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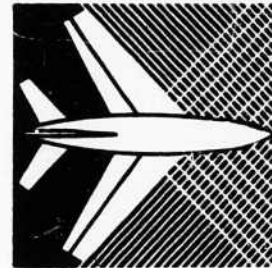
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INTERIM REPORT

Project No. 102-11R
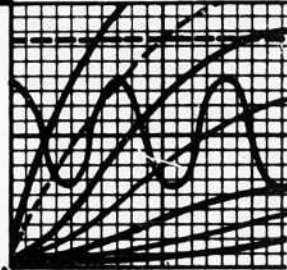
CONTROL LOAD,
CONTROL CAPACITY
AND
OPTIMAL SECTOR DESIGN

DECEMBER 1963
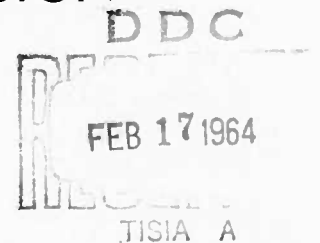
FEDERAL AVIATION AGENCY

Systems Research & Development Service

SYSTEM DESIGN TEAM

Washington, D. C.

and

RESEARCH DIVISION

Atlantic City, New Jersey

INTERIM REPORT

CONTROL LOAD, CONTROL CAPACITY

AND OPTIMAL SECTOR DESIGN
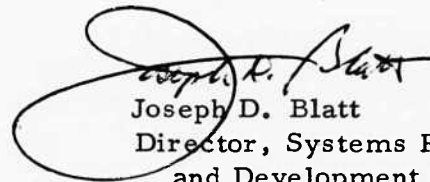
Project No. 102-11R
RD-64-16

Prepared by:

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December 1963

This report has been approved for general distribution.

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FOREWORD

The fresh mathematical approach to the problem of air traffic control reported here has not only pointed the way to a more efficient sector design but has also provided a technique of assessing the work and load imposed on the controllers that man the sectors.

Concerning the design of sectors, this report presents the basic theoretical model in complete detail and the first study conducted in the on-going program to convert the model to an empirical, operationally useful tool. The model is unique in that it ties sector design to the traffic phenomena on the one hand and the load imposed on the sector on the other hand. Work now in progress will result in the completion of this task and promises to culminate in the production of a "do-it-yourself" manual enabling sector designers to apply the method in the field. The hope here is to convert the "art" of sector design as it is now practiced by seasoned, experienced controllers into a "science" (more objective method), which will essentially combine the experience of many controllers and transform this "know-how" into numerical terms which can be used by all.

Concerning the measurement of control load and work, the methodology of working with intervening variables will provide a rallying point for other human factors work in the air traffic control area. The way is opened up for cross-validation studies at the behavioral and physiological levels.

Although the several authors were primarily responsible for specific parts of the task, there existed a symbiosis of minds of those engaged in the effort such that no one claims the complete credit nor bears the complete burden of blame for any particular chapter or verse. Be that as it may, however, Arad [1] was primarily responsible for the mathematical theory lying behind the work and Mayfield [2] had a similar responsibility for the experimental design of the paired-comparison

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[1]   Bar-Atid Arad, Co-Manager of the Project, recently Chief of the Operations Division of the Department of Civil Aviation of Israel, is currently on a sabbatical basis with the System Design Team of the Federal Aviation Agency.

[2]   Clifton E. Mayfield, Senior Research Psychologist, The Franklin Institute, Philadelphia, Pa., on contract with the Agency.

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study. Grambart [3] made the major contribution to the design of the displays employed in the study and van Saun [4] conducted the administration of the judgment scaling device at most of the Air Route Traffic Control Centers. Golden [5] made the major contribution to the reduction and analysis of the data.

The authors are indebted to a large number of people whose inputs to the effort ranged from very important ideas to simple hard work. It is, of course, impossible to cite everyone who contributed in this manner, but mention must be made of the following:

> Mr. Joseph Ritz of the Eastern Region Headquarters Staff whose early support of the project provided the necessary initial entree to the operational personnel whose genuine interest and wholehearted cooperation made the project possible.

> The staff and controllers of the following Air Route Traffic Control Centers who participated in the first study:

> > Albuquerque, New Mexico
> > Atlanta, Georgia
> > Boston, Massachusetts
> > Chicago, Illinois
> > Denver, Colorado
> > Jacksonville, Florida
> > Kansas City, Kansas
> > Los Angeles, California
> > New Orleans, Louisiana
> > Oakland, California
> > Salt Lake City, Utah
> > Washington, D. C.

ABSTRACT

The complexity of total traffic phenomena in a controlled airspace
is described by a model that relates the variables of the traffic (number
of aircraft, distribution, speed), the rules of operation (separation
minima) and the airspace (volume and flow organization) to the load
which is imposed on the control position of the sector. Basic units
of control load and control work are defined and used for quantifica-
tion of the control effort required. The relationship between the load
imposed on the control position and the geometry and the orientation
of the sector is demonstrated and a method for optimizing the design
of the sector is analyzed and described in a numerical example. The
control capacity is quantified in units of control load and method of
matching the size of the sector to the capacity for maximum efficiency
of sector design is demonstrated and discussed. A paired comparison
study is used to scale the amount of control work involved in handling
the traffic in each of 20 control problems. From the relative scale
values thus obtained, the proper weights to be assigned to the several
routine traffic variables are found by a method of solving simultaneous
equations. The problem of model validation is discussed and future
plans are outlined.

PART I

THEORY

INTRODUCTION

The structure of the Air Traffic Control Subsystem in the enroute environment is subdivided into well defined jurisdictional units for the exercise of control. These units, commonly known as "control sectors," subdivide the entire navigable airspace in the enroute environment. Thus:

> (1) any point in the navigable (enroute) airspace must belong to a control sector and

> (2) any point in the navigable airspace must belong to one and only one control sector at any given time.

The magnitude, shape and orientation of these sectors vary considerably. The only planning criteria in existence today[1] are primarily directed toward manning and does not provide enough guidance for the proper and efficient design of the sector.

It is interesting to note that at present there are more than 380 enroute control sectors in the continental U.S.[2]. Consequently, any improvement in sector design will yield appreciable benefits to the system. However, any assessment of the gained benefits is possible only if:

> (1) the term "improved sector design" is well defined and

> (2) there is a method to measure the benefits gained.

More than 50% of the annual recurring system cost is directly proportional to the number of the operating sectors[3]. Moreover, total reduction in the number of sectors will reduce the total amount of sector associated equipment[4] on a nationwide basis, save control Air-Ground-Air frequencies, yield better frequency management and reduce cockpit load.

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(1) Airway Planning Standard No. 5, FAA Nov. 1961

(2) For further details see Appendix I

(3) This cost does not include management and other overhead expenditures that are not sensitive to the number of operating sectors. See also Appendix I.

(4) This statement is true only for a given level of equipment complexity.

The potential benefits to be gained by reducing the total number of control sectors defines an ultimate goal, i.e., a reduction in the total number of operating sectors for any given level of service and traffic, by increasing the size of the control sector.

The responsibility to provide a given level of service and the traffic phenomena[5] in the airspace generates a requirement for a control effort. Every situation requires control effort by the sector. This required effort is consequently a basic measure of traffic activity or, conversely, the total traffic activity is a measure of the control effort required.

This approach needs further clarification. The total control effort can be measured in two places:

    (1) at the control position, by measuring the actual work performed, or

    (2) in the airspace, by measuring the total traffic phenomena.

In case (1), the results do not necessarily indicate the relationship between the traffic, the airspace, the rules and the effort of the control position. On the other hand, case (2) excludes all effort which does not directly affect the control of traffic.

The second method is preferred, i.e., measurement of the traffic variables and definition of the effort required by the control position as proportional to the total traffic activity. This method was selected because the traffic and the airspace parameters are, by nature, more tangible and measurable quantities. Any direct measures of the human effort both at the behavioral and the physiological levels could, at best, be used for cross validation of some basic assumptions.

The control effort required has been defined as directly proportional to the total traffic phenomena. The measurement of this effort must be:

    (1) sensitive to all the parameters of airspace, traffic and rules of operation

    (2) consistent throughout the navigable airspace and

    (3) sensitive to the size, shape and orientation of the sector.

---

(5) i.e., the amount, behavior and characteristics of the traffic flow.

The effort required is not measured at the control position and, therefore, is independent of the human controller, the control equipment, or any combination of man-machine. These, however, are of a great significance when the capacity of the sector is considered. It should be realized that for any given level of service and safety, the ratio between the total traffic activity and the internal capacity of the system will determine the "level of discomfort" to the user. In other words, when the total effort required by the control position exceeds the capacity, and the required level of safety and service are maintained, the system will generate "discomfort" to the user (i.e., delays, change of original intent, etc.).

On the other hand, by adjusting the capacity and the effort required, a given level of efficiency can be maintained. Moreover, any potential increase of capacity by implementing new and better equipment can be balanced by delineating sector boundaries to fully utilize this latent capacity.

The adjustment of sector boundaries as a function of the ratio between the effort required and the capacity, for any given level of equipment and for any desired level of control efficiency (degree of discomfort), is of special interest in System Design. The application of this method will provide:

(1) a tool to measure the total traffic activity and determine the amount of control effort required

(2) a sensitive and consistent unit of measurement to quantify the effort required and the capacity

(3) a method to determine the shape, orientation and size of sectors.

THE CONTROL LOAD

The total load L imposed on the control position is composed of the following components:

$$L = L_0 + L_1 + L_2 + L_3 + \ldots + L_n \qquad \ldots 1$$

where L_0 is the background load,
L_1 is the routine load,
L_2 is the airspace load and
$L_3 + \ldots + L_n$ are system induced loads.

(A) THE BACKGROUND LOAD, L_0, includes all the loads that are developed internally in the system and are not, in any way, affected by the sector geometry, size or by the traffic phenomena. In an automated environment a certain amount of power is required to drive the mechanical parts of the machine and a level of energy is required to heat the computer. This power is not related to any external conditions, but is constantly consumed. The same applies to a manual environment. Any control position has to be manned by a crew, irrespective of the traffic or sector size and geometry. The crew has to perform some administrative and technical functions, and these functions are completely independent of any external conditions. Moreover, the morale of the crew, the general working conditions, etc., are contributing factors, and undoubtedly impose considerable load. But, since all this load, by definition, is independent of any external conditions, and we are primarily interested in the loads generated by these external conditions, we could consider the value of L_0 as a constant and a reference line above which all the dynamic loads (L_1 and L_2) can be determined. The actual value of L_0 will be considered again when the question of control capacity (C_p) is discussed (see Figure 1).

(B) THE ROUTINE LOAD L_1 is the load imposed by all the routine control functions associated with any aircraft traversing the system when no interaction between the aircraft is considered. Every aircraft is handed-off into the sector and then handed-off to an adjoining control unit. A certain amount of communication, coordination and administration of flight strips is connected with the movement of the aircraft through the sector and all these operations and functions generate work which is performed by the control system. This work is by definition directly proportional to the number of aircraft in the system:

$$W_1 = k_1 N \qquad \ldots 2$$

(4)

