_j	time all aircraft will be unintentionally delayed, $j = 1, 2, \ldots, N$
D	drag
$\underline{D}$	delay of aircraft
$\overline{D}(\overline{F}_i, \overline{P}_i)$	difference vector quantity $= \overline{F}_i - \overline{P}_i$
$E[C]$	expected value of cost
f_λ	probability density function of free path length
$f_\beta(z)$	probability density function for encounter angle β
$F_i(\rho \ \theta \ h)$	flight plan vector of aircraft i
$F_\lambda(x)$	probability distribution function of free path length
g	acceleration of gravity
g_i	time aircraft i is to be intentionally delayed on ground
GA	number of general aviation flights over the peak hour in the year 1995
G_i	cost in dollars to delay aircraft i on ground for one second
h	altitude
$\dot{h}$	vertical rate of climb or dive

$\dot{h}_c$	rate of climb
$\dot{h}_d$	rate of descent
$\overline{H}_{ij}$	hazard criterion
$\underline{I}$	information available to flow regulation system
IAC	instantaneous airborne count
J	current number of airline flights per day crossing route segment R
k	number of aircraft crossing the route segment R during the time t_s
k_o	uniform distribution value of k
k_{max}	maximum value of k which one can permit and still expect an aircraft to be able to cross with high probability
K	fractional speed deviation
L	lift
m	mean
m_{max}	maximum value of the mean number of conflicts allowed and still expect an aircraft to be able to cross with high probability
M	mach number
n	maximum number of conflicts that can be resolved over the route segment R
n_c	number of airways an aircraft intersects
n_T	number of airways within area A
n. c.	longitudinal non-conformance of aircraft in units of distance

n. c. l.	lateral non-conformance of aircraft
n. c. v.	vertical non-conformance of aircraft
N	number of aircraft in flow regulation system
O	flow regulation decision
p	number of flight levels in mixed airspace
$P(c)$	probability of an aircraft having c conflicts
$\vec{P}_A(t)$	$= \begin{bmatrix} X_A(t) \\ Y_A(t) \end{bmatrix}$ position vector of aircraft A
$\vec{P}_B(t)$	$= \begin{bmatrix} X_B(t) \\ Y_B(t) \end{bmatrix}$ position vector of aircraft B
$\vec{P}_i(\rho, \theta, h)$	position vector of aircraft i
P_{res}	probability of resolving a conflict
PAA	peak airborne aircraft
PAAC	peak airborne aircraft count
q	an integer with values 0, 1, 2, or 3
r	radius of turn
R	length of route segment
R_f	range factor (n. mi. /lb of fuel)
s	distance traversed
S_f	specific fuel consumption
$\vec{S}_{ij}$	separation standard
t	time

t_a	time it takes to change altitude
t_c	time for completing acceleration
t_h	time taken for an aircraft in the high density stream of traffic to traverse a route segment in a given sector of the L. A. Basin
t_o	time required to advance an equivalent distance from destination in undeviated flight
t_s	time required to traverse the route segment R
t_{in}	time to intersection
$t_{n.c.}$	non-conformance of aircraft in units of time
T	net thrust in pounds
T_a	atmospheric temperature
T_o	sea level value of T_a
T_t	total number of intersecting aircraft over the peak hour in 1995 flying between the altitudes of 18,000 and 40,000 feet
T/W	thrust-to-weight ratio
u	constant which includes the wing area
U_i	hazard volume
V	velocity of aircraft
V_A	velocity of aircraft A
V_B	velocity of aircraft B
V_i	maneuver volume

V_r	relative velocity between two aircraft
$\bar{V}_r$	average relative velocity between two aircraft in a given region
V_{app}	runway approach speed
V_{ref}	reference speed for runway approach
V_{stall}	stall speed
$w(\beta)$	frontal width
W	weight of aircraft
W_f	fuel flow in pounds per hour
x, y	cartesian coordinates
x_1	projected horizontal distance in a climb (see Figure 26)
$X_A(t),\ Y_A(t)$	rectangular coordinates of aircraft A
$X_B(t),\ Y_B(t)$	rectangular coordinates of aircraft B
X_D	miss distance
X_P	decrease in distance to destination
α	a constant ≥ 1
β	encounter angle
β_m	mean encounter angle
β_o	maximum allowed heading relative to nominal direction
γ	bank angle
ζ	fractional increase in perceived acceleration
θ	azimuth from some reference origin
κ	fraction of cases in which the free path is $> \lambda_c$

λ	distance to path intersection
λ_c	characteristic length
λ_m	mean free path between encounters
λ_r	conflict resolution distance
$\lambda_r(-)$	conflict resolution distance for the minus speed change
$\lambda_r(+)$	conflict resolution distance for the plus speed change
$g_\mu(z)$	probability density function for the area density of aircraft with a given heading
μ_o	total aircraft density including aircraft at all headings
υ	ratio of mean free path λ_m to the conflict resolution distance
ξ	conflict parameter (see Figure 16)
ρ	range from some reference origin
ρ_a	atmospheric density
ρ_o	sea level value of ρ_a
σ	standard deviation
σ^2	variance
τ	time elapsed in a turn
τ_i	warning time required by aircraft i in order to avoid a hazard
τ_f	time into the future for which a CFFP is generated
ϕ	angle of ascent or descent

ϕ_c	climb angle
ψ	angle pertaining to turn maneuver (see Figures F.1 and F.2)
ω	rate of turn
Λ	dimensionless quantity = $\frac{\rho_a}{\rho_o} \quad \frac{T_a}{T_o}$

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 disturbances. 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.

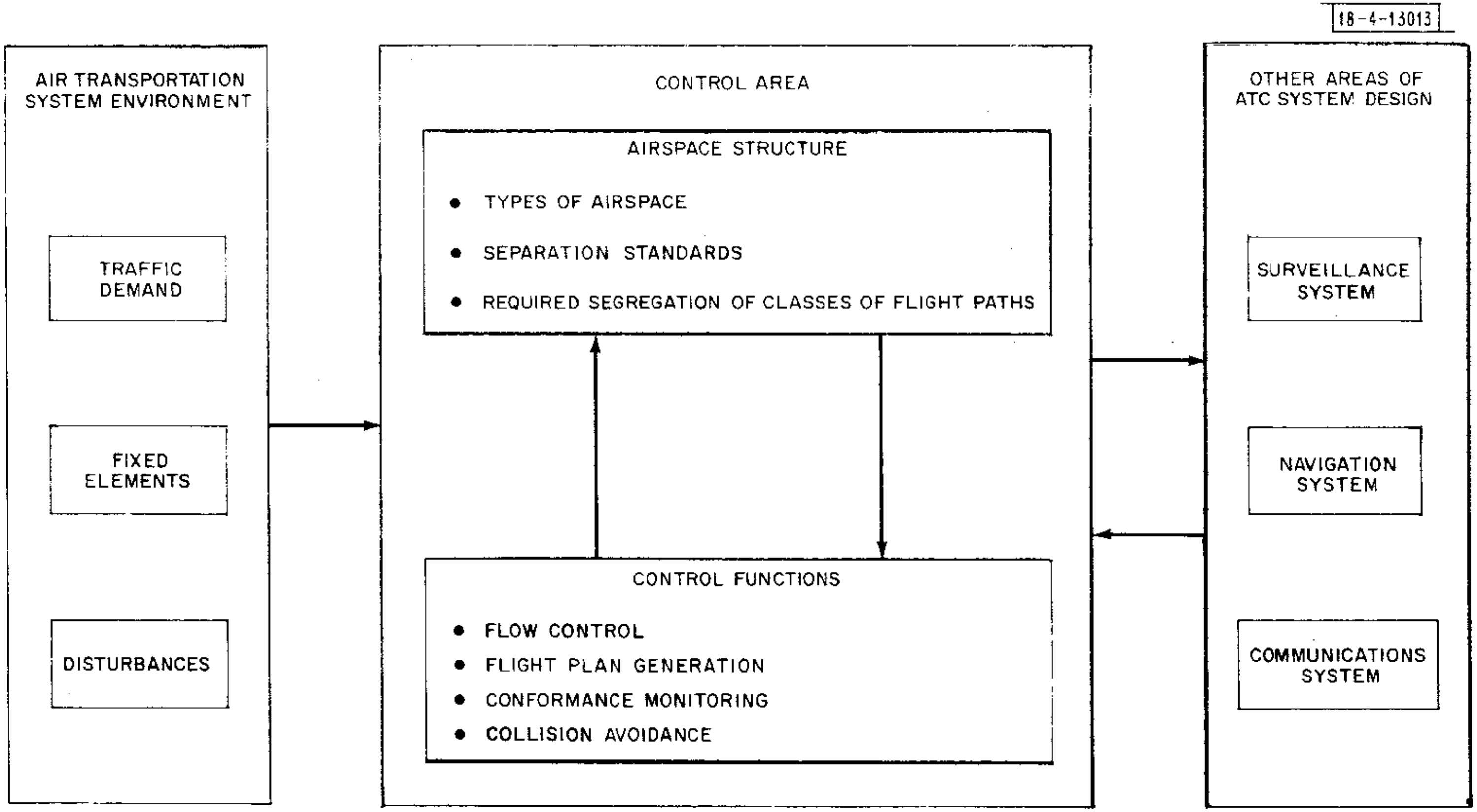

Fig. 1. Interacting parts of the ATC system design.

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

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* 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. frequency 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 uncontrolled aircraft. We designate as cooperative aircraft 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 controlled airspace. The ATCAC Report also uses the terms mixed and controlled airspace interchangeably.

According to this rationale the airspace is organized as follows:

1. Positive Controlled Airspace
    - Controlled Aircraft
2. Controlled Airspace
    - Controlled Aircraft
    - Cooperative Aircraft
3. Uncontrolled Airspace
    - 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:

$$\vec{D}(\vec{F}_i, \vec{P}_i) = \vec{F}_i - \vec{P}_i. \tag{1}$$

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

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[*] 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,*

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* 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

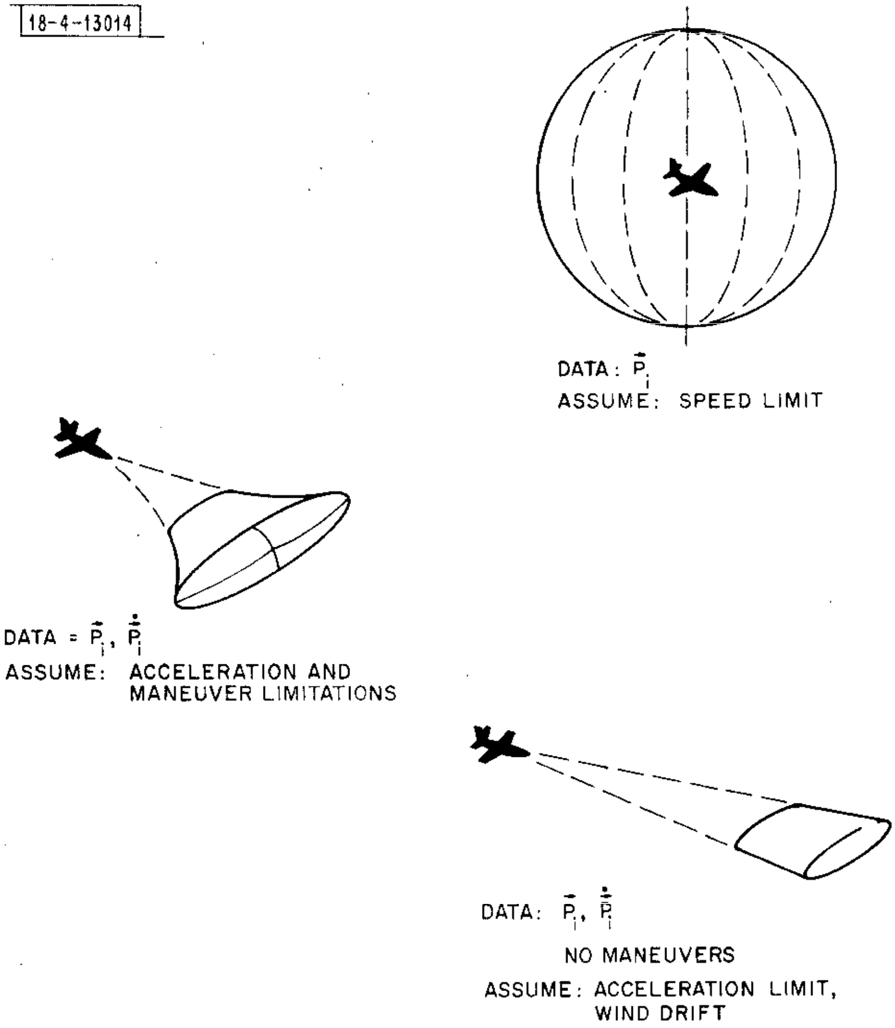


Fig. 2. Hazard volumes which can be used in monitoring hazards.

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 1

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.

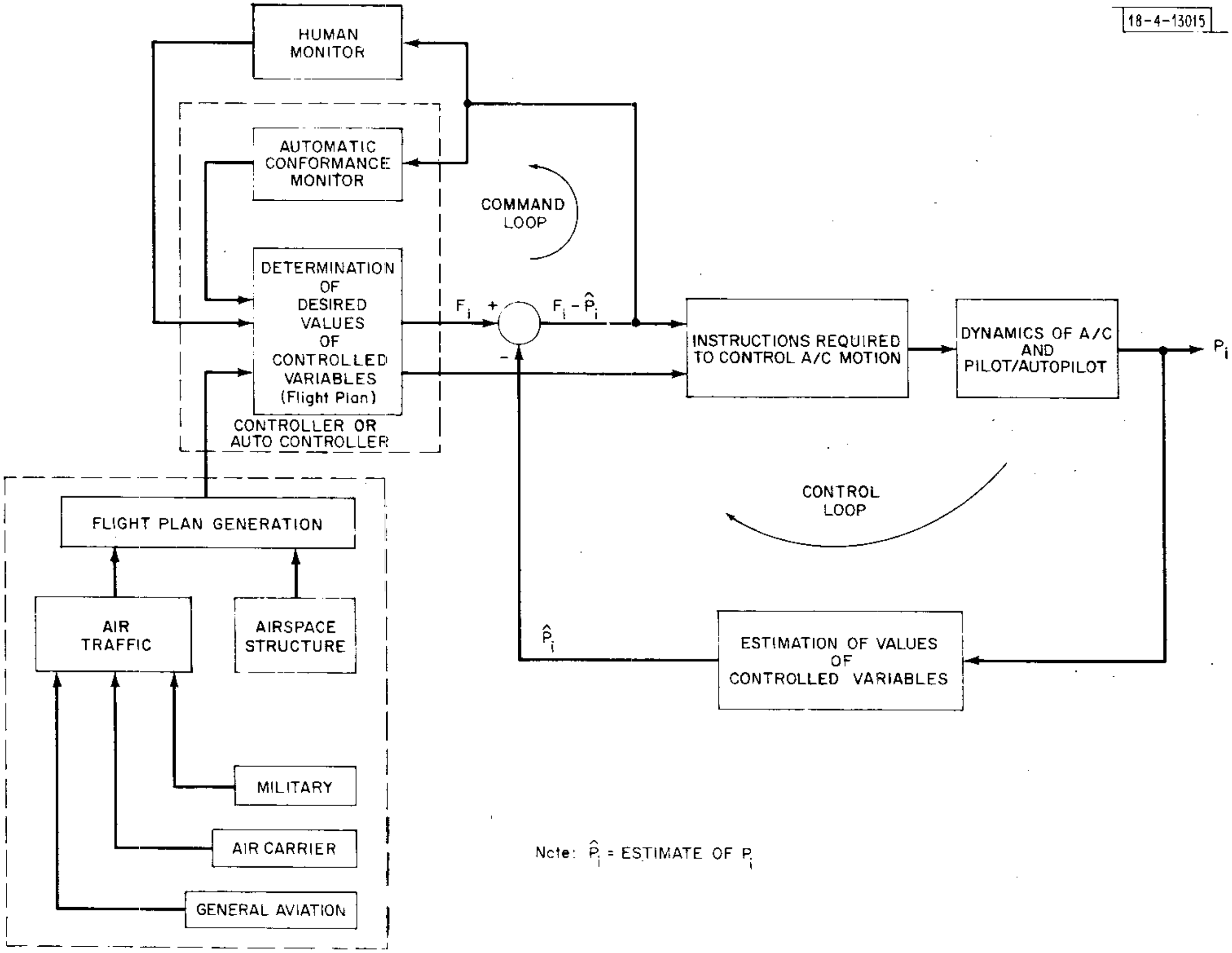
When aircraft deviate significantly from the flight plan due to navigational errors or disturbances, the ATC system must detect and react to this deviation. The aircraft may be sent conformance commands which serve to restore it to the original flight plan. On the other hand, the aircraft may be given 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,



Note: $\hat{P}_i$ = ESTIMATE OF P_i

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.

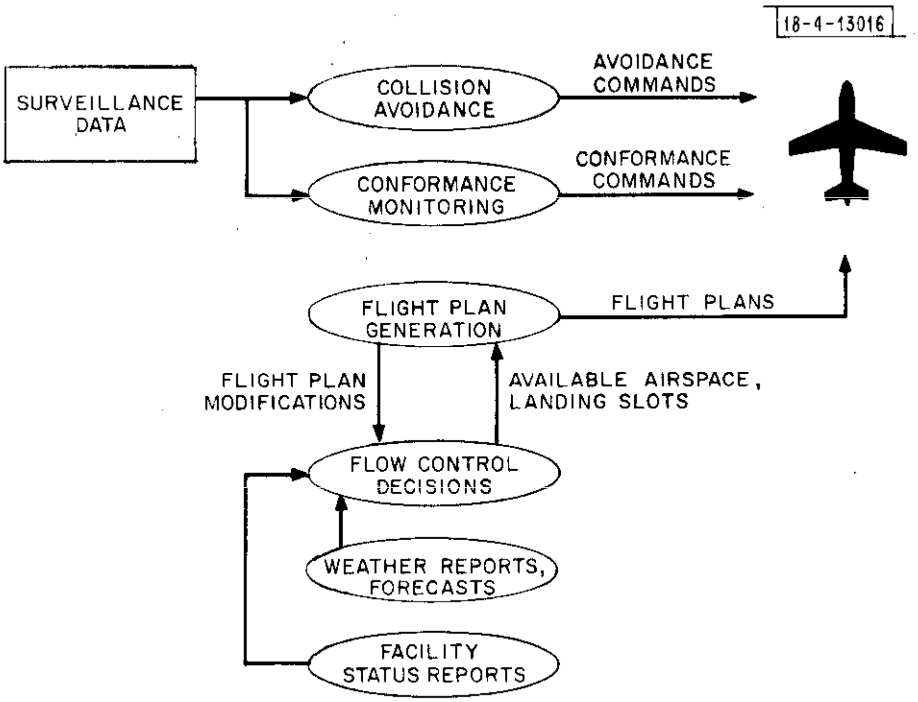


Fig. 4. Basic integration of ATC functions.

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 east 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.

IX. BASELINE CONTROL SYSTEM CONCEPT

A. Introduction

The fundamental issues in the control area which one must resolve before embarking upon a detailed design of the fourth generation ATC system have been previously discussed. In order to resolve these issues analytical studies and simulations must be performed. However, one can initially specify a baseline control system concept which will be subject to modification as results from these analyses and simulations are obtained. The critical problem areas and the interrelation among the fundamental issues are more easily understood when one focuses on a baseline system rather than a general description of ATC functions. In addition, the baseline concept will facilitate further analyses directed toward resolving the critical areas of uncertainty and will provide a framework for studies in the areas of surveillance, navigation and communications.

A baseline system should be developed according to rationale rather than arbitrarily defined. Quantitative analyses can then be used for baseline modification as well as for providing the detailed requirements of the control system design. We have defined a baseline control system which is presented in this section. The rationale which we have used is also described.

B. Scope of the Baseline System

The airspace organization described in Section VI is used as a foundation for defining the baseline system. In this organization the airspace is subdivided into five areas: high density positive controlled airspace containing only controlled aircraft (HDPC), low density positive controlled airspace containing only controlled aircraft (LDPC), high density controlled airspace containing both controlled and cooperative aircraft (HDC), low density controlled airspace containing both controlled and cooperative aircraft (LDC), and uncontrolled airspace containing only uncontrolled aircraft.

We assume that control is never required in uncontrolled airspace. This does not imply that traffic advisories are excluded in uncontrolled airspace. The baseline system defines the control concept for each of the other types of airspace as a function of the flight regime. The flight regimes included are pre-flight, takeoff, departure, en route or oceanic, approach, and landing.

The terminal area may be considered to include the takeoff-departure and approach-landing stages. The terminal area has historically been defined as a specified area surrounding an airport through which an aircraft descends and makes an approach to the runway. We define the terminal area in terms of the control system rather than the aircraft performance. At some point in flight, particularly in high density positive controlled airspace, it is necessary to begin to sequence individual aircraft for a specified runway. We define the terminal area as the area in which sequencing is required in order to accurately space arrivals for a given runway. The actual sequencing is done in the approach stage while rigid 4D control is exercised by all aircraft during the landing stage. Although this definition of terminal area differs from the historical definition, the size of the terminal is likely to be about the same. The departure stage is the inverse to the approach stage.

Although sequencing could be planned well in advance for positive controlled airspace and execution of the plan attempted by rigid 4D control during the entire flight, the likelihood of some disturbance occurring probably makes this approach difficult to implement. Thus the consequences of disturbances have influenced the choice of where 4D control is executed as well as several other choices in the baseline system.

C. Rationale

A fundamental assumption in our baseline system is the requirement for strategic 4D planning for all controlled aircraft. With 4D planning the control system can easily limit the arrival rate to some level below saturation for any positive controlled runway. In addition, control centers can be informed of the identity, approved route, and approximate time of arrival at that control center for each aircraft. Hence, we have tacitly assumed central processing for all controlled aircraft and central flow control for all aircraft destined for high density positive control terminals.

The assumption of 4D strategic planning through a central processing system leads to another assumption, which involves a particular version of the concept of distributed management. In order to execute 4D strategic planning it is necessary to establish a precise three dimensional flight path (ρ, θ, h) for all controlled aircraft as a function of time. Some aircraft may be required to conform to the 4D flight path somewhat rigidly in certain stages of flight while other aircraft may have less rigid or even highly relaxed 4D conformance requirements. The degree of relaxation depends primarily on the density and type of airspace and the stage of flight. Conformance in each of the lateral, longitudinal, and vertical dimensions for a certain aircraft may be relaxed by different degrees. The planned 4D flight path and the associated dimensional conformance requirements will, however, guarantee separation for each aircraft from any other controlled aircraft. It is assumed in our baseline system that the pilot is delegated the responsibility of conforming to his 4D flight path within the conformance requirements although his flight path may change from time to time during a specified flight. If conformance is satisifed and hazards do not exist the control system does not intervene until it is necessary to change a flight plan. It should be pointed out that in a strategically planned system, hazards between controlled aircraft should not exist, since conflict free flight paths generated by the control system prohibit them. Of course, in all cases the system checks for hazards even though they theoretically should never occur. Thus we have assumed a distributed system in the sense that the pilot has the responsibility to conform to his flight plan within specified conformance requirements and the control system intervenes only to give a change in flight plan or in the event that conformance is not satisfied.

Our baseline system also assumes that disturbances, which have been discussed previously, will prohibit rigid 4D control for some stages of flight in high density positive control airspace. Therefore, assigning precise landing time slots at specified runways during the early stages of flight is not feasible. In the baseline system the sequencing process is initiated during the approach stage and an accurate spacing of aircraft at the outer marker is accomplished by computed path stretching and corner cutting techniques. Of course, holding patterns are required for particulary adverse disturbance conditions in the terminal area.

Sequencing techniques can be very effective in maximizing runway capacity at a high density terminal provided the arrival rate in the terminal area does not deviate excessively from the saturation level. In order to avoid excessive variation of arrival rates at high density positive control terminal areas we have provided for en route metering of aircraft through use of a central processor. Metering is a less rigid form of flow control than sequencing, since metering controls the aircraft flow rate across a specified boundary with no regard for the order. On the other hand, sequencing not only controls the flow rate of aircraft but also specifies the order in which aircraft are to cross a boundary.

The concept of high density controlled airspace is one which requires some discussion. The high density of aircraft in this airspace is probably due to a large number of cooperative aircraft rather than controlled aircraft. Cooperative aircraft, as defined in Section VI, are those which are under minimal control. A cooperative aircraft must be capable of receiving and conforming to intermittent positive control (IPC) commands when a potential hazard exists as well as conforming to a flight plan in certain localities as discussed below.

For high density airspace the use of IPC could cause the system to generate a sufficiently large number of "do" commands to force cooperative aircraft to fly inconvenient or excessively long paths to arrive at their destination. In order to avoid this situation we have assumed that in some localities (e.g., high density terminal areas) conflict free flight plans are required for cooperative aircraft. These flight plans will not be centrally processed unless central flow control is desirable for high density controlled runways. In our baseline system we have not provided for central flow control for aircraft destined for runways in either high or low density controlled airspace.

D. Outline of Baseline Control System

The outline of the baseline control system is contained in Tables 2 to 5. Some of the terms and the notation used in this outline require additional explanation.

For positive control terminals we have assumed that the airspace would be defined by one of the forms shown in Fig. 5. Communications functions required for the baseline control system are illustrated by either a single or double headed arrow between two parts of the air traffic control system, e.g., AC ↔ Surveillance. This notation indicates that there is a down-link from the A/C to the surveillance system and an up-link back to the A/C. The up-link from the surveillance system to the A/C is specified for high density positive control airspace in order to provide the pilot with position data as observed by the control system. In high density positive

TABLE 2

CONTROL SYSTEM BASELINE CONCEPT

High Density Positive Control Airspace

Pre-Flight		Strategic 4D Planning is required for all controlled A/C to guarantee conflict free flight paths.
Terminal	Takeoff	High Density Positive Control Runway: 1. Controlled A/C sequenced for takeoff. Disturbances may force changes in flight plans. 2. Rigid conformance to 4D flight plan in order to maximize runway capacity.
	Departure	High Density Positive Controlled Hubs {cylinders, inverse wedding cakes, climb-descent corridors}: 1. Controlled A/C may enter this airspace from both high density and low density runways. 2. Controlled A/C are dispersed to en route and oceanic stages. 3. Rigid conformance to 4D flight plan for A/C that expect to remain in HDPC airspace. 4. Less rigid conformance to 4D flight plans for A/C that expect to leave HDPC airspace provided runway capacity is not affected and separation can be guaranteed.
En Route or Oceanic		High Density Positive Control En Route or Oceanic Areas: 1. Controlled A/C may enter from any departure area. 2. A/C that expect to enter high density positive control approach areas are given relaxed conformance requirements to a 4D flight plan except at mergings, crossings, and passings where rigid conformance is required. 3. Metering is used to eliminate high queues at high density positive control approach areas. 4. Conformance for A/C that expect to leave HDPC airspace may be greatly relaxed in time ("tubes"), since performance of these A/C does not adversely affect flow control.
Terminal	Approach	High Density Positive Controlled Hubs {cylinders, inverse wedding cakes, climb-descent corridors}: 1. Controlled A/C may enter this airspace from any en route or oceanic areas. 2. Controlled A/C are sequenced for specified runways, necessitating changes in flight plans. 3. Rigid conformance to flight plans is required. 4. Disturbances may force additional flight plan changes thus requiring holding patterns under particularly adverse conditions. 5. Path stretching and corner cutting are required in order to accurately space arrivals at the outer marker.
	Landing	High Density Positive Control Runway: 1. Controlled A/C may enter from a HDPC approach area in sequence for landing. 2. Rigid conformance to a 4D flight plan is required in order to maximize runway capacity.
Navigation		Precise 4D navigation (ρ, θ, h, t) is required.
Surveillance		Surveillance of A/C position data (P_i) is required from which velocity data ($\dot{P}_i$) may be derived and hazards continually checked.
Communications		A/C ↔ Surveillance → Central Flow Control ↔ Control Center ↔ A/C

A continual update of flight plans of all controlled A/C is required in order to monitor arrival rates at terminal areas and identify A/C that expect to enter a control center's designated airspace.

<u>TABLE 3</u>

CONTROL SYSTEM BASELINE CONCEPT

Low Density Positive Control Airspace

Pre-Flight		Strategic 4D planning is required for all controlled A/C in order to guarantee conflict free flight paths.
Terminal	Takeoff	Low Density Positive Control Runway: 1. Controlled A/C sequenced for takeoff. Disturbances may force change in flight plans. 2. A/C that expect to enter HDPC at a later stage are given priority for takeoff. 3. Conformance to 4D flight plan is relaxed in the time dimension.
	Departure	Low Density Positive Controlled Hubs {cylinders, inverse wedding cakes, climb-descent corridors}: 1. Controlled A/C enter this airspace from low density runways. 2. Controlled A/C are dispersed to en route and oceanic stages. 3. Conformance to a 4D flight plan is relaxed in time.
En Route or Oceanic		Low Density Positive Controlled En Route or Oceanic Areas: 1. Controlled A/C may enter this airspace from both low and high density departure areas. 2. Metering is used for all A/C that expect to enter HDPC terminal areas. 3. Conformance to a 4D flight plan is relaxed for A/C that expect to enter HDPC. 4. Conformance to a 4D flight plan is greatly relaxed for other A/C.
Terminal	Approach	Low Density Positive Controlled Hubs {cylinders, inverse wedding cakes, climb-descent corridors}: 1. Controlled A/C that expect to land on a low density positive controlled runway may enter this area from either high or low density en route stages. 2. Controlled A/C are sequenced for specified runways necessitating changes in 4D flight plans. 3. Path stretching and corner cutting have limited use since A/C spacing at the outer marker does not have to be accurate. Holding patterns are required for disturbance effects. 4. Conformance to a 4D flight plan is relaxed in time.
	Landing	Low Density Positive Controlled Runway: 1. Controlled A/C may enter from either a LDPC or HDPC approach area in sequence for landing. 2. Conformance to a 4D flight plan is relaxed in time.
Navigation		Precise 4D (ρ, θ, h, t) navigation for all A/C that expect to enter HDPC at any stage. Point to point navigation is sufficient for other flights (VOR or RNAV).
Surveillance		Surveillance of A/C position data (P_i) is required from which velocity data $(\dot{P}_i)$ may be derived and hazards continually checked.
Communications		A/C → Surveillance → Central Flow Control ↔ Control Center ↔ A/C

A continual update of flight plans of all controlled A/C is required in order to monitor arrival rates at terminal areas and identify A/C that expect to enter airspace designated to a control center.

TABLE 4

CONTROL SYSTEM BASELINE CONCEPT

High Density Controlled (Mixed) Airspace

Pre-Flight		Strategic 4D planning is required for all controlled A/C in order to guarantee conflict free flight paths. 4D planning is required for cooperative aircraft in some localities.
Terminal	Takeoff	High Density Runway used by both controlled A/C and cooperative A/C: 1. Controlled A/C that expect to enter HDPC at a later stage are given priority. 2. Conformance to a 4D flight plan is relaxed for all A/C.
	Departure	High Density Departure Zone used by both Controlled A/C and Cooperative A/C: 1. A/C may enter this airspace from both low and high density runways and are dispersed to en route or oceanic stages. 2. Conformance to a 4D flight plan is relaxed for both controlled and cooperative A/C. 3. IPC is used in addition to local flight plans for cooperative A/C. Commands are given as required.
En Route or Oceanic		High Density En Route or Oceanic Stage for both Controlled and Cooperative A/C: 1. A/C enter this airspace from any departure stage. 2. Metering is used for all A/C that expect to enter HDPC at a later stage. 3. Conformance to a 4D flight plan is relaxed for all A/C. 4. IPC is used for cooperative A/C in addition to local flight plans.
Terminal	Approach	High Density Approach Stage used by both Controlled and Cooperative A/C: 1. A/C enter the airspace from both high and low density en route stages. 2. A/C are sequenced for specified runways. Poisson distribution of A/C arrivals is expected since A/C arrival rates are not regulated. 3. Path stretching and corner cutting are required to space A/C at the outer marker. 4. Holding patterns are frequently used. 5. Conformance to a 4D flight plan is not rigid.
	Landing	High Density Runway used by both Controlled and Cooperative A/C: 1. A/C enter from a high density approach area in sequence for landing. 2. Conformance to a 4D flight plan is not rigid.
Navigation		Precise 4D navigation (ρ, θ, h, t) is required for all A/C that expect to enter HDPC at any stage. Point to point navigation is sufficient for other A/C (VOR or RNAV).
Surveillance		Surveillance of A/C position data (P_i) is required from which velocity data ($\dot{P}_i$) may be derived and hazards continually checked.
Communications		A/C → Surveillance → Central Flow Control ↔ Control Center ↔ A/C Surveillance → Control Center

For controlled A/C a continual update of flight plans is required in order to monitor arrival rates at terminal areas and identify A/C that expect to enter a control center's designated airspace. For cooperative A/C local flight plans are required in addition to IPC equipment. These flight plans are used by a control center to minimize the number of intermittent positive control commands.

TABLE 5

CONTROL SYSTEM BASELINE CONCEPT

Low Density Controlled (Mixed) Airspace

Pre-Flight		Strategic 4D planning is required for all controlled A/C to guarantee conflict free flight paths. No flight planning is required for cooperative aircraft.
Terminal	Takeoff	Low Density Runway used by both Controlled and Cooperative A/C: 1. Controlled A/C that expect to enter HDPC at a later stage are given priority. 2. Conformance to a 4D flight plan is relaxed for all A/C.
	Departure	Low Density Departure Zone used by both Controlled and Cooperative A/C: 1. A/C enter this airspace from low density runways and are dispersed to en route or oceanic stages. 2. Conformance to a 4D flight path is greatly relaxed for controlled A/C that do not expect to enter HDPC. A/C that expect to enter HDPC have relaxed conformance requirements. 3. IPC is used to resolve hazards for cooperative A/C.
En Route or Oceanic		Low Density En Route or Oceanic Areas used by both Controlled and Cooperative A/C: 1. A/C enter this airspace from both high and low density terminals. 2. Controlled A/C that do not expect to enter HDPC terminals have greatly relaxed conformance requirements and may change flight plans frequently. 3. Metering is used for controlled A/C that expect to enter HDPC terminals. Conformance requirements are more rigid than for other controlled A/C. 4. IPC is used for cooperative A/C.
Terminal	Approach	Low Density Approach Stage used by both Controlled and Cooperative A/C: 1. A/C enter this airspace from both high and low density en route stages. 2. A/C are sequenced for specified runways. 3. Path stretching and corner cutting have limited use. Holding patterns are required in order to take care of disturbance effects. 4. Conformance to a 4D flight path is greatly relaxed for all controlled A/C. 5. IPC is used to resolve hazards for cooperative A/C.
	Landing	Low Density Runway used by both Controlled and Cooperative A/C: 1. A/C enter from either high or low density approach areas in sequence for landing. 2. Conformance to a 4D flight plan is greatly relaxed for all A/C.
Navigation		Precise 4D navigation (ρ, θ, h, t) is required for all controlled A/C that expect to enter HDPC. Point to point navigation is sufficient for other A/C (VOR or RNAV).
Surveillance		Surveillance of A/C position data (P_i) is required from which velocity data $(\dot{P}_i)$ may be derived and hazards continually checked.
Communications		A/C → Surveillance → Central Flow Control ↔ Control Center ↔ A/C Surveillance → Control Center

For controlled A/C a continual update of flight plans is required in order to monitor arrival rates at terminal areas and identify A/C that expect to enter a control center's designated airspace.

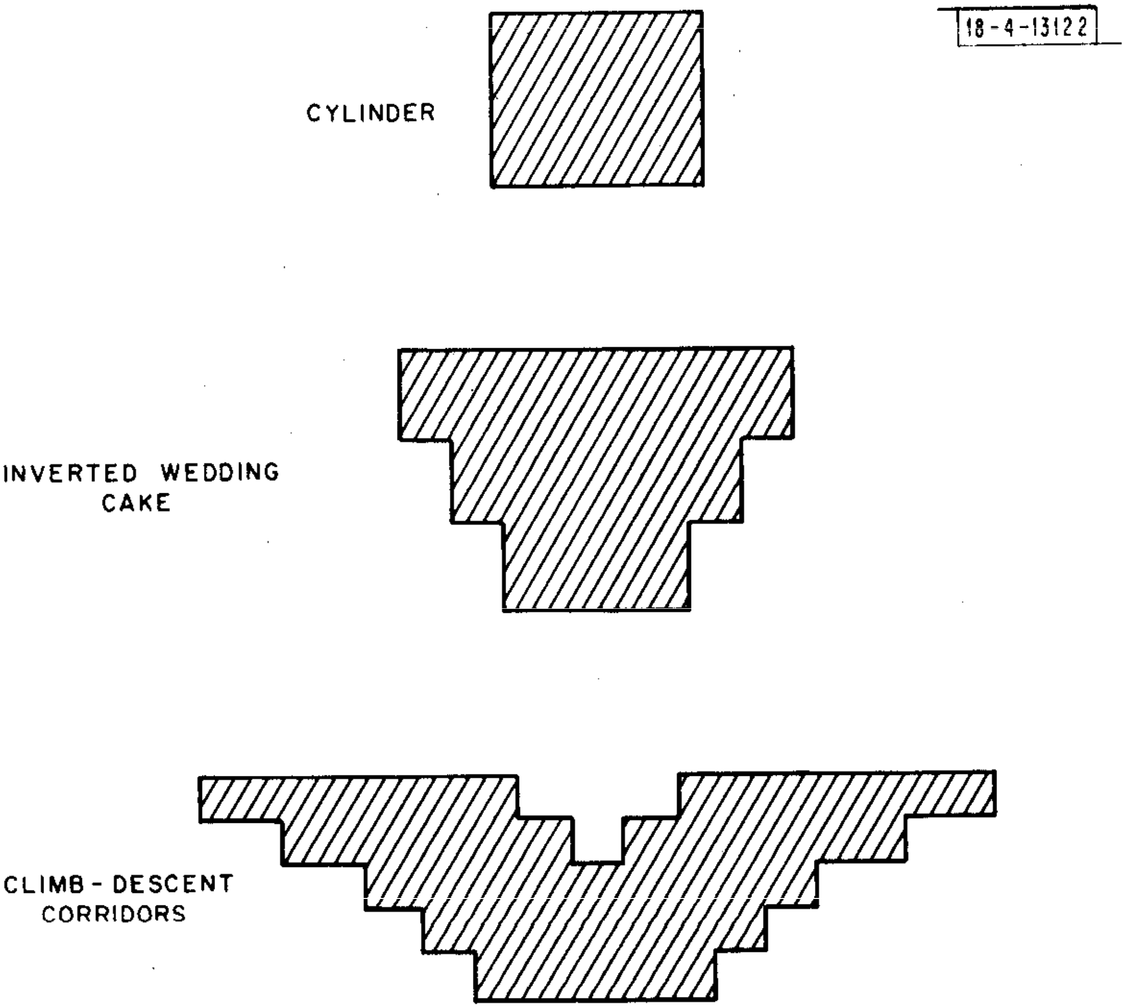


Fig. 5. Terminal control airspace volumes.

control airspace rigid conformance to a flight plan is required at various stages in the flight. It is assumed that the A/C navigation system will have to be calibrated with the data obtained by the surveillance system at regular intervals during the flight in order to maintain rigid conformance to the flight plan. Further study of navigation and communications will determine whether this up-link is essential.

Two types of navigation functions are defined by the baseline control system: precise 4D navigation and point to point navigation. Precise 4D navigation is specified whenever A/C are required to conform rigidly to a 4D flight plan. Point to point navigation is specified as a means of flying from one waypoint to another. The navigation equipment may be in the form of VOR-DME or RNAV, either of which will enable the A/C to conform to a 4D flight plan with relaxed requirements.

In specifying the baseline control concept we have used qualitative terms such as relaxed, greatly relaxed and rigid to specify conformance to a flight plan. Further analyses will be required to quantify these terms and to formulate the details of control system design. A first iteration of this analysis can be found in Sections XI and XII.

X. DECISION MAKING IN ATC

A ground based control system is required in order to coordinate traffic in a high traffic density area or in weather conditions below certain acceptable established minimums. The see-and-avoid strategy becomes unsafe under such conditions. ATC has evolved into a system in which a number of services are provided by various distributed ground based centers, each making decisions independently to ensure the safe and efficient flow of air traffic within their respective areas of control. Decisions made are based on various local inputs. It is evident that safety and efficiency can be degraded in today's system. Until recently, all sectors of the country were allowed to independently feed traffic into all terminal areas. This practice saturated several high traffic density terminal areas and led to intolerable delays for both departures and arrivals. To overcome this saturation, reservations are now required to keep traffic down to a manageable level at these high traffic density areas.

A fourth generation control system study is now underway. Candidate fourth generation system concepts ranging from the completely tactical to the highly strategic have been described, but in a manner too vague to convey how the concepts might work. In order to characterize a proposed concept we have drawn up a list of decisions which we find must be made in the course of a flight. We then consider where these decisions are made and thereby characterize the system.