Fig.1   THE COMPONENTS OF THE CONTROL LOAD

$L_1 + L_2$

L_1

L_0
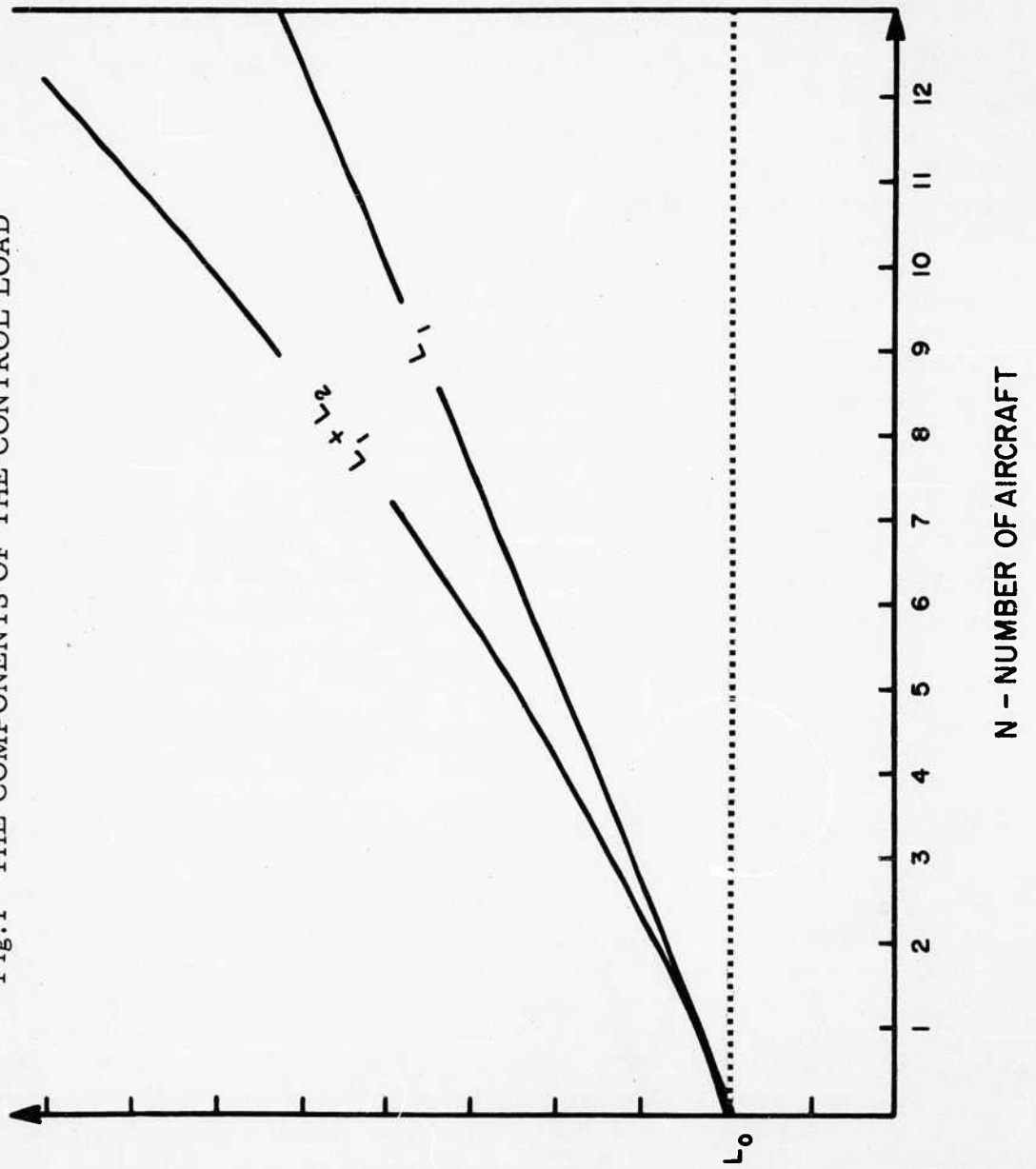
L - DEL

N – NUMBER OF AIRCRAFT

where W_1 is the routine work

               N is the number of aircraft in the system, and

               k_1 is a coefficient

If we define load L as the rate of doing work W then:

$$L_1 = \frac{W_1}{T} = k_1 \frac{N}{T} \qquad\qquad \dots 3$$

where $\overline{T}$ is the average time that an aircraft is in the sector.

From eq. 2 the meaning of k_1 can be defined as W_1/N or, the work generated by the average aircraft (typical aircraft) in the system. This statement needs some clarification.

(1) The amount of work associated with an aircraft in the system varies considerably with the classification of the user and its performance in the sector. It is reasonable to assume that in general the average (or typical) general aviation aircraft will generate different (probably more) amounts of work than an airliner performing identically in the sector. Furthermore, the performance of the aircraft in the sector (changing altitude, vertical hand-offs, hand-offs to and from terminal area), all generate a different amount of work.

(2) The traffic in any particular sector is repetitive in nature[6]. If P_O is the average percentage of airline type aircraft that populate the sector then the work generated by the average aircraft in the system is

$$k_1 = \frac{W_1}{N} = \frac{P_o\, \tau_o + (100 - P_o)\tau_1}{100} \qquad\qquad \dots 4$$

provided that the total traffic is flying straight and level through the sector and no interaction between the aircraft is considered.

(3) Since P_O is a non-dimensional number (%), γ_o is the work generated by one "standard aircraft" in the system. The term standard aircraft will refer to any aircraft that does not require special handling in terms of frequencies and procedures. In general, all air-carrier traffic, MATS, and some executive type aircraft could be considered as "standard aircraft."

(4) The rest of the aircraft that populate the system (100 - P_o) are expected to generate a different amount of work (γ_1). Extending this line of reasoning to the performance of the aircraft in the sector where:

---

(6) The implication and significance of the repetitive nature of the traffic will be considered separately.

P_2 is the average percentage of aircraft handed-off vertically

P_3 is the average percentage of aircraft handed-off to or from a terminal area

P_4 is the average percentage of transitioning aircraft

P_5 is the average percentage of pop-up targets,

or in general P_i (i=2, 3, ...,m) represents the average percentage of aircraft in a sector performing in i manner than:

$$k_1 = \frac{P_0 \, \tau_0 + (100 - P_0) \, \tau_1 + \sum_{i=2}^{m} P_i \, \tau_i}{100} \qquad \ldots 5$$

where γ_i is the work associated with one aircraft when performing in a $_i$ manner.

(5) The values of P_i are measurable quantities for any given sector but the values of γ_i should be determined through tests and simulations. It should be realized that the values of γ_i are the only element associated with W_1 (or L_1) that connect the traffic with the effort of the human controller. Therefore, the final test for γ_i must be through the actual controller's reaction to various percentages of P_0 and P_i. However, it is possible that a test of the set of all γ_i might prove that any given γ_i will be very small. A final finite form of equation 5 could be determined after the evaluations of the tests.

(6) We will refer to the units of control work as DEW (dynamic element of work). It has been previously stated that 1 DEW is equal to the work generated by one standard aircraft crossing the sector in a straight and level flight. The unit of control load will be DEL (dynamic element of load) and 1 DEL represents the load imposed on the control position by one standard aircraft crossing the sector in straight and level flight for 1 hour. The dimension of k_1 is defined by equation 2 and the units of k_1 are DEW per aircraft.

(7) The unit of work (DEW) represents an operational phenomenon in a given system of control. The validity of this unit, and consequently the value of k_1, is maintained throughout the system. However, it should be realized that a change in the system of handling aircraft (e.g. - introduction of machine assistance at the control position) might result in a different absolute value of 1 DEW and different ratios of γ_i.

(C) THE AIRSPACE LOAD. The most important control function is to provide separation between aircraft. This function requires the prediction of an expected conflict and its resolution. The load which is expected to be imposed by the interaction of the aircraft in the system is therefore related to the capacity of the airspace, or, in other words, to the availability of conflict-free airspace.

(7)

$$L_2 = \frac{k}{A} \qquad \qquad \ldots 6$$

where   A   is the available conflict-free airspace and
                k   is a coefficient.

The available airspace (A) can be defined as the inverse of the number of conflicts (C) expected to develop in the sector in a unit of time. C can be expressed as:

$$C = \frac{2\bar{a}\bar{V}N^2}{g_0 S} \qquad \qquad \ldots 7$$

where $\bar{a}$ is a linear measure of the separation minima (nm/ac)
                $\bar{V}$ is the average traffic speed (nm/hr)
                g_0 is the flow organization factor (non-dimensional) and
                S   is the area of the sector $(nm)^2$

Substituting $C = \frac{1}{A}$ in eq. 6 we get:

$$L_2 = \frac{2k_2\bar{a}\bar{V}N^2}{g_0 S} \qquad \qquad \ldots 8$$

where k_2 is the coefficient of the airspace load. The dimension of C is ac /hr, the dimension of k_2 is DEW per aircraft and the dimension of L_2 is DEW per hour or DEL.

(1) The validity of eq. 8 is limited to area type of traffic when the density of aircraft can be defined:

$$N = DS \qquad \qquad \ldots 9$$

where   D   is ac per unit area.

Substituting the value of N in eq. 8 we get:

$$L_2 = \frac{2k_2\bar{a}\bar{V}D^2S}{g_0} \qquad \qquad \ldots 10$$

However, the case of airway traffic requires different considerations since the traffic field is defined only along predetermined lines of flow. The term "aircraft density" has a meaning only along a line and therefore should be expressed as aircraft per nautical mile. The average number of expected conflicts (C) will be the sum of two distinct classes:

         (a)   - the class of all conflicts expected to develop in an inter-
                     section of two (or more) airways, and

(b)   - the class of all conflicts expected to develop along an
airway by the action of overtaking aircraft[8].

(2) The number of expected conflicts in an intersection is not affected
by the sector area around the intersection. On the other hand, the average
number of expected overtakes will increase with the length of the airway.
Since we are dealing with statistical averages, we can define the average
number of expected overtakes per unit length of track (G/s) as a function of
the speed differential ($V_2 - V_1$) and the average traffic flux (ac /hr) or the
average airway density[9]. The total number of overtakes is therefore
directly proportional to the length of the airway, provided there is no change
in the traffic variables.

(3) In an area S with a given structure of airways and a given traffic
the total average number of expected conflicts ($C = \varphi + G$) is a constant.
Any conflict involves an action between a pair of aircraft. In effect the
average number of expected conflicts is always a function involving inter-
action between any possible pairs of aircraft or:

$$C = f(N^2) \qquad \qquad \ldots 11$$

The number of expected conflicts can also be expressed by eq. 7:

$$C = \frac{2\bar{a}\,\bar{V}N^2}{g_e\,S} = \left[\varphi + G\right]_s \qquad \ldots 12$$

or

$$g_e = \frac{2\bar{a}\,\bar{V}N^2}{S[\varphi + G]_s} \qquad \ldots 13$$

and since both φ and G are functions of N^2, g_e does not depend on the number
of aircraft and will be referred to as the "equivalent flow organization
factor. " The numerical value of g_e could be determined by analytical
methods or by simulating a flow through different geometrical configurations
and measuring the average number of expected conflicts[10]. The variables
of g_e are measurable quantities completely independent of the controller
effort.

---

(8) The case of "head-on" conflict is not considered in the system by
     directional stratification of the traffic. Special consideration will be
     given to the case of head-on conflict associated with transitioning traffic.

(9) The speed (V), the flux (F) and the density (d) are interchangable through
     the relation: $F = dV$.

(10) See Appendix II

(9)

(4) The coefficient of the airspace load (k_2) represents (in units of work per aircraft) the work involved by the expectation of, search for, detection and resolution of conflicts and the communications and coordination that are involved in the reorganization of the traffic. In fact, the airspace load represents the effect of the total traffic phenomena on the control position and the airspace load coefficient k_2 transforms the variables of traffic ($\overline{V}$, $V_i - V_j$, D,) the flow organization (g_o, g_e) and the rules of operation ($\overline{a}$) into effort required at the control position.

(5) The airspace load L_2 is directly proportional to the average number of expected conflicts (C). k_2 is a constant provided all classes of expected conflicts are treated equally and require an equal effort at the control position. If, however, different classes of expected conflict impose different load, k_2 is a function of the proportion of the various classes of conflict:

$$k_2 = \frac{1}{100} \sum P_{ci}\ \delta_i \qquad \ldots 14$$

where Pc_i is the percentage of expected number of conflicts of class i and

            δ_i is the work generated by an expected conflict in class i.

In the case of random (isotropic or directional) traffic all expected conflicts are treated equally whereas in the case of airway traffic the value of k_2 can be calculated where:

$$P_{\mathscr{C}} = \frac{100\,\mathscr{C}}{C}\ ;\ P_{\mathscr{G}} = 100\,\frac{\mathscr{G}}{C} \qquad \ldots 15$$

Further refinements of this process might include all transitioning aircraft in intersection and overtake and finally the case of "head-on" conflict of transitioning aircraft with an aircraft flying straight and level.

(6) Equation 7 and consequently equation 12 express the expected number of conflicts in a single altitude layer. The true expression of airspace availability could be determined by summing the expected number of conflicts at each altitude layer where the thickness of the layer is determined by the vertical standard of separation:

$$C = \frac{2\,\bar{a}}{g \circ S} \sum_{i=b}^{t} N_i^2\ \bar{V}_i \qquad \ldots 16$$

where   b and t are the bottom and top altitudes of the sector,

         N_i is the number of aircraft in altitude i and

         $\overline{V}_i$ is the average speed of the traffic at altitude i.

It should be emphasized, however, that equation 16 has a meaning and significance in this context if, and only if, the traffic distribution with altitude, and the speeds associated with this distribution are given. The distribution of traffic by altitude forms a part of the general traffic pattern which is highly repetitive and therefore could be considered as a constant for any particular locality. The speed distribution with altitude is a function of the performance of the aircraft types and actual statistical data indicates that in the enroute environment the distribution of the average speed with altitude forms part of the repetitive nature of the traffic.

The total number of conflicts in the sector could also be expressed as:

$$C = \frac{2\bar{a}}{g_h S} N^2 \bar{\bar{V}} \qquad \dots 17$$

where

N is the total number of aircraft that populate the sector,

$\bar{\bar{V}}$ is the average speed of the total traffic. Equating eq. 16 with 17 and solving for g_h:

$$g_h = g_o \frac{N^2 \bar{\bar{V}}}{\sum_{i=o}^{t} N_i^2 \bar{V}_i} \qquad \dots 18$$

g_h is the "volumetric flow organization factor, " and by substituting its value in equation 8 in place of g_o we get an expression of load (L_2) which is determined by the availability of airspace throughout the altitude limits of the sector:

$$L_2 = \frac{2 k_2 \bar{a} \bar{\bar{V}} N^2}{g_h S} \qquad \dots 19$$

(7) The expansion of the equivalent flow organization factor (g_e) to include the distribution of traffic with altitude and the distribution of speed with altitude is somewhat more involved in airway structure since the expected number of overtakes is a function of the speed distribution, and this differential will change (decrease) with altitude.

Analysis of the effect of speed differential distribution will yield:

$$g_{eh} = \frac{g_h}{g_o} + \frac{\sum_{i=o}^{t} \bar{V}_i N_i^2}{\sum_{i=o}^{t} \frac{\bar{V}_i N_i^2}{(g_e)_i}} \qquad \dots 20$$

where

g_{eh} is the "equivalent volumetric flow organization factor." Obviously when no speed differential is defined[11] the transformation of g_e to g_{eh} will follow the transformation of g_o to g_h. (See eq. 18)

---

(11) Where more than two distinct classes of speed are considered we get $\sum f_i f_j / V_i - V_j /$ where $\sum f_{ij}$ is equal to 1 and $0 < f_{ij} < 1$.

(11)

(D) THE INDUCED LOADS $(L_3 + \ldots + L_n)$. In the previous paragraphs we have discussed the load which develops internally in the ground environment (L_o), the load imposed by any aircraft in the system (L_1) and the load imposed by the interaction between the aircraft in the system (L_2). Some considerations should be given to the class of loads that are imposed on the system through the interaction between sectors. This class of loads will be considered in a general form. No analytical approach has been attempted at this stage of the program. It is assumed that in general these loads will not affect our consideration for sector design. In general, when two sectors A and B are adjacent, a certain load L_n is imposed on A through the activity in B. Basically, this load is a result of a load differential that exists between the two adjoining sectors. Following are two basic examples:

(1) Suppose a radar control sector (A) is adjacent to a non-radar sector (B). Any flow of aircraft between the two sectors will impose much higher load on B (through the increase in the value of separation minima) affecting the handling (sequencing) of aircraft in segment A. This change in the handling of aircraft in sector A will result in an increase of load not accounted for in the routine and airspace loads.

(2) When sector B is heavily loaded any communication from A to B might be delayed (or not answered promptly) resulting in increased activity in the control position of A.

(E) NUMERICAL EXAMPLE.

To illustrate the concepts of control work and control load, consider the following numerical example:

A low altitude radar control sector with a jurisdiction of control between flight levels 050-180. The sector area $S = 2600 \ nm^2$. All traffic is radar controlled. $\bar{a} = 5$ nm per ac. The active aircraft in the sector are divided according to their user and performance classification as follows:

$$
\begin{aligned}
P_o &= 60\% \ \text{airlines} \\
P_1 &= 40\% \ \text{non airline aircraft} \\
P_2 &= 20\% \ \text{handed-off vertically} \\
P_3 &= 50\% \ \text{are handed-off to or from terminal area} \\
P_4 &= 50\% \ \text{are climbing or descending in the sector} \\
P_5 &= \ \ 5\% \ \text{of the aircraft "pop-up" and request IFR clearance.}
\end{aligned}
$$

We will assume the following γ_i values[12]

---

(12) The determination of the numerical values of γ_i is discussed in detail in "MEASUREMENTS."

$\gamma_o = 1.0;$ $\gamma_1 = 1.1;$ $\gamma_2 = 0.25;$ $\gamma_3 = 0.3;$ $\gamma_4 = 0.2;$ $\gamma_5 = 1.1$
(DEW per ac)

The average speed of the total traffic - $\overline{\overline{V}}$ - 188 knots. The average length of an aircraft track = 66 nm. The average time under control 21 min. The flow organization factor $g_o = 1.0$ (random directional flow). The distribution of traffic with altitude and the average speed at each altitude are given in the following table:

Table 1.   Distribution of aircraft in altitude and
average traffic speed $\overline{V}_i$

Altitude	Percentage	$\overline{V}$ (K)
5 - 6	16.88	155
6 - 7	28.53	168
7 - 8	12.01	180
8 - 9	16.66	193
9 - 10	3.69	205
10 - 11	8.38	218
11 - 12	1.13	230
12 - 13	4.96	243
13 - 14	1.13	255
14 - 15	2.72	268
15 - 16	.95	280
16 - 17	.81	293
17 - 18	.64	305

We will assume an average k_2 value of 3.0 DEW per ac.

By substituting the values of P_i and γ_i into eq. 5 we get:

$$k_1 = \frac{60 + 1.1 \times 40 + 0.25 \times 20 + 0.3 \times 50 + 0.2 \times 50 + 1.1 \times 5}{100} = 1.4 \frac{DEW}{ac}$$

and again by substituting the value of k_1 and $\overline{T}$ in eq. 3:

$$L_1 = 1.4 \frac{N}{0.35} = 4N \ DEL$$

The value of g_h is given by eq. 18:

$$g_h = g_o \frac{18800}{2254} = 8.35$$

(13)

substituting the value of g_e in the airspace load eqation (L_2)

$$L_2 = .26 \, N^2 \; DEL$$

The total control load is given by eq. 1.

$$L = Lo + 4N + .26 \, N^2 \; DEL$$

Figure 2 shows (A) the control load as function of the number of aircraft and (B) the distribution of the load during a busy day. Figure 3 shows the cumulative load, in units of work, during a busy day from the beginning to the end of the first watch (8 a.m. to 4 p.m.) and second watch (4 p.m. to 12 midnight).

Figure 2

(A) THE LOAD AS A FUNCTION OF THE NUMBER OF A/C

(B) DISTRIBUTION OF LOAD DURING A BUSY DAY
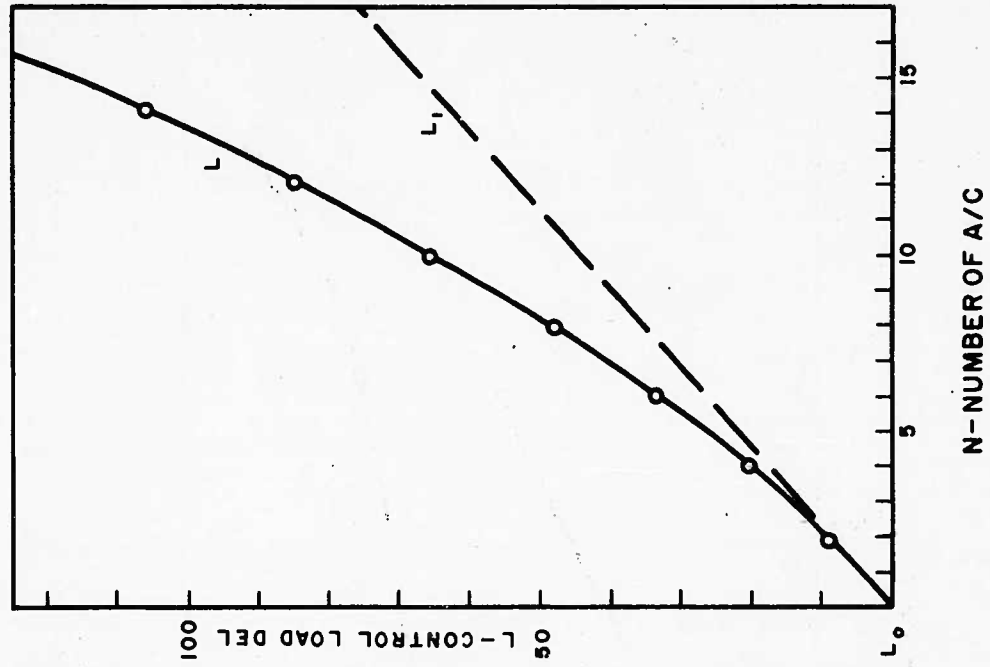
Figure 3

CUMULATIVE LOAD DISTRIBUTION IN A BUSY DAY

(16)
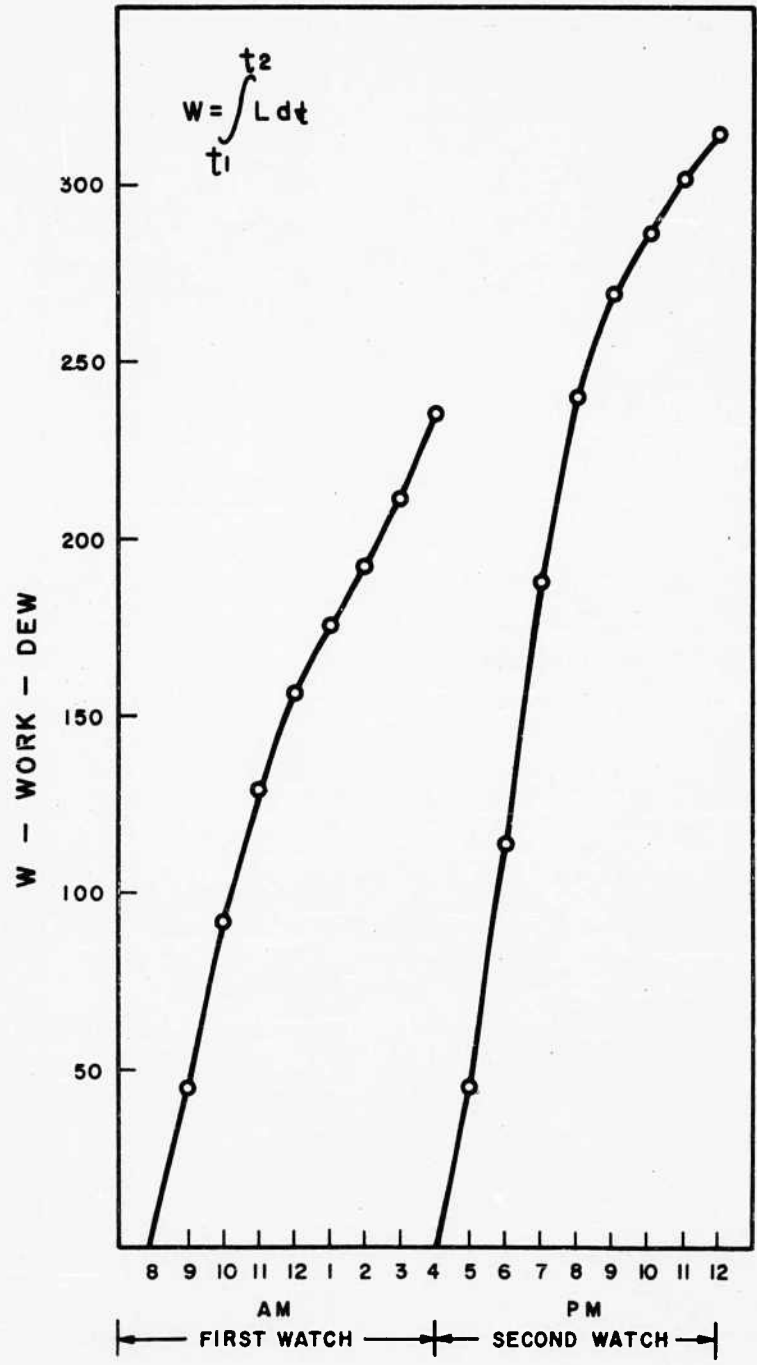
THE THEORY OF SECTOR DESIGN

There is a distinct difference between the routine load L_1 and the airspace load L_2. The airspace load is generated by the total traffic phenomena and basically is a reflection of the desires and intents of the flying public to go from place to place. In fact, the total traffic phenomena, as reflected by the interaction between aircraft (C), is completely independent of the way we select to control traffic. On the other hand, the constraints imposed on the system generate a requirement for a limited size sector and the routine load is, in effect, a quantative expression of load imposed on the control position by the system limitations[12].

(A) Following this line of reasoning we could define the effectiveness of our system as the ratio between the "objective" load imposed by the total traffic phenomena and the total load (L)

$$E = \frac{L_2}{L} \qquad \qquad \ldots 21$$

substituting the expression of L_2 and L we get

$$E = \frac{1}{1 + \left(\frac{k_1}{2k_2}\frac{g_0}{a}\right)\left(\frac{1}{D\bar{s}}\right)} \qquad \qquad \ldots 22$$

where $\quad D = N/S$ and $\bar{s} = \overline{VT}$.

(1) Examining eq. 22 we see that the effectiveness increases with the average track length ($\bar{s}$) for any given aircraft density (D). In other words, the best sector design will be achieved by maximizing the value of $\bar{s}$. This criterion could be considered as necessary and sufficient for optimizing the design of a sector when random (isotropic or directional) traffic is considered.

(2) However, an airway traffic requires additional considerations. Maximizing E_L, by itself, is not sufficient and some other conditions have to be defined and applied. In the following paragraphs the problem of optimizing the sector design is discussed (for a simplified airway structure), and some general conclusions are drawn.

---

(12) Some of the system limitations are discussed later in this paper. The general problem of system limitations is outside the scope of this paper.