In today's system the responsibility of making the appropriate decision has been divided between the pilot and ground control centers. These centers are distributed throughout the country and the system is organized so that no two centers have simultaneous control of an aircraft. A rudimentary form of central ground control which is called advance flow control has now emerged. Thus, decision centers exist in three forms: flight crew stations, distributed ground control stations, and central ground control stations. A central control function encompasses the entire national system by exercising control based on inputs which describe the performance of the system as a whole. Distributed ground control functions encompass relatively small geographical areas, perform a specialized function, and are oblivious to what is happening in the system as a whole. The capacity of a distributed center depends on the personnel and automation available and the function it serves. System capacity is limited by the capacity of the more specialized distributed ground control centers. Flight crew stations are concerned primarily with themselves and coordinate only with other flights in the immediate vicinity in order to provide the required level of safety.

A fourth generation control system can likewise be divided into the same decision centers. Inputs to each may change due to new hardware becoming available which may allow some center to provide a new service in the interest of safety and efficiency. Each new functional requirement proposed can be placed into one of the three decision centers described. Without first specifying the inputs available to assist in performing a given function, it is difficult to determine the level of control to which it should be assigned.

Matrices denoting decisions and decision centers for a number of flights under different levels of control are provided in the following pages. We include flights covered by the present control system for comparison. Tables 6 to 9 provide descriptions of the present ATC system; Tables 10 and 11 are descriptions of candidate fourth generation control concepts for selected airspace categories.

XI. FEASIBILITY OF PROVIDING CONFLICT-FREE FLIGHT PLANS

A. Importance of Analysis of the Flight Planning Process

In previous sections, primarily in Section VIII, some basic issues in the Control Area which must be resolved are discussed. For convenience, these issues are briefly described below.

1. Airspace structure including the types of airways or flight trajectories, e.g. 1D, 2D, 3D, etc., most desirable for high density positive controlled airspace, and controlled airspace must be specified.

2. One must determine the flight regime and type of airspace where precise aircraft position control as a function of time, i.e., 4D, should be enforced.

3. The size of the region over which a Conflict-Free Flight Plan (CFFP) for a controlled aircraft must be maintained should be determined. This issue is part of the broader issue of tactical vs. strategic control.

4. The occurrence of a disturbance will make it necessary to change one or more flight plans. The frequency with which disturbances occur for different flight regimes and types of airspace must be determined

TABLE 6

Decision Centers			VFR Flight Between Two Uncontrolled Airports
Ground Central	Ground Distributed	Flight Crew	Decision areas
		X	1. Can the proposed flight be made based on preflight input data? (reservation requirements, notams, advisories, terminal and equipment capabilities)
		X	2. Is the flight plan acceptable as filed? (route accuracy, destination, traffic density, required coordination with other traffic)
		X	3. Can aircraft be taxied to active runway? (coordinate with arrivals, merge traffic into queues, avoid difficult situations)
		X	4. Can aircraft safely use runway for takeoff?
		X	5. Can a conflict free route be provided during the transition from the takeoff phase to the enroute phase?
		X	6. Can the required separation be provided enroute? (conformance monitoring)
		X	7. Does a hazard exist? How should it be resolved?
		X	8. Can a change in flight plan be accommodated? (unpredicted changes in atmospheric conditions, difficulties on ground, operational anomalies, destination change)
		X	9. Does an airborne emergency exist? (The procedure which is warranted to deal with the emergency depends on the nature of the emergency)
		X	10. Can the arrival be handled at a terminal's initial approach fix for transition to the approach phase? (expected delays)
		X	11. How is the aircraft in the approach phase to be sequenced for landing?
		X	12. Can aircraft safely use assigned runway for landing?

TABLE 7

Decision Centers			VFR Flight Between Two Terminal Control Area Airports (high density). **Decision areas**
Ground Central	Ground Distributed	Flight Crew	
		X	1. Can the proposed flight be made based on preflight input data? (reservation requirements, notams, advisories, terminal and equipment capabilities)
		X	2. Is the flight plan acceptable as filed? (route accuracy, destination, traffic density, required coordination with other traffic)
	Ground Control		3. Can aircraft be taxied to active runway? (coordinate with arrivals, merge traffic into queues, avoid difficult situations)
	Local Control (Tower)		4. Can aircraft safely use runway for takeoff?
	Departure Control (1)		5. Can a conflict free route be provided during the transition from the takeoff phase to the enroute phase?
		X	6. Can the required separation be provided enroute? (conformance monitoring)
		X	7. Does a hazard exist? How should it be resolved?
		X	8. Can a change in flight plan be accommodated? (unpredicted changes in atmospheric conditions, difficulties on ground, operational anomalies, destination change)
		X	9. Does an airborne emergency exist? (The procedure which is warranted to deal with the emergency depends on the nature of the emergency)
	Approach Control (1, 2)		10. Can the arrival be handled at a terminal's initial approach fix for transition to the approach phase? (expected delays)
	Approach Control		11. How is the aircraft in the approach phase to be sequenced for landing?
	Tower		12. Can aircraft safely use assigned runway for landing?

1. Various stages of safety are provided depending on the particular terminal and requested service.
2. VFR traffic may not be accepted at terminals where the reservation rule is in effect if it is saturated with IFR operations.

TABLE 8

Decision Centers			IFR Flight Between Two Uncontrolled Airports Under IFR Conditions
Ground Central	Ground Distributed	Flight Crew	Decision areas
		X	1. Can the proposed flight be made based on preflight input data? (reservation requirements, notams, advisories, terminal and equipment capabilities)
		X	2. Is the flight plan acceptable as filed? (route accuracy, destination, traffic density, required coordination with other traffic)
		X	3. Can aircraft be taxied to active runway? (coordinate with arrivals, merge traffic into queues, avoid difficult situations)
		X	4. Can aircraft safely use runway for takeoff?
	ARTCC*		5. Can a conflict free route be provided during the transition from the takeoff phase to the enroute phase?
	ARTCC		6. Can the required separation be provided enroute? (conformance monitoring)
	ARTCC		7. Does a hazard exist? How should it be resolved?
	ARTCC	Requests	8. Can a change in flight plan be accommodated? (unpredicted changes in atmospheric conditions, difficulties on ground, operational anomalies, destination change)
		X	9. Does an airborne emergency exist? (The procedure which is warranted to deal with the emergency depends on the nature of the emergency)
	ARTCC		10. Can the arrival be handled at a terminal's initial approach fix for transition to the approach phase? (expected delays)
	ARTCC		11. How is the aircraft in the approach phase to be sequenced for landing?
		X	12. Can aircraft safely use assigned runway for landing?

*Air Route Traffic Control Center

TABLE 9

Decision Centers			IFR Flight Between Two Terminal Control Area Airports Under IFR Conditions Decision areas
Ground Central	**Ground Distributed**	**Flight Crew**	
Advanced Central Flow Control	Terminal Flow Control	X	1. Can the proposed flight be made based on preflight input data? (reservation requirements, notams, advisories, terminal and equipment capabilities)
		X	2. Is the flight plan acceptable as filed? (route accuracy, destination, traffic density, required coordination with other traffic)
	Ground Control		3. Can aircraft be taxied to active runway? (coordinate with arrivals, merge traffic into queues, avoid difficult situations)
	Local (Tower) Control		4. Can aircraft safely use runway for takeoff?
	Departure Control		5. Can a conflict free route be provided during the transition from the takeoff phase to the enroute phase?
	ARTCC		6. Can the required separation be provided enroute? (conformance monitoring)
	ARTCC		7. Does a hazard exist? How should it be resolved?
	ARTCC	Requests	8. Can a change in flight plan be accommodated? (unpredicted changes in atmospheric conditions, difficulties on ground, operational anomalies, destination change)
		X	9. Does an airborne emergency exist? (The procedure which is warranted to deal with the emergency depends on the nature of the emergency)
	Approach Control		10. Can the arrival be handled at a terminal's initial approach fix for transition to the approach phase? (expected delays)
	Approach Control		11. How is the aircraft in the approach phase to be sequenced for landing?
	Tower		12. Can aircraft safely use assigned runway for landing?

TABLE 10

Decision Centers			Future High Density Positive Control Airspace Decision areas
Ground Central	Ground Distributed	Flight Crew	
		X	1. Can the proposed flight be made based on preflight input data? (reservation requirements, notams, advisories, terminal and equipment capabilities)
Generate CFFP*			2. Is the flight plan acceptable as filed? (route accuracy, destination, traffic density, required coordination with other traffic)
	Flow Control directed Ground Control		3. Can aircraft be taxied to active runway? (coordinate with arrivals, merge traffic into queues, avoid difficult situations)
CFFP	Monitored by Local Control		4. Can aircraft safely use runway for takeoff?
CFFP			5. Can a conflict free route be provided during the transition from the takeoff phase to the enroute phase?
Conformance Monitoring			6. Can the required separation be provided enroute? (conformance monitoring)
Hazard Monitoring			7. Does a hazard exist? How should it be resolved?
Generate new CFFP		Requests	8. Can a change in flight plan be accommodated? (unpredicted changes in atmospheric conditions, difficulties on ground, operational anomalies, destination change)
Generate new CFFP		Declare Emergency	9. Does an airborne emergency exist? (The procedure which is warranted to deal with the emergency depends on the nature of the emergency)
Conform to CFFP			10. Can the arrival be handled at a terminal's initial approach fix for transition to the approach phase? (expected delays)
Conform to CFFP			11. How is the aircraft in the approach phase to be sequenced for landing?
Conform to CFFP			12. Can aircraft safely use assigned runway for landing?

* Conflict Free Flight Plan

TABLE 11

Decision Centers			Future Low Density Controlled (Mixed) Airspace (Controlled and Cooperative A/C compared)[a] Decision areas
Ground Central	Ground Distributed	Flight Crew	
		X	1. Can the proposed flight be made based on preflight input data? (reservation requirements, notams, advisories, terminal and equipment capabilities)
Generate CFFP for controlled A/C		Cooperative A/C	2. Is the flight plan acceptable as filed? (route accuracy, destination, traffic density, required coordination with other traffic)
	Ground Control		3. Can aircraft be taxied to active runway? (coordinate with arrivals, merge traffic into queues, avoid difficult situations)
	Tower		4. Can aircraft safely use runway for takeoff?
CFFP[b]	IPC for Cooperative A/C		5. Can a conflict free route be provided during the transition from the takeoff phase to the enroute phase?
CFFP[b]		Cooperative A/C	6. Can the required separation be provided enroute? (conformance monitoring)
	IPC		7. Does a hazard exist? How should it be resolved?
New CFFP for Controlled A/C		Cooperative A/C	8. Can a change in flight plan be accommodated? (unpredicted changes in atmospheric conditions, difficulties on ground, operational anomalies, destination change)
		Declare Emergency	9. Does an airborne emergency exist? (The procedure which is warranted to deal with the emergency depends on the nature of the emergency)
CFFP[b]	IPC for Cooperative A/C		10. Can the arrival be handled at a terminal's initial approach fix for transition to the approach phase? (expected delays)
	Computer Aided Approach Sequencing		11. How is the aircraft in the approach phase to be sequenced for landing?
	Tower		12. Can aircraft safely use assigned runway for landing?

(a) Multiple entries are made in matrix where control differs.
(b) Relaxed conformance to CFFP.

for realistic disturbance models. This issue is also part of the broader issue of tactical vs. strategic control.

5. A methodology for choosing flight plan trajectories must be developed. One must consider the need for minimum cost routes to satisfy the air carriers, for absence of conflicts in all trajectories, and for flow control to reduce delays. In addition, the flight plan generation process should be computationally simple because flight plans must be updated in real time due to disturbances.

6. There are two options for providing ground based collision avoidance. In the first option, 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 option, the control system generates CFFP's for all aircraft and assures that they are controlled to conform to the flight plans, thus insuring that no collisions occur. These two options must be examined in detail to determine their level of safety and ease of automation. Economic implications of these options must be examined.

7. The degree of automation in the ATC system that is both feasible and desirable must be determined. Different flight regimes, types of airspace, and levels of disturbances may imply different levels of automation.

8. Rules and procedures for pilots and capabilities of the ground system must be specified so that in the event of major disturbances or system failures there will follow a graceful degradation of system capability with a successful switch from the automatic mode to a manual or semi- manual mode. Human factor considerations will be particularly important in this area.

9. The ground system has final responsibility for maintaining safe and expeditious flow of traffic. An important issue is that of determining

how much responsibility for the actual operations necessary to achieve safe and expeditious flow of traffic should be delegated to the pilot.

The analysis of the feasibility of providing CFFP's contained in this section applies either directly or indirectly to all nine issues as summarized below.

1. A flight plan is a trajectory through the airspace which is to be followed within certain altitude, cross-track, and along-track conformance limits. In the generation of a CFFP a nominal requested trajectory is modified in the computer to resolve all conflicts before an approved trajectory is released. The maneuver planned to resolve a conflict may take the form of an altitude, heading, or speed change. Selection of a particular type of maneuver determines which type of flight trajectories are permissible, e.g. 1D, 2D, 3D. If constant altitude turns are permitted, flight trajectories with freedom to choose routes in a plane, i.e., 2D, must be permitted. This implies that aircraft must be equipped with area navigation equipment. If altitude change maneuvers are also permitted, freedom to choose routes in three dimensional space, 3D, must also be permitted. If only speed changes are permitted, a 1D airspace structure is permissible. Thus, strategies adopted for resolving conflicts are directly related to the types of trajectories which are permissible.

2. Determining the flight regime and type of airspace where 4D control should be enforced is part of the larger issue of specifying the required degree of conformance to a CFFP. As the degree of conformance required of an aircraft is relaxed, each flight plan requires a larger volume of airspace and thus the frequency with which conflicts will occur and be resolved in the computer will increase. As the degree of conformance required is tightened, the conflict frequency will decrease but the difficulty of maintaining conformance to the plan during the actual flight will increase. The following analysis deals directly with the larger issue of determining the required degree of conformance under certain idealized conditions.

3. Determining the size of the region over which plans should be generated is equivalent to determining how far into the future it is productive to specify a CFFP. This depends in part on whether the achievable conformance degrades as the flight progresses. The analysis of the flight planning process also is directly applicable to this issue.

4. Various effects will cause an aircraft to deviate from its nominal flight plan in altitude, cross-track, or along-track. If an effect causes a deviation which falls outside the conformance limits of the plan, we classify it as a significant disturbance. The size of the conformance limits, i.e., the degree of conformance required, influences the frequency with which significant disturbances occur and thus determines the sensitivity of the system to disturbances. Factors which influence the conformance capability of various categories of users are discussed.

5. The analysis of the feasibility of providing CFFP's is a necessary first step in the development of the methodology for choosing CFFP's.

6. The two options for providing ground based collision avoidance, hazard resolution and conflict resolution plus conformance monitoring, have a place in the fourth generation ATC system. The analysis is directed toward determining the feasibility of various ways of preventing collisions using the second option.

7. The results of the studies which are summarized here are an essential first step toward determining the degree of automation that is feasible in the ATC system.

8. The results of these studies are indirectly related to providing graceful degradation of system capability in that a system which generates CFFP's is better able to coast through a period when part or all of the ground complex is not working.

9. The degree of responsibility delegated to the pilot is influenced by whether CFFP's are provided, what degree of conformance is required, and the ease with which requested changes in flight plans can be examined and approved. The analysis of this section is a first step in examining this broad issue.

As evidenced by the above discussion of these nine issues, analysis of the process of generating CFFP's is an important step in the fourth generation ATC studies in the control area. It is only a first step, however. Further steps which must be taken are discussed in Section XIII.

B. Factors which Influence the Flight Plan Generation Process

The process of designing a system for generating CFFP's is a complex one. The analysis contained in this report is a first step toward the design of such a system. Table 12 lists the most important factors which are relevant to the problem. These factors are grouped into three categories: inputs to the design process, major decisions to be made, and measures of performance. All of these factors have been considered in obtaining the results of this section. Since the analysis is approximate and some factors have been treated in less detail than others, the conclusions are tentative. As would be expected, further work is required before many of the issues can be resolved with finality. However, when the methods described in this report are refined, they can be used to resolve many aspects of these issues.

Figure 6 illustrates the relevant factors from a different point of view. The ATC system must satisfy certain needs which imply, in the case of conflict free flight planning, that aircraft must satisfy certain conformance requirements. At the same time, the ATC system designers, operators, and users have only certain means available for achieving various levels of conformance. Studies of the feasibility of providing CFFP's for aircraft in various situations involves an iterative process of comparing that which is

TABLE 12

Design of a System for Generating Conflict Free Flight Plans

Inputs	Major Decisions to be Made	Measures of Performance
Traffic Aggregate level Distribution Mix of aircraft	Type of Airspace in which to Employ Conflict Free Flight Plans	Economic Implications Cost to user Cost to government
Constraints on Aircraft Maneuvers Passenger Comfort Rules and Procedures Aircraft Capability	Time Duration over which Plan Should be Conflict Free	Operational Considerations
Operational and Economic Factors Climb and Descent Profiles Cruise Conditions	Degree of Conformance to be Required	Acceptance of System by Users
Capability to Conform to Plan Navigation Equipment Guidance and Control System Design Pilot Proficiency Error in Wind Forecasts Error in Temperature Forecasts	Type of Maneuver to Resolve Conflict	
Technological Constraints Computer Memories Computer Processing Speed Communications		
Characteristics of Disturbances Frequency Duration Spatial Extent Predictability		

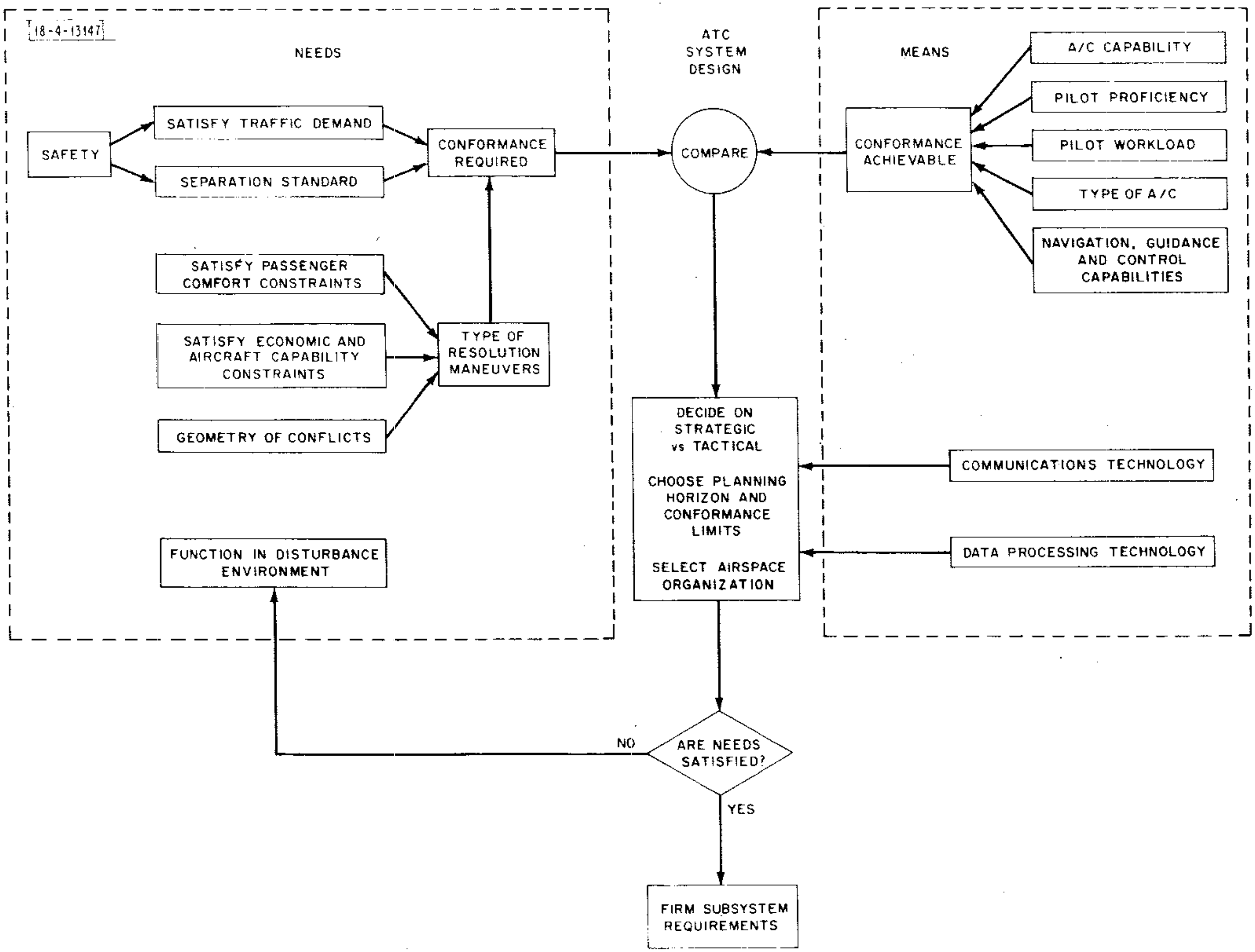


Fig. 6. Iterative design process.

achievable with that which is required and then changing one or both until either an acceptable system configuration is found or until bounding calculations show that the problems are insurmountable or at least that the basic approach is less desirable than some other.

C. Predicted Frequency of Conflicts

1. Introduction

There are many important issues to be resolved in the Fourth Generation ATC studies involving the methodology of CFFP generation. The level of 4D strategic control of aircraft which is necessary will depend upon the aircraft density, the constraints imposed by the pilot/aircraft combination, the surveillance and navigation accuracies, and the ease of maintaining conformance to a CFFP. A logical starting point in resolving these very complex issues is to determine approximately the frequency of potential conflicts expected in the fourth generation time period. As previously defined a conflict exists when the magnitude of the distance between two flight plans is less than a prescribed minimum separation. With CFFP generation, conflicts are resolved in the computer which generates the plans.

Both the en route and the terminal areas are considered. For the en route case, the demand model generated by R. Dixon Speas Associates (Ref. 7) is used to determine the peak hour traffic distribution in the Continental United States (CONUS). This model was based on a generally accepted forecast that by the year 1995 the air carrier IFR activity will increase by a factor of three while the general aviation IFR activity will increase by a factor of six. In using the above model, only aircraft flying above 18,000 feet in what is presently called positive controlled airspace was considered. The theoretical analysis to follow gives the probability distribution of the number of conflicts over a given length of route segment between an origin/destination pair. For the en route area, two cases are considered:

a. An entire route between a pair of major hubs.

b. A small segment of a route which crosses the most dense set of airways in the CONUS; this case gives an upper limit for the frequency at which potential conflicts occur.

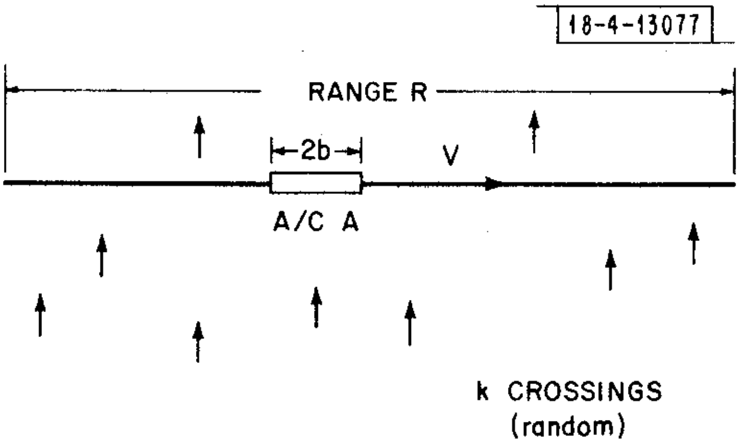
For the terminal area case, the Los Angeles Basin was taken as representative of a high density, mixed airspace region. The estimated instantaneous peak airborne count for that region in 1995 is given in Appendix D and is used to determine the frequency of conflicts among all IFR traffic flying below 10,000 feet in the L. A. Basin.

2. Theory

Probability theory is used to determine the approximate frequency of occurrence of potential conflicts. Consider aircraft A moving along a route segment of length R during the peak hour of traffic as shown in Fig. 7. Assume there are k aircraft crossing perpendicular to this route segment in a random fashion during the time aircraft A is traversing the route segment R. These k aircraft are assumed to be completely independent and are equally likely to cross anywhere along R. The conformance limits plus separation standard of an intersecting pair of aircraft are represented by an effective length 2b for aircraft A. A conflict exists whenever one of the intersecting aircraft, which are represented by points, hits within this length of 2b. Therefore, the probability of each one of the k aircraft being in conflict with aircraft A is simply $\frac{2b}{R}$. The probability P(c) of aircraft A having c conflicts with the k intersecting aircraft is given by the discrete binomial probability law (Ref. 8),

$$P(c) = \binom{k}{c}\left(\frac{2b}{R}\right)^{c}\left(1 - \frac{2b}{R}\right)^{k-c} \qquad (2)$$

where $\binom{k}{c}$ is a binomial coefficient.



2b = Length of route segment effectively taken up by A/C A

Fig. 7. Model of crossings at one flight level.

In order to determine the quantity k for a particular route segment, use was made of the (computer generated) graphic presentation of the 1969 airline traffic (Ref. 7) as derived from data in the Official Airline Guide. The number of airline flights per day between a given city pair can be approximately determined according to the width of a scaled line on this map. For a selected route segment R, the total number of flights per day intersecting this route, denoted by J, is obtained by adding all the crossing city pair traffic. Assuming that the peak hour traffic is 10 percent of the daily traffic, the number of intersecting aircraft per peak hour for 1995 is determined from the following formulas (Ref. 7):

Air Carrier: $AC = (3)\ (0.1)\ (J)$

General Aviation Turbojets: $GA = \frac{(52/40)\ AC}{3.41}$

Military: $Mil = \frac{8AC}{40}$

Total: $T_t = 0.474J$ (3)

The above relationships are based upon the 1969 hourly distribution of the three types of aircraft flying in positive control airspace as well as the forecasted increase of a factor of three in air carrier and a factor of six in general aviation activity. This total T_t is, therefore, the total number of aircraft crossing the route segment R between the altitudes of 18,000 and 40,000 feet during the peak hour of traffic. Assuming these aircraft to be evenly distributed over flight levels separated by a distance d, the number of intersecting aircraft flying at each flight level is

$$k = \frac{T_t}{22,000/d} t_s \tag{4}$$

where t_s is the time required to traverse the route segment, i.e., $t_s = R/V$ where V is the aircraft speed. As will be shown later, a uniform distribution of aircraft among flight levels will lead to extremely tight conformance requirements for certain cases involving the crossing of high density routes. In these cases the value of k for certain flight levels may be reduced below that given by equation (4) in order to obtain more reasonable conformance limits. This can be accomplished by imposing a structure on the airspace in a manner described in Section F.

Equations (2) through (4) can now be used to determine the probability distribution for the number of conflicts encountered by an aircraft over a route segment R. The mean, variance, and standard deviation of this distribution are

$$m = \frac{2kb}{R}, \tag{5}$$

$$\sigma^2 = m(1 - \frac{2b}{R}), \tag{6}$$

$$\sigma = \sqrt{m(1 - 2b/R)}, \tag{7}$$

respectively. For large values of k and for $\frac{2b}{R} \leq 0.1$ the binomial distribution can be approximated by the Poisson distribution (Ref. 8) with both the mean and the variance equal to $\frac{2kb}{R}$. Then

$$P(c) = e^{-2kb/R} \frac{\left(\frac{2kb}{R}\right)^c}{c!} \tag{8}$$

Figure 8 illustrates this probability distribution for different values of the mean number of conflicts. The standard deviation is a measure of the spread of the probability distribution about the mean. For all cases considered here the probability that c exceeds $m + 3\sigma$ is less than 0.01. It is useful to define the quantity $c_{max} = m + 3\sigma$ as a practical maximum number of conflicts expected. The number of conflicts will rarely exceed c_{max}. In a later section we deal with less rare events by defining a quantity $m + q\sigma$ where $q = 0, 1, 2$. In all cases this represents a convenient way of summarizing with a single quantity the information contained in a probability distribution as it applies to a particular problem. Figure 9 shows how c_{max} varies with $2kb/R$ assuming that $2b/R << 1$.

Because of constraints on aircraft motion, only a certain number of conflicts can be resolved every R miles. Denoting this number as n and setting it equal to c_{max}, we determine the maximum value of k which one can permit and still expect aircraft A to be able to cross with high probability. Combining the expression for c_{max} with equation (7) gives

$$c_{max} = n = m_{max} + 3\sqrt{m_{max}(1 - \frac{2b}{R})}. \tag{9}$$

Solving for m_{max} yields

$$m_{max} = \frac{f - \sqrt{f^2 - 4n^2}}{2} \tag{10}$$

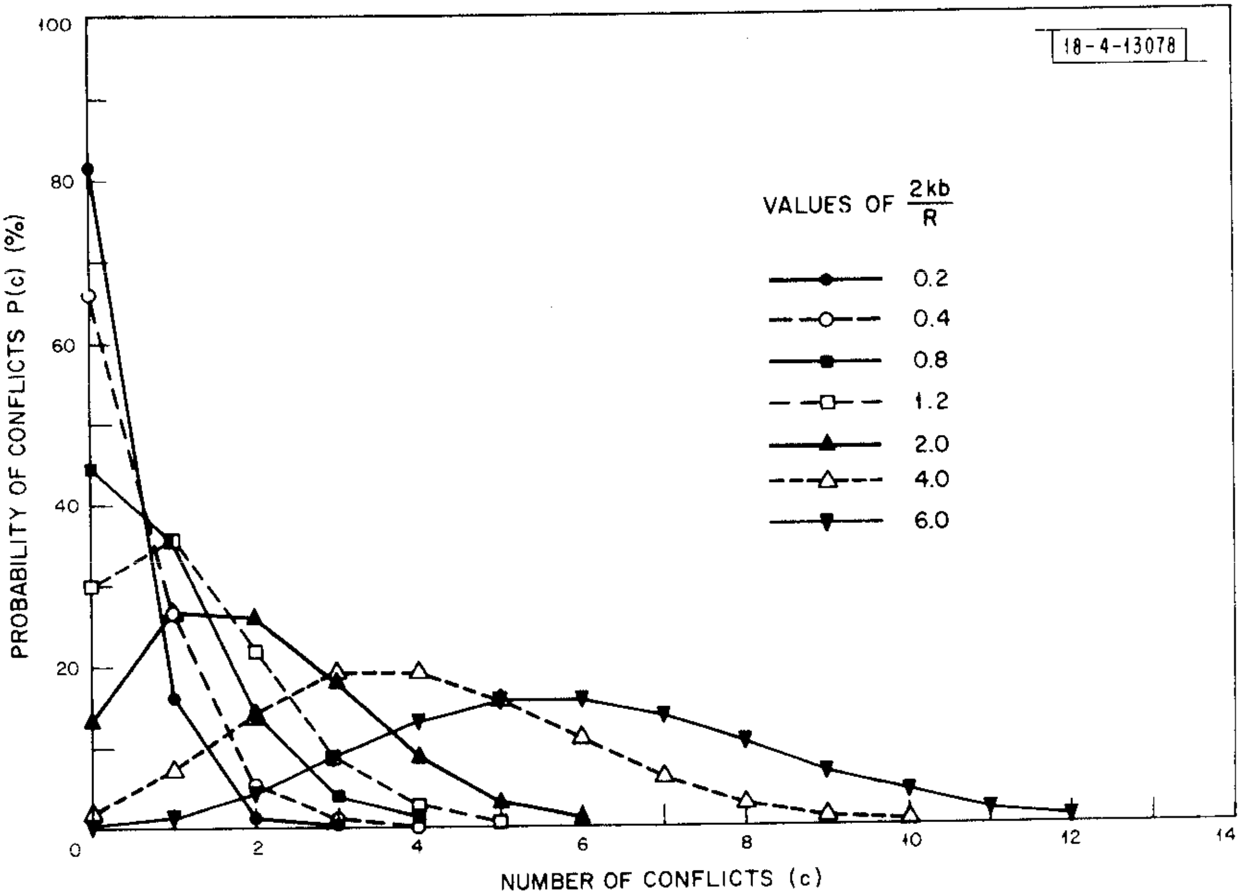


Fig. 8. Probability of conflicts for different values of the mean number of conflicts, m = 2kb/R.

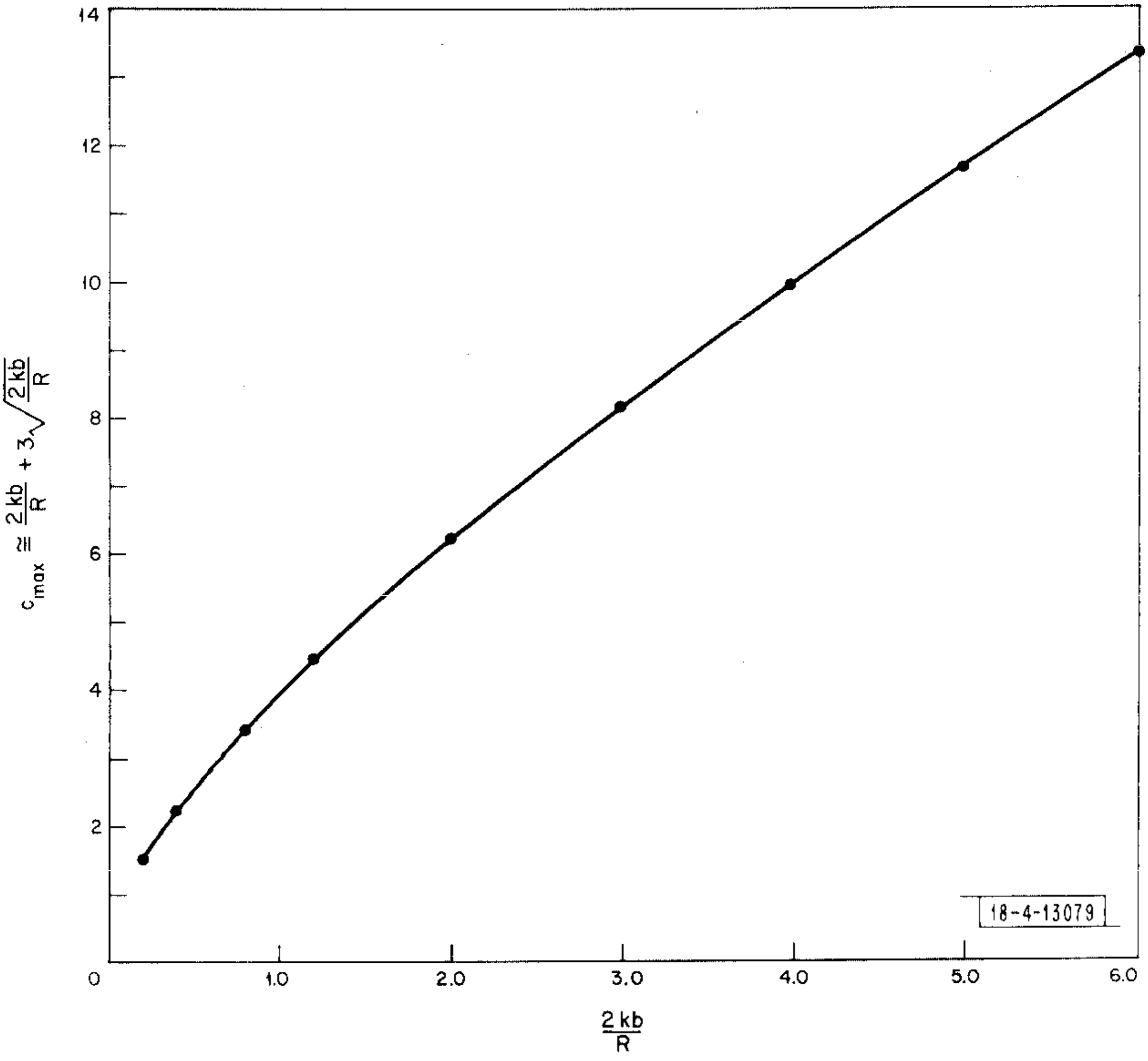


Fig. 9. c_{max} vs the mean number of conflicts, $m = 2kb/R$.

where $f = 2n + 9(1 - 2b/R)$. From equation (4),

$$k_{max} = m_{max} \left(\frac{R}{2b}\right) \qquad (11)$$

Figures 10 and 11 illustrate how the mean and k_{max} vary with the range for two different ratios of $\frac{n}{R}$ and for $2b = 6$ mi. There is approximately a factor of 3 increase in both parameters, m_{max} and k_{max}, when the ratio $\frac{n}{R}$ is changed from $\frac{1}{20}$ to $\frac{1}{10}$.

3. Results and Conclusions

a. En Route Area

Two different cases in the en route area are examined to determine the probability distribution of the frequency of conflicts expected in the 1995 time period. The first case is a 518 mile route between two major terminals, Chicago and Washington. Following the procedure outlined in the previous section, the number of intersecting aircraft flying at each flight level with a cruise speed of Mach 0.8 during the peak hour is found to be $k = 31$. A uniform distribution of aircraft over flight levels separated by a vertical distance $d = 1000$ feet is assumed in this calculation. Substituting k and $R = 518$ into equation (2) with 2b assumed to equal 6 miles (e.g. perfect conformance and 3 mile separation standard or ± 1 mile conformance and 2 mile separation standard) results in the probability distribution for conflicts given in Figure 12. Note that the probability of having greater than $c_{max} = 2$ conflicts is only 0.6%. Also shown in this figure is the probability distribution for the case where $d = 2000$ feet, which is the present required altitude separation for flight at or above FL 290. Here, the probability of having greater than $c_{max} = 3$ conflicts is only 0.2%. This latter curve also represents the case in which the altitude separation remains at 1000 feet while the effective length of the aircraft is increased to 12 miles by relaxing conformance requirements.

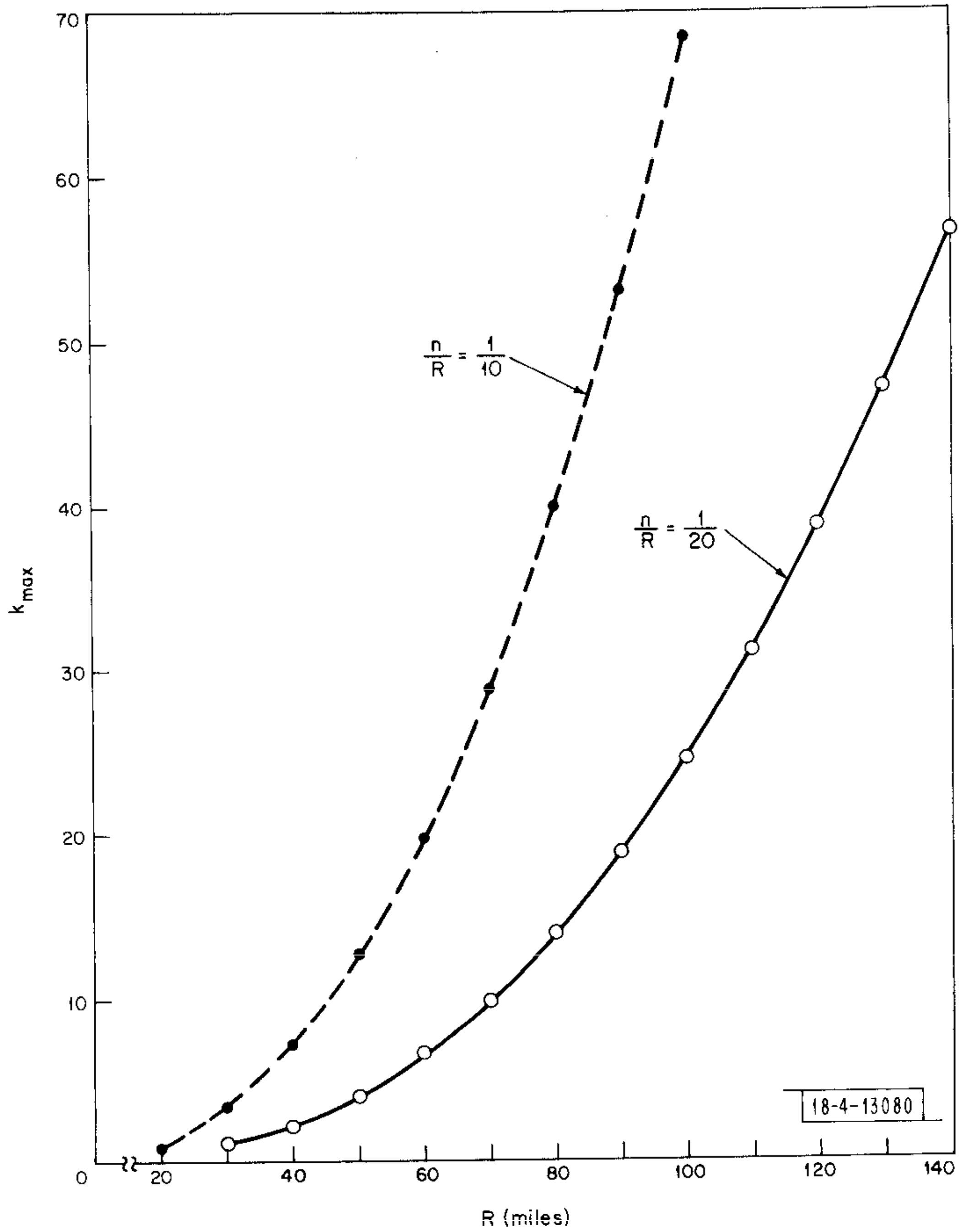


Fig. 10. k_{max} vs R for different values of the conflict frequency ratio n/R (2b = 6 mi.).

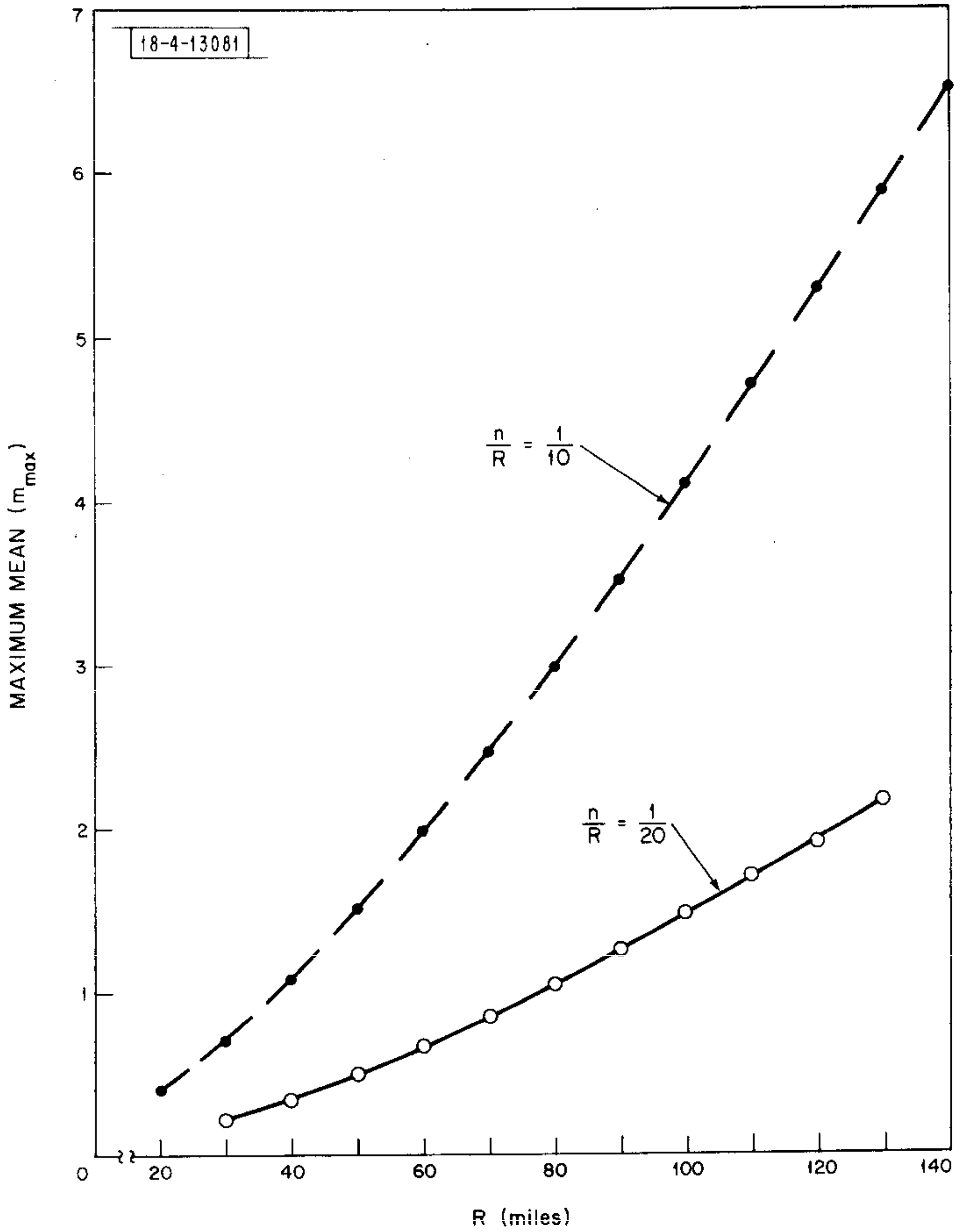


Fig. 11. m_{max} vs the range R for different values of the conflict frequency ratio n/R (2b = 6 mi.).

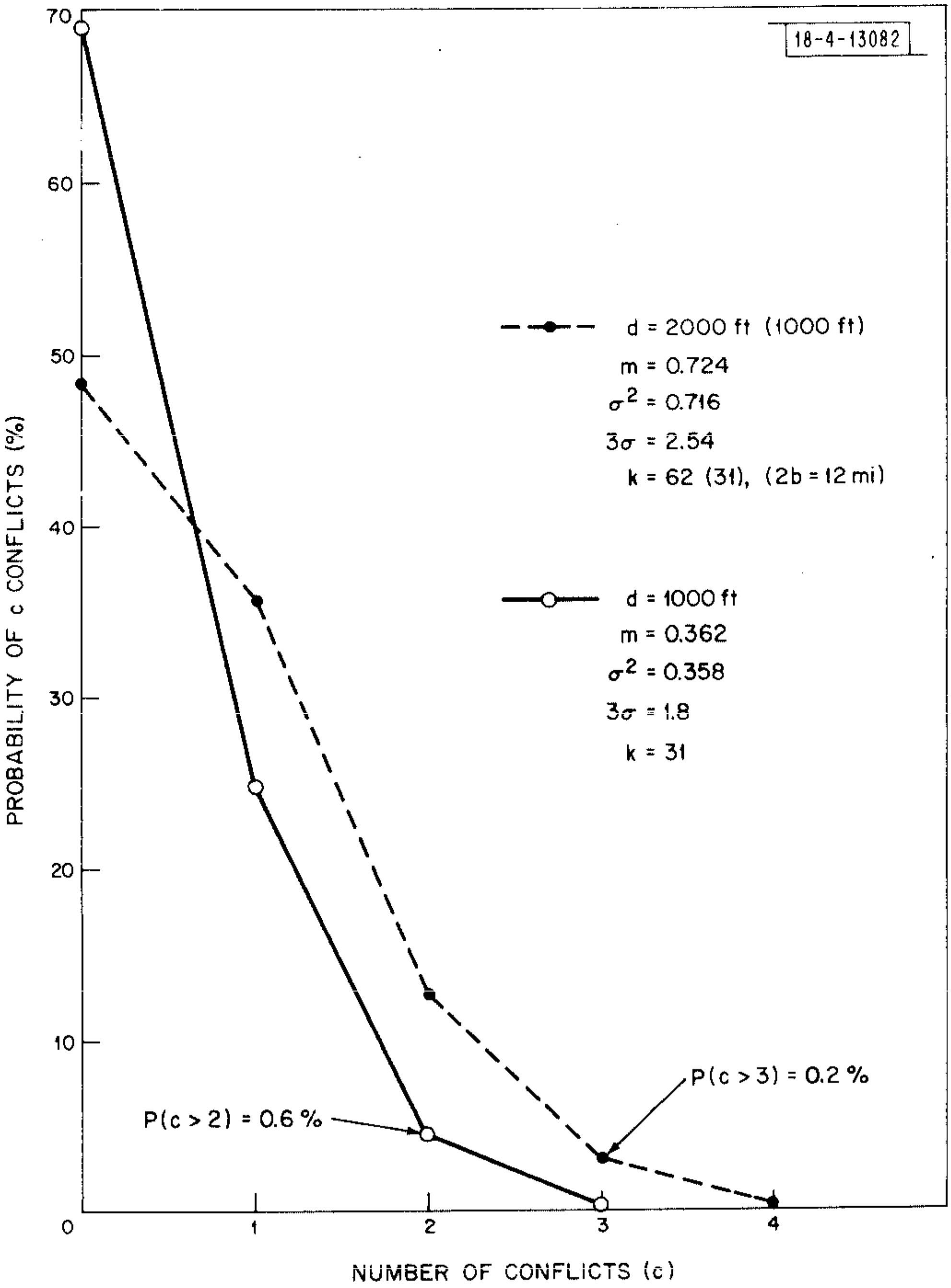


Fig. 12. Probability of conflicts for the Chicago-Washington route (R = 518 mi., 2b = 6 mi.).

From the above results one concludes that the task of resolving this small number of conflicts by modifying a submitted flight plan is simple for this case. However, the mathematical model used to reach this conclusion is not entirely realistic since it is based on the assumption that the crossing points of the intersecting aircraft are uniformly distributed over the entire route between the city pair, which is not exactly true for the route considered. Thus, it is necessary to examine small route segments over which there is a more uniform distribution of crossings before reaching a final conclusion. The worst case that could be found was that of aircraft crossing a dense set of airways converging on the New York metroplex from terminals west of the area. Only part of a route which crosses over this dense set of airways is analyzed for conflict prediction. This crossing occurs about 120 miles west of the metroplex airports and represents the situation which yields the highest frequency of conflicts as seen from the graphical presentation of present-day traffic mentioned earlier. The results for this route segment of length $R = 50$ miles are shown in Figure 13. As indicated by these results, it is likely that as many as two or three conflicts will occur over the 50 mile route segment. Results for different altitude separations and effective aircraft lengths are also shown in Figure 13.

b. Terminal Area

The L. A. Basin, a region 60 nm. by 120 nm. around Los Angeles, is chosen to represent a high density terminal area. According to the 1995 forecast analysis given in Appendix D, which is based on annual operations, the total number of instantaneous peak airborne IFR aircraft operating below 10,000 feet in this area is predicted to be 367. Assuming that in the L. A. Basin there are as many as 12 airports which handle IFR traffic on a total of 18 runways, it is estimated that there will be 102 IFR aircraft on final approach at one time (Ref. 10). This leaves an instantaneous peak airborne count of 265 aircraft in mixed airspace, which is assumed here to be between the altitudes of 6000 ft. and 10,000 ft. The

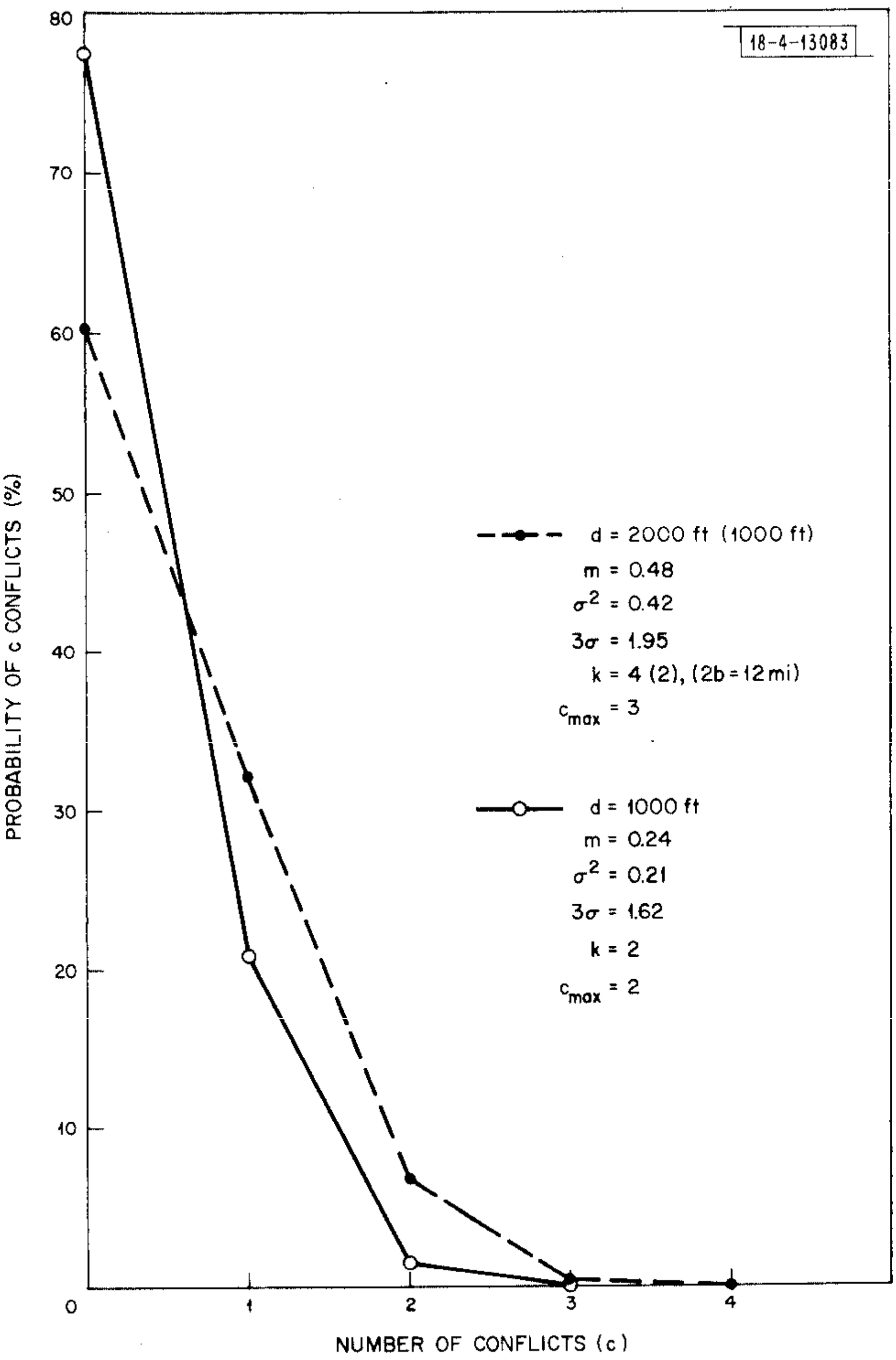


Fig. 13. Probability of conflicts for the highest density portion of the route between Washington and Syracuse (R = 50 mi., 2b = 6 mi.).

itinerant aircraft are distributed according to the current air traffic route distribution (Ref. 10) shown in Figure 14 with the distribution of the general aviation types (single engine, multi-engine, or turbojet) somewhat dependent upon the range over which they fly. Using the average ranges for traffic flowing in the various directions from Los Angeles, the corresponding aircraft type distribution (Ref. 7) and their average speeds (Ref. 11), the number of aircraft per peak hour T_t was calculated for each direction with the equation

$$T_t = \frac{IAC}{t_h} \tag{12}$$

where IAC is the instantaneous airborne count and t_h is the average time taken for aircraft to traverse a given high density route segment. Since the location of the airports relative to the sides of the rectangular area were not included in this approximate analysis, it was assumed that all of them were located within a small region around the center of the Basin.

With the traffic given above, it is possible to predict the number of conflicts expected for an aircraft crossing the high-density streams in the various sectors. For the case considered, the crossing aircraft is assumed to be on a local flight traveling at a speed of 130 mph over the width of the sector. (For the north and south sectors, $R = 60$ mi. ; for the east and west secotrs, $R = 120$ mi.). Figure 15 shows the conflict probability distribution for crossings of the north, south, and east sectors. Note that the worst conditions for a crossing occur in the north sector where the mean frequency of conflicts is one conflict every 12 miles and the maximum frequency is about one every 6 miles. The average speed for the main stream of north-south traffic is assumed to be 200 mph. If the speed of the crossing aircraft were increased to 275 mph, then the mean frequency of conflicts would be reduced to 1 every 30 miles while the maximum would be 1 every 9 miles. However, Section E shows that the conflict resolution distance is greater than for the lower velocity case and this makes the limits of required

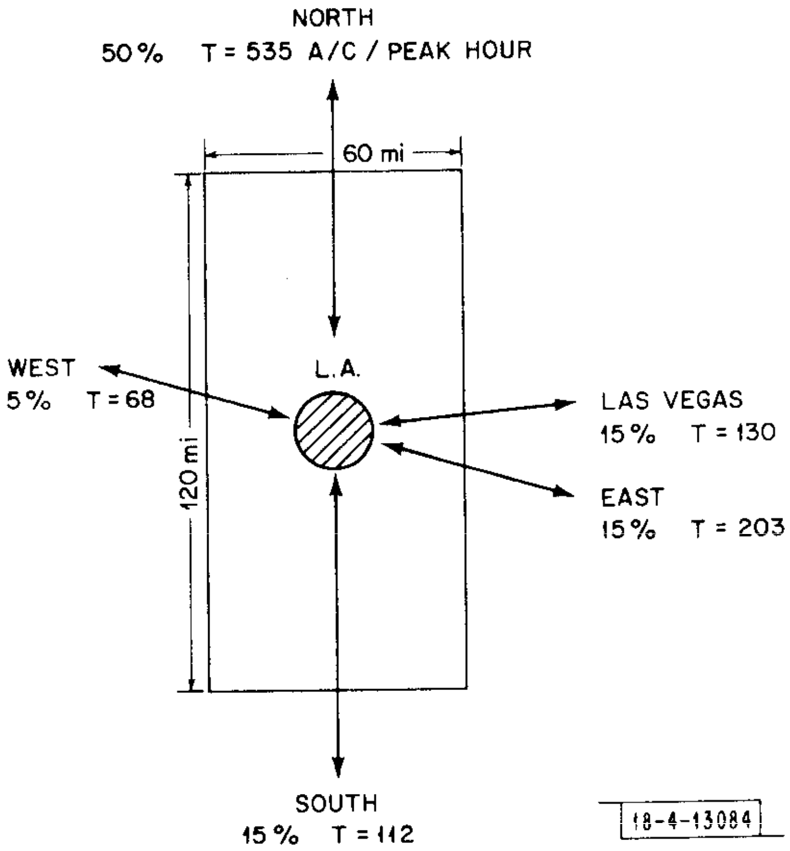


Fig. 14. Air traffic route distribution to/from L. A. Basin area.

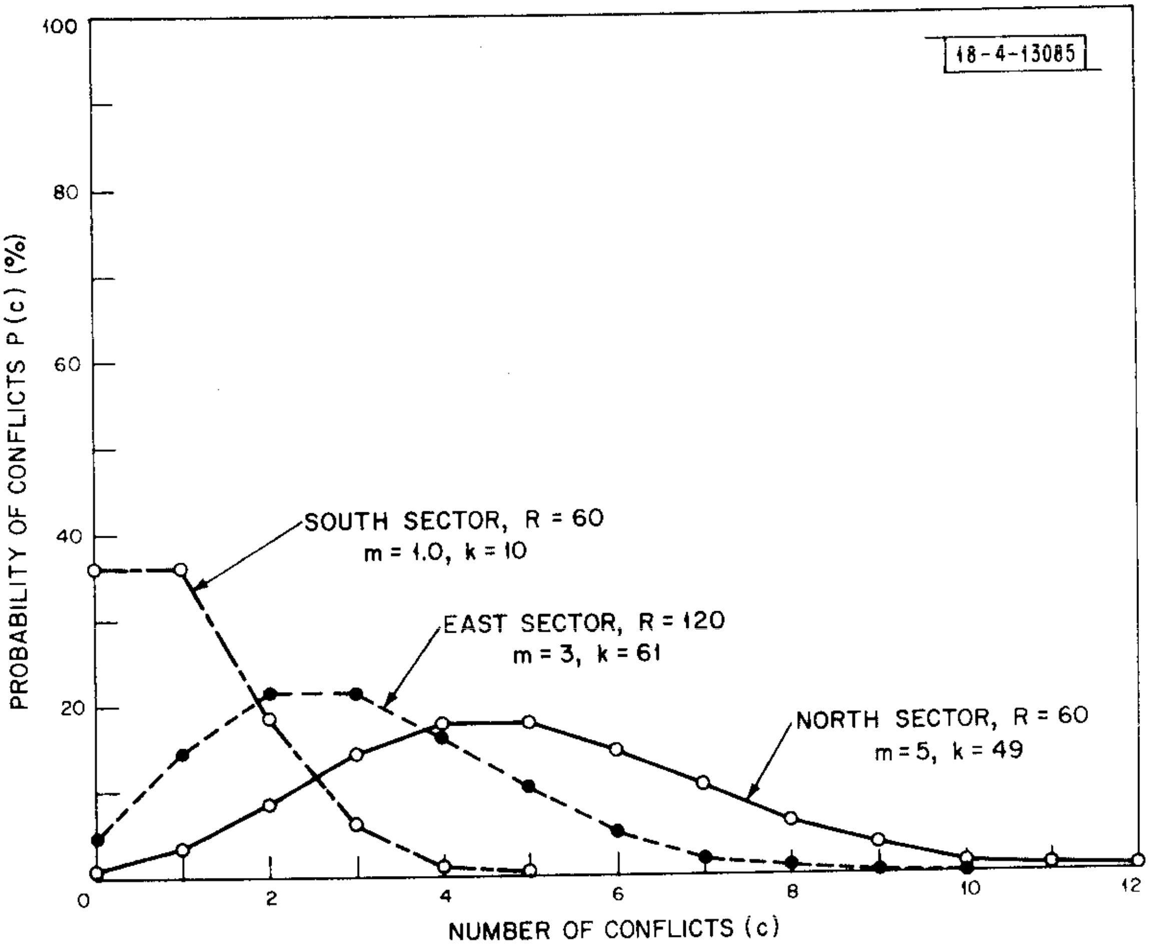


Fig. 15. Probability of conflicts for mixed airspace (6 - 10K ft.) in L.A. Basin (2b = 6 mi.).

time conformance to a flight plan about the same. It will become evident in Section E that these conflict frequencies nearly equal the maximum number that can possibly be resolved. When the effective length 2b of the aircraft is increased to 12 miles, the frequency of conflicts is approximately doubled and therefore exceeds the maximum conflict resolution frequency.

c. Restructuring the Airspace

As is evident for the L. A. Basin area, there will be instances in which the airspace must be restructured in order to reduce the conflict frequency. A method for doing this is given in Section F. The method is based on the results of this section which deal with perpendicular crossings of airways and the results of the following section which deal with crossings of airways at an arbitrary angle θ. The calculations made are based upon a "gas" model (Ref. 10). It is shown in Appendix E that the expression for the number of conflicts is approximately the same whether a gas model or a number of airways which cross one another are considered.

D. Conflict Resolution

1. Introduction

A conflict exists whenever the flight plans of two aircraft could bring them closer together than the permissible separation distance. In order to resolve the conflict the initial flight plan of at least one aircraft must be altered. The problem of conflict resolution bears a close resemblance to the problem of hazard resolution, with the principal difference being that conflict resolution deals with the projected flight plan position instead of actual aircraft positions and thus allows the planning for the encounter to be completed long before a hazardous situation actually arises. This preplanning allows time for human checking of computer generated solutions and can allow an optimization of the flight plan over a longer distance instead of requiring each traffic encounter to be resolved independently.

A basic question is whether both aircraft involved in a conflict are to be given flight plan alterations ("maneuver instructions") or if only one aircraft is to be diverted. If both aircraft flight plans are altered, then the individual deflections from the intended path become smaller and resolution becomes easier. But in the context of an ATC system which must generate, check, and transmit flight plans to the user there may be advantages to using single aircraft alterations. For instance, consider the entry of a new aircraft into a region of airspace in which a number of aircraft are already flying on approved CFFP's. If the newcomer requires a change in the flight plan of each aircraft it encounters then a new flight plan must be generated for each aircraft encountered, in addition to the generation of the newcomer's flight plan. This results in a greatly increased load on data handling and communication facilities, and produces an undesirable addition to the workload of the pilot who must continually monitor flight plan changes. Thus it may be desirable that the first flight plans issued be left intact, if at all possible, with conflicts involving new flight plans being resolved by alterations in the later plans. This does not exclude exceptions which may be allowed in order to avoid undue inconvenience to one aircraft.

For the analysis performed in the remainder of this section, it is assumed that one of the conflicting aircraft, designated aircraft B, is not asked to alter its path, and thus the remaining aircraft, aircraft A, is required to effect the resolution by altering its flight plan.

The following considerations constrain the resolution of a conflict:

PASSENGER COMFORT - required maneuvers must be sufficiently gentle so that activities in the airliner passenger cabin are not disrupted by aircraft acceleration or pitch.

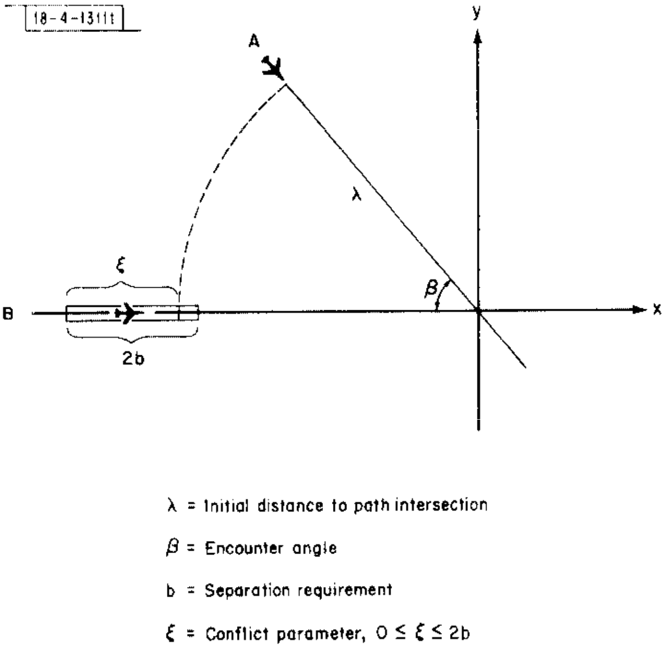
ECONOMY - the resolution must not result in excessive delay over the course of the flight nor should it require long periods of flight at uneconomical thrust settings or altitudes.

AIRCRAFT PERFORMANCE - required maneuvers must be well within the capability of the aircraft.

AIRSPACE RULES AND PROCEDURES - maneuvers must be consistent with any necessary airspace rules or structure.

2. Conflict Geometry

Figure 16 illustrates the basic conflict geometry. At the moment at which the resolution maneuver begins aircraft A is at a distance λ from the intersection point with flight path B. The encounter angle is β . The separation required is determined by the parameter b which should include both the minimum separation standards and the conformance errors expected of both aircraft. By placing a protected region of length 2b around aircraft B only, considerable mathematical simplification is obtained. It is implied here that the cross-track conformance errors are negligible compared to those along the track. The conflict parameter ξ indicates the point at which aircraft A's initial flight plan intersects B's protected region. For instance, if ξ = 2b, then A's flight plan is tangent to the leading edge of B's protected region.



λ = Initial distance to path intersection

β = Encounter angle

b = Separation requirement

ξ = Conflict parameter, $0 \le \xi \le 2b$

Fig. 16. Geometry of conflict between two aircraft.

3. Types of Maneuvers

Flight plan alterations can be thought of as consisting of certain maneuvers which must take place at prescribed points during the flight. Table 13 lists the basic types of resolution maneuvers and introduces terminology to indicate the sense or direction of a turn, acceleration, or altitude change. In this analysis, it is assumed that the choice of one maneuver is exclusive and independent. Thus, if a decision is made to execute a turn, the aircraft's speed and altitude are kept constant.

The resolution constraints vary from one maneuver to another and from one type of aircraft to another. Some conflict situations can be resolved only if the more efficient maneuvers are employed. For these reasons, it is useful to consider the constraints and capabilities of the various maneuver options separately in order to understand the region of applicability of each.

TABLE 13

Type of Maneuvers	Descriptions
PLUS TURN	(turn to pass in front of conflicting aircraft)
MINUS TURN	(turn to pass behind conflicting aircraft)
PLUS SPEED CHANGE	(accelerate)
MINUS SPEED CHANGE	(decelerate)
PLUS ALTITUDE CHANGE	(climb)
MINUS ALTITUDE CHANGE	(descend)
DELAY OR HOLD	(turn of more than 90° from desired heading)

4. Secondary Conflicts

In a general sense every other assigned flight plan imposes a certain constraint on the flight plan being generated. By assigning flight plan alterations by a method which considers only one conflict at a time, we may therefore generate a secondary conflict, i.e., one which occurs prior to the conflict being resolved and which would not arise until aircraft A was assigned a resolution maneuver. If a secondary conflict arises, we must look for a flight plan alteration which resolves both the primary and secondary conflict. Often this means abandoning the original resolution technique and utilizing another, for instance abandoning a turn maneuver and utilizing a speed change instead. These considerations imply that a single resolution maneuver will not be satisfactory in denser airspace.

5. Dependent Conflicts

When traffic encounters occur far enough apart to be resolved independently there is little difficulty in generating an acceptable conflict free flight plan. However, when encounters occur close together it may be impossible to resolve one conflict due to constraints placed on the maneuver options by another conflict. In such a case the aircraft in difficulty may be given a wide diversion (or a change in flight level) in order to eliminate both of the dependent conflicts. Alternatively, a solution may be sought which considers both conflicts simultaneously rather than sequentially so that a solution to the first conflict is chosen which makes the solution of the second possible.

When multiple conflicts are common, aircraft will be subject to large diversions from their desired flight paths due to the encounters. For this reason it is desirable to develop an airspace structure which allows the majority of conflicts to be resolved independently. In the analysis which follows we will seek to determine the distance needed to resolve a single, independent conflict and relate this to the allowable traffic density.

6. Turn Maneuvers

For the analysis of the turn maneuver the following formulas are derived from simplified kinematical considerations:

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

$$r = \frac{V^2}{g \tan\theta}, \qquad (13)$$

$$\zeta = \frac{1 - \cos\theta}{\cos\theta},$$

where ω = rate of turn,

θ = bank angle,

V = aircraft velocity,

r = radius of turn,

ζ = fractional increase in perceived acceleration.

With regard to ζ it should be noted that in a properly executed turn the centripetal force is balanced by a component of the gravitational force, and thus the additional acceleration experienced by the passengers in the aircraft is normal to the cabin floor. A turn for which $\zeta = 0.1$ produces a force equivalent to a 10 percent increase in gravitational attraction. For airlines, ζ must be kept at a low value in order to avoid interference with activities in the passenger cabin. Figure 17 presents the turn parameter for an aircraft at a jet cruising speed of Mach 0.8 as a function of ζ. To facilitate conflict resolution it is desirable to reduce the radius of turn as much as possible. The decreasing slope of the r vs. ζ curve leads to rapidly diminishing benefits as ζ is increased beyond 0.1. For several examples that follow, a value of $\zeta = .05$ (bank angle 17.8°) is used to define the turn radius. It should also be noted that the turn radius increases as the square of the velocity. For this reason the resolution distance is significantly smaller for slower aircraft.

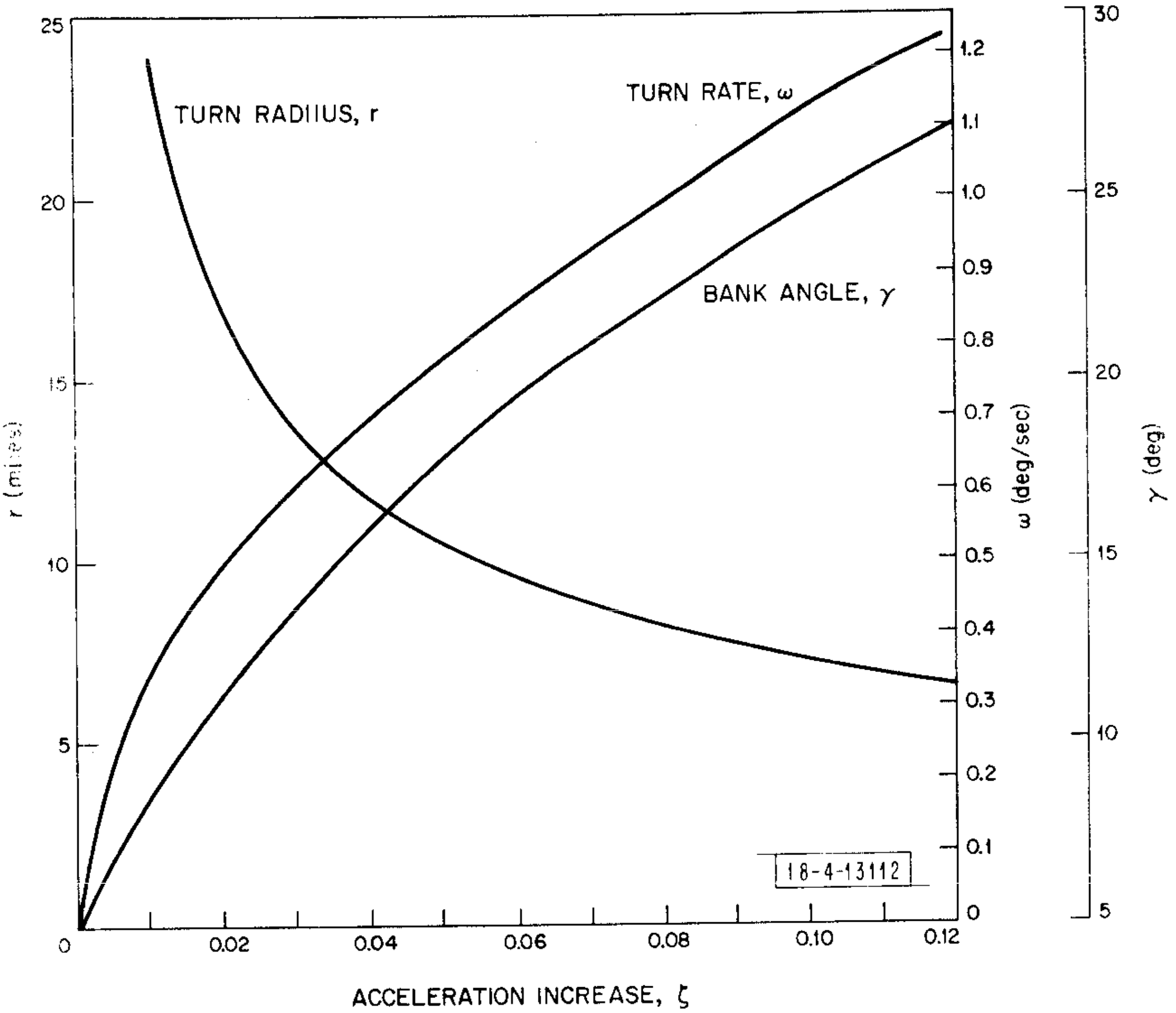


Fig. 17. Maneuver parameters for turn as a function of allowed fractional increase in acceleration experienced by passengers (velocity = Mach 0.8).

The geometry of a turn at a constant radius of curvature is indicated in Fig. 18. We desire to choose the turn direction so as to minimize the required deviation of aircraft A from its original flight path. This choice depends principally on the parameter ξ. If $\xi \simeq 0$, then aircraft A intersects the rear boundary of B's protected region and thus a turn in the minus sense resolves the conflict most efficiently. On the other hand, if $\xi \simeq 2b$, then A intersects the leading edge of B's protected region and a turn in the plus sense is preferred.

Note that when the encounter angle, β, is near $\pi/2$ we have a near symmetry between the achievable deviations and would thus expect each direction to be chosen approximately 50 percent of the time. However, as β decreases a marked asymmetry arises which favors the minus sense. For purposes of comparison let us consider the case for which $\xi = b$, i.e., the case in which a direct collision would occur if the original flight plans were not altered. In one sense the direct collision type of conflict is a worst case requiring the greatest deflection to achieve the required separation standards.

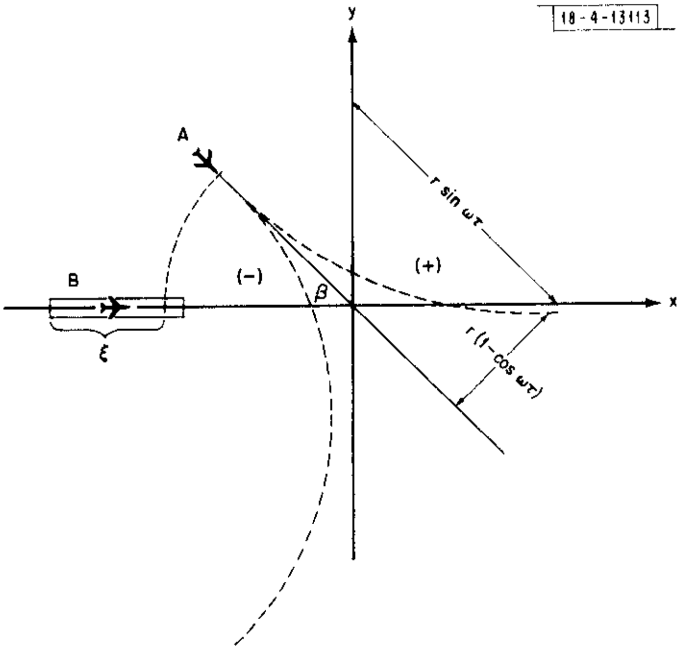


Fig. 18. Basic geometry of turn maneuvers.

Note that in the geometry of the current problem the heading of aircraft A differs from the original heading by an angle $\omega\tau$ at the time of intersection. If another resolution maneuver immediately ensues, aircraft A may be deflected even further from its original heading. Thus the distance between conflicts should be greater than λ_r in order to allow time for return to the original heading. For the <u>minimum</u> resolution distances given in later figures, the aircraft is banked during the entire maneuver, i.e., there is no period of straight flight. Thus the distance required to return to the original heading is the same as the distance λ_r. The distance between conflicts which ensures zero heading deflection is thus $2\lambda_r$.

In discussing the conflict resolution problem for widely varying airspace categories and aircraft types it was found that several models for the turn resolution were necessary to provide the flexibility needed. A geometric model is presented first which gives a conservative bound to the resolution distance when β is near 90°. Then a fixed-deflection model is presented which yields a closed form solution for the resolution distance. Finally, a third model is presented which allows a variable-deflection time-dependent solution. This latter model, however, requires computer evaluation and thus provides data only for those parameter values which are presented in the figures of this section. The three models are described below.

a. Geometrical

Geometrical considerations can provide a useful approximation to the required inter-conflict distance for the case of perpendicular incidence. First note that resolution can always be accomplished if the point of intersection of aircraft A with the flight path of aircraft B can be shifted by a distance b from its original intersection point. Figure 19 illustrates the basic geometry of the maneuver which involves two turns which are executed in a way such that at the time of intersection aircraft A has returned to its original heading. It is shown in Section 1 of Appendix F that $\lambda_r \leq r + b$ for this maneuver.

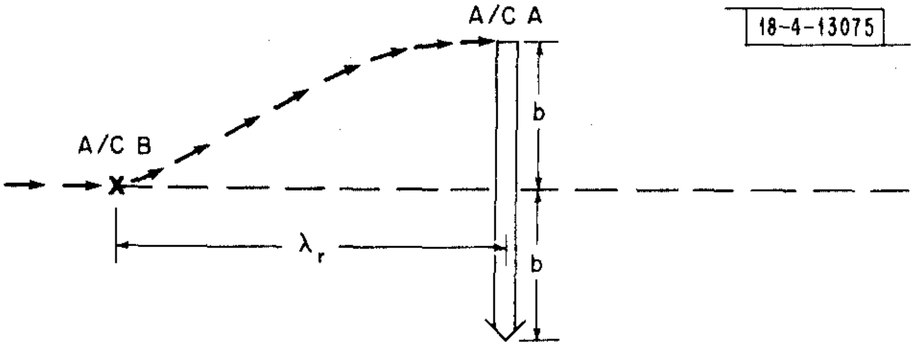


Fig. 19. Geometric approach to determining required conflict resolution distance.

b. Fixed Deflection

A closed form solution for the minimum resolution distance can be derived if we specify that aircraft A always changes its course by 90° during the turn. As shown in Section 2 of Appendix F, the resolution distance for this maneuver is

$$\lambda_r = \frac{b \cos \beta + r \sin \beta - r \left(\frac{\pi}{2} - 1 \right) \cos \beta + r}{\sin \beta - \cos \beta + 1} . \tag{14}$$

This formula is valid for $0 \leq \beta \leq \pi/2$.

c. Variable Deflection

The most realistic turn maneuver model is one in which aircraft A is banked for some period τ, thus turning to a heading which differs by $\omega\tau$ from its original heading. Straight flight then ensues until aircraft A crosses the path of aircraft B. The equations which describe the relative paths of the two aircraft are given in Section 3 of Appendix F. We can now determine the minimum resolution distance which will allow us to achieve the required separation between aircraft. This distance is called λ_r and is given in Fig. 20 for minus turns and in Fig. 21 for plus turns.

7. Evaluating Delay

In order to be acceptable, a conflict solution must not only generate the required separation between aircraft, but it must produce only a modest deviation of the maneuvering aircraft from its original path. Consider the plus turn maneuver when the speeds of the two aircraft are essentially the same. As aircraft A turns toward the heading of aircraft B, the relative velocity between the aircraft approaches zero. Thus they may fly a substantial distance before the separation between them allows one to cross the path of the other. For this reason the delay involved in resolution can present a significant economic penalty. If alternate ways of resolving conflicts are to be considered, it is important that delay be evaluated.