SCHEMATIC LAYOUT OF AN INTERSECTION
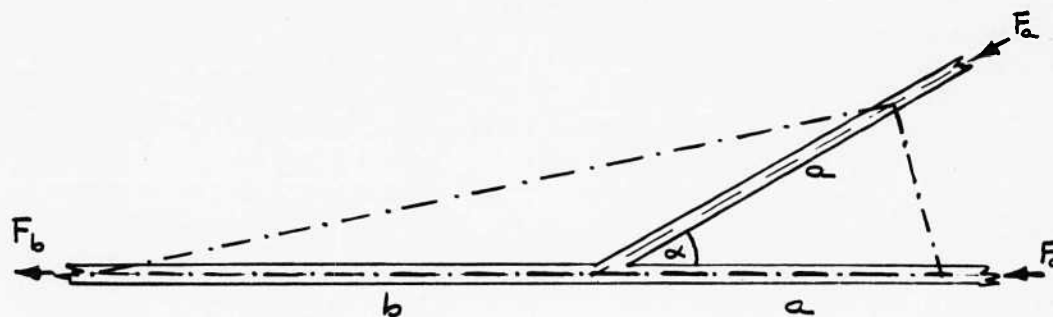
Figure 4

(B) THE PROBLEM

(1) Let us consider a simplified route structure (see Figure 4) and examine the relationship between the load and the geometry of the sector. We define the sector area (S) as the area inscribed by the lines connecting the end of the segments (a, a, and b.).

(2) As a further simplification (without affecting the general principle) we make the following assumptions:

(a) The two segments meet at an intersection and feed aircraft to segment b. The rate of flow (F = ac/hr) is equal at the two "a" segments and therefore any sector design will have two equivalent "a" segments.

(b) The following numerical values have been assigned:

$$\frac{F_a}{V} = 10 \text{ ac/hr.} \qquad\qquad d_a = .05 \text{ ac/nm.}$$
$$V = 200 \text{ knots} \qquad f_1 f_2 \,/V_1 - V_2/ = 12.5 \text{ knots.}$$
$$k_1 = 1 \qquad\qquad\qquad k_2 = 2 \text{ (for any kind of}$$
$$\alpha = 30^\circ \,(\sin\alpha = .5) \qquad\qquad\qquad \text{conflict).}$$
$$\overline{a} = 5 \text{ nm/ac}$$

(3) The problem is how to define the best sector for any given designed load (L_D).

(18)

(C) DISCUSSION

(1) Consider the loads imposed on the sector:

$$L_1 = k_1 \frac{N}{T} = 2k_1 Fa = 20 \text{ DEL} \qquad (1)$$

obviously the routine load will not be affected by the sector design. The routine load is directly proportional to the flux (F) and since the value of the flux is determined by the flow of traffic, and not by the sector design, the value of L_1 is constant.

(2) The average number of expected conflicts in the intersection is a function of the flux or the density (d_a) of the "feeding" segments, the separation minima $(\overline{a})$ and the traffic speed $\overline{V}$. Therefore, the expected number of intersection conflicts (ζ) is a constant not affected by the sector design.

$$I_I = 2k_2 da^2 \, \overline{a} \, \overline{V} = 10 \text{ DEL} \qquad (2)$$

(3) The average number of expected overtakes (ζ_0) is a function of the respective segments length.

$$I_O = 2k_O f_1 f_2 |V_2 - V_1| (2ad_a^2 + bd_b^2) \qquad (3)$$

substituting the numerical values and $d_b = 2d_a = 0.1$ we get:

$$I_O = .3a + .6b$$

(4) The area of the sector is:

$$S = \frac{(a+b)a}{2} \frac{\sin \alpha}{} = \frac{a^2 + ab}{4} \quad (\text{nm})^2 \qquad (4)$$

(4) We will examine the sector design for the following designed load (I_D) levels.

$$I_D = 50, 60, 70, 80 \text{ DEL}$$

Since both the routine load (L_1) and the average number of expected intersection conflicts (ζ) are constants for the given traffic variables, the load generated by the expected number of overtakes will be:

$$I_O = 20, 30, 40 \text{ and } 50 \text{ respectively}$$

where I_O is:

$$I_O = I_D - (L_1 + I_I) \qquad (5)$$

and I_I is the load generated by the average number of expected intersection conflicts.

(5) Substituting I_O = 20 in eq. 3, we get a relationship between segments "a" and "b" and for any given value of "a" we can compute the value of "b" and substituting the segments in eq. 4 we get the corresponding area (see table 2 and Figure 5).

Table 2

a - nm	b - nm	S (nm)^2	S%
0	33.3	0	0
10	28.3	96	8.6
20	23.3	215	19.3
30	18.3	362	32.3
40	13.3	531	47.8
50	8.3	730	65.6
66.7	0	1116	100%

The meaning of the results shown in table 2 is that if our policy was to cover the largest possible area the best sector will consist of the triangle inscribed between the "a" segments.

(6) However, the most efficient sector will be achieved by maximizing the following ratios:

(a) $S/\bar{s}^2$ where $\bar{s}$ is the average track length

(b) $\bar{s}/\Sigma s$ where Σs is the total airway length covered by the sector and

(c) $\dfrac{L_2}{L}$

(1) We will refer to ES = $S/\bar{s}^2$ as the area effectiveness, $E_s = \bar{s}/\Sigma s$ as the airway effectiveness, and to $EL = \dfrac{L_2}{L}$ as the load effectiveness. The total effectiveness of the sector is:

$$E = ES \cdot E_s \cdot EL \qquad \ldots 23$$

where the values of E_s, ES and E_L are normalized to 100% between their minimum and maximum values.

Note: In our specific problem the ratio L_2/L is kept constant and therefore we can consider

$$E = ES \times E_s \qquad \ldots 24$$

(2) Table 3 gives the values of E as a function of the segment "a."

Table 3

a	$\bar{s}$	ES	ES%	$\sum s$	Es	Es%	E
0	33.3	0	0	33.3	1.0	100%	0
10	38.3	.065	26.1	48.3	.795	59	.154
20	43.3	.115	45.8	63.3	.682	36.4	.166
30	48.3	.155	61.7	78.3	.615	23	.142
40	53.3	.187	74.5	93.3	.572	14.4	.107
50	58.3	.215	85.6	108.3	.539	7.8	.0685
66.7	66.7	.250	100%	123.3	.500	0	0

Note the following relationships:

$$\bar{s} = a+b ; \quad \Sigma s = 2a+b$$

(C) CONCLUSIONS

(1) We see from Figure 5 that the value of E reaches its maximum when the segment "a" is 13.3 nm. Substituting this value in eq. (3) and solving for "b":

$$b = \frac{20 \quad .3a}{.6} = 26.6 \text{ nm}$$

(2) It should be noted, however, that the optimal ratio between the segments "a" and "b" is completely independent of the designed load (I_D) and consequently a/b is independent of I_D. (See eq. 5)

(3) The ratio a/b is directly proportional to the line density of each segment: for a given average speed $(\bar{V})$ and speed differential function $f_1 f_2 /V_2 - V_1/$. For any structure of airways we can construct the best (E = max) sector for any given designed load level. Figure 6 shows the boundaries of the sector for the designed load levels of 50, 60, 70 and 80 DEL.

(4) The problem we have just considered was based on a flow of traffic in one altitude layer. It should be noted here that when a full altitude range is considered the expression of I_D should be corrected by a factor of

(21)

$$Q_i = \frac{[f_1 f_2 /v_2 - v_1 / d^2] \ average}{\overset{t}{\underset{i=b}{\Sigma}} [f_1 f_2 /v_2 - v_1 / d^2]_i} \qquad \ldots 25$$

where b and t are the bottom and the top altitude layers under consideration. It is assumed, however, that the value of $(f_1 f_2 / V_2 - V_1 /)$ is a known quantity for any altitude in any given geographical area. This value is in effect an expression of the distribution of the weighted $(f_1 f_2)$ speed differential $(/V_2 - V_1 /)$ with altitude. Since this value is a function of the performance and distribution of aircraft types, it is reasonable to assume that its value is not very sensitive to the locality. In other words, the value of Q_i could be considered in general as a function of the aircraft distribution with altitude. Then,

$$\left(\partial_{eh} \right)_{overtake} = \frac{1}{\overset{t}{\underset{i=b}{\Sigma}} \left(\frac{1}{\partial_e} \right)_i \left(\frac{1}{Q_i} \right)} \qquad \ldots 26$$

where

$$\left(\partial_e \right)_{overtake} = \frac{\overset{m}{\underset{j=1}{\Sigma}} d_j^2 \ s_j}{\bar{d}^2 \ \Sigma \ s} \qquad \ldots 27$$

where   j (=1, 2, 3, .. m) are airway segments having dj density.

Figure 5

NORMALIZED EFFECTIVENESS CURVES
AS A FUNCTION OF SEGMENT "a"

(23)
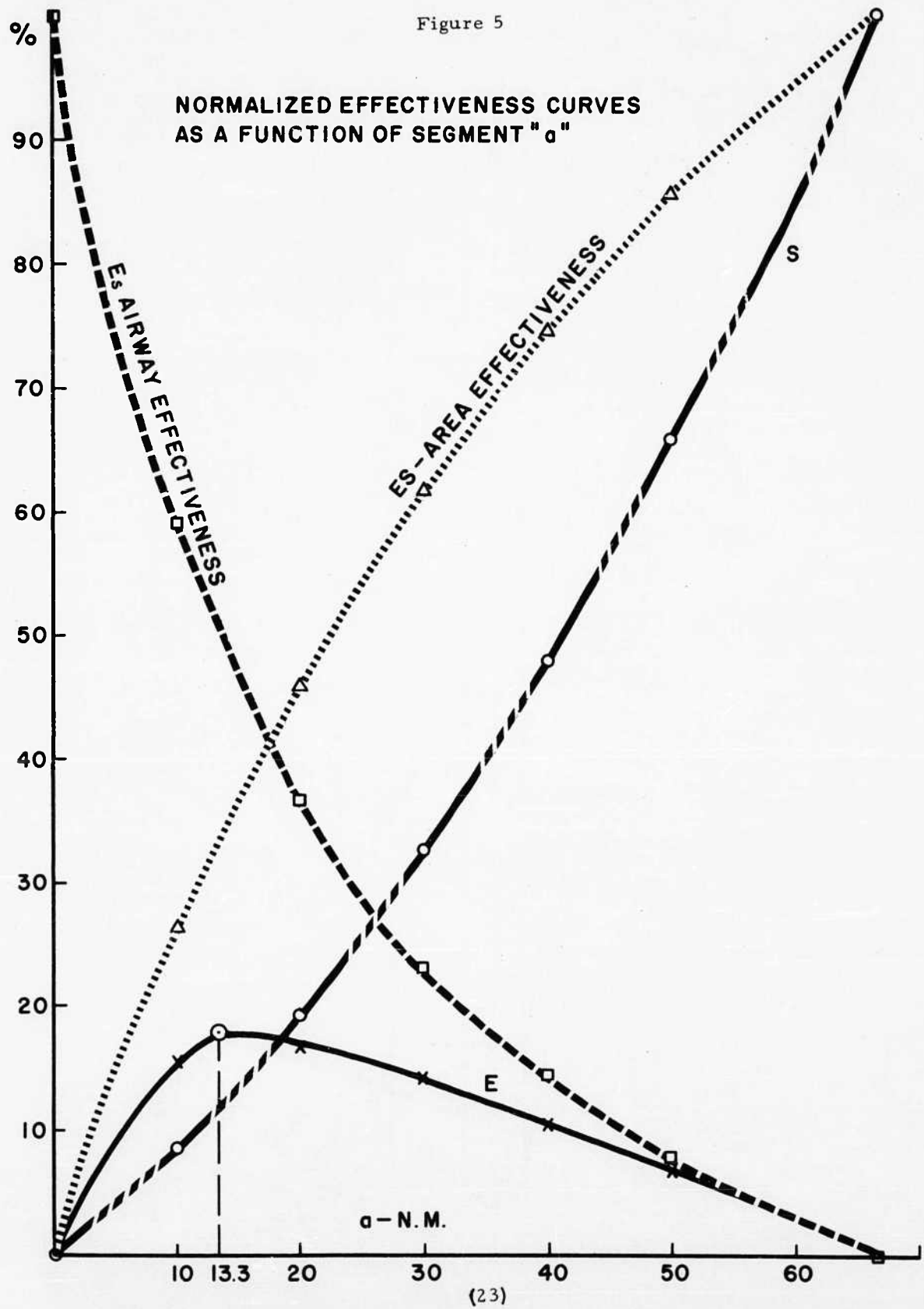
Figure 6
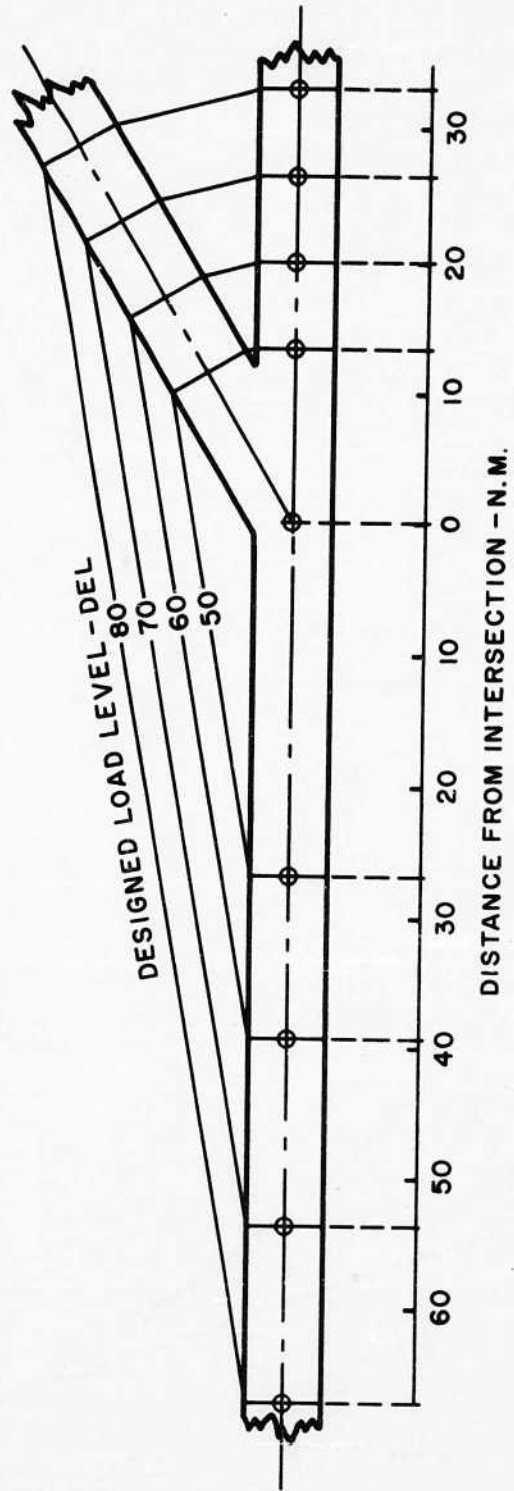
DESIGN OF THE OPTIMUM SECTOR FOR DIFFERENT LOAD LEVELS

DESIGNED LOAD LEVEL – DEL

DISTANCE FROM INTERSECTION – N. M.