The flight path for a turn resolution can be thought of as consisting of three segments: first, a turn at constant rate to a new heading; second, a period of straight flight; and third, a turn at constant rate back to the initial heading. (The assumption that the aircraft returns to its original heading is valid when the distance flown during resolution is small compared to the distance of the aircraft from its destination). The delay incurred can be defined as the difference between the time taken to fly the curved path and the time which would have been required in undeviated flight to reach a point at an equivalent distance from the destination (see Fig. 22). The decrease in distance to the destination is

$$X_p = 2r \sin \omega\tau + V_A(t_{in} - \tau)\cos \omega\tau . \qquad (15)$$

The time required for the initial turn is τ; the period of straight flight is

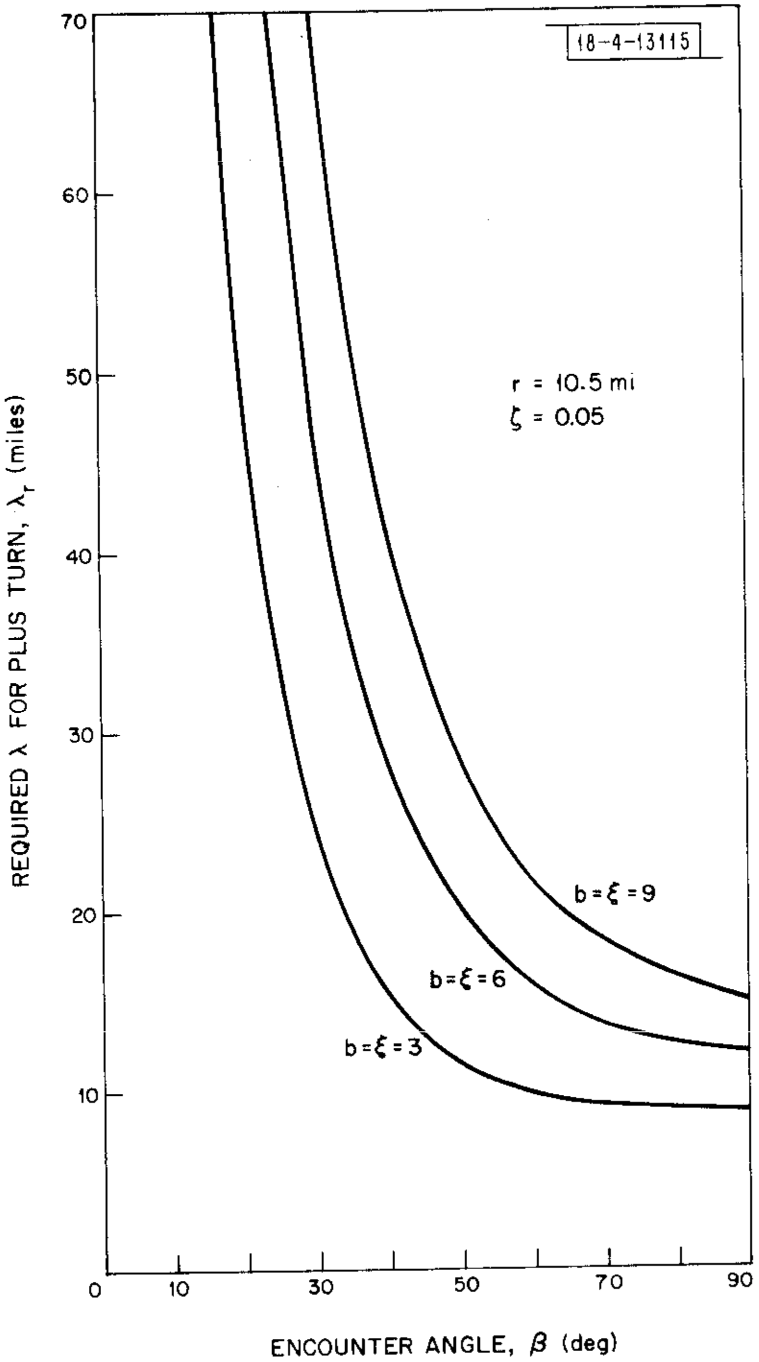


Fig. 20. Required resolution distance for minus turn maneuver (radius of turn = 10.5 mi., velocity = Mach 0.8).

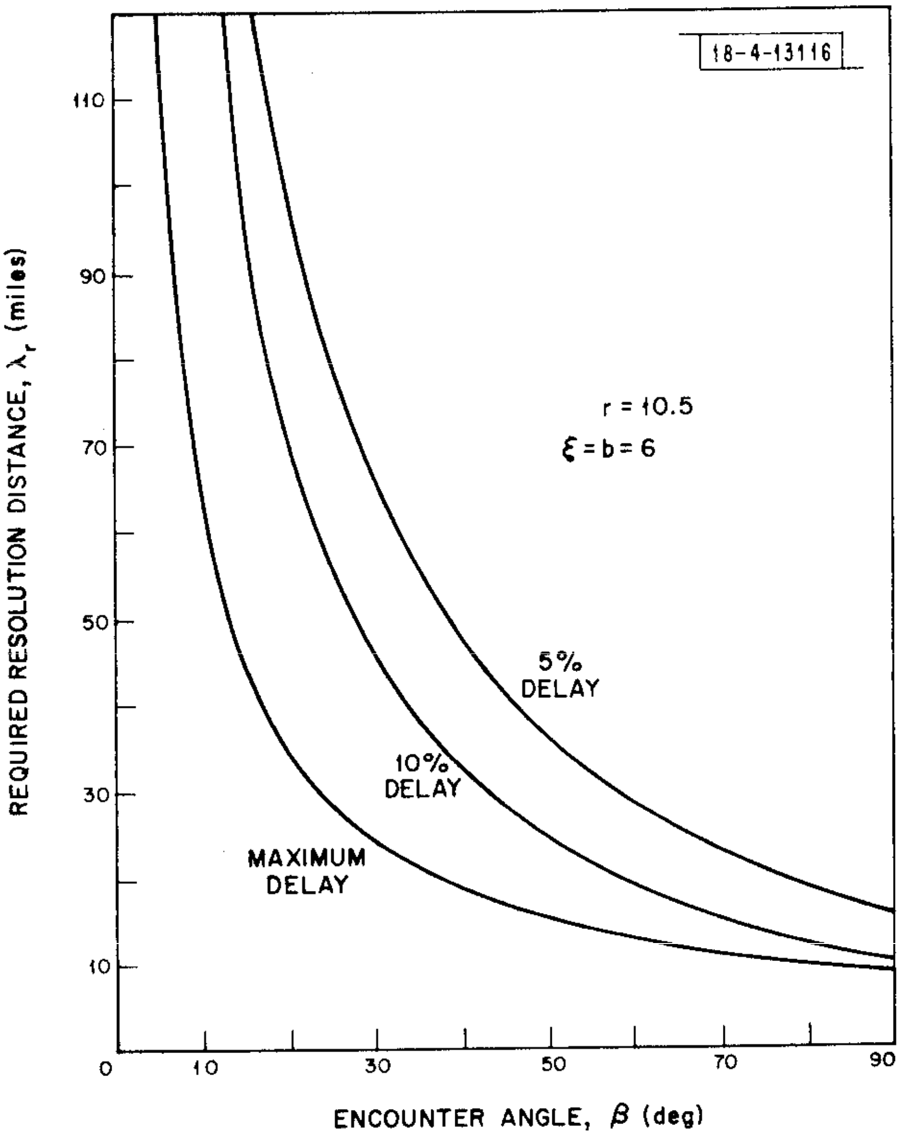


Fig. 21. Required resolution distance for plus turn maneuver (radius of turn = 10.5 mi., velocity = Mach 0.8).

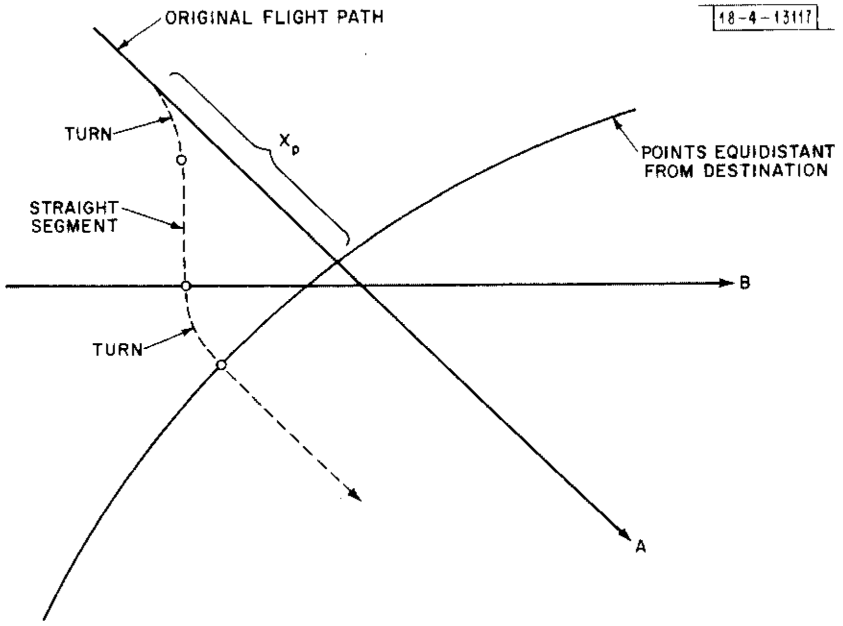


Fig. 22. Turn resolution maneuver showing X_p, the distance advanced in the direction of the destination during the maneuver.

of duration $t_{in} - \tau$, and a time τ is required to return to the original heading. Thus a time $t_{in} + \tau$ is required to advance a distance X_p. In undeviated flight the time required would have been simply X_p/V_A. We can thus define the maneuver delay as the percentage increase in the time taken to advance X_p toward the destination, i.e.,

$$\text{maneuver delay} = \frac{t_{in} + \tau - X_p/V_A}{X_p/V_A} \times 100 \text{ percent} \qquad (16)$$

If we require the maneuver delay to be small, we will need a greater resolution distance than the minimum distance presented in the previous figures. The minus turn maneuver exhibits a smaller maneuver delay than the plus turn at a given value of λ. Figure 23 gives the required resolution distance, λ_r, for a minus turn maneuver constrained by delays of 5% and 10%. The curve for "maximum delay" corresponds to the minimum resolution distance of Fig. 20.

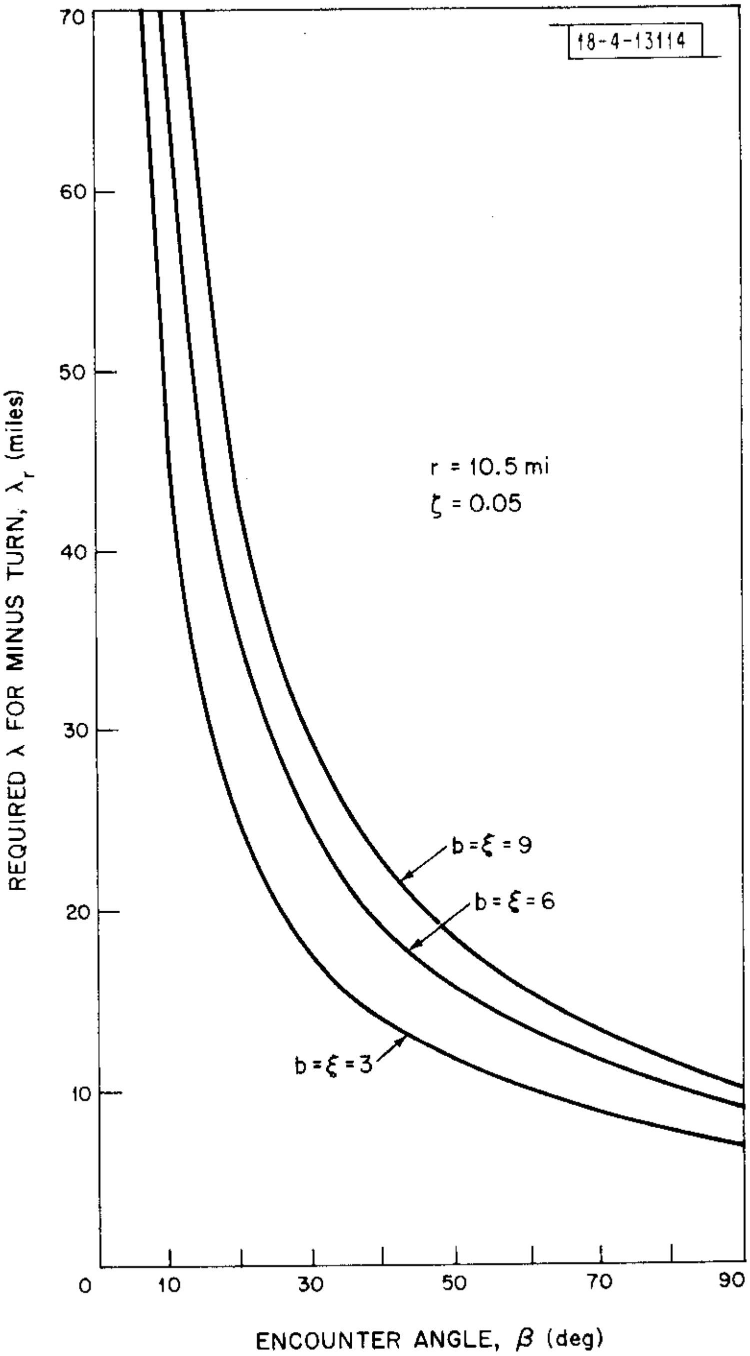


Fig. 23. Required resolution distance for minus turn maneuver under various constraints of maneuver delay.

8. Speed Changes

The efficiency of speed changes in resolving conflicts depends on the acceleration capability of the aircraft and on the deviation from normal speed which is allowable. An aircraft flying near its ceiling may find it impossible to increase its airspeed while maintaining altitude. In addition, engine characteristics exclude certain operating practices. Some discussion of these factors appears in Section XII. In order to compare the speed change technique with other resolution maneuvers we will make certain simplifying assumptions. Let us consider an aircraft which is capable of positive or negative accelerations of equal magnitudes. The speed deviation allowable is a fraction ±K of the original speed. Thus for a plus speed change the aircraft accelerates at an acceleration, a, to a final speed $V(1 + K)$.

For the case in which acceleration is completed at a point prior to the path intersection the required resolution distance for the minus speed change is

$$\lambda_r(-) = \frac{b(1 - K)}{K} + K\frac{V^2}{2a} . \tag{17}$$

For the plus speed change the required distance is slightly greater at the same values of K and a, and is given by

$$\lambda_r(+) = b\frac{(1 + K)}{K} + \frac{KV^2}{2a} . \tag{18}$$

The value of $\lambda_r(-)$ for various parameters is shown in Fig. 24. Note that even if a speed change as large as 10 percent is allowed, the speed change resolution requires a much longer distance than the turn resolution for crossing angles above 12^o.

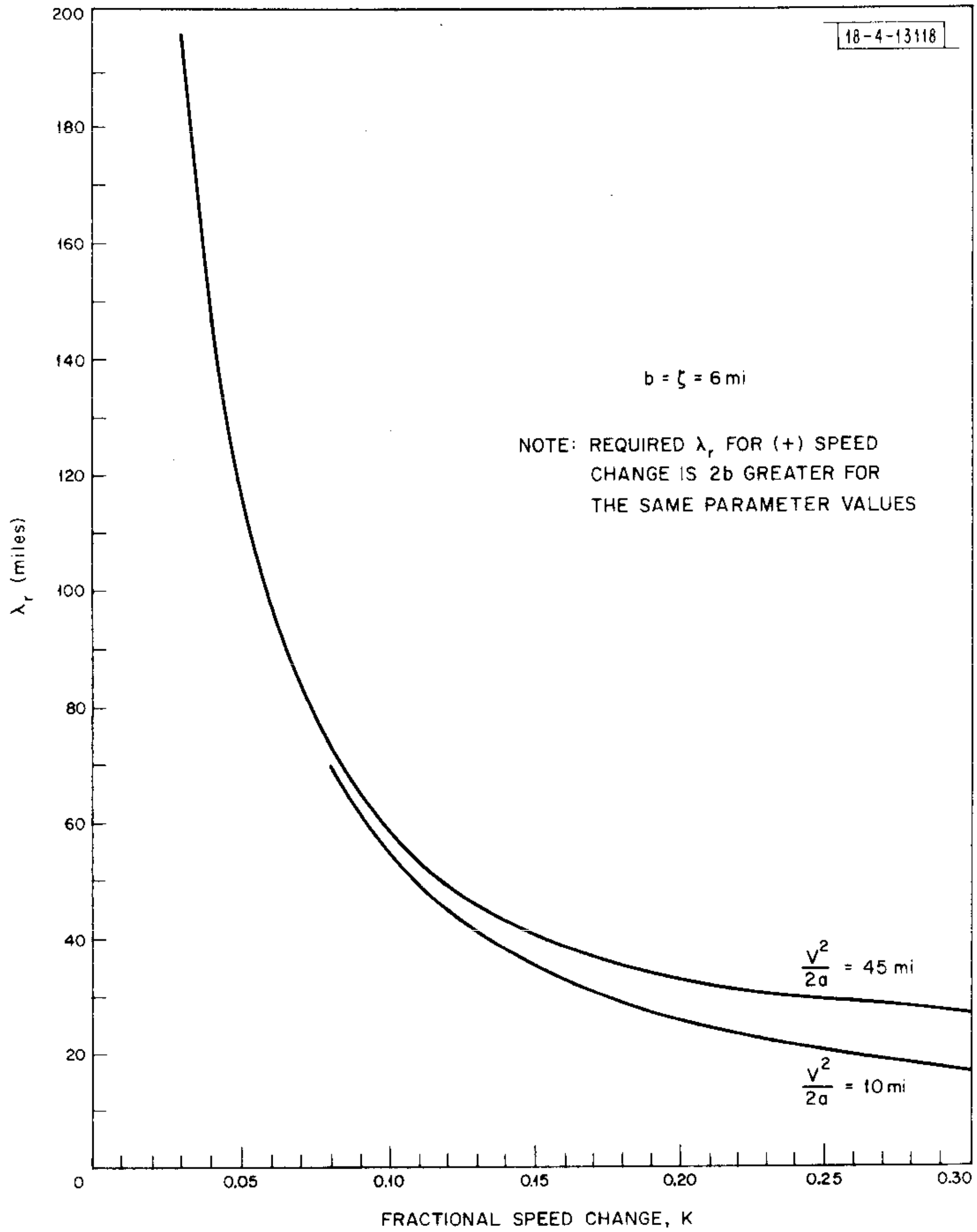


Fig. 24. Required resolution distance for minus speed change.

The above expressions are evaluated for the condition $\xi = b$. It is of interest to note that if we assume that ξ is uniformly distributed between 0 and 2b, then we can write the probability that an encounter can be resolved with either a plus <u>or</u> minus speed change as

$$P_{res} = \frac{K}{b(1 - K^2)} \left(\lambda - \frac{V^2}{2a} K\right)$$

for $$\lambda > \frac{V^2}{2a} (2K + K^2). \tag{19}$$

The distance which is then required to ensure resolution is

$$\lambda_r = \frac{b(1 - K^2)}{K} + \frac{V^2}{2a} K. \tag{20}$$

9. Altitude Changes

If aircraft fly at discrete flight levels separated by the minimum vertical separation distance, resolution of conflicts through altitude changes can be accomplished by having the maneuvering aircraft climb or descend to the adjacent flight levels. Presumably the original flight altitude has been chosen after consideration of wind, weather, and engine operating conditions. All of these factors vary with altitude, and thus basic objections may arise to conflict resolution techniques which require flight level changes. The question of the true cost of altitude changes will not be addressed here, but their efficiency in resolving conflicts will be considered. Suppose the aircraft climbs at an angle ϕ to a flight level a distance d above the original one. The horizontal distance flown during the climb is then $d/\sin \phi$ which is the resolution distance. If the non-conformance of aircraft A produces an uncertainty as to the point at which the climb will begin or in the rate of climb, then the resolution distance must be increased to allow for this uncertainty. Further discussion of this point follows in Section E. Note also that a secondary conflict may exist at the new flight level which precludes the use of the maneuver. If uncertainties in conformance force us to consider an aircraft climbing between two flight levels as occupying both flight levels simultaneously, secondary encounters may occur relatively frequently.

10. Summary: Comparison of Types of Maneuvers

The required resolution distance for the various types of maneuvers described in this section are composed in Fig. 25. The value of λ_r for turn maneuvers was obtained from Fig. 20 and Fig. 21, which do not include constraints on the maneuver delay. Since speed change and climb maneuvers are not dependent on the encounter angle, they are represented by constant λ_r values. It can be seen from Fig. 24 that the value of λ_r for speed changes is mainly a function of K and that the aircraft's acceleration and initial speed have little effect on the required resolution distance. The value of λ_r required for altitude changes can vary significantly with operating practices and the value shown in the figure is only an example. The two dimensional λ_r vs. β region is divided into nine areas which differ in the combination of maneuver options available for resolution. From this figure it is apparent that turn and climb maneuvers have a much larger effective range than speed changes except at very low encounter angles.

E. Conformance Requirements

1. Introduction

This section describes a quantitative analysis which can be used to determine the conformance limits required of IFR aircraft for various parts of the airspace. The analysis is based on the capability of resolving conflicts by turning, changing speed, or changing altitude. Each of these alternatives will be analyzed for the specific cases treated in Section C, "Predicted Frequency of Conflicts".

2. Theory

The conformance requirements are determined by combining the results of two mathematical models. The first model is used to

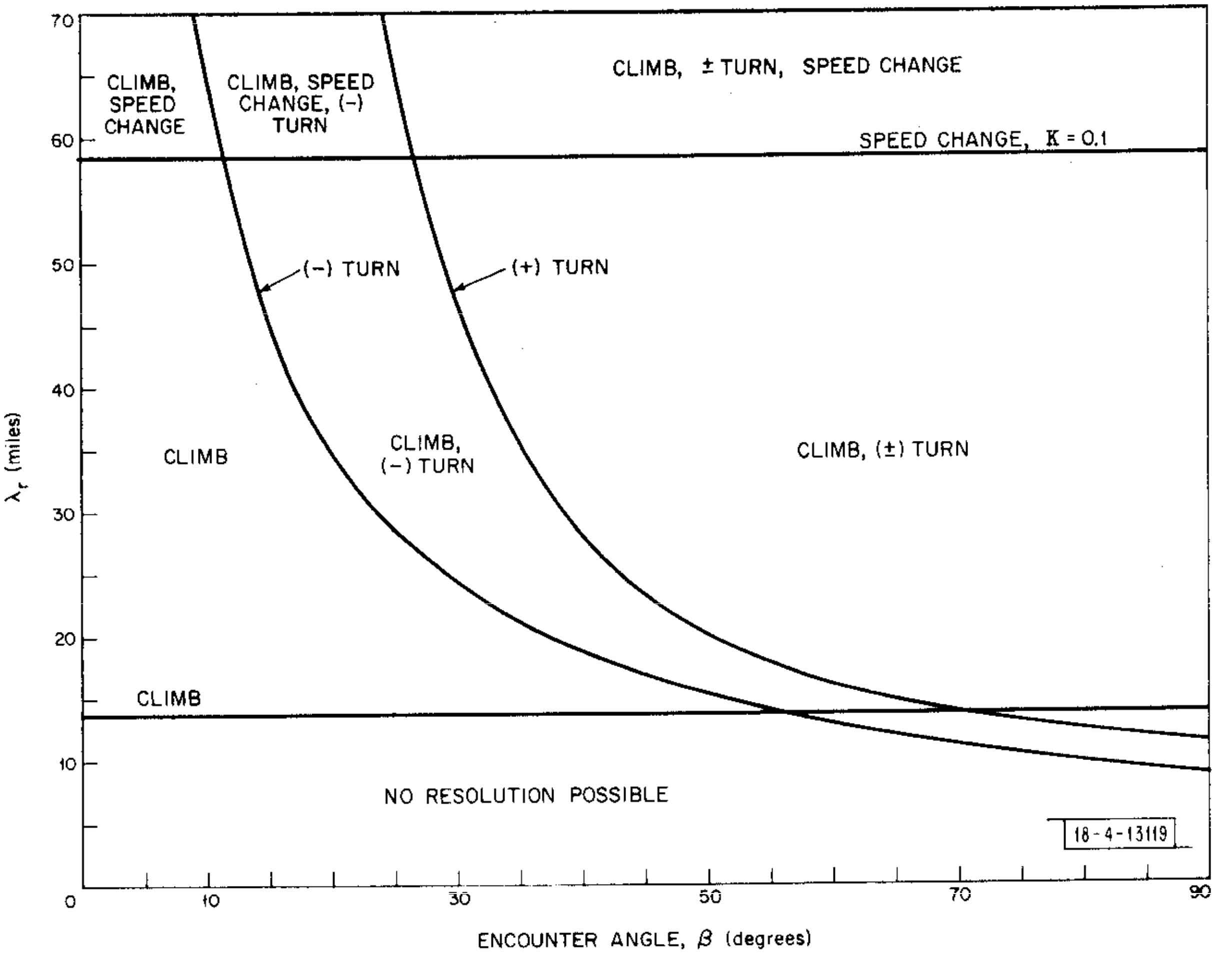


Fig. 25. Comparison of required resolution distance for various maneuver options ($r = 10.5$, V_A = Mach 0.8).

determine the maximum number of conflicts which can be resolved. The second model is used to determine the maximum number of conflicts which are likely to occur. The former assumes equally spaced conflicts along the route of the aircraft with one conflict resolved at a time. It is recognized that if we look ahead to more than the next conflict, more of them can be resolved. This factor tends to make the value of the conflict resolution distance λ_r determined from this model to be larger than the value derived from a perfect traffic model. It is also recognized that if we have unequally spaced conflicts, fewer conflicts can be resolved when treating them one at a time. This factor tends to make the value of λ_r determined from this model smaller than the value that would be derived from a perfect model. Thus, the first model is approximate only to the extent that the above two errors tend to cancel each other. Upon knowing the conflict resolution distance, the maximum number of resolvable conflicts c'_{max} is

$$c'_{max} = \frac{R}{\lambda_r} \tag{21}$$

where R equals the length of the route segment to be analyzed.

The second model is that described in Section C which assumes an exponentially distributed inter-conflict time. With the randomness of this model, it is impossible for all the conflicts to be resolved. However, as discussed in Section C most of the time the number of conflicts encountered will be less than the quantity c_{max} where

$$c_{max} = m + q\sqrt{m}. \tag{22}$$

(m is the mean of the conflict probability distribution and q is a positive integer equal to 0, 1, 2, 3 depending upon how often one can tolerate not being able to resolve all conflicts and thus not being able to generate a CFFP on the first try). Equating the expression for c_{max} to the expression for the maximum number that we can resolve, c'_{max}, gives

$$\frac{R}{\lambda_r} = m + q\sqrt{m}. \tag{23}$$

To determine the effective length, 2b, of the aircraft, we use the previously derived expression for the mean,

$$m = \frac{2bk}{R}, \tag{24}$$

where k is the number of aircraft crossing an aircraft's path during the time it is on the route segment of length R. Substituting Eq. (24) into (23) yields an expression for b,

$$b = \frac{R}{2k}\left[\frac{q^2}{2} + \frac{R}{\lambda_r(b)} - \sqrt{\frac{q^4}{4} + \frac{q^2 R}{\lambda_r(b)}}\,\right], \tag{25}$$

where it is noted that the conflict resolution distance λ_r is a function of b. This function is obviously different for each of the three different conflict avoidance maneuvers.

In order to determine the non-conformance of each aircraft from knowledge of the effective length 2b, use is made of the assumption that there must be a longitudinal separation standard of $b_o = 3$ miles.* This means that with perfect conformance to a flight plan the effective length is $2b_o = 6$ miles. Dividing the non-conformance equally between being

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* The separation standard is selected somewhat arbitrarily here as 3 miles, the standard for today's system. With conflict free flight planning and improved surveillance capability, it may be possible to reduce this separation standard in the future.

ahead and being behind gives the range of non-conformance (n. c.) as

$$\text{n. c.} = \pm \frac{b - b_o}{2} = \pm \frac{b - 3}{2} \tag{26}$$

Expressing n. c. in units of time gives

$$t_{\text{n. c.}} = \pm \frac{\text{n. c.}}{V}, \tag{27}$$

where V is the velocity of the aircraft.

Mathematical expressions which give $\lambda_r(b)$ for the three possible conflict avoidance maneuvers will be given in the sections to follow. Only perpendicular crossings will be treated here for obtaining this parameter.

a. Turn Maneuver

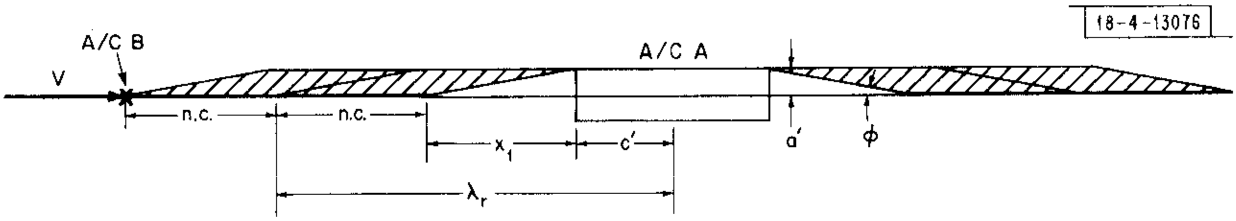
As shown in Appendix F, a conservative estimate of the conflict resolution distance $\lambda_r(b)$ for the turn maneuver is given by the following expression which is derived by a purely geometrical approach:

$$\lambda_r(b) = \alpha(r + b) \tag{28}$$

where the constant α is ≥ 1. The case $\alpha = 1$ is only slightly on the conservative side. In deriving this expression it was assumed that the maneuvering aircraft must always have a positive component of velocity in the direction of its original path so that adequate lateral separation would be ensured. Also, the maneuvering aircraft must have returned to its original heading at the termination of the maneuver. In order to determine the effective length 2b, the above expression is substituted into Eq. (25). Knowing b, all the other quantities, m, c_{max}, λ_r, n. c., and $t_{\text{n. c.}}$, can be obtained from Eqs. (22) through (27).

b. Change in Altitude

Another way of resolving a conflict when there is freedom to choose routes in three dimensional space (3D flight planning) is by using climb or descent maneuvers. Consider aircraft A which has the effective vertical dimension a' and lateral dimension c' shown in Fig. 26. The requirement for resolving a conflict is for aircraft B to avoid intersecting the effective rectangular area (2a' x 2c') of aircraft A. The effective vertical dimension a' must include the separation standard a_o plus the combined vertical non-conformance 2(n. c. v.) of both aircraft A and B (in today's system, only the separation standard is used). The effective lateral dimension c' includes only the combined lateral non-conformance of the two A/C, (n. c. l.), since the projected distance required to climb x_1 is always greater than the longitudinal separation standard of 3 miles. Using the same reasoning, the only important part of the effective length of aircraft B for the climb or descent maneuver is the longitudinal non-conformance n. c. of one aircraft.



n.c. = Longitudinal nonconformance

$a' = a_o + \text{n.c.v.}$
$c' = 2\,\text{n.c.}\ell$

Fig. 26. Altitude change maneuver.

Assuming that the along-track velocity V of the maneuvering aircraft remains constant throughout the maneuver and the vertical rate of climb or descent is $\dot{h}$, then the angle of ascent or descent is equal to

$$\phi = \sin^{-1} \frac{\dot{h}}{V}. \tag{29}$$

The time it takes for aircraft B to change altitude by a vertical distance a' is

$$t_a = \frac{a'}{\dot{h}} . \tag{30}$$

Then the horizontal distance travelled during this time is

$$x_1 = Vt_a \cos\phi = \frac{V a'}{\dot{h}} \cos\left[\sin^{-1}\frac{\dot{h}}{V}\right] . \tag{31}$$

The expression for the conflict resolution distance is

$$\lambda_r(b) = \alpha\left[c' + x_1 + n.c.\right] \tag{32}$$

where α is ≥ 1. To be more conservative one might include in c' the longitudinal separation standard of 3 miles. However, this was not done in obtaining the numerical results that will follow. Substituting Eqs. (26) and (31) into the above equation gives

$$\lambda_r(b) = \alpha\left[(c' - 1.5) + \frac{V a'}{\dot{h}} \cos(\sin^{-1}\frac{\dot{h}}{V}) + \frac{b}{2}\right] \tag{33}$$

This expression for $\lambda_r(b)$ can be used in Eqs. (22) through (27) to determine the allowed non-conformance of the aircraft as well as other pertinent quantities.

c. Speed Change

A third method of resolving a conflict is with a speed change, which may imply a 1D airspace structure. From Section D the probability of resolution using this type of maneuver is given by

$$P_{res} = \frac{K}{b(1-K^2)} \left(\lambda - \frac{V^2}{2a} K\right) \tag{34}$$

where $K = \frac{\Delta V}{V}$ = fractional amount of speed change,

a = acceleration or deceleration of the aircraft,

V = initial velocity of the aircraft,

λ = distance to point of intersection of aircraft if no maneuver is made.

Upon setting $P_{res} = 1$, λ becomes the conflict resolution distance $\lambda_r(b)$ which is given by

$$\lambda_r(b) = \frac{b(1-K^2)}{K} + \frac{V^2}{2a} K . \tag{35}$$

As in the other two maneuvers, the allowed non-conformance and other desired quantities can be determined by using Eq. (35) in conjunction with Eqs. (22) through (27).

3. Numerical Results and Conclusions

The above theory was applied to the four cases treated in Section C: (1) the Chicago-Washington route; (2) the portion of the Washington-Syracuse route which crosses the dense set of airways west of New York City; (3) a mixed airspace route crossing the north sector of the L. A. Basin with the crossing aircraft traveling at 130 mph; and (4) the same as the previous case except that the crossing aircraft are traveling at 275 mph. For each of the three conflict resolution maneuvers the proper expression for

$\lambda_r(b)$ was substituted into Eq. (25) to determine the effective length of the aircraft. A root-finding computer program was written for use with the Hewlett-Packard 9100B Programmable Calculator to obtain b for values of $q = 0, 1, 2, 3$ and $\alpha = 1, 2$. The allowed non-conformance as well as m, c_{max}, and λ_r can be determined for all the above cases once b is known. The values of the constants used in the equations are given in Table 14. For the descent or climb maneuver, the altitude separation standard a_o was taken to be 1000 feet while the vertical non-conformance, n. c. v., for each aircraft was ±250 feet. The lateral non-conformance, n. c. l., for each aircraft was assumed to be ±0.5 miles. In determining the radius of turn r from Fig. 17, a gravitational acceleration increase of $\zeta = 0.05$ was assumed. Appendix G gives the numerical results for the parameters obtained by solving Eqs. (22) through (27). A reduced form of the data showing the effective lengths and longitudinal conformance requirements for $q = 0$ and 3 and $\alpha = 1$ is shown in Table 15. Some of the conclusions that can be drawn from this set of data are the following:

1. The assumed airspace organization with a uniform distribution of aircraft among flight levels does not look very desirable for cases (2), (3), and (4) because of the required strict conformance of less than ±28 seconds for $q = 3$, i.e., $c_{max} = m + 3\sqrt{m}$. Thus, a restructuring of the airspace is necessary. One or more levels could be opened up for crossing traffic by reducing the number of aircraft from the uniform distribution value of $k = k_o$ to a new value $k = k_1$. If we take case (3) as an example and reduce k from $k_o = 49$ to $k_1 = 20$, then the new effective lengths and conformance requirements would become those indicated in Table 16. These are believed to be much more practical numbers for the pilot/aircraft combination to achieve.

2. For the two en route cases, the descent or climb maneuver looks most favorable in terms of requiring the least degree of conformance. However, because the turn maneuver has conformance requirements which are not very much different from the descent or climb, other considerations

TABLE 14

ASSUMED CONSTANTS FOR EN ROUTE AND TERMINAL AREA CASES

Cases	General Constants (from Part III-3)			Special Maneuver Constants					
				Turn	Dive or Climb			Speed Change	
	R (mi)	V (mph)	k	r (mi)	$\dot{h}$ (mph)	a' (mi)	c' (mi)	K	a (mi/hr^2)
<u>En Route</u>									
(1) Chic.-Wash. Route	518	514	31	10.5	17.0 (1500 fpm)	0.284 (1500 ft)	1.0	0.05	3000 (50 mph/min)
(2) Portion of Wash.-Syr. Route	50	514	2	10.5	17.0 (1500 fpm)	0.284	1.0	0.05	3000
<u>Terminal Area</u>									
(3) L. A. Basin V = 130mph	60	130	49	0.672	5.69 (500 fpm)	0.284	1.0	0.05	1500 (25 mph/min)
(4) L. A. Basin V = 275 mph	60	275	23	2.96	11.4 (1000 fpm)	0.284	1.0	0.05	1500

TABLE 15
NUMERICAL RESULTS FOR CONFORMANCE REQUIREMENTS

$\alpha = 1$

Case	Parameter*	Turn		Descent or Climb		Speed Change	
		$q = 0$	$q = 3$	$q = 0$	$q = 3$	$q = 0$	$q = 3$
(1) Chic.-Wash. R = 518 mi.	2b	121	74.4	170	111	28.2	13.0
	n.c.	±28.8	±17.1	±41.0	±26.3	± 5.6	± 1.8
	$t_{n.c.}$	± 3.4 min	± 2.0 min	± 4.8 min	± 3.1 min	±39.0 sec	±12.3 sec
(2) Portion of Wash.-Syr. R = 50 mi.	2b	40.6	14.3	56.4	22.0	Ineffective	
	n.c.	± 8.7	± 2.1	±12.6	± 4.0		
	$t_{n.c.}$	± 1.0 min	±15.0 sec	± 1.5 min	±28.0 sec		
(3) L.A. Basin V = 130 mph R = 60 mi.	2b	11.5	7.5	9.0	4.0	Ineffective	
	n.c.	± 1.4	± 0.4	± 0.7	-		
	$t_{n.c.}$	±39.0 sec	±11.0 sec	±20.0 sec	-		
(4) L.A. Basin V = 275 mph R = 60 mi.	2b	14.9	8.2	15.3	6.8	Ineffective	
	n.c.	± 2.2	± 0.6	± 2.3	± 0.2		
	$t_{n.c.}$	± 29.0 sec	± 8.0 sec	± 30.0 sec	± 3.0 sec		

* NOTE: All distances (2b and n.c.) are in miles.

TABLE 16

CONFORMANCE REQUIREMENTS FOR CASE (3) (L. A. BASIN, V = 130 MPH) WHEN k = 20.

Parameter	Turn		Descent or Climb		Speed Change
	$q = 0$	$q = 3$	$q = 0$	$q = 3$	
2b (miles)	18.3	11.2	17.4	7.9	Ineffective
n. c. (miles)	± 3.1	± 1.3	± 2.9	±0.5	
$t_{n.c.}$	± 1.4 min	± 36 sec	± 1.3 min	±13.4 sec	

such as passengers' comfort and cost may change the order of maneuver preference. It is not within the scope of this work to thoroughly investigate the human factors aspects of the problem.

3. For the mixed airspace cases (L. A. Basin), the turn maneuver appears to be somewhat better than the descent or climb maneuver; this is due to the moderate aircraft speed. However, if other numbers for turn rate and rate of climb or descent are used and if human errors are thoroughly considered, the choice between these two types of maneuvers might be reversed.

4. For crossing a dense set of airways over a short route segment as in cases (2) through (4), the speed change maneuver is totally in-effective because of the long conflict resolution distance that is required $[\lambda_r(b) > R]$. Even for the long route case (1), changing speed to resolve a conflict does not appear to be nearly as desirable as the other two alternative maneuvers.

F. Airspace Structure

1. Introduction

It has been suggested that the traffic capacity of a given segment of airspace can be increased by imposing a velocity structure on it. This can be done by specifying the range of aircraft headings which is allowable at a given flight level or in a given sector of a congested area. Segregation by speeds is another example of velocity structure. The current ATC system uses a "hemisphere rule" (FAR parts 91.109 and 91.121) in uncontrolled airspace which is based on the general idea of separating traffic onto even or odd numbered flight levels according to their magnetic course. This allows heading intervals of 180° at each flight level. For the fourth generation traffic situation new and possibly more complex structures may be needed to solve particular traffic problems, especially in high density controlled (mixed) airspace.

2. Effect of Structure on Frequency of Conflicts

Figures 27 and 28 illustrate the effect of velocity structure on a small segment of airspace. The first drawing represents the flight paths for eastbound aircraft at a given flight level. The headings are distributed between 0° and 180°. Suppose that a redistribution of aircraft takes place in which those aircraft flying between 80° and 110° heading are brought to this level and those flying at other headings are relegated to other flight levels. The statistically expected result is that the distance between crossings and, therefore, the total number of crossings in the sector will be decreased as illustrated in the figures.

In a traffic situation in which the distribution of headings is uniform, we could impose a structure on p flight levels with heading intervals of $\frac{360^\circ}{p}$ at each level and thereby define one permissable flight level for each aircraft. In actual situations such as the case of the Los Angeles Basin discussed previously, the distribution of headings is not uniform and the allowed heading intervals may be adjusted accordingly. For example, the width of the intervals can be made inversely proportional to the traffic density in the interval so that the number of aircraft on each flight level is the same.

The calculations discussed in Section D indicate that the distance required for resolution of a conflict through a turn maneuver increases as the angle of encounter, β, becomes smaller. The distance required to resolve the conflict with a speed change is independent of angle but is usually much greater than that required for a turn. A question thus arises as to whether or not the velocity structuring that is described will provide an increase in the traffic capacity. If the distance required to resolve a conflict increases more rapidly than the average distance between conflicts, structuring will not prove useful.

A model for determining the conflict frequency in structured airspace can be developed as follows. Consider two aircraft with velocities V_A and V_B.

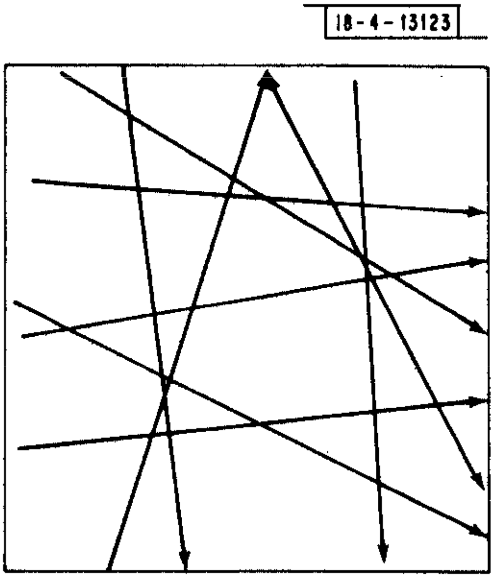


Fig. 27. Flight path crossings with loose velocity structure.

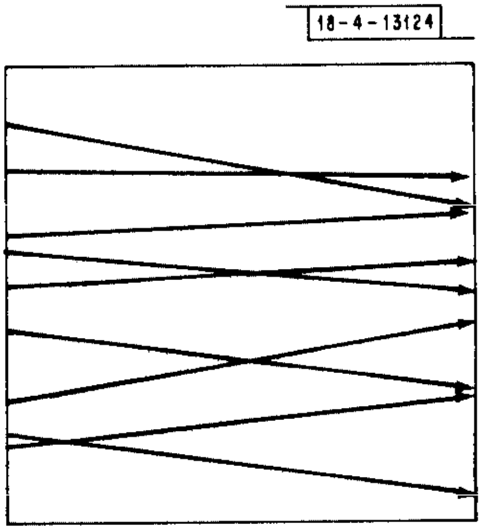


Fig. 28. Flight path crossings with more restrictive velocity structure.

The relative velocity between these aircraft is

$$V_r = (V_A^2 + V_B^2 - 2V_A V_B \cos\beta)^{1/2},$$

or if $V_A = V_B$ we have

$$V_r = V_A\sqrt{2}\,(1 - \cos\beta)^{1/2} = 2V_A \sin\beta/2. \qquad (36)$$

In the coordinate system which has aircraft A at its origin, all other aircraft of relative heading β are seen to be moving at a relative velocity V_R. If one of these aircraft passes through a protected region of length 2b centered on aircraft A, then a conflict exists. Consider the area in Fig. 29 which is swept out by moving the protected area of aircraft A with a velocity V_R. This area grows linearly with the interval of future time considered. It is easily seen that if the position of an aircraft of relative veloctiy V_R lies within this area, then a conflict exists for the time interval considered. If this area is empty, then no aircraft of relative velocity V_R produces a conflict in the time interval. This formulation allows us to find the probability distribution of conflicts on the basis of the area density of aircraft. Unless the protected region is spherical, the swept area has a frontal projection w which varies with β. The rate with which the area is swept is then

$$\frac{dA(\beta)}{dt} = w(\beta)V_r(\beta). \qquad (37)$$

Now let the area density of aircraft be $\mu_o = N_A/A$ where A is the area of the flight level being considered and N_A is the total number of aircraft on the flight level. We now define a function $g_u(z)$ such that the area density of aircraft with course headings between $\beta = z$ and $\beta = z + dz$ is

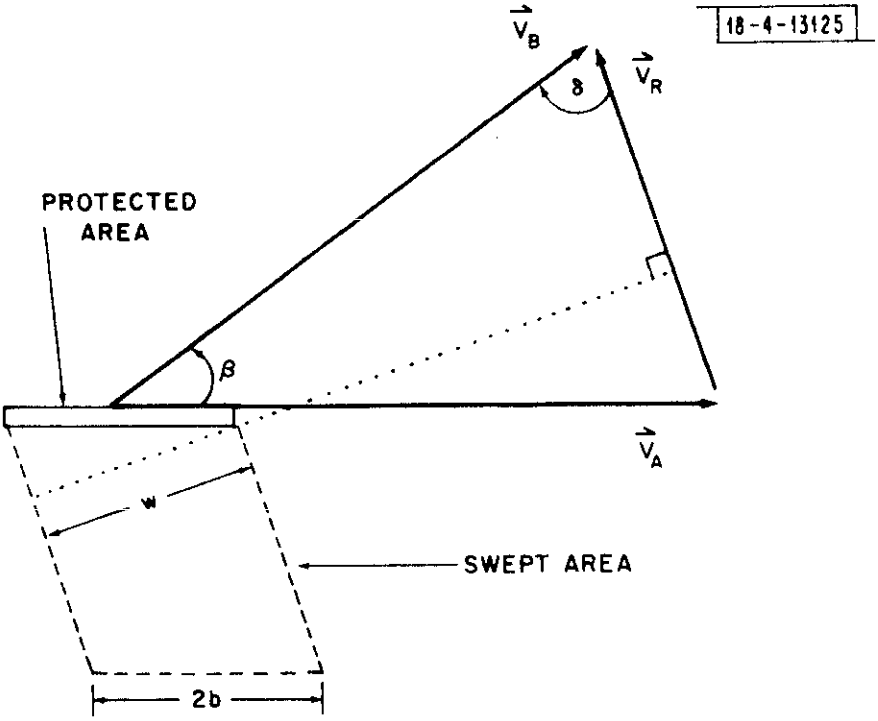


Fig. 29. Concept of swept area as used in deriving probability distributions for conflicts.

$$g_{\mu}(z)\,dz = \frac{\text{expected number of aircraft between } \beta = z \text{ and } \beta = z + dz}{A}$$

$$= \frac{N_A f_{\beta}(z)dz}{A} = \mu_o f_{\beta}(z)\,dz \qquad (38)$$

where $f_{\beta}(z)$ is the probability density function for β which corresponds to a random sampling of β from the population of all aircraft on the flight level. Thus, if β is uniformly distributed between 0 and β_o such that $f_{\beta}(z) = 1/\beta_o$, $g_{\mu}(z) = \mu_o/\beta_o$. It can be shown that the probability distribution of the free path λ is

$$\text{Prob}\left[\lambda \geq x\right] = F_{\lambda}(x) = \exp \frac{-x}{V_A} \int_o^{\beta_o} g_{\mu}(z) \left(\frac{d\,A(z)}{dt}\right)dz \quad . \qquad (39)$$

Table 17 presents the distribution functions for both the case of a spherical protected region and the case of an elongated rectangular region for which the cross-track extent is negligible. For these cases it is assumed that the aircraft encounter angles are uniformly distributed between 0 and β_o which corresponds to aircraft heading at angles between $-\beta_o$ and $+\beta_o$ with respect to the path of an intersecting aircraft. When aircraft A flies near the edge of the heading interval, it will, on the average experience encounters at greater angles than when it flies near the center, so these distributions apply only to the free path of an aircraft flying near the prime heading.

The distribution of encounter angles is found by noting that the expected number of conflicts between $\beta = z$ and $\beta = z + dz$ is proportional to $g_{\mu}(z)$ $w(z)\ V_r(z)dz$. The total expected number of conflicts is thus proportional to $\int g_{\mu} w V_r dz$.

TABLE 17

	Case 1 spherical protected region, radius b	Case II protected region 2b in length, cross-track dimension negligible
frontal projection w	2b	2b cos $\beta/2$
relative velocity V_r	for $V_A = V_b$ $\sqrt{2}\, V_A(1 - \cos\beta)^{1/2}$	for $V_A = V_B$ $\sqrt{2}\, V_A(1 - \cos\beta)^{1/2}$
area density distribution (see text) $g_\mu(x)$	$\frac{\mu_o}{\beta_o} \quad 0 \leq \beta \leq \beta_o$	$\frac{\mu_o}{\beta_o} \quad 0 \leq \beta \leq \beta_o$
free path probability density $f_\lambda(x) = \frac{-dF_\lambda}{dx}$	$\alpha e^{-\alpha x}$ where $\alpha = \frac{8b\mu_o}{\beta_o}(1 - \cos\frac{\beta_o}{2})$	$\alpha e^{-\alpha x}$ where $\alpha = \frac{2b\mu_o}{\beta_o}(1 - \cos\beta_o)$
encounter angle distribution function $F_\beta(x)$	$\frac{1 - \cos\frac{x}{2}}{1 - \cos\frac{\beta_o}{2}}$	$\frac{1 - \cos x}{1 - \cos\beta}$
characteristic free path λ_c	$\frac{\ln(1./\kappa)\beta_o}{8b\mu_o(1 - \cos\frac{\beta_o}{2})}$	$\frac{\ln(1./\kappa)\beta_o}{2b\mu_o(1 - \cos\beta_o)}$
mean free path between encounters λ_m	$\frac{\beta_o}{8b\mu_o(1 - \cos\frac{\beta_o}{2})}$	$\frac{\beta_o}{2b\mu_o(1 - \cos\beta_o)}$
mean encounter angle β_m	$\frac{2\sin\frac{\beta_o}{2} - \beta_o\cos\frac{\beta_o}{2}}{1 - \cos\frac{\beta_o}{2}}$	$\frac{\sin\beta_o - \beta_o\cos\beta_o}{1 - \cos\beta_o}$

Thus

$$\text{Prob}\left[\beta \text{ between } x \text{ and } x + dx\right] = \frac{g_\mu(x) w(x) V_r(x)}{\int g_\mu w V_r \, dx} dx = \left[\frac{dF_\beta(x)}{dx} dx\right] \quad (40)$$

where $\left[\frac{d F_\beta(x)}{dx}\right]$ is the probability density function of β which corresponds to a random sampling of β from the population of all aircraft that are encountered. Table 17 gives the $F_\beta(x)$ expression for the two cases considered and also gives the mean encounter angle,

$$\beta_m = \frac{\left[F_\beta(\beta_o) - F_\beta(0)\right]}{\beta_o} \quad (41)$$

A first order approximation to β_m which is valid for both cases is

$$\beta_m \cong \frac{2}{3} \beta_o, \quad (42)$$

We may define a characteristic length λ_c such that the free path between encounters is greater than λ_c in a fraction κ of the cases. Then

$$\lambda_c = \frac{V_A \ln(\frac{1}{\kappa})}{\int g_\mu w V_r \, d\beta}. \quad (43)$$

The average value of λ occurs at $\kappa = 1/e$, that is, $\ln(1/\kappa) = 1$.

3. Effect of Structure on the Amount of Traffic which can be Accommodated

In considering the effect of structure let us examine the ratio of the mean free path between encounters, λ_m, to the required resolution distance for the mean encounter angle, $\lambda_r(\beta_{av})$. When this ratio, which we will call ν, increases, capacity increases.

For case II we have from Table 17,

$$\nu = \frac{\lambda_m}{\lambda_r(\beta_m)} = \frac{\beta_o}{2b\mu_o(1-\cos\beta_o)\lambda_r(\beta_m)} \tag{44}$$

where $\beta_m = (\sin\beta_o - \beta_o\cos\beta_o)/(1-\cos\beta_o)$ and

$\lambda_r(\beta_m)$ is obtained from Fig. 20 if only turns are used,

$\lambda_r(\beta_m)$ is obtained from Fig. 24 if only speed changes are used,

$\lambda_r(\beta_m)$ is obtained from Section E if only altitude changes are used.

The dependence of ν on β_o is illustrated in Fig. 30. It can be seen that for the turn maneuver there is essentially no change in the ratio ν as structure is increased, i.e., as β_o is decreased. For speed and altitude changes the ratio does improve due to the fact that for these maneuvers $\lambda_r(\beta_m)$ remains constant as β_m decreases. This implies that for turn maneuvers the probability of resolution cannot be significantly improved by structuring, although the mean free path can still be increased as much as desired.

4. An Example: The Los Angeles Basin

Consider the case of the Los Angeles Basin. In the region of highest density, the north sector, aircraft will be required to fly with almost perfect conformance to their flight plans if a uniform distribution of aircraft among the five flight levels is assumed (see Section E). It was shown that if the number of north-south aircraft, k, at one or each of several flight levels designated for crossing traffic is decreased to a value of $k \leq 20$, the conformance requirements can be considerably relaxed. This would increase the density of aircraft at the remaining flight levels which would then contain the bulk of the north and south bound traffic. The question arises

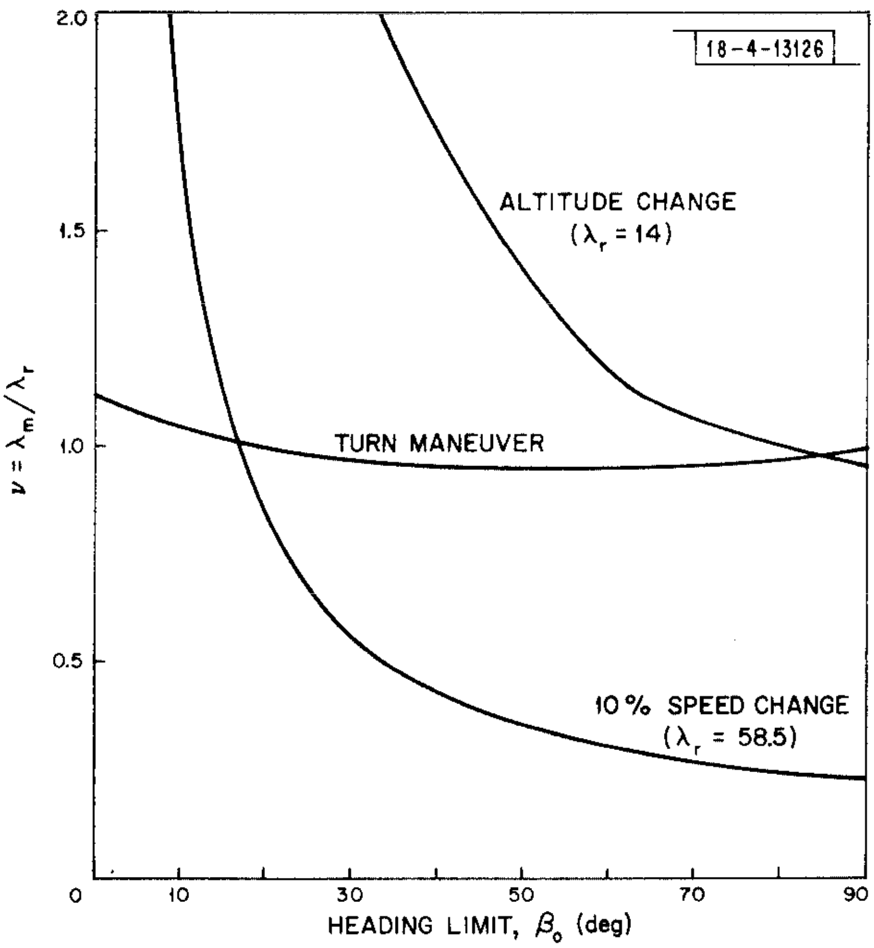


Fig. 30. Ratio V as a function of the imposed heading limitation.

as to what structuring is necessary for these high density levels. Eq. (44) can be used to determine what traffic density levels allow the mean free path between conflicts to exceed the required conflict resolution distance. An approximate formula for the quantity λ_r evaluated at the mean encounter angle, $\beta_m \cong \frac{2}{3}\beta_o$, is given by (see Appendix F),

$$\lambda_r(\beta_m) = \frac{b \cos\beta_m + r \sin\beta_m - r(\frac{\pi}{2} - 1)\cos\beta_m + r}{\sin\beta_m - \cos\beta_m + 1} . \qquad (45)$$

In evaluating this parameter, a turn radius r of 1.6 miles was used (assuming a speed $V = 200$ mph and the fractional increase in perceived gravitational acceleration $\zeta = 0.05$).

The density μ_o is related to the total number of aircraft at a given flight level N_A by the expression $\mu_o = N_A/A$, where A is the area of the north sector which is assumed to be 60 mi. x 60 mi. Assuming each aircraft conforms perfectly to a flight plan, i.e., $b = 3$ mi., the value of N_A which causes the ratio ν to approach unity at very small values of β_o is 216. As the aircraft's level of non-conformance becomes larger, it is evident from Eqs. (44) and (45) that the value of ν is reduced and so is the "threshold" value of N_A. Unity is not truly the threshold of acceptable values of ν since λ_m and $\lambda_r(\beta_m)$ are mean values of probability distributions. A certain safety factor for ν must be used to account for the randomness of the actual inter-conflict distances and resolution distances. The need for this safety factor is discussed below. Also, there is uncertainty about the effect of local variations in traffic density, since the flying patterns and positions of the airports have not been thoroughly examined for the Los Angeles Basin case.

Using the results of Appendix D and the traffic distribution described in Section C, the total instantaneous airborne count over all flight levels between 6,000 and 10,000 feet in the north sector is estimated to be IAC = 160. Let us first treat an extreme way that the previously assumed uniform distribution of aircraft among flight levels could be modified. Assume that all the itinerant traffic must fly on only two levels, one for north-bound and the other for south-bound. Crossing traffic and local flights would only use the remaining three flight levels. Fig. 31 shows that ν is about three for each of the high density levels containing $N_A = 80$ aircraft. (Note that if a spherical protected region (case I) were assumed, there would only be about a 6.5% decrease in the value of ν for all the curves shown in the figure). If λ_m and $\lambda_r(\beta_m)$ were the same for all conflicts, any value of ν greater than one would be acceptable. Because of the previously mentioned variations in λ_m and $\lambda_r(\beta_m)$, ν must be considerably greater than one to insure that $\lambda_m > \lambda_r$ for nearly all conflicts. The value of ν of about three may not be acceptable. One must examine higher order statistics of the ratio of the distance between conflicts divided by the distance required to resolve conflicts to determine what value of ν is acceptable. Even if the value $\nu = 3$ is not acceptable, the maximum heading angle β_o can be decreased to the point where the average distance between conflicts is on the order of the length of the sector, $R = 60$ miles. Then it should be possible to assign flight plans so that the first conflict does not occur until after the aircraft has left the high density region. Using Eqs. (44) and (45) the value of β_o for the Los Angeles Basin case which results in a mean free path at about 60 miles is about three degrees. Assuming all the IFR aircraft to be equipped with area navigation equipment, it might be possible to require the 80 aircraft to fly on 10 parallel airways extending across the north sector with an airway separation of 6 miles and with each one of the north-south airways having a maximum of about 8 aircraft separated longitudinally by 8 miles.

Another possible traffic distribution which would require marginally acceptable conformance requirements for crossing aircraft is the one shown in Fig. 32. The north-south traffic density for each of two levels desig-

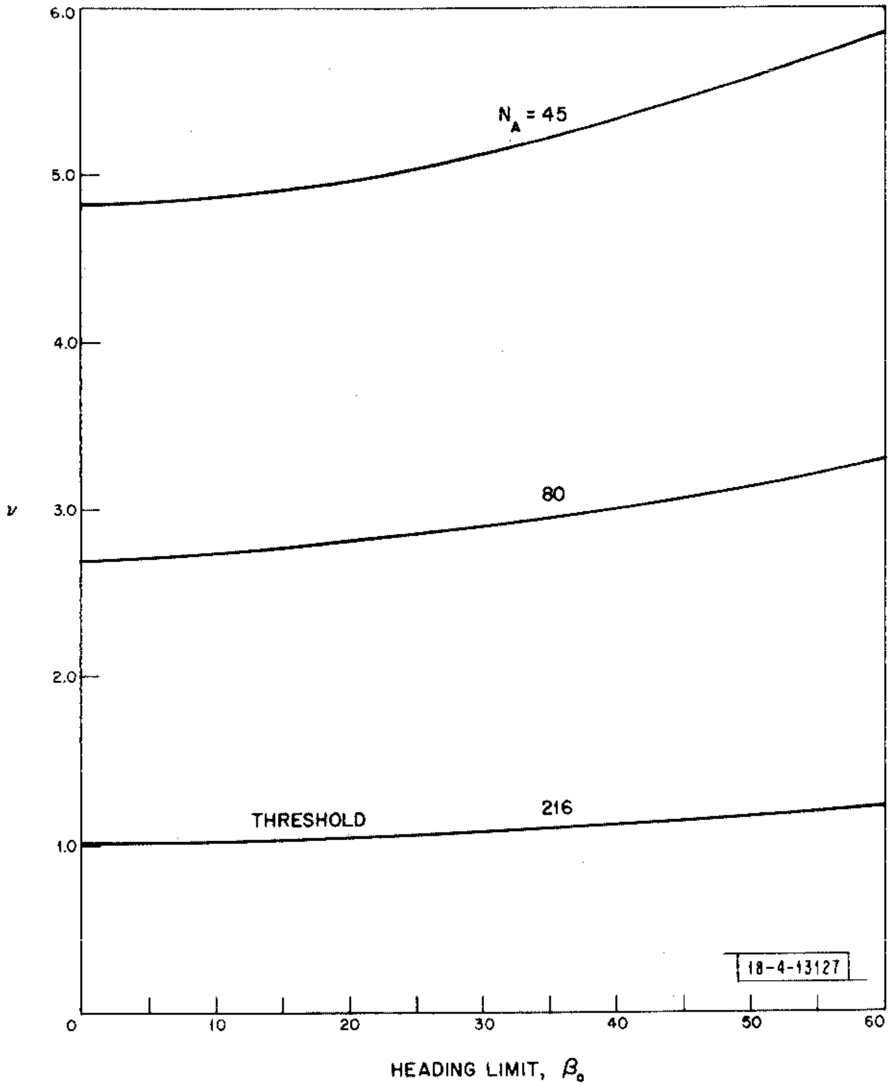


Fig. 31. Ratio V vs the heading limit β_O for the north sector of the L. A. Basin (2b = 6 mi., V = 200 mph, A = 60 mi. x 60 mi.).

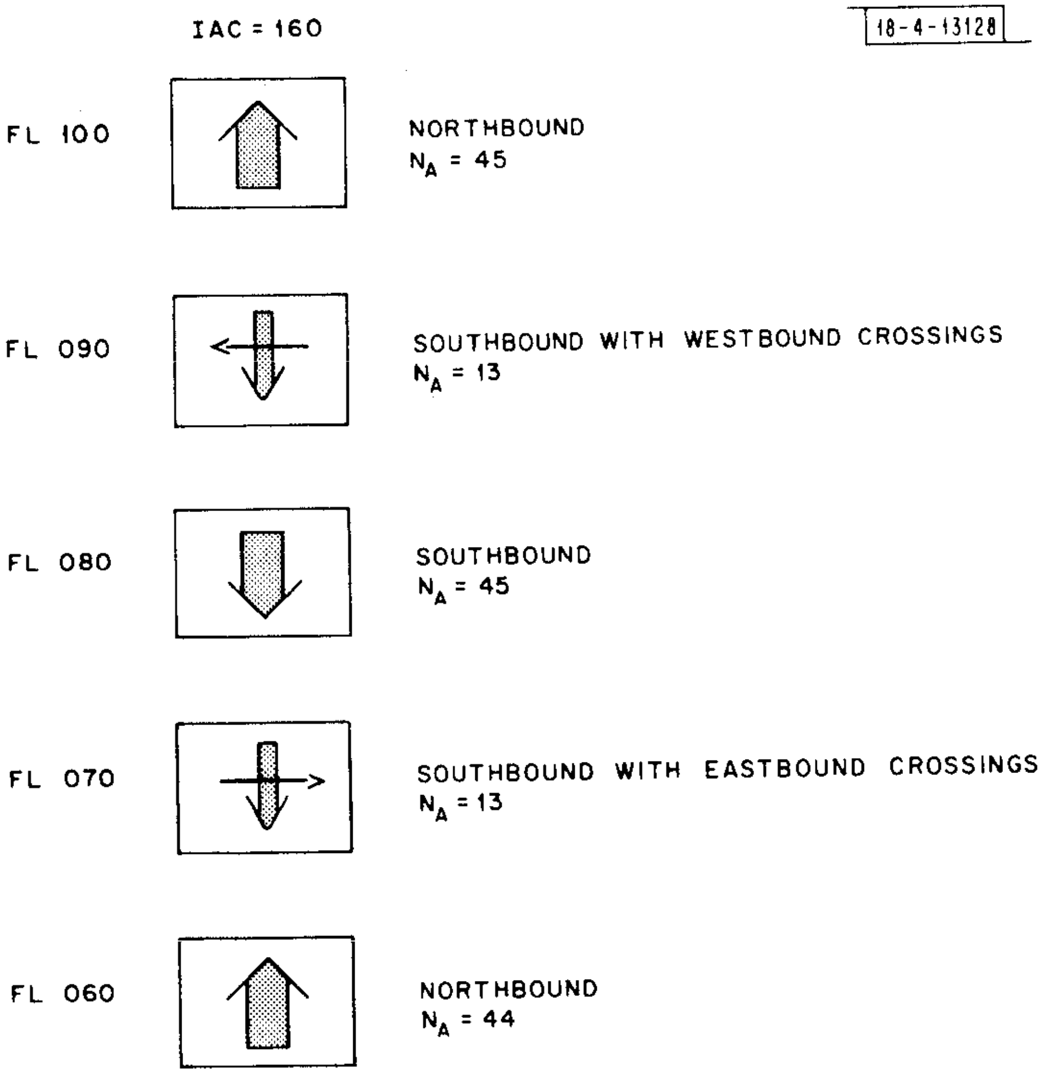


Fig. 32. Example of non-uniform distribution of aircraft among flight levels for north sector of L. A. Basin.

nated for accommodating cross-traffic is adjusted to a level that would expose the crossing aircraft to only $k = 20$ crossings. In order to determine the corresponding value of N_A, Eqs. (4) and (12) in Section C are combined to give the expression

$$N_A = \frac{k\,t_h}{t_s} \tag{46}$$

where t_s is the average time needed for the crossing aircraft to traverse the width of the sector and t_h is the average time needed for an aircraft in the north-south traffic to traverse the length of the sector. Assuming the average speed of the crossing traffic to be 130 mph and that of the north-south traffic to be 200 mph, $N_A = 13$ when $k = 20$. The value of N_A for each of the remaining three high density levels is 45. Figure 31 shows that the ratio ν for the latter case is about 5.0 and is about 17.0 for the low density levels. Because of the relatively large values of ν, no structuring according to heading angle is believed necessary for this distribution of aircraft.

5. Conclusions

Velocity structuring obtained by imposing a heading limit β_o increases the mean free path between conflicts and thus decreases the expected number of conflicts which occur in traversing a given region. If only turn maneuvers are employed, the probability of resolving a given conflict remains approximately constant as β_o is decreased. For speed changes or altitude changes the probability of resolution will increase as the distance between conflicts increases. Thus, the primary benefits of structuring lie in

a. A decrease in the number of conflicts for a given route length,

b. Increased effectiveness of the altitude change and speed change maneuver.

If altitude change maneuvers cannot be used freely due to a limited number of available flight levels, weather constraints, or aircraft performance factors, then factor (a) above predominates.

It can be concluded that the best way of restructuring the airspace for cases of excessive conflict frequency is by way of non-uniformly distributing aircraft among flight levels according to heading in order to reduce the number of crossings. If it is necessary to have the density at any flight level large enough to make the ratio $\nu = \lambda_m/\lambda_r$ near unity, the aircraft at that level should be required to fly along parallel airways until they leave the high density region.

G. Factors to be Considered in Determining Capability of Aircraft to Conform to Flight Plans

1. Introduction

Conformance to a flight plan has three dimensions: altitude, cross-track, and along-track. We focus our discussions primarily on along-track conformance since it is expected to be the most difficult dimension to hold within acceptable levels. Before proceeding with the main part of our discussion we briefly examine general aviation's ability to hold altitude in order to obtain some measure of their ability to conform.

2. Altitude Conformance Ability of General Aviation

Limited tests conducted on several general aviation aircraft (Ref. 12) showed that under manual control most deviations from the mean altitude were within ±600 feet. A maximum deviation of 900 feet was recorded during the tests. This performance compares to a deviation which was usually held to within ±400 feet during manual control of airline aircraft and ±250 feet when the autopilot was used. The effects of turbulence have not been considered in presenting any of these figures. An automated ATC system in dense airspace based on the current 1000 feet vertical separation standard could not accommodate aircraft exhibiting such non-exacting control as indicated above without disasterous results.

3. Need for Accurate Prediction of Ground Track and Ground Speed

Precise control of along-track position will be a new requirement placed on the guidance and control system in a 4D environment. The means of providing the accuracy required to accomplish strategic control have yet to be specified. That is, the control laws and control system mechanization have yet to be developed subject to the requirements of satisfying desirable flight characteristics (e.g., control activity, passenger comfort).

Conflicts are resolved in the strategic system by the preflight generation of CFFP's. Whereas in today's ATC system, the flight plan provides timely information and serves as a guide against which the actual progress of the aircraft is compared, it becomes a standard to be closely followed in a strategic control environment. An essential part of the task of generating CFFP's is the prediction of the track and ground speed of each aircraft in the system. The inability to predict these variables precisely is reflected in the size of the conformance limits associated with each aircraft. The final selection of conformance requirements should reflect the projected traffic density expectations and airway structure as well as pilot workload and equipment cost in order to be cost effective in a growing industry already producing concern of excessive cost. (Ref. 13).

4. Cause of Errors in Prediction of Ground Track and Ground Speed

The requirement of defining the ground speed of each aircraft places increased demands on the aviation weather forecast service to provide accurate data both in terms of wind velocity and air temperature at all flight levels. Depending on the aircraft's control and guidance system, an inaccurate forecast places increased requirements on either the aircraft's performance characteristics or its conformance limits.

Apparently, it is recognized that present day forecasts are not sufficiently detailed or accurate to support an improving ATC system. The

FAA has stated a requirement to the National Weather Service for provision of upgrading aviation forecasts. This upgrading is to be in the form of

a. providing terminal forecasts for all terminals with sufficient operations to qualify for a control tower and

b. improved forecasts of high level winds and temperature. (Refs. 14, 15)

Ellsaesser (Ref. 16) has analyzed the variation of the mean scalar wind and mean 24 hour vector wind error as a function of altitude. Tabulated results are shown in Table 18. Eastern Airline Weather Department (Ref. 17) presented these partial results as a standard against which they could compare their own record. The acceptance of this as a standard provides us with some insight on the performance of winds aloft predictions. One significant aspect of this analysis is the large mean error present in a forecast. It must be kept in mind that individual errors can be much larger. A similar general result is also found in the data presented by Reed (Ref. 18). Fig. 33 shows the mean wind error using four different forecasting procedures in which error is presented as a function of altitude for one season. Data illustrated was from a weather station in Ely, Nevada, but it was presented as representative of the conditions found at more than 50 other stations. The implications of these forecasting errors on conformance are discussed in the next section.

Recent experiments (Ref. 19) have revealed that large temperature changes are encountered in the stratosphere. Changes as large as $10^{\circ}C$ over a horizontal distance as small as three nautical miles have been recorded. Our calculations show that a $10^{\circ}C$ inaccuracy in the air temperature used in a computation of true air speed at cruise results in an error of approximately 2% in the actual true air speed. These computations were made for pressure altitudes varying from 25 thousand to 40 thousand feet with air temperature decreasing with increasing altitude at the standard

TABLE 18

VARIATION OF MEAN 24-HOUR VECTOR ERRORS WITH ALTITUDE (MEANS TAKEN FOR THE WHOLE YEAR)

Approximate Height Above Mean Sea Level (feet)	Level(mb)	Mean Scalar Wind (knots)	Mean 24-Hour Vector Errors (knots)	Percentage Error of Mean Scalar Wind
53,000	100	25	17.6	70
39,000	200	49	29.0	59
30,000	300	48	28.4	59
18,000	500	35	20.2	58
10,000	700	24	16.2	67

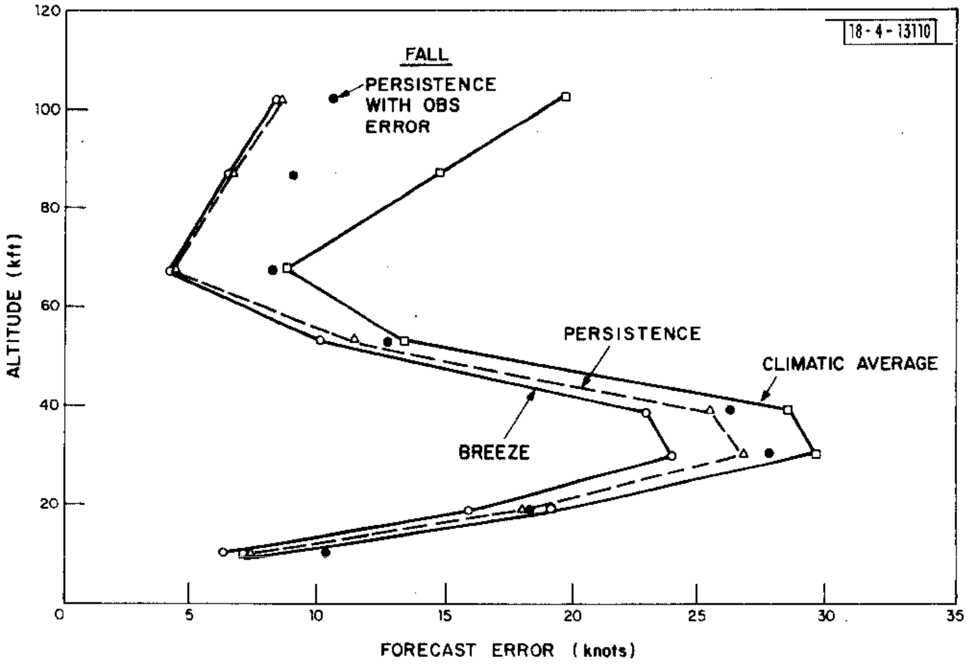


Fig. 33. East-west wind 24-hour forecast errors at Ely, Nevada.

lapse rate. The range of true air speed covered by the calculations varied from 200 knots to 600 knots. Thus, inaccuracies in temperature and wind velocity have similar effects on prediction of track and ground speed since they both cause velocity errors.

5. Concepts for Guidance and Control

The Boeing Aircraft Company suggests that the simplest form of guidance and control will use range and ground speed errors in an autothrottle system to satisfy the new requirement of along-track conformance. Thus, the propulsion system will be called upon to maintain flight plan conformance through changes in power setting to compensate any effect tending to change the planned ground speed and position. An accurate forecast would allow one to select an initial cruise setting close to optimum. Aircraft equipped with such a control system potentially have the capability of conforming to the along-track dimension limited only by the accuracy of the navigation environment. This, however, may require a control loop gain which does not satisfy the equally important requirements of exhibiting the desirable flight characteristics mentioned earlier. To resolve this, one would resort to flight control system studies by analytic simulation and flight testing.

A control system which does not use range and ground speed inputs is one based on indicated air speed errors as presently incorporated in several automatic flight management systems. The size of the conformance limits one can obtain is limited to the accuracy to which one can predict the true air temperature and winds aloft.

The least sophisticated user of the airspace, general aviation, will continue to control flight path manually. In a strategic control environment this might be accomplished by either a manual selection of power to maintain a calculated indicated air speed (based on, presumably, an accurate preflight forecast) or an en route power adjustment to minimize a guidance error (signal source or display hardware remain unspecified at the present) in the along-track direction. The latter alternative requires a constant scan of the flight instruments as the situation presented to the pilot is constantly changing. Fatigue becomes a factor to be considered in determining the ability to conform during any extended flight in which one attempts to maintain minimum acceptable errors in all three dimensions manually. The need to be at a predetermined point in space which changes with time increases a pilot's workoad and is experienced in today's system during an ILS or Localizer approach to a landing. During an approach, however, the workload is further increased due to, in part, an increased sensitivity of the guidance signals. Additionally, small changes in power setting require compensating manual pressures exerted to cancel yaw and pitch motion about their respective axes and must be considered. Further, the unprofessional attitude in the ranks of general aviation is yet another factor to be considered. The above must be included in any consideration attempting to assign a figure to represent the most probable error value associated with manual along-track control by the general aviation sector.

6. Effect of Forecasting Errors on Conformance Capability

We have presented the data cited in Section 3 in an attempt to convey some indication of the variability and uncertainty of the weather elements which most directly affect an aircraft's ground speed. The net effect on conformance will depend on which of the concepts for guidance and control described in the previous section is adopted.

A concept which employs range and ground speed errors in an autothrottle system may encounter difficulty with limited performance capability aircraft which cannot compensate for large variations in weather elements. Excessive variations must be considered by either including them in the flight planning phase if they can be anticipated accurately or by an increase in the size of the conformance limits if they are unknown. An additional factor to consider is the difference in performance characteristics between propeller driven aircraft and jet aircraft. The performance of the former make the proposal of maintaining a desired ground speed extremely unattractive when there are large errors in the wind velocity and air temperature. However, due to the large range of economical cruise speeds exhibited by jet aircraft such a proposal becomes attractive and can be further considered as a method of increasing capacity along a high density airway at optimum altitude. This, of course, is subject to the ability to forecast winds aloft, true air temperature, and locations of significant weather disturbances with a high probability of obtaining the desired accuracy. Convincing arguments for or against strategic control should result from a cost effectiveness study which compares

a. a control system in which ground speed is maintained at optimum altitude and

b. a control system in which aircraft are free to fly at any desired air speed at a flight level generally lower than the optimum level with some holding required due to random arrivals at the destination.

With a guidance and control concept which is based on indicated air speed, the conformance limits due to errors in both air temperature and wind velocity grow with the time flown if the errors along the track are all in the same direction. An error in the wind velocity forecast of 25 knots, which is typical of the cruise altitudes of jet aircraft as seen from Fig. 33, results in a conformance error of 50 nm and 100 nm for 2 and 4 hour flights, respectively. The results of Section E indicate that conformance errors of this magnitude cannot be tolerated in any of the 1995 traffic density cases considered. Thus, it appears that either weather forecasting techniques must be improved over the present state of the art or a guidance and control concept which is based only on indicated air speed or constant mach number is not feasible.

Similarly, one obtains a second time dependent error based on an inaccurate calculation of ground speed due to any inaccuracy in the temperature preflight data. For this source of error, a good approximation is 2% of the aircraft's velocity, as stated earlier. Thus, at a ground speed of 500 mph, the size of the along-track conformance limit increases at the rate of 10 mph.

A third source of error which increases the size of the along-track conformance limit is the inability to reach the initial en route fix (from which point on all conflicts are to be resolved) at the precise time specified in the flight plan. The rms value of all three sources of error must be decreased in order to decrease the size of the conformance limits assigned to each aircraft. A decrease in the error associated with one source will not necessarily decrease the total error significantly.

It is not inconceivable that a strategic control environment may require a radically new method of providing information on the winds aloft and temperature in order to obtain the desired level of accuracy of these data. Supplying automatic upper level weather reports by aircraft appropriately equipped is one method to accomplish this task. Only minor modifications would be required to already existing sophisticated avionics packages to provide for an onboard computer calculation of these variables from directly measured data. The down-linked weather data in conjunction with the surveillance data on position would provide an accurate current weather profile of the high density routes. It is precisely in this airspace where the information would be most valuable. The reduced data is routed to flight plan central where these are supplemented by medium and long range forecasts. This integration would serve to provide the level of accuracy required on these variables in the task of generating CFFP's.

H. Technological Considerations

1. Introduction

The generation of CFFP's requires effective use of the technology of computers, communications equipment, and avionics. The latter category includes cockpit displays and/or devices which provide an interface with flight control equipment on the aircraft. An examination of the constraints presented by this technology as well as the costs and complexity of the equipment required to generate CFFP's is beyond the scope of this study. Further study pertaining to this technology is an essential step in the fourth generation ATC studies. This section contains a brief discussion of the important issues in the relevant technology.

2. Computer Technology

The computer memory required to generate CFFP's depends on the way in which the flight path is specified. The present airways system utilizes a number of waypoints which are primarily over navigation aids. An area navigation system (2D airspace structure) would require either many more waypoints or an alternate coordinate scheme for specifying the flight trajectory. A 3D airspace structure which permits an aircraft to fly more complex three-dimensional trajectories may require even more computer memory for the generation of CFFP's.

The number of computer instructions required to generate a CFFP which is valid for a particular time τ_i into the future will increase as τ_i increases. Thus, the total computational power required in units of million instructions per second (MIPS) will increase as τ_i increases. This implies that strategic planning will require more computational power than tactical planning, at least for generating the initial plan.

Due to weather changes, pilot distraction, blunders, equipment failures, etc. in an operational system, some flights will deviate from their plans to such an extent that new plans will have to be generated. Thus, the total computational power required will also increase as the frequency of updating plans increases. The system designer can choose the value of τ_i and can influence the frequency with which plans must be changed by his selection of the conformance requirements of the aircraft and the design of the control loops which determine the capability of the aircraft and pilot to conform within these limits. Studies which determine the constraints placed on the generation of CFFP's by computer technology are an essential part of a more detailed study of the feasibility of generating CFFP's.