THE CONTROL CAPACITY

The capability of an aircraft to penetrate into a controlled airspace with a given level of safety and with minimum discomfort is closely related to the capacity of the control system to handle aircraft. It can be generally stated that for a given level of safety the "degree of discomfort" to air traffic (i.e., delays, change in original intent, etc.) is directly proportional to the load which is imposed on the control system and inversely proportional to its capacity.

On the other hand, any control system designed to handle much higher loads than are actually imposed on it, should be considered as "over designed" and correspondingly inefficient. This thought, translated into planning standards, means that a method should be established that will enable the planner of control systems to design a system in such a manner that

$$\frac{L_D}{C_p} \to 1 \qquad \qquad \dots 28$$

where L_D is the designed load of the control system and Cp is the control capacity. It is assumed that if $L_D/Cp < 1$, the control system will generate delays (discomfort) and if $L_D/Cp > 1$ the system is, by definition, "over designed" and therefore inefficient.

(A) The capacity (Cp) of this system could be defined as the measured capability of the control position to do control work in a given rate. Subsequently, capacity is measured in units of DEW and DEL. In other words, any measured capacity is an expression of the limitation of the control position to handle control loads, or, when integrated between two time limits, could be an expression of the limitation to do control work:

$$C_{p_W} = \int_{t_o}^{t_o} C_{p_L} \, dt \qquad \qquad \dots 29$$

where C_{pw} is the work capacity in the time duration $t - t_o$ and C_{pL} is the load capacity of the system.

Over and above the work and load limitation, we should consider also the willingness of the controller, at the control position, to accept responsibility for the number of aircraft assigned to his jurisdiction. An improved control environment with highly automated control machines might yield considerably improved capacity. Nevertheless, it should be realized that automated control processes do not necessarily affect by the same degree the responsibility that the human controller is willing to undertake. The responsibility that the controller is willing to accept is expressed in terms of a limit on the maximum number of aircraft under control (C_{p_n}).

(25)

(B) Obviously, any improvement in the control environment is aimed towards improved control capacity. This change in the capacity could be expressed numerically as the change in the values of k_1 and k_2. If:

$$k_1 = f(R, Pi) \qquad \ldots 30$$

where R is an ordered set of $)_i$ values. Then the change in the capacity of the system could be expressed as a function of the change in the γ_i values and the change in k_2:

$$\Delta C_p = f(\Delta k_1, \Delta k_2) \qquad \ldots 31$$

(1) In the numerical example given above (see page 13), we have assumed R (1, 1.1, 0.25, 0.3, 0.2, 1.1) and $k_2 = 3$. Implementation of identity and altitude as part of the plan position display might yield:

$$R (0.8, 0.9, 0.1, 0.1, 0.1, 1.0); \quad k_2 = 2.0$$

The new value of k_1 will be 1.02 as compared to 1.4 before. Substituting the new values of k_1 and k_2 in the load equation we get:

$$L = 2.9 N + .17 N^2 \quad DEL$$

The effect of the change in the values of k_1 and k_2 is demonstrated in Figure 7. We can see that the same effort required to control 8 aircraft (50 DEL) in the manual system will be imposed by 10.6 aircraft in the improved environment. Conversely, if the sector was designed for a load of 70 DEL (see Figure 7 (B)), the improved capacity reduces the effort required to 51 DEL (between 6 - 7 p.m.), leaving a difference between the load and the capacity of 19 DEL. Remembering our design criteria ($I_D / C_p \longrightarrow 1$), we can increase the design load in the sector to 70 DEL by increasing the size of the sector in a manner described in the previous chapter.

(2) It should be noted that the change in the capacity is treated as a equivalent to the change in the effort required by the controller to handle a given traffic phenomena. This change in the effort required is due to the effect of the control environment on the value of the traffic features parameters (γ_i) and the coefficient of the airspace load (k_2). However, the basic measurement of the system capacity requires different approach and considerations.

(26)

Figure 7

(A) THE EFFECT OF ΔK_1 AND ΔK_2 ON ΔC_P

(B) THE CHANGE IN THE EFFORT REQUIRED
DUE TO THE CHANGE IN THE CAPACITY
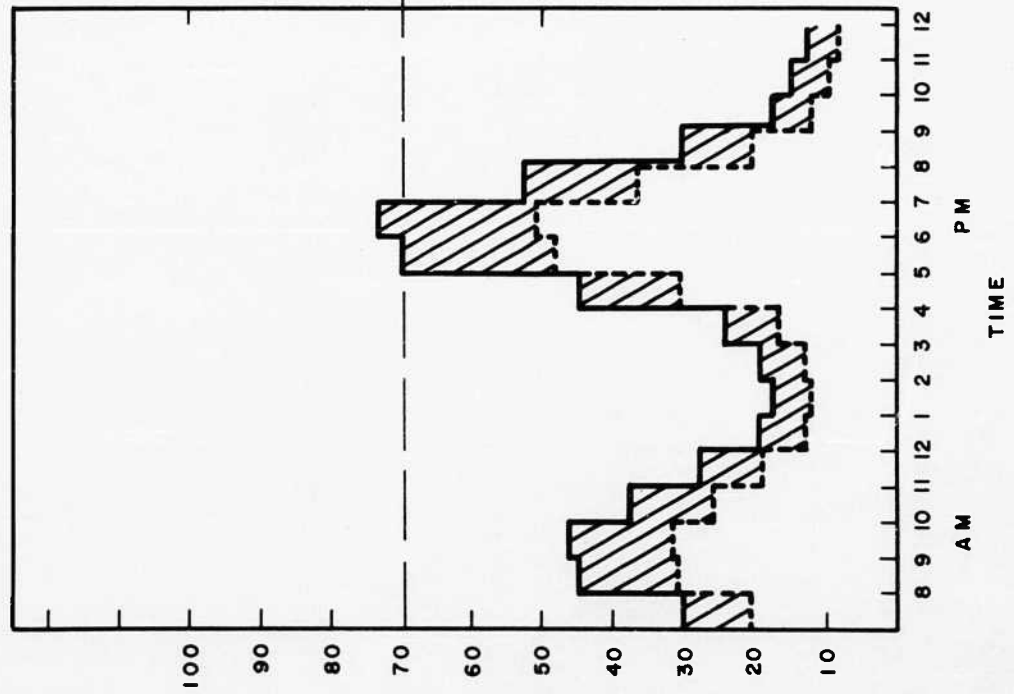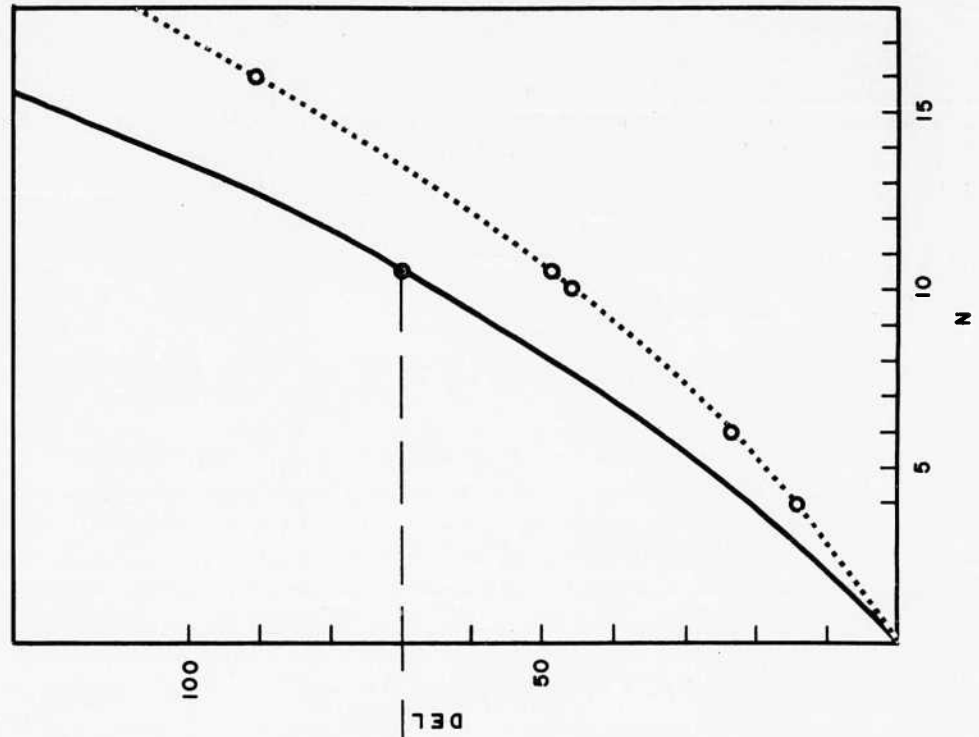
(C) SECTOR DESIGN EFFICIENCY. The peaking characteristics of traffic require a certain amount of judgment and flexibility in the design and manning of sectors. The design criteria is based on balancing the design load with the capacity. However, designing the sector for the peak hour of a busy day might reduce the total efficiency of the sector. If we define the sector design efficiency as:

$$\mu = \frac{\int_{t_o}^{t} \ell \, dt}{\int_{t_o}^{t} c_{p_{\ell}} \, dt} \qquad \qquad \cdots 32$$

we could, by good management, increase the efficiency of our design.

(1) In Figure 8 (A) we can observe the design load exceed the capacity by 15 DEL (6 - 7 p.m.), when operating with two controllers, whereas the rest of the watch operates well above the designed load. If we will reduce the designed load (by reducing the size of the sector) to match the designed capacity or, alternatively, add another controller to the control team, the total design efficiency of the sector (as defined by eq. 32) will be reduced considerably.

(2) On the other hand, if a third controller will be added to the sector between 5:30 and 7:30 p.m., the sector size can be maintained and no appreciable loss in design efficiency is expected.

(3) The same procedure (in reverse) is recommended for the slack hour, when the total load imposed on the control position is very low. By combining two sectors to one control position, the level of design efficiency can be maintained.

Figure 8

(A) THE PEAKING CHARACTER OF THE TRAFFIC IN RELATION TO DIFFERENT LEVELS OF CONTROL CAPACITY

(B) THE DESIGN EFFICIENCY OF THE SECTOR IN RELATION TO DIFFERENT LEVELS OF CUMULATIVE CONTROL CAPACITY

(29)

APPLICATIONS

Subsequent to the validation of the theory and determination of the numerical values, a method can be established for application to sector design for any given level of equipment implementation. Whenever increased capacity is available through implementation of new equipment or systems, the full potential will be exploited only if sector size is adjusted to match the increased latent capacity while maintaining the optimum sector effectiveness (E).

Every element of the NAS Air Traffic Control Subsystem is directly related to decreasing load, increasing capacity, or both. Improvements in communication techniques to provide sector air/ground/air channel coverage to match desired sector configurations and the provision of mosaic displays will free the system from the constraint of a single radar source for the sector display and allow designation of sectors based on the load imposed by the traffic activity balanced with sector capacity.

The addition of alphanumerics depicting identification and altitude of aircraft on the controllers active display will increase the sector capacity by assigning this association task to the machine and freeing the controller from this function.

Through an extension of this model it may be possible to more accurately predict and compare the control loads of existing and proposed route structures.