Another important issue is the trade-off between distributed and centralized data processing facilities. This trade-off involves comparison of the cost and complexity of a large central facility with that of many somewhat smaller regional facilities as well as the cost and complexity of the communications network necessary to tie together the flight planning system. It seems likely that conflict free flight planning on a national scale will be most economically handled by a central facility if the planning is highly strategic, i.e., if a CFFP for the entire flight is selected prior to departure and changes in the plan are fairly infrequent.

3. Communications Technology

The dominant communications problem is likely to be that of conveying changes in flight plans from the flight planning computers to the aircraft. A secondary problem is that of conveying requests for changes to the computers.

Cost and constraints of communications technology will be an important factor in trade-off studies to specify parameters of a CFFP system. In particular, if conformance requirements are made so tight that they are frequently violated in such a way as to require a revision of a flight plan, a large number of messages must be sent and thus communications capacity must be high. At the other extreme, if conformance requirements are very loose, flight plans of many aircraft may interact strongly so that if one plan must be changed others might also have to be changed. This could also lead to a requirement for high communications capacity. The system should be designed to operate in a middle ground where the number of messages required due to flight plan changes is relatively small. Further study is required to make these considerations quantitative.

XII. THE EFFECT OF FLIGHT OPERATIONS AND KINEMATICS ON CONFLICT RESOLUTION

A. Introduction

This section constitutes a first iteration in the analysis of the conflict free flight planning process. It is the first step in a second, more detailed iteration which must be completed before a system for generating CFFP's can be designed.

The control system baseline concept (Section IX) specifies a "4D flight plan" for all "controlled aircraft" and for "cooperative aircraft" when they enter high density airspace. In the baseline concept conformance to a flight plan was defined qualitatively by using the terms "rigid" or "relaxed". The development of quantitative conformance requirements in any of the spatial or time dimensions can be approached in one of two ways. One approach is to maximize the potential flow of traffic, in which case conformance to a 4D flight plan would be as rigid as possible. The other approach is to minimize the frequency of flight plan changes, in which case conformance requirements would depend primarily on the traffic density. In both approaches one must evaluate conformance capability to determine if the requirements can be met.

Conformance capability for the first approach, that of maximizing the potential flow of traffic, would be evaluated from the operational characteristics of the aircraft and from the ability of the pilot to conform to a 4D flight plan under expected operating conditions. Thus the conformance limits would be as rigid as possible within the constraints of the expected "4D navigational errors" in order to generate a maximum number of flight plans in a given airspace. Of course, under these conditions the pilot would have little flexibility in deviating from his flight plan. In addition, minor disturbances could force frequent changes in 4D flight plans, which in turn could saturate the control system with a continual updating of flight plans. Hence, we conclude that this approach to the development of quantitative conformance requirements may be unnecessarily rigid.

For the second approach, in which the frequency of flight plan changes is minimized, quantitative conformance requirements depend on the traffic density along the flight trajectory. This approach gives the pilot maximum flexibility. If the traffic density is not excessively high, conformance in any of the spatial or time dimensions could be greatly relaxed. The limitations on the amount of relaxation for a low density traffic environment will depend on the metering and flow control procedures which are required to maintain a controlled flow rate into high density hubs. If the traffic density is sufficiently high, however, quantitative conformance requirements are constrained by operational limitations of the aircraft and the ability of the pilot to maintain conformance. It also must be recognized that all of the 4D flight plans in a high density environment are not optimum or "minimum cost" routes. Thus it is important to consider the economics of flight trajectories as well as the operational performance of the aircraft in determining quantitative conformance requirements, in generating CFFP's and in updating flight plans.

In this section we discuss some of the current operational considerations and flight kinematics pertinent to updating flight plans and resolving conflicts.

The discussion is centered around airline operations of large jet transports for two reasons. First, airline transport jets will constitute a major portion of the aircraft in high density positive control segments of the airspace as defined by the baseline system. This is evident from the 4D navigation requirements for that part of the airspace, the cost of which will discourage large numbers of other types of users. Hence, most flight plan conflicts in high density positive control airspace will be between two or more airline transports. Secondly, airline jets flying at high altitudes and high speeds and operating near maximum gross weight have less latitude in making the speed, heading, or altitude changes required to resolve conflicts. In this sense airline jets represent the worst case for conflict resolution.

B. Flight Operations

We now direct our discussion to flight operations and aircraft performance pertinent to conflict resolution. We consider a typical jet transport and its performance characteristics, from which we develop techniques which can be used in the control system design. The present discussion is limited to high speed performance (>Mach 0.4) flight regimes which are characteristic of the en route and sequencing stages of the baseline control system. Flight stages which require the use of flaps and spoilers are not considered.

The flight performance of a jet transport can be evaluated from the basic aerodynamic and engine data for the aircraft. The aerodynamic data required is the high speed drag polar (coefficient of lift vs. coefficient of drag for constant airspeeds), which is obtained by the manufacturer from wind tunnel tests and is further validated during flight tests. The high speed drag polar for a typical jet transport is shown in Fig. 34.

Basic inflight engine data is usually presented as a series of graphs for "bleed on" or "bleed off" conditions. One set of curves gives net thrust (T/Λ) vs. engine pressure ratio (EPR) for constant airspeeds. The term $\Lambda = (\rho_a/\rho_o)(T_a/T_o)$ is used to parameterize effects on net thrust of the

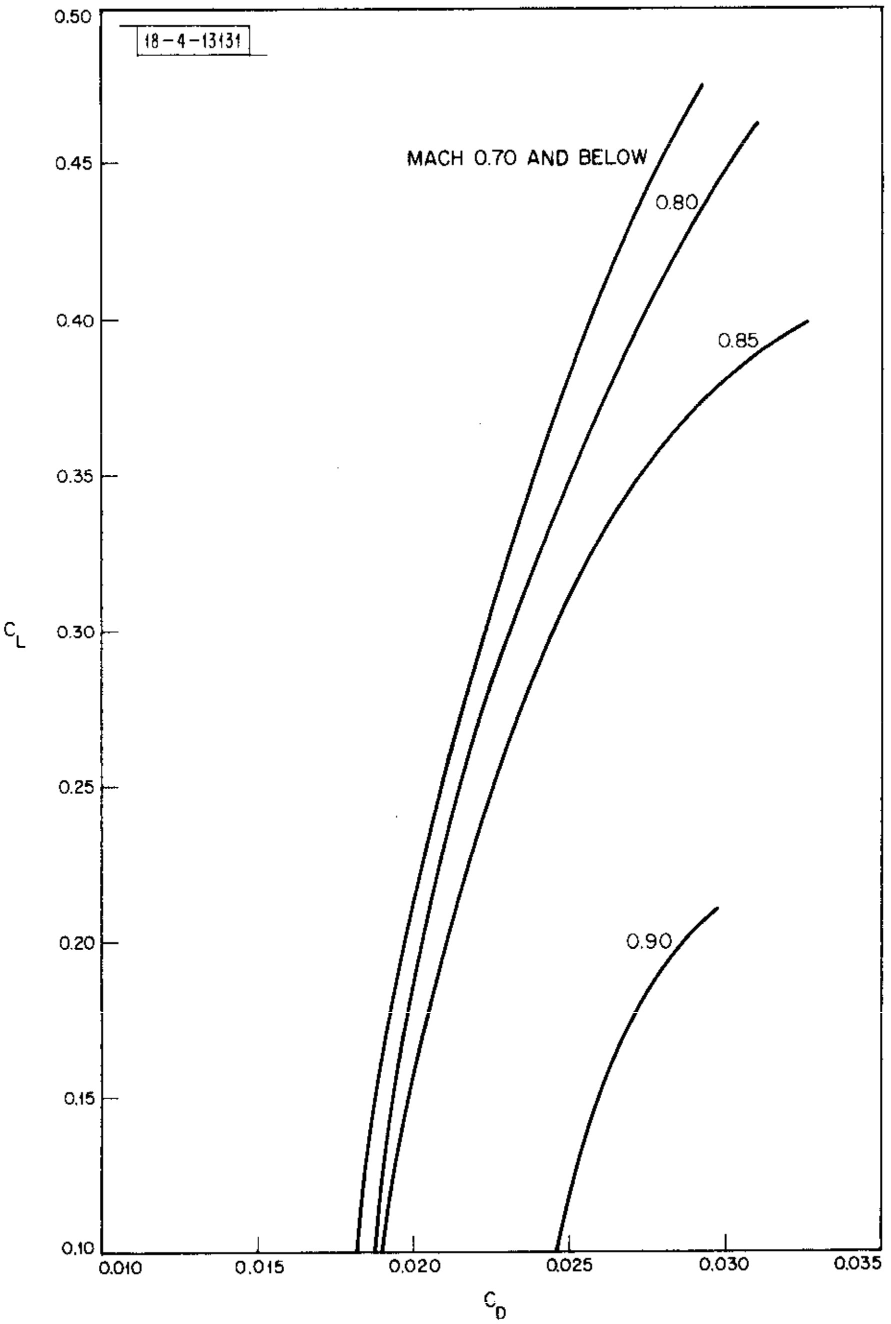


Fig. 34. High speed drag polar.

density (ρ_a) and temperature (T_a).

A second set of curves gives the engine pressure ratio vs. inlet air temperature for various engine thrust ratings. Engine thrust ratings which are customarily used are defined as follows:

1. Takeoff Thrust

   This is the maximum thrust available for takeoff. The design turbine inlet temperature is approximately 1600°F for this rating and the duration of this thrust is normally limited to 5 minutes.

2. Maximum Continuous Thrust

   This rating is the maximum thrust which may be used continuously and is intended only for emergency use at the discretion of the pilot.

3. Maximum Climb Thrust

   This rating is the maximum thrust approved for normal climb and therefore is sometimes called "normal rating". For many engines "maximum climb" and "maximum continuous" ratings are identical.

4. Maximum Cruise Thrust

   This is the maximum thrust approved for cruising.

5. Idle Thrust

   This is not an engine rating but is a thrust lever position suitable for minimum thrust operation.

The specific fuel consumption (S_f) vs. net thrust for constant airspeeds at specified altitudes can be obtained from a third set of engine curves. The fuel flow (W_f) is related to the specific fuel consumption by $W_f = S_f T$. These three sets of curves can be combined into one set appropriate for inflight performance calculations. This set is illustrated by Fig. 35 in which net thrust is plotted against air speed for constant flow rates and thrust ratings

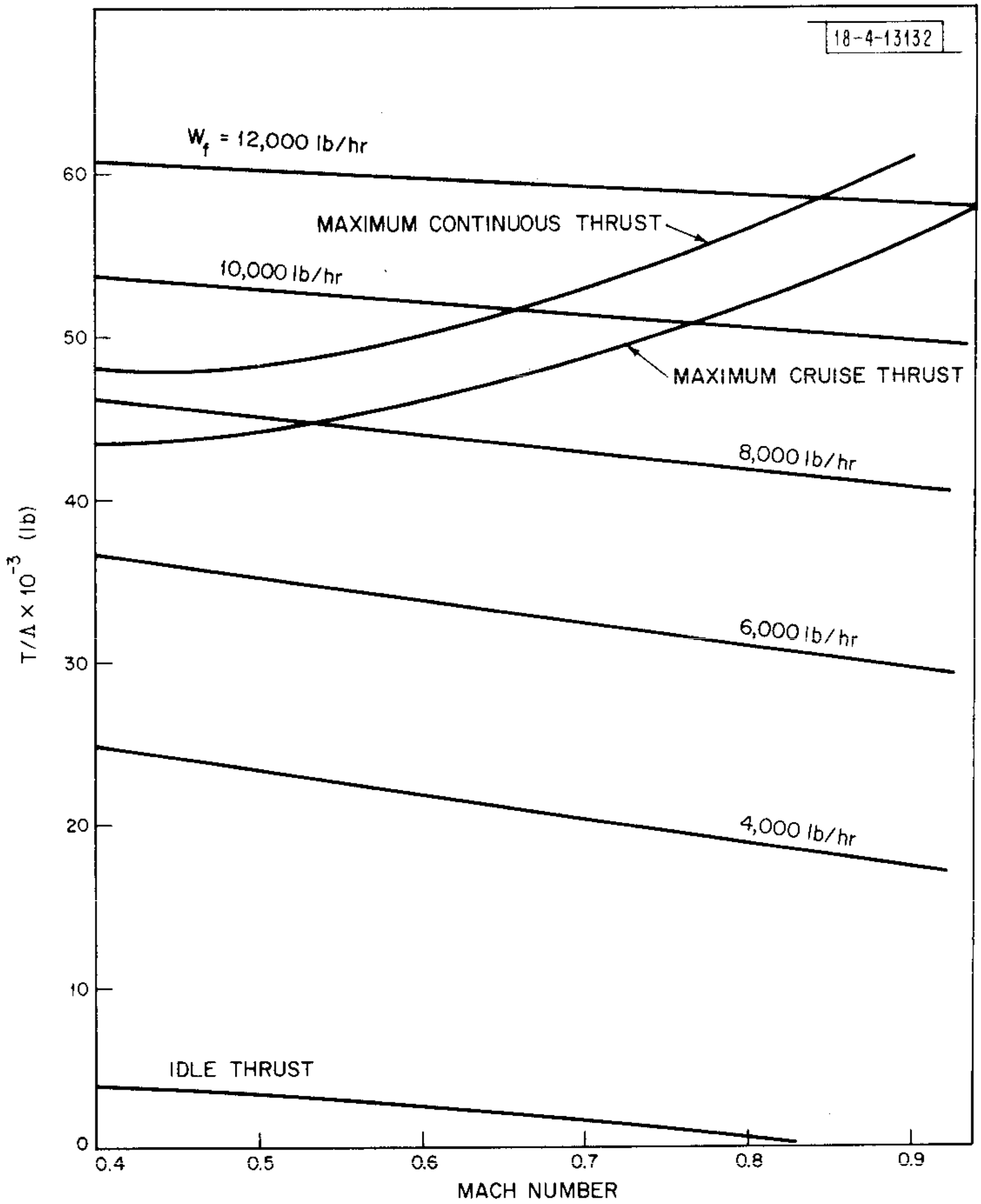


Fig. 35. Aircraft engine data.

at a selected altitude of 35,000 ft. assuming standard atmospheric conditions. The aerodynamic data of Fig. 34 and the engine data of Fig. 35, given at a sufficient number of altitudes, provides a basis for evaluating methods of conflict resolution maneuvers.

For an aircraft flying in level unaccelerated flight the well known (thrust-drag) and (lift-weight) equality relationships,

$$L/\Lambda = W/\Lambda = u\,C_L M^2, \qquad (47)$$

$$D/\Lambda = T/\Lambda = u\,C_D M^2,$$

can be used to determine the maneuver margin available to the aircraft. By maneuver margin we mean the thrust change available for conversion into changes in airspeed or for climbs or turns. The thrust available for conflict resolution purposes will be taken as equal to the "maximum cruise thrust" rating value for a specific airspeed and altitude minus the thrust required to maintain level flight. The value of the thrust required is easily obtained from Eqs. (47) for selected values of aircraft weight (W/Λ) and is illustrated by Fig. 36. Having specified a W/Λ value, there exists a C_L for each Mach number (M), which is computed from the first of Eqs. (47). The value of the constant u includes the wing area of the aircraft. For our typical aircraft we have used a wing area of about 1600 square feet, thus giving $u = 2.3 \times 10^6$. This value of u is consistent with the units of lbs for the aircraft weight (W/Λ). The value of C_D is then obtained from the drag polar (Fig. 34), and thus the thrust required to maintain level flight is completely specified. Also shown in Fig. 36 is the "maximum cruise thrust" rating for two altitudes. The use of these curves in evaluating methods of conflict resolution will be discussed in later sections.

There are four basic types of cruise conditions which are used in jet transport inflight operations. These conditions are summarized in Table 19.

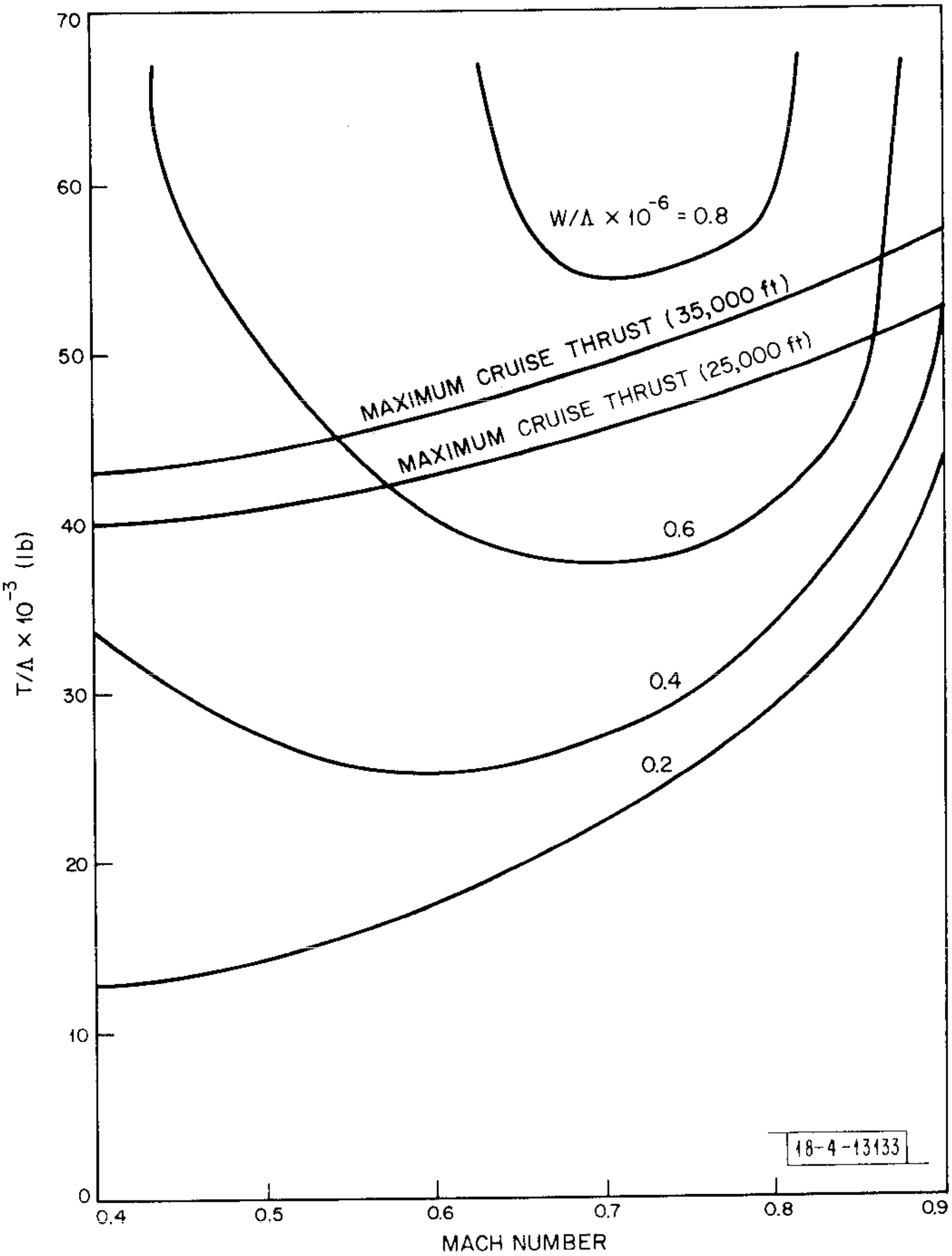


Fig. 36. Level flight thrust.

TABLE 19

BASIC CRUISE CONDITIONS

TYPES OF CRUISE	EFFECT OF WEIGHT DECREASE
1. Constant Mach Number and Altitude	Decreasing Thrust
2. Constant Altitude for Maximum Range or Long Range Cruise	Decreasing Mach Number and Decreasing Thrust
3. Constant Mach Number and W/Λ	Increasing Altitude
4. Rated Thrust	Increasing Altitude at Constant Mach Number or Increasing Mach Number at Constant Altitude

These cruise conditions are best illustrated by Fig. 37, which is a plot of the range factor (R_f in n mi per pound of fuel) vs. airspeed for constant values of aircraft weight at a selected altitude (35000 ft.). The range factor is calculated from the expression

$$R_f = V/W_f = M\,C_o\sqrt{T_a/T_o}\,/W_f, \tag{48}$$

where V is the airspeed in n mi/hr. and C_o is the speed of sound at sea level.

The construction of one of the curves of Fig. 37 begins by selecting a constant aircraft weight and several Mach numbers from which the curve is generated. The value of Λ is evaluated from the standard temperature and density at the specified altitude, unless higher or lower temperatures are desired. For each Mach number the required thrust to maintain level flight is specified by Eqs. (47) and the aerodynamic data of Fig. 34. A value of fuel flow, W_f, is determined from the engine data plotted in Fig. 35 for each pair of thrust-Mach number values. The range factor, R_f, is then evaluated from Eq. (48).

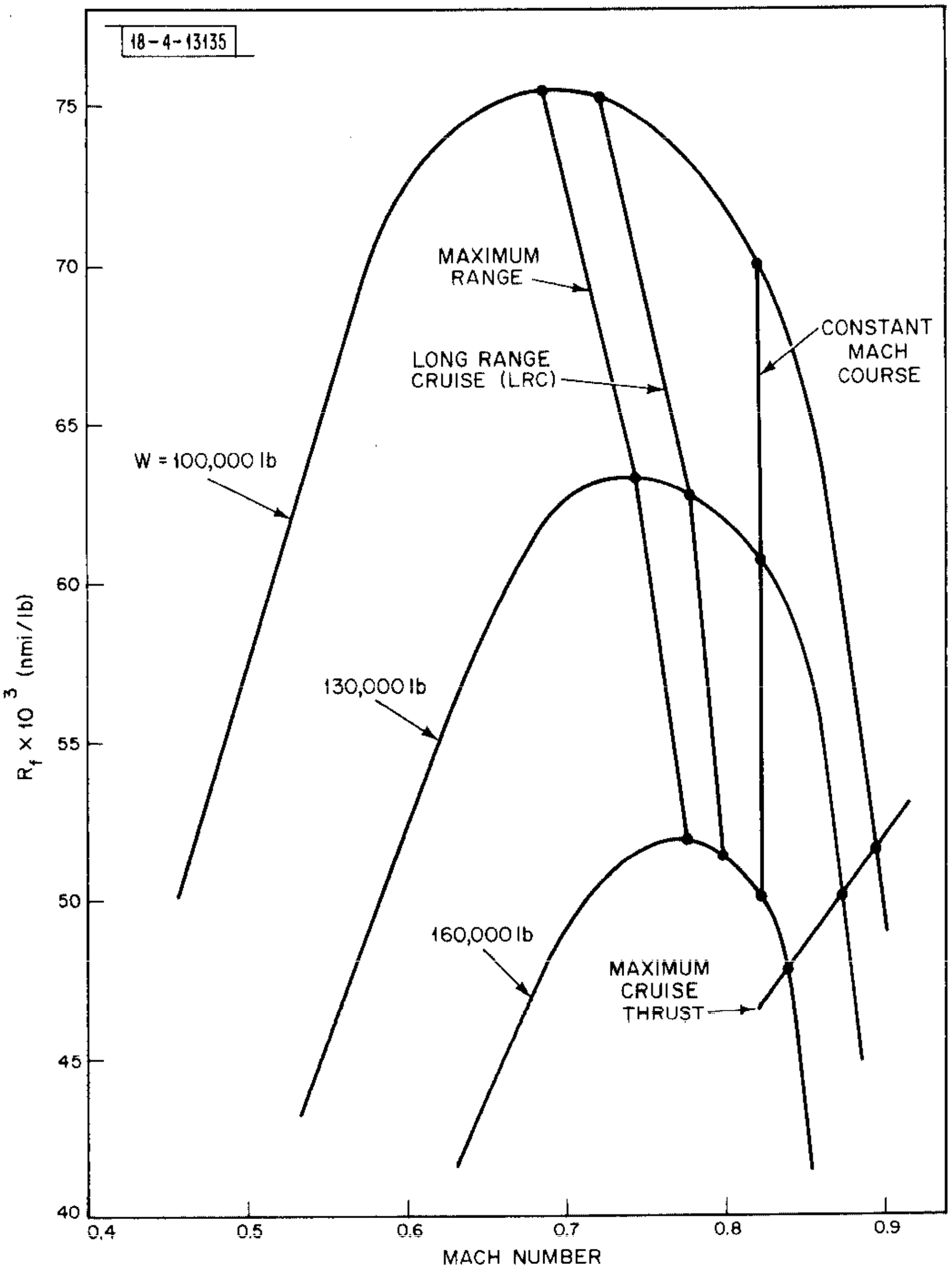


Fig. 37. Range comparison for various cruise conditions.

The cruise operating conditions are easily inserted in Fig. 37. The condition of "long range cruise" (LRC) is defined as a flight regime which achieves 99% of maximum range. The "maximum cruise thrust" condition is determined for Fig. 37 by computing the airspeed at which the thrust required for level flight equals the "maximum cruise thrust" value for the specified weight. It is defined by the intersection of the thrust available and maximum cruise curves of Fig. 36.

In general the effect of increasing altitude is to increase the range factor. However, at higher aircraft weights, the thrust requirements are such that a lower value of R_f is obtained at a higher altitude. Hence, there exists for each aircraft weight an optimum altitude, which increases as the aircraft weight decreases. Thus the aircraft must change altitude during the flight in order to fly at either maximum range or long range cruise.

If an airplane is required to fly at a constant W/Λ for maximum range conditions, its altitude at any weight is specified. It may be advantageous to fly at a higher or lower altitude, because the wind effects may more than offset the loss in range due to flying at the non-optimum altitudes. For these reasons transport jets often use the constant Mach number-constant altitude cruise condition rather than fly at the continuously changing long range cruise altitude which is optimum purely from the point of view of range. The winds aloft forecasts are used to minimize flight time or cost for cruise conditions in which the altitude is not fixed.

The direct cost for an airliner to fly between any two cities is an important consideration in the choice of flight plans and in conflict resolution. Any change in flight plans which resolves a conflict but adversely affects the cost margin, in comparison to other ways of conflict resolution, may be unsatisfactory. The total cost of a flight to an airline is a complex calculation, which includes the amortization of airplane and engine purchase costs, maintenance and fuel costs, crew day/night pay costs, and overtime, marketing and insurance costs. However, simplified techniques or "rules of thumb" can be used for estimating the relative operating cost to an airline and in determining optimum methods for conflict resolution. A reasonable estimate for airline flight cost is that the cost in time is about ten times the fuel cost. If delays force the airliner to arrive later than the scheduled arrival time, the time costs may be significantly higher. Therefore, conflict resolution procedures should attempt to minimize the total flight time. Fuel costs should not be totally neglected, however, because the optimum conflict resolution procedure might in some cases depend on fuel costs. This would be true for cases in which two different conflict resolution procedures would allow the aircraft to arrive at its destination at the same time, but one of the procedures would force the aircraft into a higher fuel flow rate than the other.

C. Kinematics Pertinent to Conflict Resolution

The change in a 4D flight plan required to resolve a conflict can be accomplished by an increase or decrease in airspeed, by a turn,or by a climb or descent. In this section we discuss the kinematics associated with aircraft performance in resolving conflicts by each of these methods. We will briefly show how the performance data described in the previous section can be used to evaluate the effectiveness of conflict resolution procedures. For purposes of illustration we assume that the flight plans of two aircraft with characteristics of the type described by Figs. 34 and 35 intersect perpendicularly at an altitude of 35,000 ft. This intersection defines a conflict. We also arbitrarily assume that each aircraft has a gross weight of 160,000 lbs. and is flying at an airspeed equivalent to the long range cruise value (Mach 0.80) for the specified weight and altitude.

In our conflict example the two flight plans, one directed along the x axis and the other along the y axis, intersect at the origin of the (x, y) coordinate system at time $(t = 0)$. A circular region at the origin arbitrarily defines the conformance plus separation limit for each of the flight plans at the point of conflict. The conflict is resolved if either of the flight plans can be modified so that a circular region of the size which is representative of the conformance plus separation limit of one aircraft at an instant of time will not overlap the time dependent circular region of the other aircraft.

The thrust-airspeed profile applicable for both aircraft is shown in Fig. 38. The "maximum cruise thrust" line defines the maximum acceleration which will be used for speed changes or other maneuvers. The level flight thrust line defines the thrust which is required to maintain level flight at 35,000 ft. for a given airspeed. This curve is generated in the same way as the more general curves of Fig. 36 are obtained. The airspeed associated with long range cruise (Mach 0.80) is obtained from Fig. 37.

1. Airspeed Increase

The airspeed of the aircraft may be increased by increasing the thrust to its "maximum cruise thrust" value. It is noted from Fig. 38 that the maximum airspeed attainable for our example is at the upper intersection point of the "maximum cruise thrust" and level flight thrust lines (Mach 0.84). The acceleration is therefore given by

$$\ddot{s} = \left[T/\Lambda \text{ (max cruise thrust)} - u C_D M^2 \right] \Big/ (W/\Lambda) \qquad (49)$$

The value of C_D is obtained from the drag polar (Fig. 34) by using a lift coefficient such that the total lift and the weight of the aircraft are equivalent. Integration of Eq. (49) gives the time required to increase the airspeed from Mach 0.80 to any value, up to the maximum of Mach 0.84. The curves of time after initial acceleration and acceleration vs. airspeed are plotted in Fig. 39. It is noted that approximately 200 seconds is required after increasing the thrust before the maximum airspeed of Mach 0.84 is attained.

2. Airspeed Decrease

For our example we note that the minimum speed associated with level flight operation is Mach 0.63, the lower intersection point of the

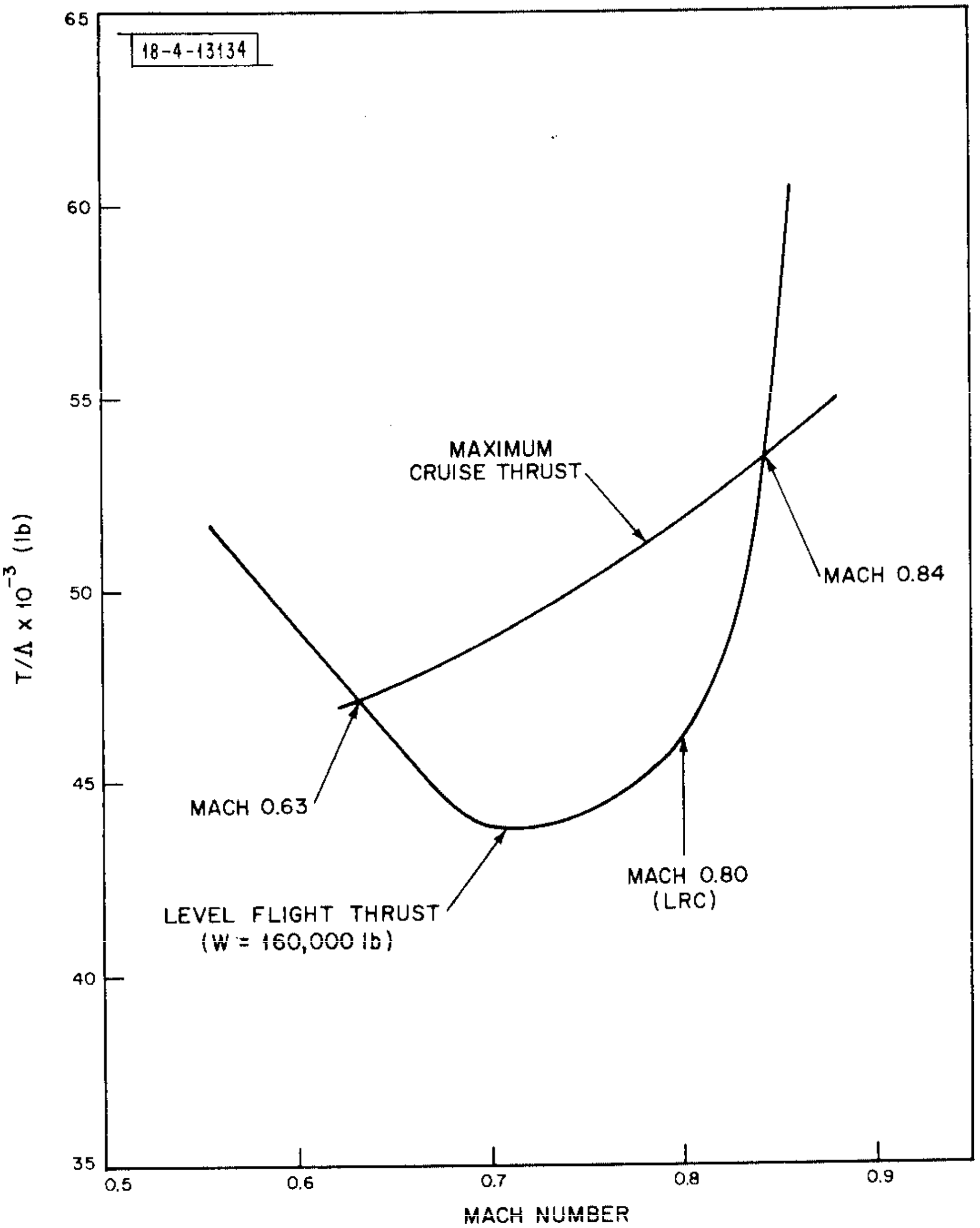


Fig. 38. Available thrust.

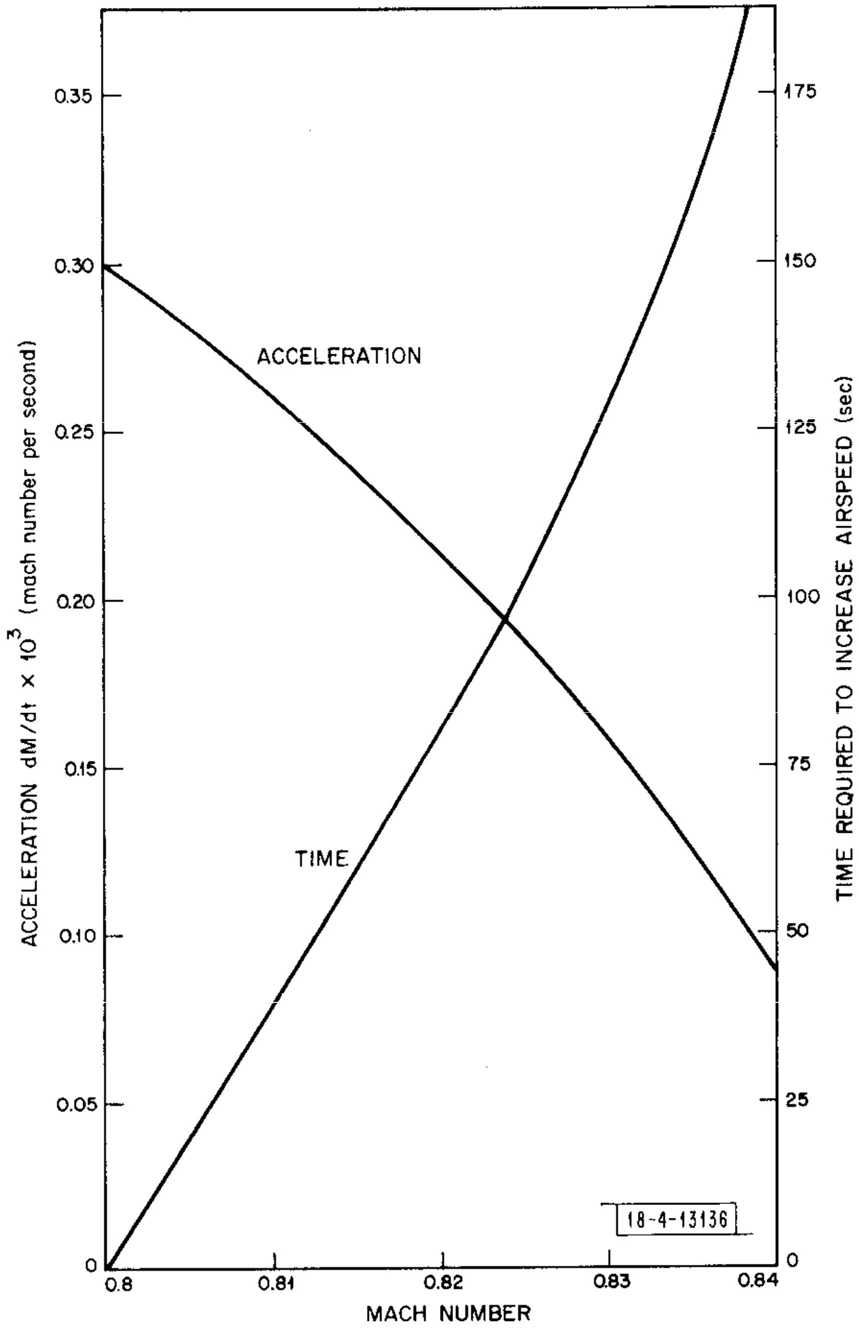


Fig. 39. Airspeed increase maneuver.

"maximum cruise thrust" and level flight thrust lines. However, if the airspeed were reduced to the minimum level flight airspeed, the aircraft could not accelerate again without either operating above the "maximum cruise thrust" rating or descending to a lower altitude. This constraint assumes that there is no weight loss due to fuel depletion during the maneuver. The minimum speed associated with a conflict maneuver then should be evaluated with attention given to the requirement for an increase in airspeed after the maneuver.

The airspeed is decreased by reducing the thrust and simultaneously increasing the angle of attack. The resulting effect is an increase in the lift coefficient and, hence, a corresponding increase in the drag of the aircraft. In order for the aircraft to maintain altitude during deceleration the lift coefficient must equal its level flight value as obtained from Eq. (47) and shown in Fig. 40. In addition, the coefficient of lift cannot exceed the buffet limit of the aircraft at any time during the reduction in airspeed. Buffeting is caused by the turbulence of the airflow separation shaking some part of the aircraft just prior to the actual stall. Another factor to consider is that the net thrust of the aircraft should approach the aircraft drag at the selected minimum airspeed in order to maintain altitude stability. Thus the deceleration must approach zero at the selected minimum speed.

A conservative approach in evaluating the minimum airspeed associated with a given aircraft weight and altitude level is to decelerate to an airspeed corresponding to minimum level flight drag. From Fig. 38 the minimum drag occurs at about Mach 0.70. If the net thrust is immediately reduced to idle and subsequently allowed to approach the minimum drag value ($T/\Lambda = 43.5 \times 10^3$lb), a minimum speed of Mach 0.70 will be attained with sufficient thrust margin to increase the airspeed after the maneuver. Deceleration is given by

$$\ddot{s} = (T/\Lambda - u\,C_D M^2)\Big/(W/\Lambda). \qquad (50)$$

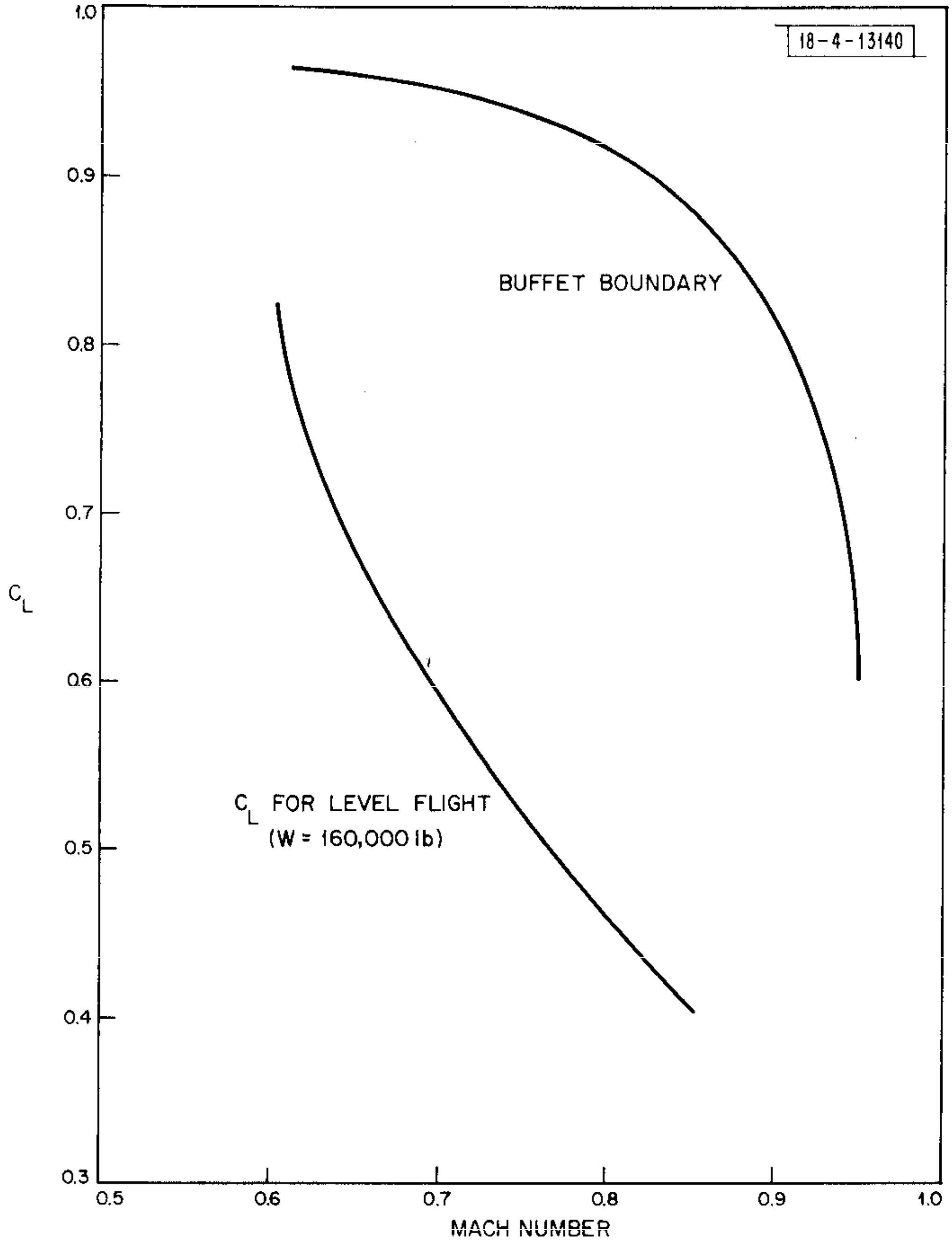


Fig. 40. Level flight coefficient of lift.

The value of C_D is taken from the drag polar of Fig. 34 using the level flight lift coefficient from Fig. 40. The net thrust is immediately set to idle and allowed to increase linearly from idle thrust to minimum drag during that part of the speed reduction from Mach 0.71 to 0.70. This procedure is conservative if the time from idle thrust to minimum drag thrust is greater than about 8 seconds, the average time required by a jet engine to develop maximum RPM (Ref. 20).

Integration of Eq. (50) gives the time required to reduce the airspeed from Mach 0.80 to any value down to a minimum of Mach 0.70. The curves showing deceleration vs. airspeed and giving the time required to reduce the airspeed to lower Mach numbers are shown in Fig. 41. It is noted that about 50 seconds is required after decreasing the thrust before Mach 0.70 is attained.

3. Turn Maneuvers

If an aircraft flies in a coordinated turn, such that no loss in altitude or airspeed occurs, the lift is no longer equal to the weight but, rather, is equal to $W/\cos\gamma$ where γ is the bank angle. The aircraft is in equilibrium vertically, but not laterally. There is an unbalanced lateral component of lift, $L \sin\gamma$, which will produce a lateral acceleration given by

$$a_L = \frac{L}{W/g} \sin\gamma = V\omega \tag{51}$$

where V and ω are the linear and angular velocity, respectively, and g is the gravitational acceleration.

Frequently in aircraft dynamics the maximum bank angle and, hence, the minimum turn radius are calculated from the maximum lift coefficient associated with the stall speed angle of attack. However, for conflict resolution computations this procedure is unacceptable, since the approach to high speed stall is not a desirable criterion. However, if the acceleration associated with "maximum cruise thrust" at a given airspeed is used to

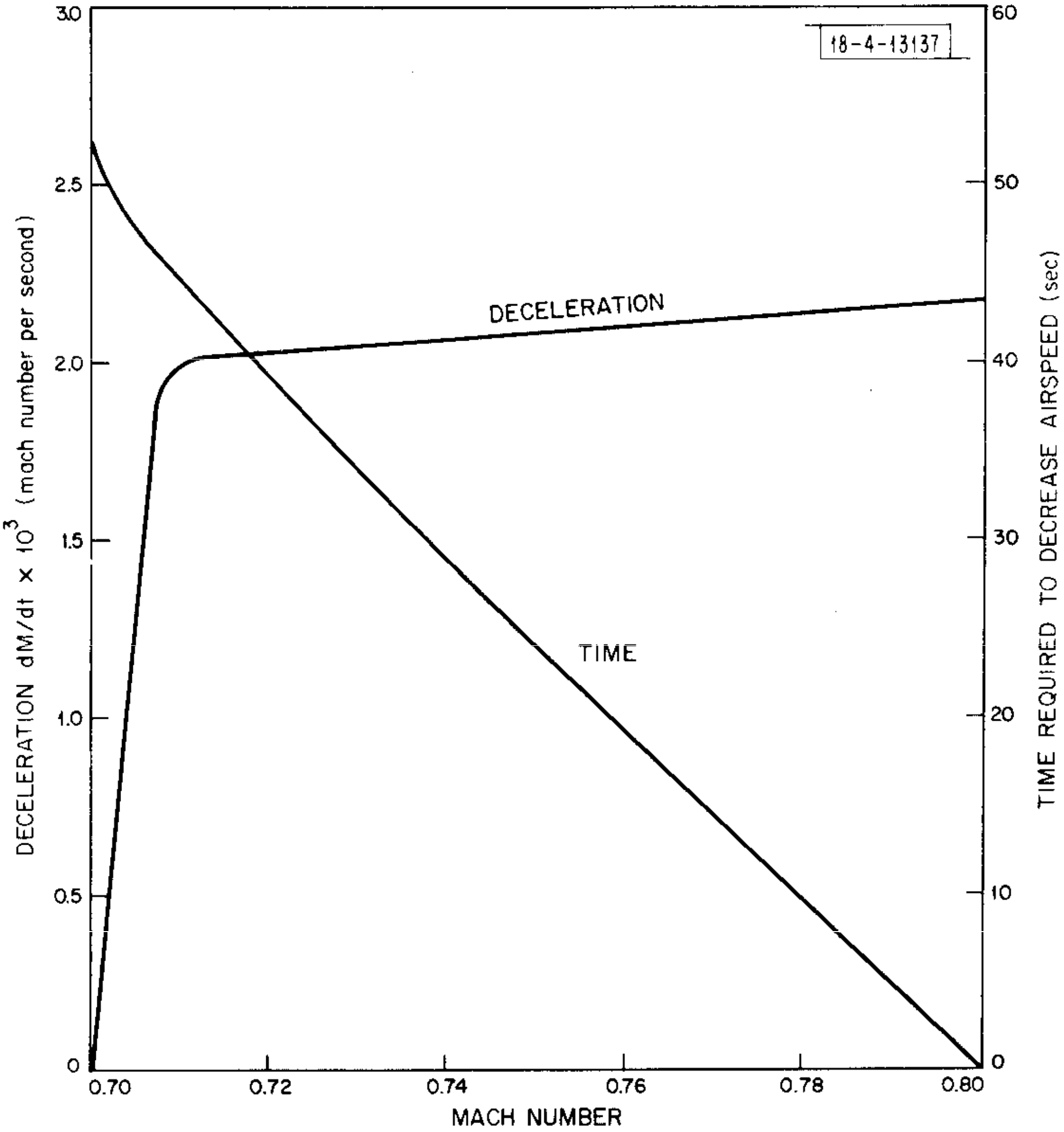


Fig. 41. Airspeed decrease maneuver.

determine the maximum drag force allowed, a reasonable value for the maximum lift for conflict resolution computations could be obtained. In this example the maximum lift coefficient is constrained by the maximum cruise thrust, but it must also be verified that the coefficient of lift does not approach the buffet limit

$$T/\Lambda \text{ (Max Cruise Thrust)} = u\left(C_D\right)_{max} M^2$$

$$L/\Lambda \cos\gamma_{max} = W/\Lambda = u\left(C_L\right)_{max} M^2 \qquad (52)$$

The maximum bank angle, γ_{max}, is then completely specified from the aircraft weight, altitude, airspeed, and maximum drag force. The circular radius of turn, r, is related to the linear and angular velocities by $V = r\omega$. Hence, we obtain

$$L \sin\gamma_{max} = \frac{L \cos\gamma_{max}}{g} V^2/r_{min}. \qquad (53)$$

Since $V = MC_o\sqrt{T_a/T_o}$, the minimum turn radius is defined by

$$r_{min} = C_o^2\left(T_a/T_o\right)M^2/g \tan\gamma_{max} \qquad (54)$$

Values of r_{min} are plotted as a function of airspeed in Fig. 42 for an aircraft gross weight of 160,000 lbs flying at 35,000 ft. As an illustration of a turn maneuver consider an aircraft with an airspeed of Mach 0.80. The minimum turn radius determined by the drag at "maximum cruise thrust" is about 6.2 n miles. If the aircraft flies a minimum radius turn in one direction for 1/4 of a circle, in the opposite direction for 1/2 of a circle, and in the original direction for the final 1/4 of a circle, the aircraft is directed along its original flight path vector at a point 2 circle diameters from the origin of the turn maneuvers. The series of turn maneuvers cost

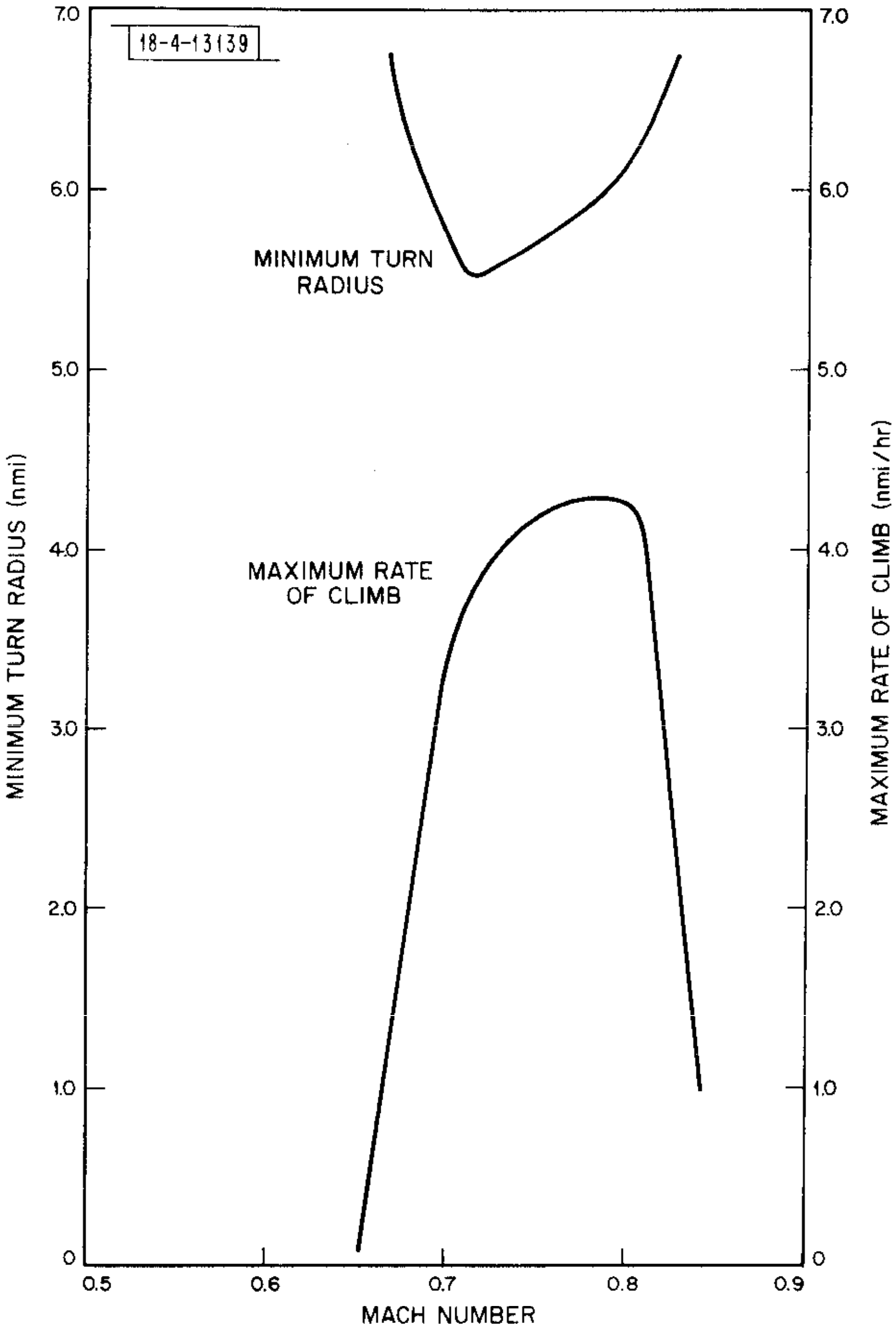


Fig. 42. Turn and climb maneuvers.

the aircraft a factor of $\pi/2$ in total time and distance plus an additional cost in fuel due to the increase in net thrust. Of course, a series of larger radius turns over significantly smaller segments of a complete circle could be used at a greater savings in time and fuel costs, provided they were initiated at an earlier point in the flight plan trajectory.

4. Climb Maneuvers

For level unaccelerated flight the thrust available from the engine is exactly equal to the thrust required to overcome the drag of the aircraft. If the thrust exceeds the drag, the aircraft will be able to either accelerate in level flight or climb. If the thrust is less than the drag, the aircraft must either decelerate or descend.

The kinematic equations which are used to compute the rate of climb, $\dot{h}_c$, assuming a climb angle φ_c, are as follows:

$$T - D - W \sin \varphi_c - \frac{W}{g} \frac{dV}{dt} = 0 \tag{55}$$

$$L + \frac{W}{g} V \frac{d\varphi_c}{dt} - W \cos \varphi_c = 0$$

The rate of climb, $\dot{h}_c$, is equal to the vertical component of the flight velocity:

$$\dot{h}_c = \frac{dh}{dt} = V \sin \varphi_c \tag{56}$$

Solving the first of Eqs. (55) for $\sin \varphi_c$ and using the relation $dV/dt = (dV/dh)(dh/dt)$, the rate of climb is reduced as follows:

$$\dot{h}_c = \frac{(T - D)V}{1 + \frac{V}{g} \frac{dV}{dh}} \tag{57}$$

The dimensionless term $(V/g)dV/dh$ is the acceleration factor, which can be set to zero if the aircraft does not accelerate or decelerate during climb. Hence, the unaccelerated rate of climb is given by

$$\dot{h}_c = (T/\Lambda - uC_D M^2)\frac{C_o\sqrt{T_a/T_o}\,M}{W/\Lambda} \tag{58}$$

Climb angles for most aircraft are sufficiently small ($< 15^o$) so that the lift and drag coefficients during climb are practically identical to those existing for level flight conditions. For T/Λ we use the thrust associated with "maximum cruise" rather than that associated with the "maximum climb rating". This procedure is consistent with the other methods of resolving conflicts. Thus, the aircraft is not forced into a higher thrust rating that is intended primarily for normal climb after takeoff.

Rates of climb for our typical aircraft (160,000 lb. at 35,000 ft.) are also plotted as a function of airspeed in Fig. 42. It is observed that the climb rate for the aircraft flying at an airspeed of Mach 0.80 (LRC) is slightly greater than 4 n miles/hour.

5. Descent Maneuvers

The rate of descent is not as easily determined as the rate of climb because of cabin pressurization requirements. Pressurization at high altitudes generally requires that the aircraft limit its descent rate to a value equivalent to about 300 ft/minute at sea level, which is an acceptable value for passenger comfort. A decrease in rate of descent with a corresponding increase in thrust is required to maintain this pressure change at high altitudes. Thrust requirements are high enough to require operation of the engines at thrust ratings above idle.

For altitudes below about 22,000 ft., sea level cabin pressure can be maintained. The rate of descent is therefore limited by the aircraft structural and performance requirements at lower altitudes. Hence, "idle thrust" may be used to obtain the maximum rate of descent for lower altitudes. The rate of descent for lower altitudes is defined by

$$\dot{h}_d = \frac{(u\,C_D M^2 - F_N/\Lambda)\,(C_o\sqrt{T_a/T_o}\,M)}{W/\Lambda} \tag{59}$$

The derivation is identical to that of the rate of climb, except that for descent the drag exceeds the thrust. The maximum rate of descent for a given airspeed occurs at idle thrust if cabin pressurization requirements will permit the use of this value.

D. Comparison of Conflict Maneuvers

In this section we compare the results of maneuvers which have been described for our selected example. We have assumed that the flight plans of two separate aircraft, one directed along the x axis and the other along the y axis, intersect at time $t = 0$. The flight plan trajectories of both aircraft correspond to the long range cruise airspeed (Mach 0.80) for a gross weight of 160,000 lbs at an altitude of 35,000 ft. (standard atmospheric conditions). We assume that only one of the two flight plans will be modified by an appropriate speed, heading or altitude change.

Table 20 gives the results for several selected examples. For airspeed increase maneuvers we assume that one of the two aircraft is given a flight plan correction to increase its airspeed for Mach 0.80 to Mach 0.84 at a given point in the time frame in which intersection of the original flight plans occurs at $t = 0$. The minimum separation, which in our notation includes both the flight plan conformance requirements and a hazard avoidance separation standard, is then computed from the change in position data. For airspeed decrease maneuvers we assume that one of the two flight plans is modified by an airspeed decrease from Mach 0.80 to Mach 0.70. The minimum radius turn maneuver is initiated at a time corresponding to one turn diameter from the point of conflict. One of the aircraft is turned into the direction of the other for 1/4 of a circular turn and then in the opposite direction for an additional 1/4 turn. Thus the original flight plan is displaced by the diameter of the turn. The change in position data is then used to compute the minimum horizontal separation. For climb maneuvers we assume that one aircraft climbs at its constant airspeed maximum rate of climb by increasing thrust to the maximum cruise rating until a predetermined altitude change has been obtained. The minimum horizontal separation is computed at the time when altitude separation is attained.

The results in Table 20, although applicable to the selected conflict example, should not be used to determine the comparitive effectiveness of conflict maneuvers. At other altitudes, gross weights, and cruise conditions a comparison of results might be significantly different. In addition, other types of aircraft are not identical in their performance characteristics. Table 20 is given, however, to illustrate that simple techniques based on aircraft performance can be used to evaluate the effectiveness of conflict maneuvers and to develop conformance capability.

XIII CONCLUSIONS

A summary of the conclusions pertaining to the process of generating conflict-free flight plans (CFFP's) is given in this section. Conclusions regarding airspace organization are developed in Section VI and conclusions as to what constitutes a reasonable fourth generation baseline system are given in Section IX. The conclusions regarding CFFP's are as follows:

1. There are various options which can be employed in a strategically planned ATC system. In all cases an automated ground system monitors conformance to the computer-generated flight plan. Three of these options follow:

(i) All conflicts are resolved in the computer prior to takeoff, i.e., a CFFP is provided. The conformance required is sufficiently rigid that only a small number of maneuvers is required to follow the CFFP.

TABLE 20

COMPARISON OF CONFLICT MANEUVERS FOR SELECTED EXAMPLE

Type of Maneuver	Initial Time (sec)	Completion Time (sec)	Thrust During Maneuver	Minimum Horizontal Separation (n mi)	Altitude Separation (ft.)
Airspeed Increase	-1000.0	-20.0	Max Cruise	4.3	0.0
Airspeed Increase	-2000.0	-50.0	Max Cruise	8.6	0.0
Airspeed Increase	-3000.0	-70.0	Max Cruise	13.0	0.0
Airspeed Decrease	- 500.0	+30.0	Idle	5.7	0.0
Airspeed Decrease	-1000.0	+60.0	Idle	11.7	0.0
Airspeed Decrease	-1500.0	+80.0	Idle	17.5	0.0
Minimum Radius Turn	- 100.0	+57.0	Max Cruise	7.3	0.0
Climb	- 300.0	-20.0	Max Cruise	3.7 0.0	< 2000.0 ≥ 2000.0
Climb	- 230.0	-20.0	Max Cruise	3.7 0.0	< 1500.0 ≥ 1500.0
Climb	- 160.0	-20.0	Max Cruise	3.7 0.0	< 1000.0 ≥ 1000.0

(ii) None of the conflicts are resolved in the computer prior to takeoff. A flight plan is assigned in an airspace structure designed to minimize conflicting traffic routes. Compared to option (i) conformance is relaxed. When two aircraft approach the conflicting segments of their flight plans, a ground controller is automatically alerted. He then monitors the progress of the two aircraft and diverts one or both of them if a potential hazard materializes. In many cases no diversion need take place. However, when diversion does take place, the diverted aircraft must either be returned to within its original conformance limits, or be assigned a new flight plan.

(iii) Flight plans are assigned in the same manner as option (ii). However, the pilots are automatically alerted when two aircraft approach the conflicting segments of their flight plans. They then monitor their progress on airborne traffic situation displays which must provide the present position and intent of all surrounding traffic. A potential hazard can then be appropriately resolved with these data. In many cases no evasion is necessary; however, when such action does take place, the pilot will return to within his original conformance limits whenever possible.

The methodology employed in Section XI and XII can be used to evaluate these options in terms of required conformance as well as the frequency with which resolved and non-resolved conflicts will occur which are functions of the conformance limits and traffic density.

2. From a comparison of an ATC system based on conflict-free flight planning with a system based on short term tactical planning to avoid hazards, the following observations can be made:

(i) In checking for conflicts one must consider both a separation standard (or an equivalent safety factor) and conformance limits, whereas in checking for hazards one need only consider a separation standard. Thus, conflicts will occur more often in the former system than hazards occur in the latter. The relative frequency depends on the ratio of the conformance limits to the separation standard.

(ii) A conflict may involve a larger diversion of a flight than a hazard, particularly when conformance limits are relatively relaxed.

(iii) The maneuver to resolve a conflict may be less sudden than that required to resolve a hazard, since the system is aware of a conflict well ahead of time whereas a hazard is somewhat of an emergency situation.

3. During flight plan generation a conflict may be resolved using three basic types of maneuvers: turns, speed changes, and altitude changes. Each type of maneuver is subject to different constraints, produces different economic costs, and varies in suitability according to the geometry of the encounter. In general the speed change technique is less efficient than turns or altitude changes due to the fact that it requires a much longer resolution distance. Altitude changes and turns are both attractive in terms of the required resolution distance. Flight economics and necessary airspace regulations must be considered in their use. The turn maneuver requires that the aircraft possess sophisticated area navigation capabilities.

4. For some classes of aircraft it is necessary to re-examine the concept of a flight plan as a set of instructions carried on the aircraft for which the entire responsibility of conformance lies with the pilot. The reason for this arises from the fact that each conflict which is resolved in the flight plan generation process makes the flight plan slightly more complicated. The set of positive commands or waypoints that is added with each resolved conflict increases the danger that the general aviation pilot, who often flies alone with a minimum of aids, will fail to properly execute some command due to momentary inattention or misinterpretation of instructions. When failure to conform invalidates the flight plan, problems arise in transmitting without error a complicated set of new instructions to the aircraft. Two alternatives arise which can alleviate this problem. One is to transmit maneuver instructions to the pilot shortly before the time

for their execution arises. This procedure is similar to that involved in Intermittant Positive Control, with the difference being that slightly more data may be involved in each transmission and the instructions transmitted would be based on the CFFP instead of mere hazard avoidance. With this procedure,changes in flight plans due to disturbances could easily be added to the CFFP on the ground without the problem of replacing the set of instructions located in the aircraft.

The second alternative is to impose a highly structured route pattern which ensures that very few conflicts arise. Only a simple set of instructions would then be necessary and the flight plan would be much easier to fly successfully. Of course, the inconvenience due to the structure would vary with the region considered, so the suitability of this approach for each terminal area has to be evaluated separately.

5. Detailed consideration of the avionics equipment necessary to comply with CFFP's is beyond the scope of this report. However, it appears that the equipment required to achieve moderate to rigid conformance to a CFFP will probably be too expensive for the majority of general aviation aircraft. In the past, the reliability of avionics in general aviation aircraft has been lower than that in air carrier aircraft. Since this situation is likely to continue and avionics failures are more crucial in a system based on CFFP's, it appears unlikely that a system which requires rigid conformance to CFFP's will be feasible for all controlled general aviation aircraft.

6. Because of the economic and operational consequences of daily and seasonal wind and temperature variations, there is a need for the flight plans of scheduled air carriers to vary from day to day with the forecasted weather conditions. There is a crucial need for improved methods of measuring the winds aloft and forecasting their future values. This may require new airborne hardware and use of an air-to-ground digital data-link. The errors which occur using today's measuring and forecasting methods are so large that if an aircraft flies at a constant airspeed, as is a common prac-

tice today, its conformance errors will rapidly increase to large values due to the unpredicted wind and, to a lesser extent, temperature. Even under the loosest conformance limits permitted by the traffic density as derived in Section XI.C, CFFP's will have to be modified every hour or so due to this effect. Tighter conformance limits imply more frequent changes in the CFFP when airspeed is held constant. Thus, for a truly strategic system, an aircraft must be controlled to hold its ground track to a desired trajectory (route-time profile). This implies that fairly sophisticated aircraft equipment is required. In some cases, holding the ground track will be impossible because the unpredicted along-track wind component will cause the performance required to exceed the aircraft's capability. A solution would be to improve measuring and forecasting techniques. It is likely that this improvement will be found essential before a strategically planned, CFFP, control system can be implemented.

7. Minimum separation between aircraft on adjacent flight levels cannot be provided solely on the basis of altitude. The low vertical separation standard (1000 feet for flight below FL 290) in conjunction with the user's limited capability to maintain altitude does not provide separation with a necessary margin of safety. As in today's manual control system, it will be necessary to provide a minimum <u>range</u> separation between aircraft on adjacent flight levels.

8. Conformance requirements must reflect the user's ability to maintain a level of performance when a maneuver is executed for conflict resolution. Certain maneuvers make this level more difficult to maintain than others. An autopilot executing each maneuver as it is required (e.g., a standard rate climb, a turn to a desired heading, etc.) provides a consistancy in performance which minimizes any additional separation required due to error generated in the conflict-resolving maneuver. Manual control during these maneuvers may generate considerably greater errors and thus require that larger separation be applied during the encounter. The above discussion suggests that in defining separation standards it is desirable

to develop a safety model which includes likely aircraft deviations in determining the closest acceptable approach of two aircraft. For a fixed level of safety, a realistic model yields a required separation distance which is a function of the geometry and time history of the encounter (i.e., a function of relative velocity, encounter angle, etc.). The "tau-criterion" of current collision avoidance systems is an example of a geometry-dependent hazard criterion which, for many cases, is a better hazard criterion than mere separation distance.

9. Some of the results of Section XI describe the frequency of conflicts and the conformance requirements when there is a uniform distribution of aircraft within a certain range of flight levels. However, certain conditions may cause a natural bunching of aircraft at certain altitudes. For instance, wind velocity and air temperature may cause certain flight levels to be favored depending upon the course of the aircraft. In most of the airspace categories, this bunching at certain altitudes results in tighter along-track conformance requirements which are expected to remain acceptable. In certain cases, such as a high density mixed airspace in a terminal region, the only way to keep the conformance requirements reasonable may be to require aircraft on the heavily populated flight levels to fly on paralle en route airways with no crossing traffic.

10. Structuring of the airspace by distributing aircraft among flight levels according to their course headings can reduce the number of conflicts which arise in traversing a given route. The greater mean free path between conflicts makes speed and altitude changes more likely to succeed, whereas the probability of success with turn maneuvers does not increase. Because most high density areas are very limited in extent, velocity structuring in these areas can make it possible to route aircraft through with very few conflicts.

11. The main problem area for the generation of CFFP's lies in a high density, mixed airspace region such as the Los Angeles Basin.

Here the frequency of conflicts among IFR flights causes the conformance requirements to be very rigid. If VFR flights are included in the analysis, it appears that it would be impossible to resolve the conflicts even with the aircraft conforming perfectly to their flight plans. Thus, it may be necessary to designate certain regions of low altitude airspace as positive control airspace in order to structure an IFR and VFR traffic environment.

XIV RECOMMENDATIONS FOR FUTURE WORK

The value of analytical models lies in their ability to identify problems, suggest solutions, and provide flexible means of answering general questions. The studies contained in this report have identified certain problem areas and have developed basic approaches to resolving them. In doing this it has become clear that only a fraction of the work needed has already been done.

In some areas information which is essential to the solution is not available in usable form. In other areas models need to be refined or made specific, and simulations need to be carried out to verify the effects of important interactions. Suggestions for future work is enumerated in the following list:

1. The goals, data inputs, and decision criteria involved in flow control must be defined.

2. The process of conflict resolution must be examined in a way that allows multiple conflicts and secondary conflicts to be considered. This implies the need for a limited simulation of the flight plan generation process which would use realistic probability distributions for the inter-conflict distance and the encounter angle.

3. The technology necessary for implementation of the control strategy must be investigated. In addition to the navigation and surveillance systems, careful attention must be given to communication links, data processing capabilities, and special avionics requirements.

4. A more detailed understanding of the concept of IPC must be developed and the integration of controlled and cooperative aircraft in mixed airspace must be examined.

5. The methodology of the flight plan generation process must be investigated. A means of combining the constraints of weather, facility availability, and aircraft performance in a way that produces flight plan modifications acceptable to the user must be delineated.

6. The interaction of the pilot and controller with a more highly automated system must be given careful consideration. The ability of the system to interpret and accommodate pilot requests must be maintained. The presentation of computer-generated decisions to the controller must be considered, and access of the controller to the automated decision-making areas must be ensured. This has an important bearing on the degree of automation that can be achieved.

7. The large volume of IFR general aviation traffic makes the characteristics of these users important. The distribution of aircraft velocities and requested flight altitudes must be combined with performance data in an investigation of airspace policies which satisfy general aviation.

8. The special characteristics of anticipated V/STOL aircraft require that they be treated in many ways as a separate class of airspace user. The emphasis in V/STOL operation is likely to be on a high frequency of service on inter-urban and even intra-urban routes. The ATC system must anticipate V/STOL development if it is to efficiently handle the volume of this type of traffic which is predicted for the 1995 time period. So far, fourth generation studies have not provided an adequate understanding of the problems of V/STOL control and V/STOL compatibility with other system users.

9. The analysis of the feasibility of generating conflict free flight plans in a nearly strategic system considered the projected traffic density expected in the 1995 time period. Calculations were based on the per-

formance of the current aircraft fleet by assuming en route cruise of about Mach 0.8. It is possible that aircraft designed with the supercritical wing will be capable of en route cruise speeds of Mach 0.98 and will replace the current fleet to a large extent. Design studies of long-range transport aircraft have been proposed. The decade 1975 - 1985 is the period in which such designs might become operational realities. Also, the SST cruising at Mach 2.5 may make up a large part of the traffic on some long-haul routes. The methods developed here should be exercised a second time to include these new categories in order to validate several preliminary conclusions.

10. Questions of terminal area design must be considered in a way that takes into account the characteristic peculiarities of each terminal area and yet provides answers for the entire national system. This may mean developing an appropriately parameterized model for a terminal area and then investigating the distribution of parameters for all major terminals. The implications of multiple airport interactions are not well understood and must be studied.

In addition to these recommendations, further analyses and simulations which resolve the fundamental issues discussed in Section VIII must be defined. In general, the results of this report are only a first iteration in the process of designing a fourth generation control system. Further iterations are required.

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:

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

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

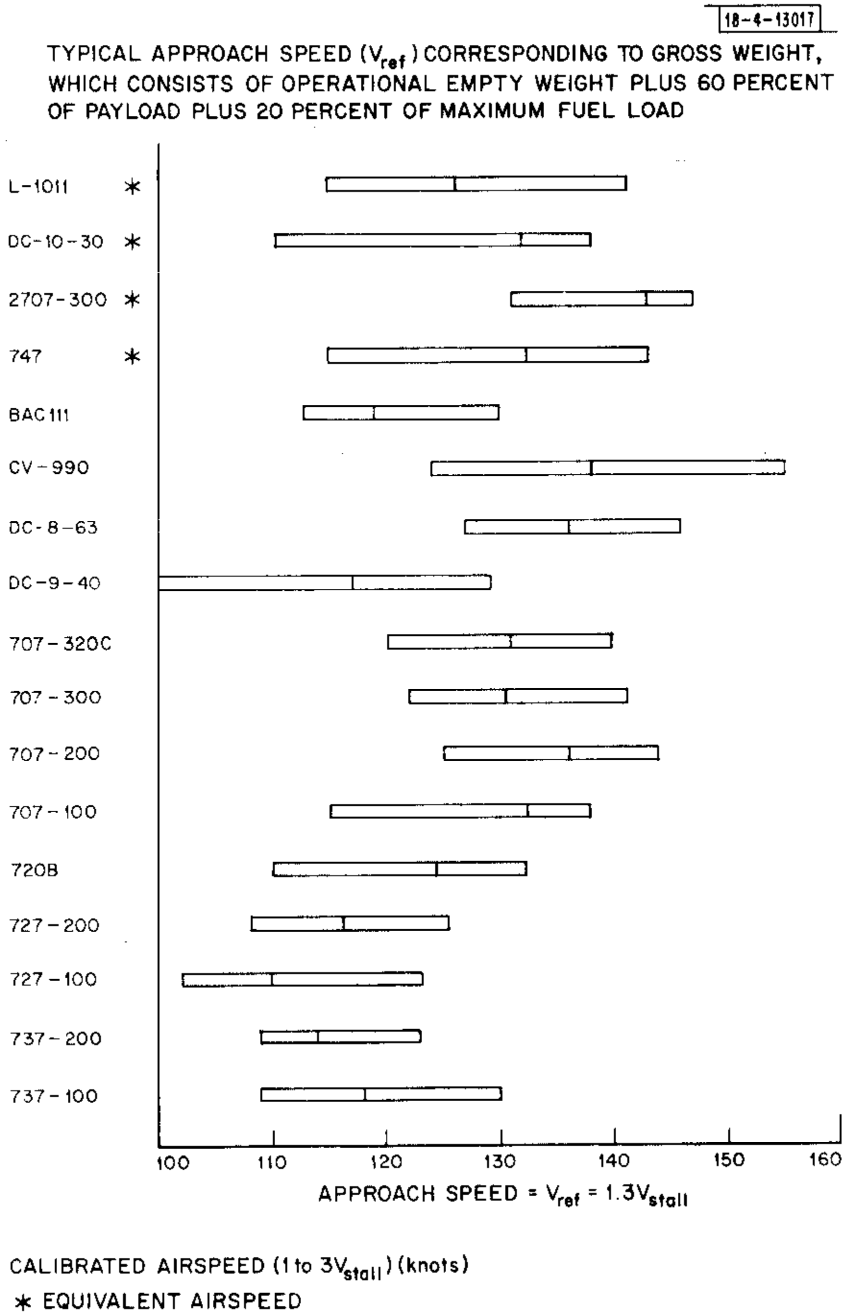


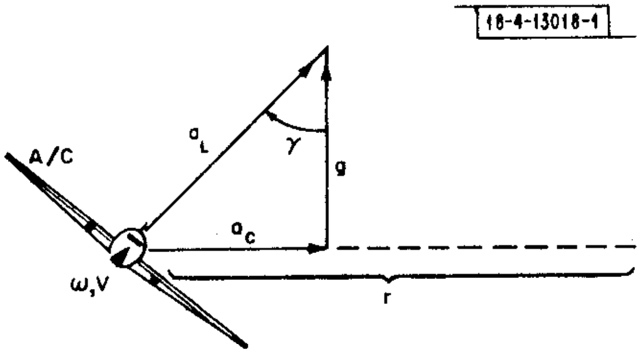
Fig. A.1. Typical approach speed (V_{ref}) for various commercial jet transport aircraft [Ref. 1].

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



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

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

$$r = \frac{V^2}{g \tan \gamma}$$

γ = bank angle;

ω = turning rate;

a_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

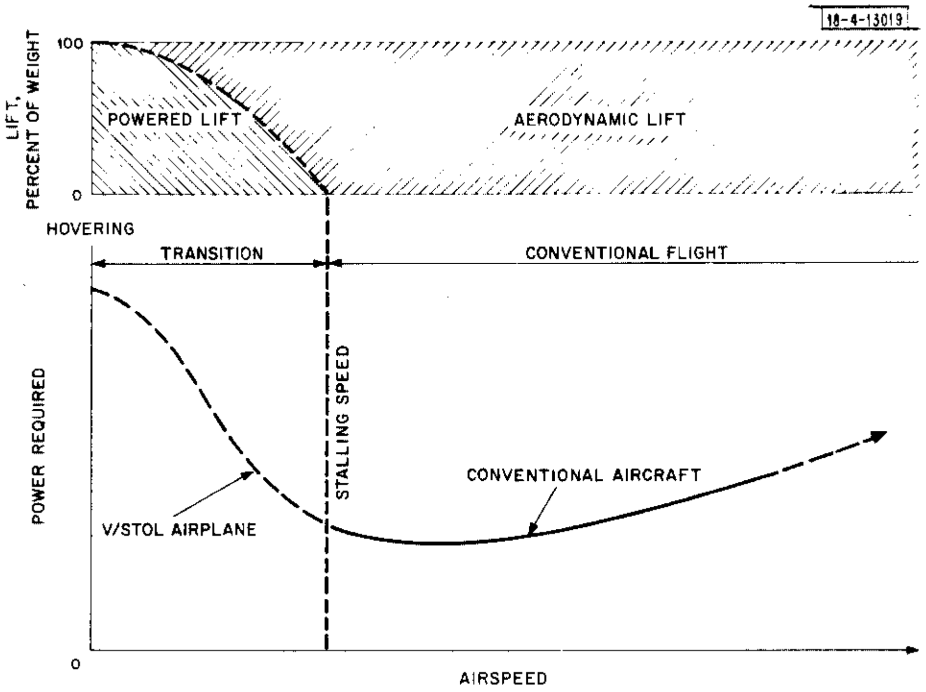


Fig. A.3. Lift and power vs airspeed [Ref. 3].

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

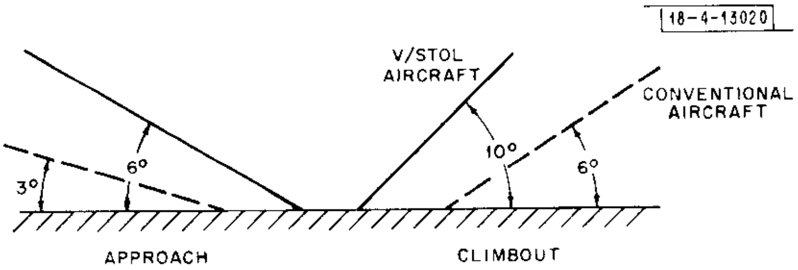


Fig. A. 4. Take-off and landing profiles [Ref. 3].

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

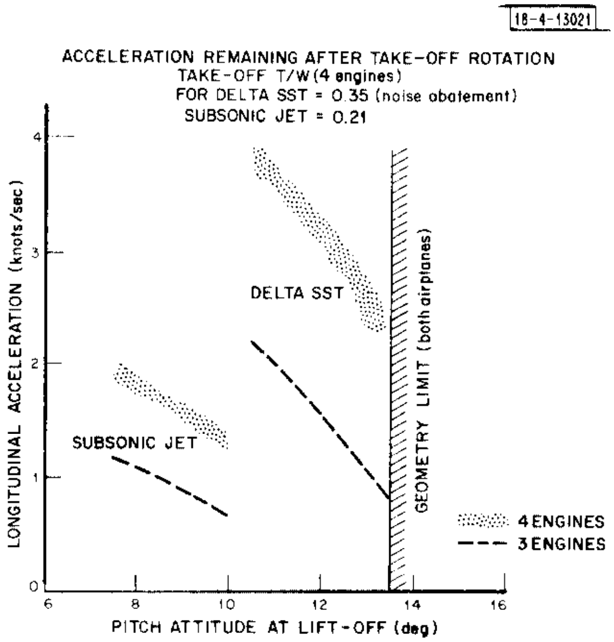


Fig. A.5. Longitudinal acceleration and pitch attitude of SST's and subsonic jets [Ref. 3].

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

Difficulties on Ground

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

Operational Anomalies

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

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

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.

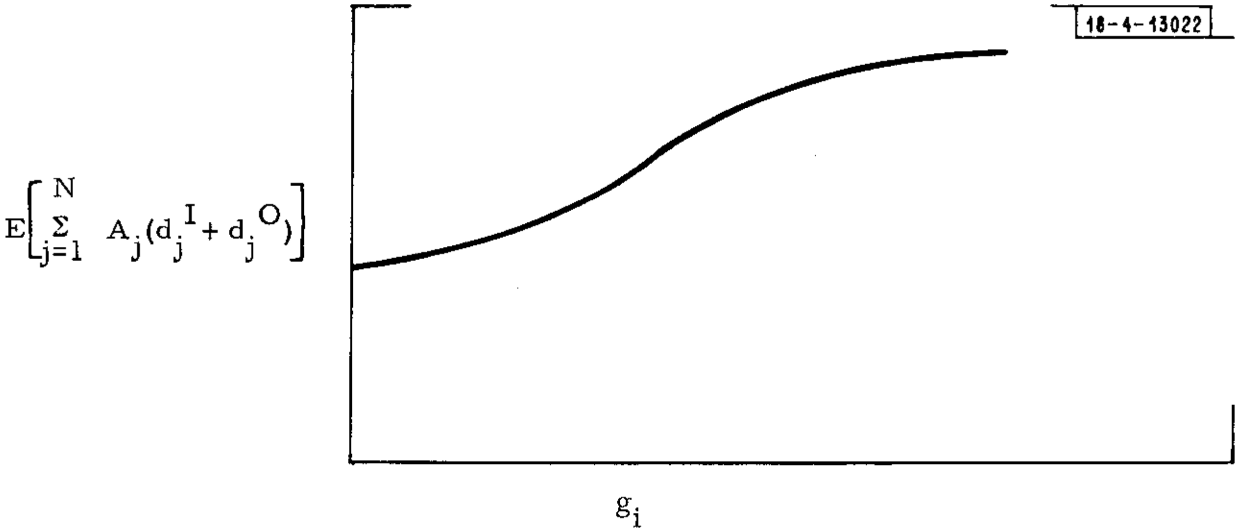


Fig. C.1.