One of the most significant benefits available would be in the areas of pre-service experimentation and evaluation. The ability to calculate the load and work imposed by the total traffic activity coupled with accepted sector capacity will permit the capacity of specific sector equipment to be determined. As a result, it will be possible to achieve more meaningful quantification of the benefits to be gained by the introduction of proposed equipments, as well as more objective cost-effectiveness assessments.

PART II

STUDIES

MEASUREMENT OF PARAMETERS

(A) INTRODUCTION

Measurement of the parameters in this model is being approached with several things in mind:

(1) This is a first approximation to the evaluation of the model.

As such, extremely sophisticated measurement is neither required nor desired. The intent is rather to obtain quickly a workable model, and then, through testing and application, determine which aspects of it require greater refinement.

(2) It is therefore desirable to keep the time required for data collection and analysis to a minimum. Also dynamic simulation, real time computer simulation, and similar techniques, should be reserved for the validation phases of the study, since, in general, they provide no measures for system elements of the type herein considered.

Since the model considers the various elements of load (background, routine, and airspace loads) as additive and therefore independent of each other, it is possible to evaluate the three terms separately. This is achieved by establishing conditions in which those load terms which are not under consideration are held constant. The traffic parameters contributing to the term which is under consideration can then be varied systematically, and the resulting load evaluated.

(B) METHODS OF ANALYSIS

Our objective is to determine the relationship between our formula parameters (k_1, the routine parameter, and k_2, the airspace parameter) and the variables which contribute to their values. These parameters are load coefficients, measured in DEW per aircraft. The model indicates that they vary with the character of the traffic, but since for design purposes we assume that traffic is repetitive, we can find, for any particular sector, average values for the k's which will be representative of the character of the traffic in that sector.[1]

---

(1) It is well to point out that, in the sense used in this paper, neither work nor load can be measured directly. They are thus intervening variables introduced for convenience to the model, and serve the function of organizing the traffic variables on a scale of measurement which must then be validated

Accordingly, any approach to the measurement of these coefficients must relate them to the features of the traffic. Only in this way will it be possible to obtain values of the coefficients for new or proposed sectors having traffic features different from existing sectors.

Since there are no objective measures of load available, it is necessary to use expert judgements. Such judgements might be obtained in either of two ways:

(1) Direct judgements of the weightings to be assigned to the several traffic variables in determining load, or

(2) Judgements of work or load in a number of known situations, from which the appropriate weightings may then be calculated.

The first alternative draws attention directly to the traffic components which the investigators deem to be of importance. The effect of this may be to bias the judges by persuading them of the importance of features of the system which they might otherwise consider trivial, and vice versa. Consequently it seems better to use the second approach where attention is directed to the total phenomenon rather than to its parts.

Some mention should be made here concerning the nature of the judgement to be made. We have a choice of obtaining judgements of:

(1) The amount of instantaneous load in a situation,

(2) The average load over a period of time, or

(3) The total work to be done.

All three methods are, of course, mathematically related, [2] but may not be of equal difficulty to the judge. Instantaneous load is extremely difficult to evaluate, since subjectively it cannot be divorced from what has led up to the situation and what will develop in the near future. Average load requires a leveling process on the part of the judges, a difficult and unnecessary task since the same thing can be derived from estimates of total work performed so long as we know the duration of the phenomena under consideration.

---

(1) continued

against some operational criterion. See: MacCorquodale and Meehl, P. E., On a distinction between hypothetical constructs and intervening variables, Psychol. Rev., 1948, 55, 95-107.

(2) See Part I - The Control Load. An average value of load may be obtained by dividing total work by the time period over which it accumulated. This, of course, has the effect of ironing out the peaks and valleys of instantaneous load. The latter may be taken into account by designing the system to operate under some agreed upon proportion of maximum peak load, where that load is established over a predetermined interval of (say) an hour.

Because of the size of the scaling effort required, it seemed best to undertake several separate studies. The first of these establishes the scale relationships between the several routine traffic variables. The second will relate this scale to the DEW scale (see Part I) and establish the scale value of a conflict. A third study may be necessary to examine the work involved in various types of conflicts, and a fourth may be required to study induced loads. In addition, methodological consistency experiments will have to be undertaken. Further work may reveal the need for still other studies or experiments as yet unforeseen.

In order to clarify the following discussion, the variables contributing to the total traffic phenomena have been named and classified as in Table 4. Definitions of these will be found in Appendix II.

MEASUREMENT OF THE ROUTINE LOAD PARAMETER

The problem of evaluating k_1, the coefficient of routine load, is one of determining what weights shall be placed upon the several variables which contribute to routine load. For purposes of a first approximation, these variables are each considered to be linearly related to k_1 and to operate independently of each other. That these assumptions may not be strictly correct will become apparent later, but for a first estimate they will provide a useful approach.

We have assumed, then, that k_1 is adequately expressed by equation (5):

$$k_1 = \frac{\sum_{1}^{m} \gamma_i P_i}{100} \qquad \ldots 5$$

where P is the percent of the traffic exhibiting traffic characteristic i (routine load variables) and the γ's are the appropriate weightings for these characteristics. The P's, of course, represent design averages for the particular sector. The problem of determining the value of k_1, then, becomes the problem of finding the appropriate weights (γ's), since the (P_i's) are known values of the routine traffic variables for any given sector. If values of k_1 are obtained for a number of traffic configurations, it will be possible to obtain the γ_i values by any of several methods for solving simultaneous equations. All that is necessary is to obtain at least as many different values of k_1 as there are i's. In order to remove the effect of k_2 from our judgements of work, we must utilize traffic situations in which the interaction effect between the aircraft is constant, and preferably with no conflicts, while varying the routine traffic variables contributing to k_1.

(33)

Table 4

TOTAL TRAFFIC PHENOMENA

1. **Traffic Variables**

   a) N the number of aircraft

   b) $\overline{V}$ the average speed of aircraft in the sector

   c) $V_1 - V_2$ the difference in velocities of overtaking and overtaken aircraft

   d) Q_h)

   e) Q_n)   Traffic distributions   -

   f) Q_v)

                                 (by altitude

                                 (by area

                                 (by velocity

2. **Rules**

   a) $\overline{a}$ separation minimum in nautical miles

3. **Airspace Variables**

   a) S sector area in nautical miles squared

   b) g flow organization factors - all are non-dimensional

       1) g_o flow organization factor - describes the area flow of traffic in a single altitude layer

       2) g_e equivalent flow organization factor - describes the airway flow of traffic in a single altitude layer independently of N

       3) g_h volumetric flow organization factor - describes the area flow of traffic as summated over altitude layers

       4) g_{eh} equivalent volumetric flow organization factor - describes the airway flow of traffic as summated over altitude levels independently of N

4. **Traffic Features (characteristics)**

   a) γ_i routine weights - work per aircraft

   b) P_i routine traffic variables - in percentages of the total traffic

       (0)   standard aircraft (e.g., aircarrier)

       (1)   non-standard aircraft

       (2)   aircraft handed off vertically

       (3)   aircraft handed off to (or from) a terminal area

       (4)   aircraft changing altitude in the sector

       (5)   aircraft requesting admission to the IFR system while in flight (Popups)

5. **Parameters**

   a) k_1 coefficient of routine load - work per aircraft

   b) k_2 coefficient of airspace load - work per aircraft

(A) These routine traffic variables must now be examined. In essence, they are those features of the traffic which are associated with the individual aircraft, but which are independent of aircraft interactions. Five such factors have been identified as probably contributing most to routine load.

P_0. The percentage of the traffic which is standard aircraft.[3]

P_1. The percentage of the traffic which is not standard aircraft $(=100-P_0)$.

P_2. The percentage of the traffic which is handed off vertically.

P_3. The percentage of the traffic which is handed off to or from a terminal area.

P_4. The percentage of the traffic which changes altitude in the sector.

P_5. The percentage of the traffic which requests admission to the I.F.R. system while in flight (Popups).

Other traffic features certainly are present and may contribute to the routine load. For example, military aircraft on special missions may require priority and greatly increase the load. However, at this stage of model development, it seems wise to concentrate upon the five aforementioned features, leaving the others, if they subsequently appear significant, for later refinement. Thus we shall consider the typical airliner, the typical climb, the typical hand-off, etc.

In our model, then, these five routine traffic variables are the determinants of the coefficient of routine load. Our procedure will be:

(1) To construct a number of traffic situations with known values of the five variables, but with constant interaction between the aircraft and no conflicts;

(2) To establish the amount of work generated by each of these situations by one of the conventional psychometric scaling procedures; and

(3) To establish the weights by one of the several methods for solving simultaneous equations. These weights can then be evaluated by applying them to a new set of situations, computing a new series of k_1 values, and correlating these with the judged values of the same set of situations.

---

(3) Standard aircraft = air carrier. For complete explanation, see Part I, Paragraph (3), page 6.

(B) DISPLAY CONSIDERATIONS

The manner of presentation of the traffic situations must now be considered. Of first importance is the validity of the situation. If the routine traffic variables are to be held at known values, the situations must be manufactured, but must not be too far removed from operational reality. For the same experimental reasons we are limited to situations in which there is no controller feedback, i.e., in which the actions of the controller do not alter the development of the traffic problem.

A choice must be made between moving and instantaneous, or "radar snapshot," displays. The former has the advantage of more closely resembling the operational situation, but it is far more difficult to construct, present, and worst of all, to control than is the static presentation. It also placed upon the judge the burden of summating the work over time, a task not easily performed in a real-time simulation.

The second approach, using radar snapshot displays, is easy to prepare and administer. Each display represents the face of a radar scope frozen at a particular instant in time. Thus the display can be printed on ordinary paper with all of the attendant advantages of this method. The development of the traffic situation is not shown; it must be extrapolated in the imagination. The judge extrapolates forward and backward in time, visualizing the amount of work required for all flights across the sector. In this way, the instantaneous displays can all present the same traffic picture, indicating differences only in the intra-sector past or future histories of the aircraft. The judgements of work will then depend solely upon the way the judges visualize the situation rather than upon apparent differences in the immediate displayed situation.

(C) SCALING CONSIDERATIONS

Several psychometric scaling methods are possible to establish values of k_1 for our displays. All of them involve the making of judgements about the displays. In general, for any given amount of time devoted to making such judgements, the higher the reliability of the judgements (repeatability from sample to sample) the more information is sacrificed. Conversely, the more information we extract from the scaling procedure, the less the reliability. A decision must be reached concerning this trade off. In general, since we are dealing with a clearly defined unit of measurement, and since all our load measurements will depend upon that unit of measurement, it seems better to lean toward the side of reliability.

An early trial study was performed using two methods: successive intervals and paired comparisons. These were selected from among the various scaling methods for the ease with which judgements are made, and because of their relative ability to provide equal interval scales in midrange.

Since we desire eventually to express our measurements in terms of
DEW or DEL, it is important to establish an equal interval scale.

A 3 x 5 matrix of routine traffic variables was developed to provide
representation for each of our five traffic parameters at each of 3 levels.

Table 5.   Design Matrix

# of aircraft	z_1	z_2	z_3	z_4	z_5
Level 1	0	0	0	0	0
Level 2	2	1	2	3	1
Level 3	4	3	4	5	2

All possible combinations of this matrix yield 3^5 = 243 possible displays.
The particular values within the table were selected because in the
judgement of experienced radar control personnel they represented
reasonable working ranges of the routine traffic variables. It will be
shown in Appendix IV that they also provide for a test of internal con-
sistency through a simple iterative procedure. These 243 displays
were constructed using a total of ten aircraft on each display. The
instantaneous positions, speeds, headings, and altitudes of the aircraft
were the same on all 243 displays, only the alphanumerics associated
with the attached shrimp boats differed, giving the data for the five
independent (routine traffic) variables. The display showed an enroute
sector adjacent to a terminal area sector. The identified aircraft were
shown, as well as a number of unidentified targets. The airway structure
was simple and no conflicts could occur between the flights as shown.

These 243 displays were given to three controllers who sorted them
on a nine category equal-appearing interval scale. It quickly became
apparent that these judges were not in fact estimating the overall work,
but were rather analyzing the situation by weighting the respective elements,
sometimes even reducing these weightings to pencil notes. Since this
seemed undesirable in that we wished an overall judgement of amount of
work performed, it was decided to construct a paired comparisons pre-
sentation on a portion of the same data.

Twenty of the original 243 displays were selected for this task,
which was administered to 10 controllers. The rank difference correla-
tion between the results of the two methods was +.95 indicating high
correspondence between the methods.

(37)

Since the binary judgement of paired comparisons is much simpler and more rapidly made than the scale evaluation required by successive (or equal appearing) intervals, thereby helping to reduce the tendency toward fixed weightings imposed by the latter method, it was decided to utilize paired comparisons in our main study. It was also decided to reduce the number of aircraft from ten to six, thereby further simplifying the required judgements.

(D) PROCEDURE

Displays were prepared based upon Table 5, using but six aircraft. Of the 243 possible displays, only those were used in which the sum of the levels across the five variables equaled eight. Thus each display held three of the variables at level one, one at level two, and one at level three. This yielded the 20 displays which are summarized in Table 6.