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.

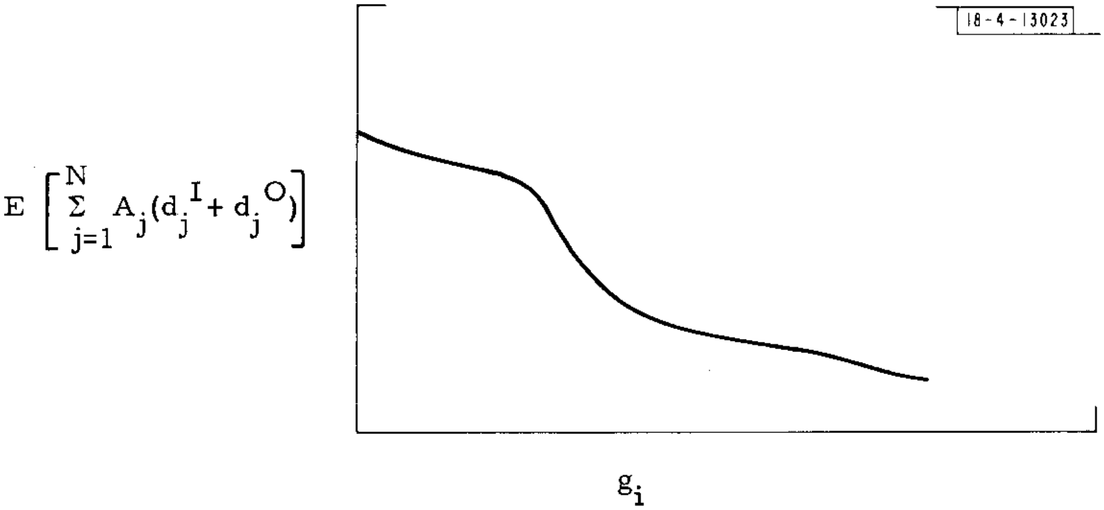


Fig. C.2.

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.

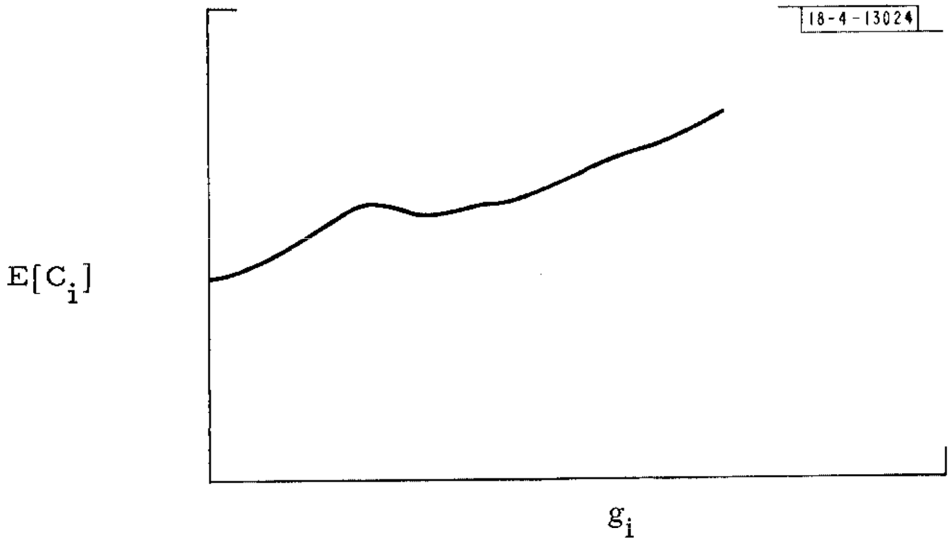


Fig. C. 3.

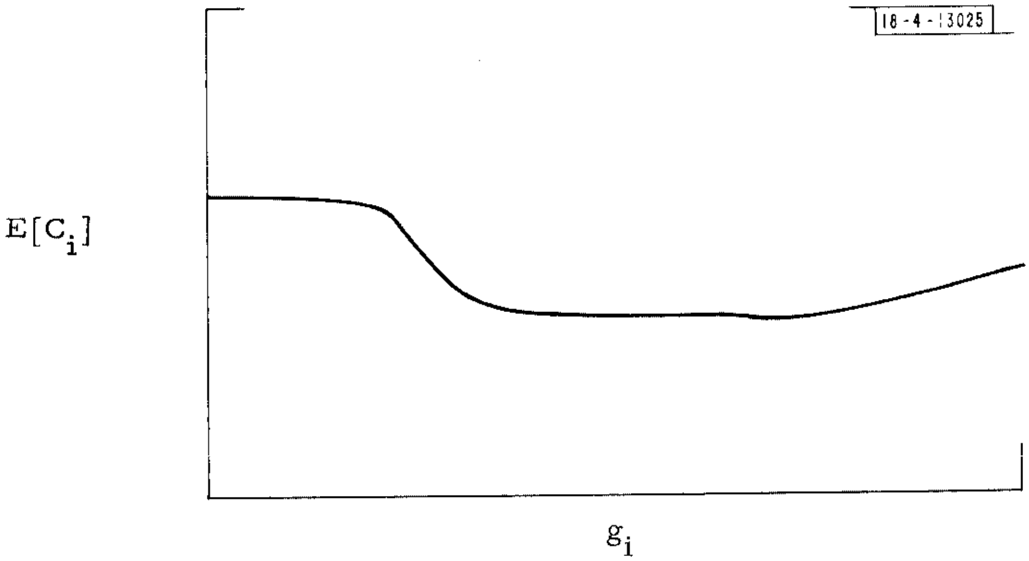


Fig. C. 4.

APPENDIX D

PEAK AIRBORNE AIRCRAFT COUNT IN THE LOS ANGELES BASIN 1980-1995*

I. INTRODUCTION

The ATCAC report (Ref. 1) presents two different estimates for the peak airborne aircraft count (PAAC) over the L. A. Basin. The first estimate, presented in Appendix C-1 of the ATCAC report, offers estimates for 1980 and 1990, whereas the second estimate, presented in section 3. 3. 2 of the ATCAC report, offers a single estimate for 1995. Moreover, the 1995 estimate is much lower than the original 1990 estimate. Compare the estimates as presented in Tables D. 1 and D. 2. In Table D. 1, the 1990 traffic is exactly three times the 1980 estimate, and no mention is made about how the 1980 estimate is derived. The estimate in Table D. 2 is derived from the aircraft activity forecasts of Appendix G-1 of the ATCAC report. The methodology of the estimates is not presented clearly; hence we will present our own estimates for a comparison.

II. METHODOLOGY FOR ESTIMATES

Appendix G-1 of the ATCAC report presents the estimated peak airborne aircraft count (PAAC) for 1968, 1980, and 1995. We are concerned with the PAAC over the L. A. Basin for 1980 and 1995. Thus, the problem is solved if we know the percentage of all peak airborne aircraft which are in the L. A. Basin area. Now,

$$\begin{aligned} \text{PAA (LA)} &= \left[\text{PAA}_{\text{local}} \text{ (NATL)}\right] \times \left[\begin{matrix}\text{(\% of all local traffic which} \\ \text{is in the L. A. Basin)}\end{matrix}\right] \\ &+ \left[\text{PAA}_{\text{itin}} \text{ (NATL)}\right] \times \left[\begin{matrix}\text{(\% of all itinerant traffic which} \\ \text{is in the L. A. Basin)}\end{matrix}\right] \end{aligned}$$

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*This Appendix was prepared by Roger Dear, Staff Member, MIT Lincoln Lab.

TABLE D. 1 - Airspace Description, Los Angeles Basin (Ref. 1)

User (0 - 10,000 ft.)	Number of Aircraft 1980	Number of Aircraft 1990
Mixed Airspace (4,000 - 10,000 ft.)		
IFR	80	240
VFR	450	1350
Uncontrolled Airspace (0 - 4,000 ft.)		
VFR	450	1350
Total	980	2940

TABLE D. 2 - Airspace Description, 1995, Los Angeles Basin (Ref. 10)

User (0 - 10,000 ft.)	VFR	IFR
AC (Air Carrier)	0	40
GA (General Aviation)	1200	100
ML (Military)	20	5
Total	1220	145
Grand Total, IFR & VFR	1365	

Aircraft Parameters, Tables D. 1 and D. 2

Maximum Speeds IFR - 500 ft/sec ≈ 300 kt

VFR - 300 ft/sec ≈ 200 kt

Maximum Turn rate - 3° sec (full rate), 1.5°/sec (half rate)

Maximum Climb and Descent Rate = 1500 ft/min

Minimum Miss Distance = 2000 ft horizontal, 500 ft vertical

Since local traffic remains in the terminal area, [% of all local traffic which is in the L. A. Basin] $= \frac{\text{(total L. A. Basin local traffic) X 100\%}}{\text{(total National local traffic)}}$.

By definition, itinerant traffic does not remain in the terminal area, so

$$\begin{array}{l}\text{\% of all itinerant traffic} \\ \text{which is in the L. A. Basin}\end{array} = \frac{\text{(total L. A. Basin ITIN traffic)}}{\text{(total national ITIN traffic)}} \text{ X}$$

(% ITIN traffic in terminal areas).

The measure of total traffic adopted is the number of annual operations. The estimate of L. A. Basin traffic is taken from the FAA's, "Aviation Demand and Airport Facility Requirement Forecasts for Large Air Transportation Hubs through 1980" (August 1967). All other traffic estimates are taken from appendix G-1 of the ATCAC report. The percentage of national traffic in the L. A. Basin is assumed to be constant from 1980 to 1995. Another assumption is that 25% of the flying time of all itinerant flights is spent in the terminal area.

III. DATA

1980	L. A. Basin Local Operations	=	7.9067×10^6
1980	L. A. Basin Itinerant Operations	=	5.8921×10^6
1980	National Local Operations	=	129.362×10^6
1980	National Itinerant Operations	=	92.854×10^6
1980	PAAC, Local	=	5,630
1980	PAAC, Itinerant	=	16,545
1995	PAAC, Local	=	12,000
1995	PAAC, Itinerant	=	42,400

IV. COMPUTATIONS

$$\frac{\text{1980 L. A. Basin Local Operations}}{\text{1980 National Local Operations}} = \frac{7.9067 \times 10^6}{129.362 \times 10^6} = 6.11\%$$

$$\frac{\text{1980 L. A. Basin Itinerant Oper.}}{\text{1980 National Itinerant Oper.}} = \frac{5.8921 \times 10^6}{92.854 \times 10^6} = 6.35\%$$

1980 L. A. PAA_{local} = 6.11% of 5,630 = 344

1980 L. A. PAA_{itin} = 6.35% of (25% of 16,545) = 263

1980 L. A. PAA_{total} = 607

1995 L. A. PAA_{local} = 6.11% of 12,000 = 733

1995 L. A. PAA_{itin} = 6.35% of (25% of 42,400) = 673

1995 L. A. PAA_{total} = 1406

Now we want to break up the PAAC into IFR and VFR flights. According to "The Applications of Satellites to Communications, Navigation, and Surveillance for Aircraft Operating Over the Contiguous United States" TRW, December 1970, 43% of all itinerant flights in 1980 will be IFR and 49% of all itinerant flights in 1995 will be IFR. There are no figures for the percent of local flights which are IFR. We will try to bound this by assuming between 5% and 10% of all local flights in 1980 are IFR and between 5% and 15% of all local flights in 1995 are IFR. Then,

1980 L. A. PAA_{IFR} = 5% (344) + 43% (263) = 129 min
10% (344) + 43% (263) = 146 max

1980 L. A. PAA_{VFR} = 561 min
578 max

1995 L. A. PAA_{IFR} = 5% (733) + 49% (673) = 367 min[*]
15% (733) + 49% (673) = 440 max

1995 L. A. PAA_{VFR} = 966 min
1039 max

V. DISCUSSION

By comparing these results with Tables D. 1 and D. 2, we find that the total PAAC is greatly overestimated (by 100%) in Table D. 1, and that the

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[*] This estimate of the peak number of IFR airborne aircraft in the L. A. Basin in 1995 is used in Section IX. C.

total PAAC in Table D. 2 agrees very closely with our results. However, both tables, especially Table D. 2, drastically underestimate the number of PAA IFR flights. This underestimate in IFR traffic will affect computations to determine the frequency of conflicts encountered in the L. A. terminal area. Because forecasts for future aircraft traffic are continuously changing, no estimate can be taken for the gospel. However, if Table D. 2 is altered to account for increased IFR traffic, it appears to be much more realistic on its estimate than Table D. 1. Also, since we based our traffic measure on annual operations, we have checked whether the proportion of PAAC x 1000 to annual operations for 1968, 1980, and 1995 is approximately constant. We arrive at 10%, 9.9%, and 10.5%, respectively, and thus are satisfied with basing our traffic measure on annual operations.

APPENDIX E

COMPARISON OF MATHEMATICAL MODELS FOR PREDICTING CONFLICTS

I. GAS MODEL

Assume k aircraft are flying within area A and that each aircraft is equally likely to be headed in any direction. Consider only one of these aircraft moving at the average relative velocity while the rest are stationary. This approach was taken by the ATCAC in Ref. 9. As shown in Fig. E.1, if the required separation is 2b, the area swept out by this aircraft in time t is $2bV_r t$. The probability of a conflict with another aircraft is $2bV_r t/A$ and the expected number of conflicts encountered is

$$C_1 = 2b(k-1)V_r t/A \tag{1}$$

Assuming all aircraft to be flying at a velocity V so that $V_A = V_B = V$ in Fig. E.1, then the time taken for each aircraft to traverse area A is $t = \sqrt{A}/V$. Using the fact that $V_r = 4V/\pi \approx V$, then the expected number of conflicts is

$$C_1 \approx 2b(k-1)/\sqrt{A}. \tag{2}$$

II. AIRWAYS MODEL

Now consider the case where the k aircraft within area A are restricted to fly only on a certain number of airways n_T. Assuming the length of each airway to be approximately $\sqrt{A}$ and the width 2b to correspond to the required separation, the probability of one aircraft intersecting another on a different airway is

$$P_2 = \frac{2b}{\sqrt{A}} . \tag{3}$$

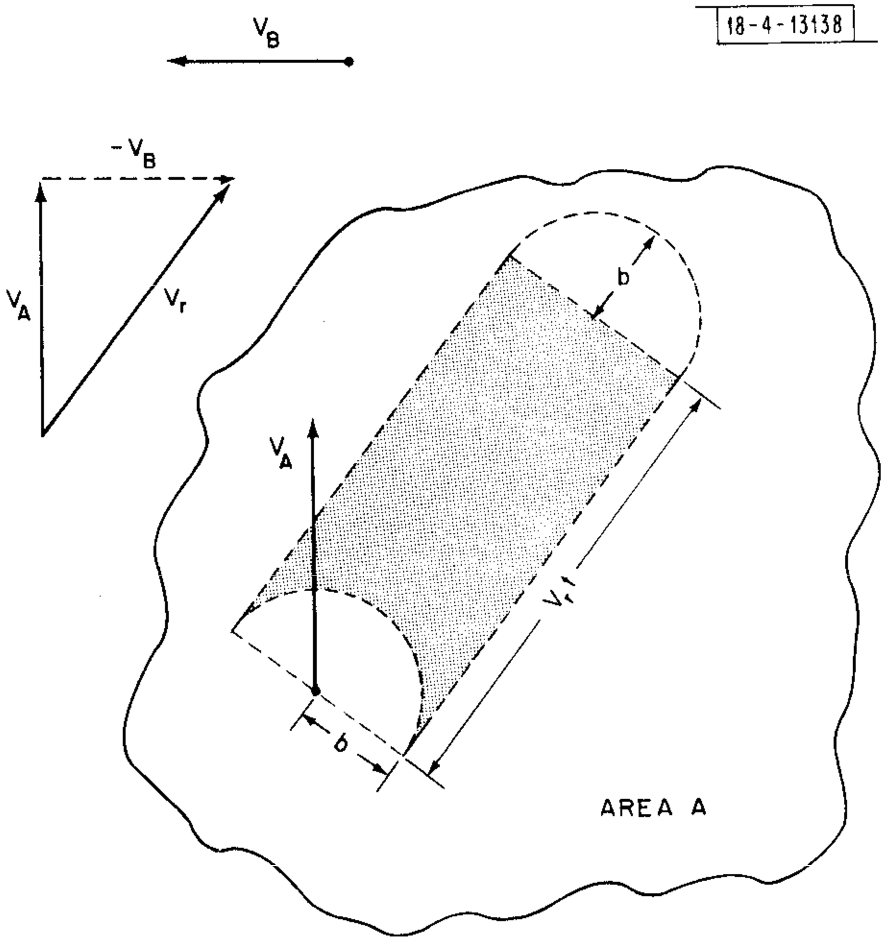

Fig. E.1. Gas model.

Assuming there are k/n_T aircraft on each airway, the number of conflicts per airway intersection is

$$C_{1I} = \frac{k}{n_T} P_2. \tag{4}$$

If the airway on which the aircraft is flying intersects n_c airways, then the total number of conflicts encountered by this aircraft is

$$C_1 = \frac{n_c}{n_T} \frac{k2b}{\sqrt{A}} . \tag{5}$$

The ratio n_c/n_T is unity when all the airways intersect one another and then the expression for the number of conflicts is approximately the same for large k as that obtained with the gas model.

APPENDIX F

CONFLICT RESOLUTION EQUATIONS

I. GEOMETRIC APPROXIMATION FOR TURN MANEUVERS

In deriving the geometrical approximation to the resolution distance two cases must be considered: one for $b \geq r$ and one for $b < r$. The maneuver for $b \geq r$ is depicted in Fig. F.1. The aircraft initially turns at radius r until it becomes tangent to the circle of radius $b \geq r$ which it then follows until the conflict is resolved. The angle ψ shown in Fig. F.1 is given by

$$\psi = \sin^{-1} \frac{r}{r+b} .$$

The conflict resolution distance is then

$$\begin{aligned} \lambda_r(b) &= (r+b) \cos \psi \\ &= (r+b) \cos \left[\sin^{-1} \frac{r}{r+b} \right] = b\sqrt{1 + 2r/b} . \qquad (1) \end{aligned}$$

For $b \geq r$ the value of $\cos \psi$ lies between 0.866 and 1.0. Therefore, a good approximation for the conflict resolution distance is

$$\lambda_r(b) \cong r + b. \qquad (2)$$

When $b < r$ a slightly different turning maneuver must be made since the A/C cannot turn at the radius b. As shown in Fig. F.2, aircraft A initially turns at the minimum radius r. At the point where it becomes tangent to another circle of radius r oriented with respect to aircraft A as shown in the figure, it follows this second circle until the conflict is resolved. For this case, the angle ψ corresponding to the point of tangency is

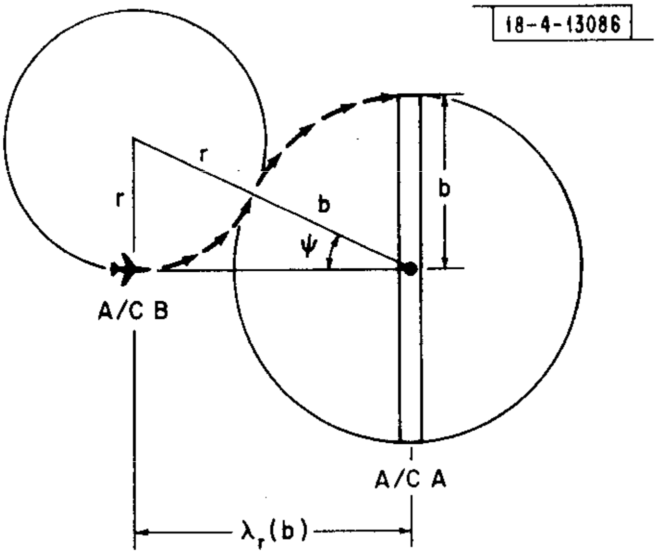

Fig. F.1. Turn maneuver when $b \geq r$.

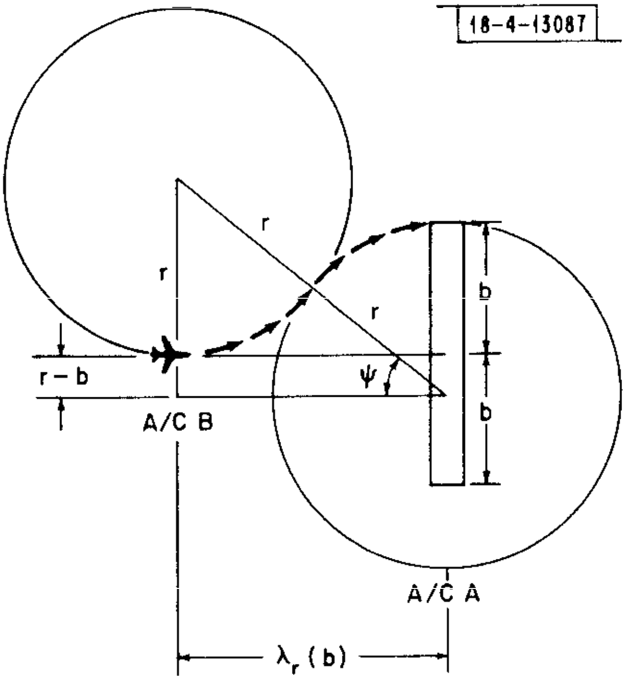

Fig. F.2. Turn maneuver when $b < r$.

$$\psi = \sin^{-1}(1 - b/2r). \tag{3}$$

The expression for $\lambda_r(b)$ is then

$$\lambda_r(b) = 2\,r \cos\psi$$

$$= 2\,r \cos\left[\sin^{-1}(1 - b/2r)\right] = b\sqrt{4r/b - 1}\ . \tag{4}$$

Table F.1 illustrates the comparison between Eqs. (2) and (4) for various values of b/r. Since the minimum value of b is the separation standard, it can be concluded that for all practical values of this quantity Eq. (2) is a good approximation to the exact result.

TABLE F.1

COMPARISON BETWEEN EQUATIONS (2) AND (4) FOR λ_r(b)

b/r	Eq. (4) $\lambda_1 = r + b$	$\lambda_2 = b\sqrt{4r/b-1}$	$\lambda 2/\lambda 1$
1.0	2r	1.73r	0.866
0.75	1.75r	1.56r	0.89
0.50	1.50r	1.32r	0.88
0.25	1.25r	0.97r	0.78

II. FIXED DEFLECTION TURN MANEUVER

A closed form solution which takes all aircraft motion into account and is valid even for small β can be derived if we hold fixed the maximum heading deviation of aircraft A. Figure F.3 illustrates the nature of the (-) turn resolution in which aircraft A is deflected 90° from its original path in order to resolve the conflict.

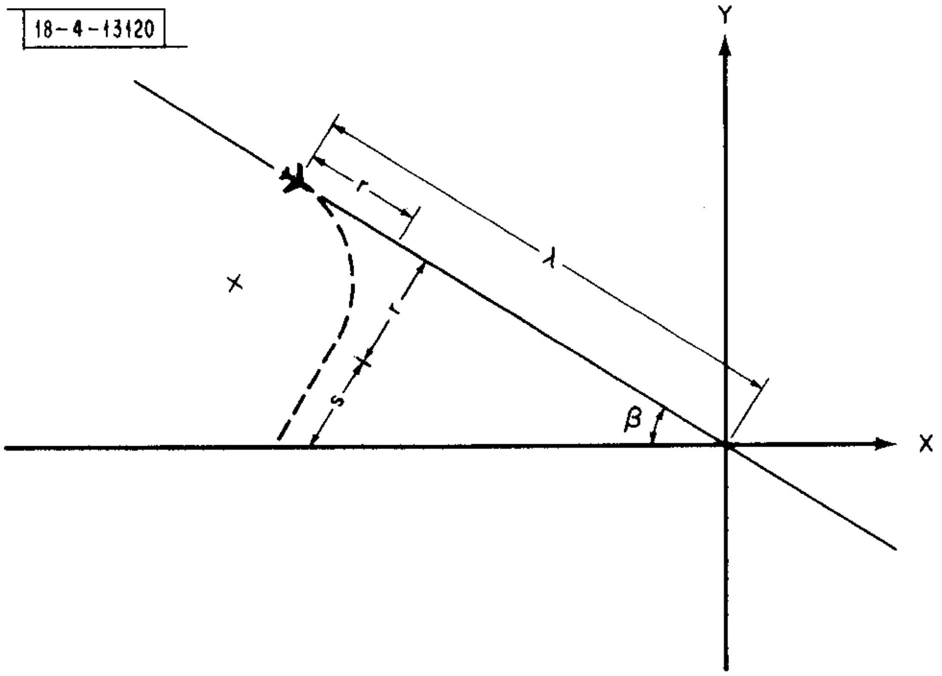

Fig. F.3. Turn maneuver for fixed 90° deflection.

The following relationships are observed to hold for $V_A = V_B = V$:

$$t_{in} = \frac{\pi/2}{\omega} + \frac{s}{V} = \frac{\pi r}{2V} + \frac{s}{V},$$

$$s = (\lambda - r)\tan\beta - r,$$

$$X_A(t_{in}) = -(\frac{\lambda - r}{\cos\beta})$$

Since $X_B(t_{in}) = V\,t_{in} - \lambda$, we can set $X_D = X_B(t_{in}) - X_A(t_{in}) = b$ and obtain

$$\lambda_r = \frac{b + r(\tan\beta + 1 + 1/\cos\beta - \pi/2)}{\frac{\sin\beta - \cos\beta + 1}{\cos\beta}}$$

$$= \frac{b\cos\beta + r\sin\beta + r(1 - \pi/2)\cos\beta + r}{\sin\beta - \cos\beta + 1} \qquad (5)$$

III. VARIABLE DEFLECTION TURN RESOLUTION

The following equations apply to a turn as depicted in Fig. 22(of Section XI) in which aircraft A changes its heading by a chosen amount and then flies straight until crossing the path of aircraft B. From these equations one can solve for the required resolution distance, λ_r, corresponding to the minimum λ necessary to provide a miss distance equal to b. If one adds the constraint that the percentage delay or path deviation be within certain limits, the required resolution distance usually increases.

When searching for optimum (e.g., minimum cost or minimum delay) solutions, it is often necessary to employ a computer program with appropriate search algorithms.

A. Plus Turn

Let the initial position of aircraft A be

$$\overrightarrow{P}_A(0) = \begin{bmatrix} X_A(0) \\ Y_A(0) \end{bmatrix} = \begin{bmatrix} -\lambda\cos\beta \\ \lambda\sin\beta \end{bmatrix}$$

Aircraft B flies on a course given by

$$\overrightarrow{P}_B(t) = V_B t - \frac{V_B}{V_A}\lambda + b - \xi \quad .$$

Note that when $0 < \xi < 2b$, there is a violation of separation requirements at the time of intersection. If A turns in a plus sense, its position is given by

$$\overrightarrow{P}_A(t) = \begin{bmatrix} -\lambda\cos\beta + r\sin\beta - r\sin(\beta - \omega\tau) \\ \lambda\sin\beta + r\cos\beta - r\cos(\beta - \omega\tau) \end{bmatrix}$$

We must now distinguish between the case in which a full turn results in A missing the path of B entirely and the case in which λ is short enough that even execution of a full turn results in a crossing of the flight paths.

Geometric considerations show that the criteria for intersection with a full turn is

$$\lambda < \frac{r(1 - \cos\beta)}{\sin\beta} \qquad (6)$$

The time of intersection is found by solving $Y_A(t) = 0$ from Eq. (2). Thus the time of intersection is

$$t_{in} = \frac{\beta}{\omega} - \frac{1}{\omega} \cos^{-1}\left[\cos\beta + \frac{\lambda}{r}\sin\beta\right]. \tag{7}$$

The X position of intersection is

$$X_A(t_{in}) = -\lambda\cos\beta - r\sin(\beta - \omega t_{in}) + r\sin\beta, \tag{8}$$

and aircraft B is then at

$$X_B(t_{in}) = V_B t_{in} - \frac{V_B}{V_A}\lambda + b - \xi. \tag{9}$$

Thus the miss distance is $X_D = X_A(t_{in}) - X_B(t_{in})$.

Now we will consider the case where a full turn is not necessary to resolve the conflict. Here the maneuver will consist of two parts: a turn for τ seconds to a new heading and a period of straight flight until flight path intersection at time t_{in}. Now we write

$$\overrightarrow{P}_A(t > \tau) = \begin{bmatrix} -\lambda\cos\beta + r\sin\beta - r\sin(\beta - \omega\tau) + V_A(t-\tau)\cos(\beta - \omega\tau) \\ \lambda\sin\beta + r\cos\beta - r\cos(\beta - \omega\tau) - V_A(t-\tau)\sin(\beta - \omega\tau) \end{bmatrix}$$

The intercept time, t_{in}, is found by setting $Y_A(t)$ equal to zero. Thus,

$$t_{in} = \frac{1}{V_A\sin(\beta - \omega\tau)}(\lambda\sin\beta + r\cos\beta - r\cos(\beta - \omega\tau) + V_A\tau\sin(\beta - \omega\tau)) \tag{10}$$

We cannot allow a turn through an angle greater than β without changing the character of the maneuver. If the velocities of the aircraft are equal ($V_A = V_B$), then the relative velocity will approach zero as $\omega\tau \rightarrow \beta$, and the paths will intersect at infinity. Thus the maximum miss distance is obtained by evaluating $X_D = X_A(t_{in}) - X_B(t_{in})$ as $\omega\tau \rightarrow \beta$. This gives

$$(X_D)_{max} = -\lambda \cos\beta + r \sin\beta + \lambda - b + \xi - r\beta. \qquad (11)$$

If this distance is unsatisfactory, a plus turn can be immediately rejected as a possible solution.

B. Minus Turn

The equations describing a minus turn are derived in a similar manner. A minus turn of radius r intersects flight path B if

$$\lambda \leq \frac{1 + \cos\beta}{\sin\beta} r.$$

In this case $t_{in} = \tau$ and the position of A is

$$\overrightarrow{P}_A(t) = \begin{bmatrix} -\lambda\cos\beta - r\sin\beta + r\sin(\omega t + \beta) \\ \lambda\sin\beta - r\cos\beta + r\cos(\omega t + \beta). \end{bmatrix}$$

But if

$$\lambda > \frac{1 + \cos\beta}{\sin\beta} r,$$

we must allow for a period of straight flight. Then

$$\overrightarrow{P}_A(t > \tau) = \begin{bmatrix} -\lambda\cos\beta - r\sin\beta + r\sin(\omega\tau + \beta) + V_A(t - \tau)\cos(\omega\tau + \beta) \\ \lambda\sin\beta - r\cos\beta + r\cos(\omega\tau + \beta) - V_A(t - \tau)\sin(\omega\tau + \beta) \end{bmatrix}.$$

Again, aircraft A intersects the path of aircraft B when $Y_A(t) = 0$, and this allows us to solve for t_{in}

$$t_{in} = \frac{1}{V_A \sin(\beta + \omega\tau)} \left[\lambda \sin \beta - r \cos \beta + r \cos(\omega\tau + \beta) + V_A \tau \sin(\beta + \omega\tau) \right]$$

IV. SPEED CHANGE RESOLUTION

A. Plus Speed Change, $\xi = b$

While undergoing constant acceleration the distance traversed by aircraft A is

$$s(t) = V_A t + 1/2\ at^2 \tag{12}$$

Acceleration is completed at a time $t_c = \frac{KV}{a}$ at which point flight at the constant speed $V_A(1 + K)$ commences. The distance traversed is now given by

$$s(t > t_c) = (1 + K) V_A t - \frac{K^2 V^2}{2a} \tag{13}$$

The time of path interception is determined by solving $s(t_{in}) = \lambda$ where Eq. (12) is used if interception occurs during the acceleration period and Eq. (13) is used if interception occurs later. Assuming the latter we have

$$t_{in} = \frac{\lambda + \frac{K^2 V_A{}^2}{2a}}{V_A(1 + K)} \ . \tag{14}$$

The separation at interception for $\xi = b$ is $X_D = - X_B(t_{in}) = \frac{V_B}{V_A} \lambda - V_B t_{in}$. The value of λ required for resolution is found by setting X_D equal to the separation length b. Then

$$\lambda(+) = \frac{V_A(1+K)}{V_B K}\left(b + \frac{K^2 V_A V_B}{2a(1+K)}\right). \tag{15}$$

If $V_A = V_B$ this reduces to

$$\lambda_r(+) = b\left(\frac{1+K}{K}\right) + \frac{K V_A^2}{2a}. \tag{16}$$

B. Minus Speed Change, $\xi = b$

The equations describing the minus speed change are derived in a similar manner. Here

$$t_{in} = \frac{\lambda - \frac{K^2 V_A^2}{2a}}{V_A(1-K)}, \tag{17}$$

and

$$X_D = X_B(t_{in}) = V_B t_{in} - \lambda \frac{V_B}{V_A}. \tag{18}$$

Then

$$\lambda_r(-) = \frac{V_A(1-K)}{V_B K}\left(b + \frac{K^2 V_A V_B}{2a(1-K)}\right). \tag{19}$$

If $V_A = V_B$ this reduces to

$$\lambda_r(-) = b\left(\frac{1-K}{K}\right) + \frac{K V_A^2}{2a}. \tag{20}$$

APPENDIX G

NUMERICAL RESULTS

I. RESULTS FOR $\alpha = 1$

Case	Parameter	Turn				Descent or Climb				Speed Change			
(1) Chic.-Wash. R = 518mi.	q	0	1	2	3	0	1	2	3	0	1	2	3
	2b	121	100	85.6	74.4	170	145	126	111	28.2	20.2	15.8	13.0
	n. c.	±28.8	±23.6	±19.9	±17.1	±41.0	±34.7	±30.0	±26.3	± 5.6	± 3.6	± 2.5	± 1.8
	$t_{n.c.}$	± 3.4 min.	± 2.8 min.	± 2.3 min.	± 2.0 min.	± 4.8 min.	± 4.1 min.	± 3.5 min.	± 3.1 min.	±39.0 sec.	± 25.0 sec.	± 17.0 sec.	±12.3 sec.
	$\lambda_r(b)$	71.0	60.7	53.3	47.7	50.3	44.7	39.5	35.7	305	225	173	148
	m	7.3	6.1	5.2	4.5	10.3	8.7	7.6	6.7	1.7	1.2	1.0	0.8
	c_{max}	7.3	8.6	9.8	10.9	10.3	11.6	13.1	14.5	1.7	2.3	3.0	3.5
(2) Portion of Wash.-Syr.	q	0	1	2	3	0	1	2	3	Ineffective ($\lambda_r(b) > R$)			
	2b	40.6	26.6	19.0	14.3	56.4	39.0	28.6	22.0				
	n. c.	± 8.7	± 5.2	± 3.3	± 2.1	±12.6	± 8.3	± 5.7	± 4.0				
	$t_{n.c.}$	± 1.0 min.	±36.0 sec.	±23.0 sec.	±15.0 sec.	± 1.5 min.	±58.0 sec.	±40.0 sec.	±28.0 sec.				
	$\lambda_r(b)$	30.8	23.8	19.2	17.2	21.7	17.2	15.6	13.5				
	m	1.6	1.1	0.8	0.6	2.3	1.6	1.1	0.9				
	c_{max}	1.6	2.1	2.6	2.9	2.3	2.9	3.2	3.7				

I. RESULTS FOR $\alpha = 1$ (continued)

Case	Parameter	Turn				Descent or Climb				Speed Change
(3) L. A. Basin V = 130mph R = 60 mi.	q	0	1	2	3	0	1	2	3	Ineffective ($\lambda_r(b) > R$)
	2b	11.5	9.8	8.5	7.5	9.0	6.7	5.1	4.0	
	n. c.	± 1.4	± 1.0	± 0.6	± 0.4	± 0.7	± 0.2	-	-	
	$t_{n.c.}$	±39.0 sec.	±28.0 sec.	±17.0 sec.	±11.0 sec.	±20.0 sec.	± 5.0 sec.	-	-	
	$\lambda_r(b)$	6.4	5.6	4.9	4.4	8.2	7.7	7.2	7.0	
	m	9.4	8.0	6.9	6.1	7.3	5.5	4.2	3.2	
	c_{max}	9.4	10.8	12.2	13.5	7.3	7.8	8.3	8.6	
(4) L. A. Basin V = 275mph R = 60 mi.	q	0	1	2	3	0	1	2	3	Ineffective ($\lambda_r(b) > R$)
	2b	14.9	11.9	9.8	8.2	15.3	11.4	8.7	6.8	
	n. c.	± 2.2	± 1.5	± 1.0	± 0.6	± 2.3	± 1.4	± 0.7	± 0.2	
	$t_{n.c.}$	±29.0 sec.	±20.0 sec.	±13.0 sec.	± 8.0 sec.	±30.0 sec.	±18.0 sec.	± 9.0 sec.	± 3.0 sec.	
	$\lambda_r(b)$	10.5	8.9	7.8	7.0	10.2	9.2	8.5	8.1	
	m	5.7	4.6	3.8	3.2	5.9	4.4	3.4	2.6	
	c_{max}	5.7	6.7	7.7	8.6	5.9	6.5	7.1	7.4	

II. RESULTS FOR $\alpha = 2$

Case	Parameter	Turn				Descent or Climb				Speed Change			
(1) Chic.-Wash. R = 518 mi.	q	0	1	2	3	0	1	2	3	0	1	2	3
	2b	82.8	65.8	54.2	45.8	116	95.0	80.0	68.6	19.7	13.3	10.0	8.02
	n. c.	±19.2	±15.0	±12.0	±10.0	±27.5	±22.3	±18.5	±15.7	± 3.4	± 1.8	± 1.0	±0.5
	$t_{n.c.}$	± 2.2 min.	± 1.8 min.	± 1.4 min.	± 1.2 min.	± 3.2 min.	± 2.6 min.	± 2.2 min.	± 1.8 min.	±24.0 sec.	±13.0 sec.	± 7.0 sec.	±4.0 sec.
	$\lambda_r(b)$	103.8	86.8	75.2	66.8	74.0	64.0	56.4	50.8	432.0	304.0	246.0	200.0
	m	5.0	4.0	3.3	2.8	7.0	5.7	4.8	4.1	1.2	0.8	0.6	0.5
	c_{max}	5.0	6.0	6.9	7.8	7.0	8.1	9.2	10.2	1.2	1.7	2.1	2.6
(2) Portion of Wash.-Syr. R = 50 mi.	q	0	1	2	3	0	1	2	3	Ineffective ($\lambda_r(b) > R$)			
	2b	26.4	15.1	9.7	6.6	36.4	22.2	14.7	10.3				
	n. c.	± 5.1	± 2.3	± 0.9	± 0.2	± 7.6	± 4.1	± 2.2	± 1.1				
	$t_{n.c.}$	±36.0 sec.	±16.0 sec.	± 6.0 sec.	± 1.0 sec.	±53.0 sec.	±29.0 sec.	±15.0 sec.	± 8.0 sec.				
	$\lambda_r(b)$	47.4	36.0	30.6	27.6	33.4	27.8	23.8	21.7				
	m	1.1	0.6	0.4	0.3	1.5	0.9	0.6	0.4				
	c_{max}	1.1	1.4	1.7	1.9	1.5	1.8	2.1	2.3				

II. RESULTS FOR $\alpha = 2$ (continued)

Case	Parameter	Turn				Descent or Climb				Speed Change
(3) L. A. Basin V = 130mph R = 60 mi.	q	0	1	2	3	Effective Length Less Than 2(separation standard)				Ineffective ($\lambda_r(b) > R$)
	2b	7.9	6.5	5.5	4.8					
	n. c.	± 0.5	± 0.1	-	-					
	$t_{n.c.}$	±14.0 sec.	± 3.0 sec.	-	-					
	$\lambda_r(b)$	9.2	7.8	6.8	6.1					
	m	6.5	5.3	4.5	3.9					
	c_{max}	6.5	7.6	8.7	9.8					
(4) L. A. Basin V = 275mph R = 60 mi.	q	0	1	2	3	0	1	2	3	Ineffective ($\lambda_r(b) > R$)
	2b	9.9	7.4	5.7	4.6	9.0	6.0	4.1	2.9	
	n. c.	± 1.0	± 0.4	-	-	± 0.8	0.0	-	-	
	$t_{n.c.}$	±13.0 sec.	± 5.0 sec.	-	-	±10.0 sec.	0.0	-	-	
	$\lambda_r(b)$	15.8	13.3	11.6	10.5	17.2	15.8	14.6	14.0	
	m	3.8	2.8	2.2	1.8	3.5	2.3	1.6	1.1	
	c_{max}	3.8	4.5	5.2	5.8	3.5	3.8	4.1	4.3	

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