These particular displays were selected because the method of paired comparisons depends upon a division of opinion between judges; where all judges are in all instances agreed upon an item, that item cannot be scaled. By balancing the levels in this manner, we eliminate very extreme cases in which high agreement among the judges might be expected. (See also Appendix IV.)

These displays were prepared on 8" x 10-1/2" paper for a paired comparisons presentation. They were enclosed in clear plastic folders and mounted in 3-ring loose leaf notebooks in such a way that each turn of a page brought up a new comparison. This yielded $n(n-1)/2 = 190$ comparisons. The order of the pairs was randomized, and the individual displays appeared equally often on left and right to balance position preferences. Temporal bias was controlled by administering the pairs in four different orders, 1/4 of the S's following each order. The four orders were: a) 1-90, 91-190; b) 91-190, 1-90; c) 90-1, 190-91; d) 190-91, 90-1. Administration time, including explanation and instructions, was approximately 90 minutes. A five minute oral presentation served to explain the purpose of the study and to arouse interest. This was followed by detailed written instructions designed to keep additional verbal explanation to a minimum. The instructions, answer sheet, and a sample comparison pair are shown in Appendix III.

Table 6

k_1 Data Coding and Reduction

Display No. and Letter	Code No. (Level-1)					Assignment (No. of Aircraft-Z)					Assignment (% of Traffic-P)				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1 (c)	1	1	2	1	3	0	0	2	0	2	0	0	33	0	33
2 (i)	1	2	3	1	1	0	1	4	0	0	0	17	67	0	0
3 (f)	1	1	3	2	1	0	0	4	3	0	0	0	67	50	0
4 (m)	2	1	1	1	3	2	0	0	0	2	33	0	0	0	33
5 (j)	1	3	1	1	2	0	3	0	0	1	0	50	0	0	17
6 (a)	1	1	1	2	3	0	0	0	3	2	0	0	0	50	33
7 (e)	1	1	3	1	2	0	0	4	0	1	0	0	67	0	17
8 (h)	1	2	1	3	1	0	1	0	5	0	0	17	0	83	0
9 (s)	3	1	2	1	1	4	0	2	0	0	67	0	33	0	0
10 (q)	3	1	1	1	2	4	0	0	0	1	67	0	0	0	17
11 (n)	2	1	1	3	1	2	0	0	5	0	33	0	0	83	0
12 (r)	3	1	1	2	1	4	0	0	3	0	67	0	0	50	0
13 (g)	1	2	1	1	3	0	1	0	0	2	0	17	0	0	33
14 (b)	1	1	1	3	2	0	0	0	5	1	0	0	0	83	17
15 (d)	1	1	2	3	1	0	0	2	5	0	0	0	33	83	0
16 (t)	3	2	1	1	1	4	1	0	0	0	67	17	0	0	0
17 (o)	2	1	3	1	1	2	0	4	0	0	33	0	67	0	0
18 (k)	1	3	1	2	1	0	3	0	3	0	0	50	0	50	0
19 (p)	2	3	1	1	1	2	3	0	0	0	33	50	0	0	0
20 (l)	1	3	2	1	1	0	3	2	0	0	0	50	33	0	0

(39)

This paired comparisons study, after satisfactory try-out with NAFEC controllers, was taken to the field, where it was administered to 179 controllers in 13 ARTCC's.

From these data a paired comparison analysis was performed to obtain the scale values of the 20 displays. Thurstone's Case 5, as outlined by Green[4], rather than one of the more rigorous methods, was used for the data reduction since internal checks (to be described subsequently) were available to confirm the method and refine its results. Actual details of the analysis are given in Appendix IV.

The scale values obtained by this method are shown in the first column of Table 7. These scale values are proportional to the standard deviation of the combined difference distribution (assuming all the difference distributions have the same dispersion). The important point to note is that the scale units are presumably equal, and proportional to our DEW units.

(A) CONSTANCY OF UNITS

The equality of the unit size is the first consideration in developing our scale of measurement. It should be noted that for our stimulus objects (the individual displays) the exact values of the variables contributing to total work are known and measurable in terms of percentages of the traffic. In other words, we know the number of aircraft which are commercial airline, the number of aircraft which are changing altitude, the number of popups, etc. These numbers have already been shown in Table 5. The model requires that each of these be linearly related to the total work (that two popups, for example, are twice as much work as one popup, at least within normal working ranges) and that the non-linear increase in work as a function of number of aircraft is entirely due to the interactions between aircraft.

This fact enables us to obtain a series of internal consistency checks for our scale values as follows. If the units of our scale are indeed equal, one should be able to add and subtract them with impunity, this being a characteristic of interval scales generally. It is possible, by appropriate additions and subtractions of selected display scale values, to compute the scale values for any other displays on the scale, thereby confirming their scale values. For example, let us look at display h. This display shows:

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(4) Green, Bert F., "Attitude Measurement". In: Lindzey, Gardner (Ed.), Handbook of Social Psychology. Cambridge, Mass.: Addison-Wesley, 1954

Table 7

Display Scale Values - σ Units

	1. Raw Values	2. Observed Values	3. Calculated from i's
A	-0.113	3.069	2.461
B	0.476	2.480	1.857
C	0.0	2.956	2.484
D	1.019	1.937	1.455
E	0.446	2.510	2.082
F	0.929	2.027	1.657
G	0.528	2.428	2.113
H	1.489	1.467	1.084
I	1.262	1.694	1.309
J	1.043	1.913	1.529
K	1.468	1.488	1.104
L	1.444	1.512	1.127
M	0.726	2.230	2.008
N	1.604	1.352	0.979
O	1.368	1.588	1.204
P	2.167	0.789	0.651
Q	1.748	1.208	1.130
R	2.238	0.718	0.705
S	2.237	0.719	0.728
T	2.956	0.0	0.357

Correlation between observed and calculated values: $r = +0.98$

(41)

0 Non-airliners
1 Vertical Handoff
0 Terminal Area Handoffs
5 Aircraft Changing Altitude
0 Popups

The scale values of display h (prior to certain adjustments yet to be explained) is 1.489.

The same combination of traffic variables can be obtained by adding and subtracting the scale values of certain other displays, for example $n + g - m = h$. For our five routine traffic variables this would appear as follows:

	n	2, 0, 0, 5, 0	6	aircraft	scale value	=	1.604
+	g	0, 1, 0, 0, 2	6	"			0.528
=	n+g	2, 1, 0, 5, 2	12	"			2.132
-	m	2, 0, 0, 0, 2	6	"			0.726
h =	n+g-m	0, 1, 0, 5, 0	6	"			1.406

The scale value of this display can be similarly computed in five additional ways, yielding a series of checks upon the original observed value. Thus we are able to examine the linearity of the scale. The rationale and results of this procedure are more fully treated in Appendix IV.

The raw scale values were inverted in order to give the highest value to the display which was most difficult. At the same time, the entire scale was shifted so that the arbitrary zero point was placed at the easiest display, i.e., the display involving the least amount of work.

The results of these adjustments are shown in the second column of Table 7.

(B) SCALE RELATIONSHIPS

The hypothetical relationships between the values of our adjusted sigma scale and the DEW scale are seen in Figure 9. The scale positions of three of the displays (t, h, and i) are shown in this figure. The position of t is the zero of our sigma scale, while the indicated zero is the zero of the DEW scale.

Table 8 below the figure shows the manner in which the DEW value would be computed for nine of the displays. These nine were selected because they lie within $1/2 \sigma$ of the mean of the distribution, and hence are expected to represent the more reliable values.

(42)

It will be noted that the method does not yield DEW values. These must be provided by our second study which will tie the present sigma scale to the DEW scale. The two scales are related by the equation $\sigma = \text{DEW } \mu$

The γ_i values were computed from the "observed" values in column 2 of Table 7 using those six nearest the mean of the distribution. The values thus obtained are shown in Table 9. It must be remembered that these weights in fact represent the work per aircraft for each aircraft performing in the designated manner (i). From these values, it is possible to compute the amount of work involved in each of our displays. These calculated values are shown in the third column of Table 7 and have been shown plotted against the observed position in Figure 10. The plot clearly shows the constant scale distance of 0.385σ between the position of display $R(0,0,0,0,0)$ and the arbitrary zero of our scale. It also shows the reliability of our displays throughout the substitution process. This reliability is further supported by the correlation between our observed and calculated display values of $+0.98$ (see Table 7).

Table 9

Routine Weights - Work per Aircraft

$$\gamma_0 = 1.000 \, \mu$$
$$\gamma_1 = 1 + 0.042 \, \mu$$
$$\gamma_2 = +0.189 \, \mu$$
$$\gamma_3 = +0.280 \, \mu$$
$$\gamma_4 = +0.179 \, \mu$$
$$\gamma_5 = +0.962 \, \mu$$

Where γ_i is the work per aircraft classified and behaving in an i manner (see Equation 5) and

$$\mu = \frac{\sigma}{\text{DEW}}$$

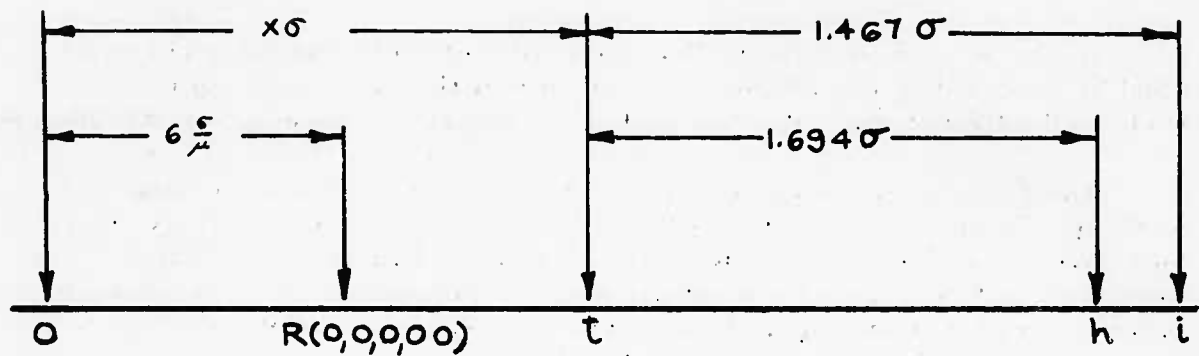Note: For details of data reduction see Appendix IV.

FIG. 9

RELATIONSHIP BETWEEN DISPLAY, σ POSITION AND DEW VALUE

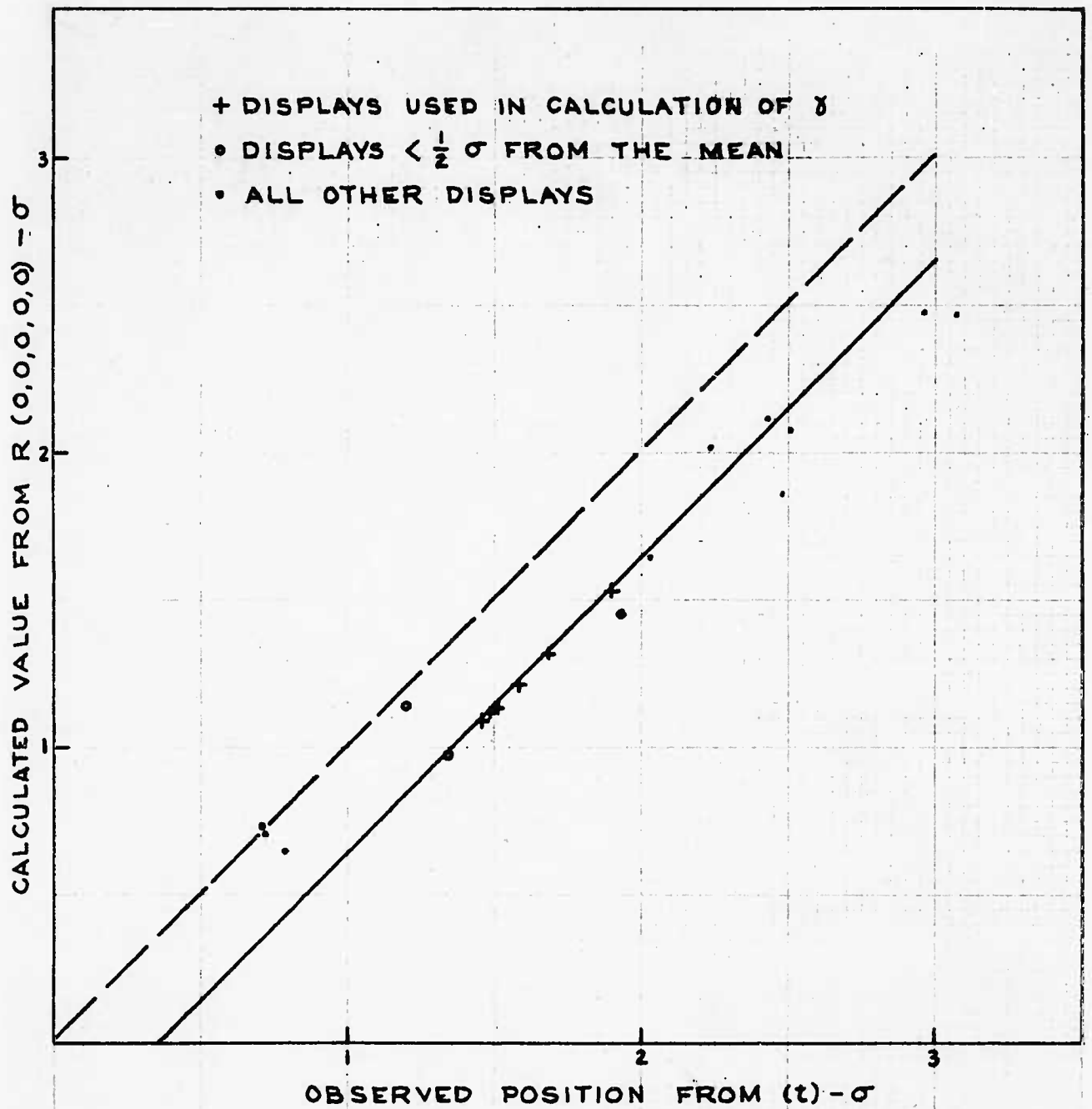| DISPLAY		POSITION	DEW VALUE VS POSITION				
CODE	Z_1, Z_2, Z_3, Z_4, Z_5		1	2	3	4	5
h	0 1 0 5 0	1.467	6	$+\gamma_2$		$+\gamma_4$	$= (1.467 - X)\mu$
i	0 1 4 0 0	1.694	6	$+\gamma_2$	$+\gamma_3$		$= (1.694 - X)\mu$
j	0 3 0 0 1	1.913	6	$+3\gamma_2$			$+\gamma_5 = (1.913 - X)\mu$
k	0 3 0 3 0	1.488	6	$+3\gamma_2$		$+3\gamma_4$	$= (1.488 - X)\mu$
ℓ	0 3 2 0 0	1.512	6	$+3\gamma_2$	$+2\gamma_3$		$= (1.512 - X)\mu$
n	2 0 0 5 0	1.352	$4 + 2\gamma_1$			$+5\gamma_4$	$= (1.352 - X)\mu$
o	2 0 4 0 0	1.588	$4 + 2\gamma_1$		$+4\gamma_3$		$= (1.588 - X)\mu$
d	0 0 2 5 0	1.937	6		$+2\gamma_3$	$+5\gamma_4$	$= (1.937 - X)\mu$
q	4 0 0 0 1	1.208	$2 + 4\gamma_1$				$+\gamma_5 = (1.208 - X)\mu$

TABLE 8

(44)

Fig. 10   Comparison Between Observed Position and
Calculated Value

(45)

PART III

CONCLUSIONS AND PLANS

MEASUREMENT OF THE AIRSPACE LOAD PARAMETER

Measurement of the airspace load parameter (k_2) will be approached in much the same fashion as was the case with the routine load parameter (k_1). A psychometric study involving the scaling of displays in which conflicts and conflict search as well as the routine load variables will be used. By selecting appropriate routine load variables, and including displays both with and without actual conflicts we can establish the relationship between the k_1 and k_2 scale units and the absolute value of γ_i in DEW per aircraft units.

Since L_o is not a factor in sector design, the work involved in any display in which actual conflict (C_a) occurs can be observed and scaled. If the assumption that k_2 is independent of N and hence of C is correct then the scaling of the displays will obey (within our limits of measurement) linear relationship between the total work and the number of actual conflicts (C_a) for any given number of aircraft and k_1 value.

It must be noted that in this exercise C_a and N are being treated as independent of each other in order to show how W varies as a function of C_a. In our model, however, C is a function of N^2 (see Equation 7), and the true relationship between the load and the number of aircraft is curvilinear.

MEASUREMENT OF THE EQUIVALENT FLOW ORGANIZATION FACTOR g_e

One variable of the total traffic phenomena which cannot be directly measured in the airspace is the equivalent flow organization factor (g_e). The value of g_e is by definition independent of the traffic density and speed. It is a non dimensional number relating the traffic density and speed to the average number of expected conflicts through the geometry of the flow.

Two distinct cases should be considered:

(1) The conflicts developed in an intersection of two (or more) airways.

(2) The conflicts developed along an airway through the speed differential of the traffic.

The two cases will be treated separately.

(A) THE INTERSECTION CONFLICT

A computer program for fast time simulation is being developed to facilitate counting the average number of conflicts that develop in an intersection where the densities of traffic (en each airway), the average speed of the traffic, and the geometry of the intersection are varied. The aircraft arrivals at the intersection will be in accordance with the Poisson distribution and at each small interval of real time (Δt) the (x, y) position of each aircraft is determined and the distance

$$R = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

is calculated, where (x_1, y_1) is the position of an aircraft A_1 in airway No. 1 and (x_2, y_2) is the position of an aircraft A_2 in an airway No. 2. If $R < \overline{a}$ then the two aircraft are considered in conflict. It is expected that the average number of actual conflicts will depend on the product of the average line densities, the average speed of the traffic ($\overline{V}$) and the intersection angle (α).

The final product of this measurement is a set of graphs that will enable us for any angle of intersection to determine the average number of conflicts (C/2) that occur in one hour as a function of the product of the two line densities and the average traffic speed (see Figure 12).

(B) THE OVERTAKE CONFLICT

The number of overtakes in conflicts will also be determined by fast time simulation as a function of the weighted speed differential (see equation 3, page 19) and the traffic density (see Figure 13). The average number of aircraft in conflict will be determined for a measured airway segment length (100 nautical miles) for a set period of time (1 hour) and a constant regime of traffic arrival distribution and the weighted traffic speed differential $f_1 f_2 \left| \overline{V}_1 - \overline{V}_2 \right|$. The case where more than two distinct traffic speeds are considered will be treated analytically.

(C) With the aid of these results any geometry of airway structure can be examined and the total number of conflicts can be determined for the total area. By substitution, the value of g_e can then be determined for the particular area (see equation 13).

(47)
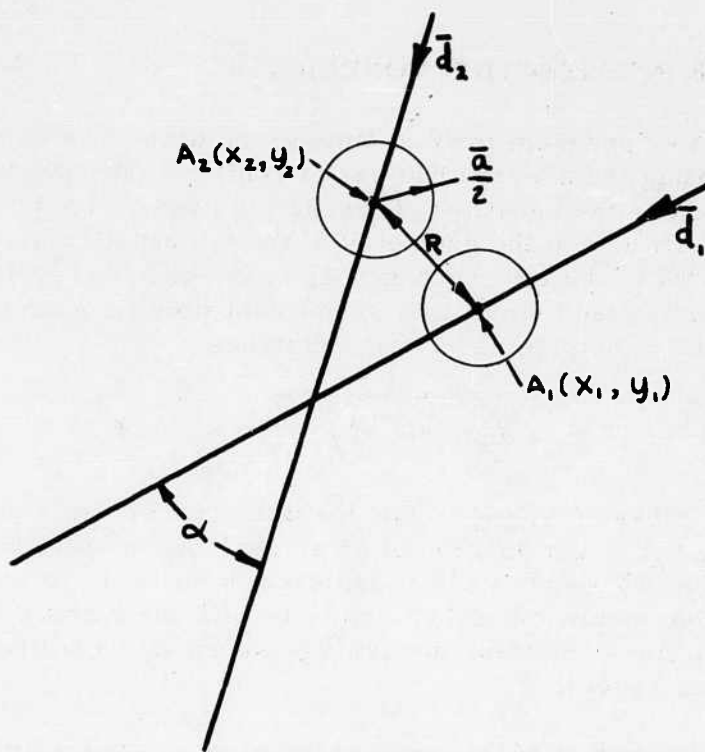
I SCHEMATIC DIAGRAM OF AN INTERSECTION CONFLICT DEVELOPMENT
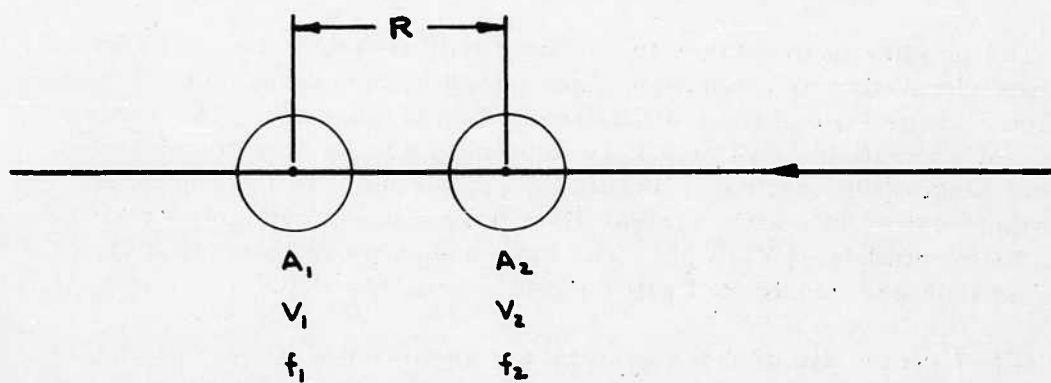
II SCHEMATIC DIAGRAM OF AN OVERTAKE DEVELOPMENT

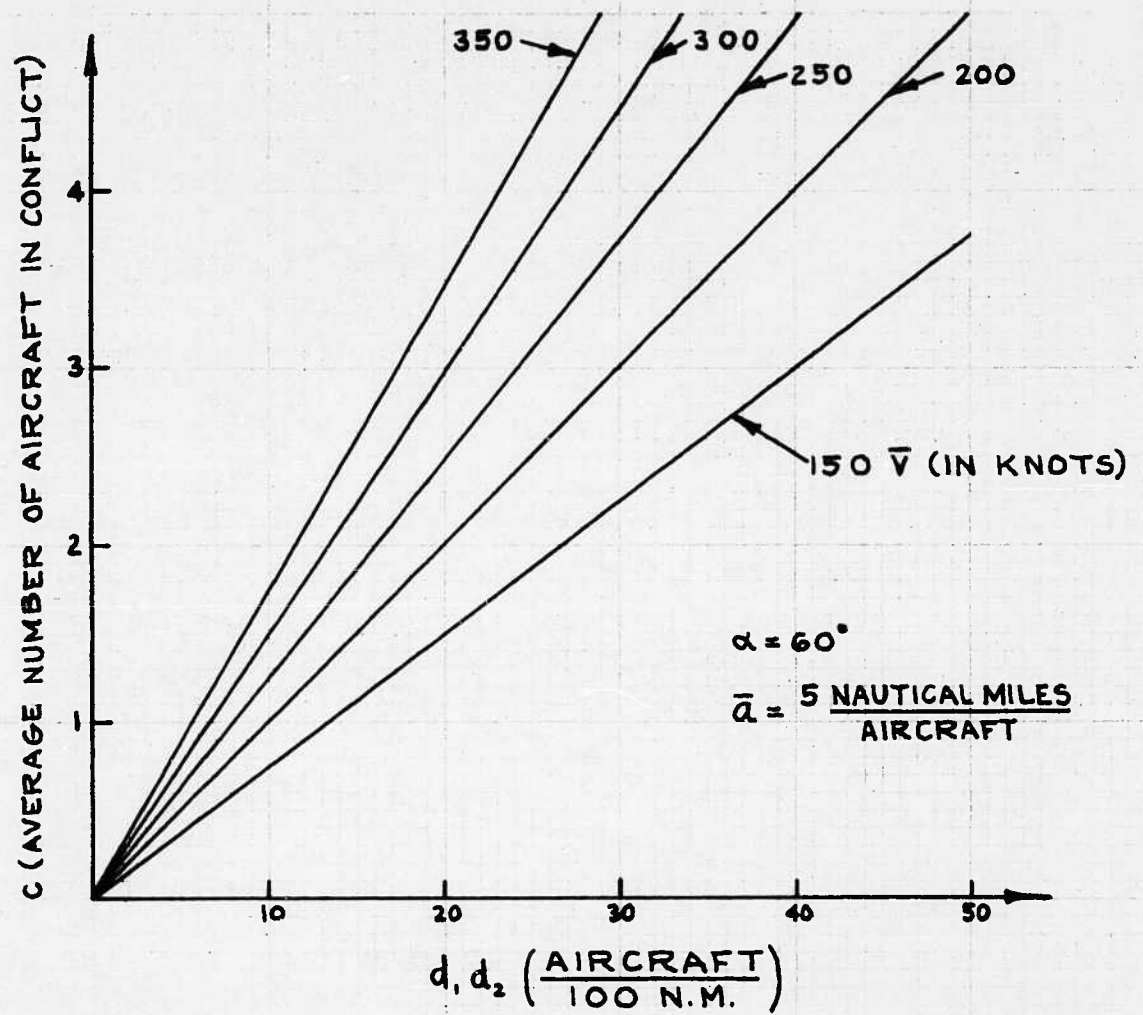Fig. 11   Schematic Development of
a Conflict

(48)

FIG. 12 DETERMINATION OF THE AVERAGE
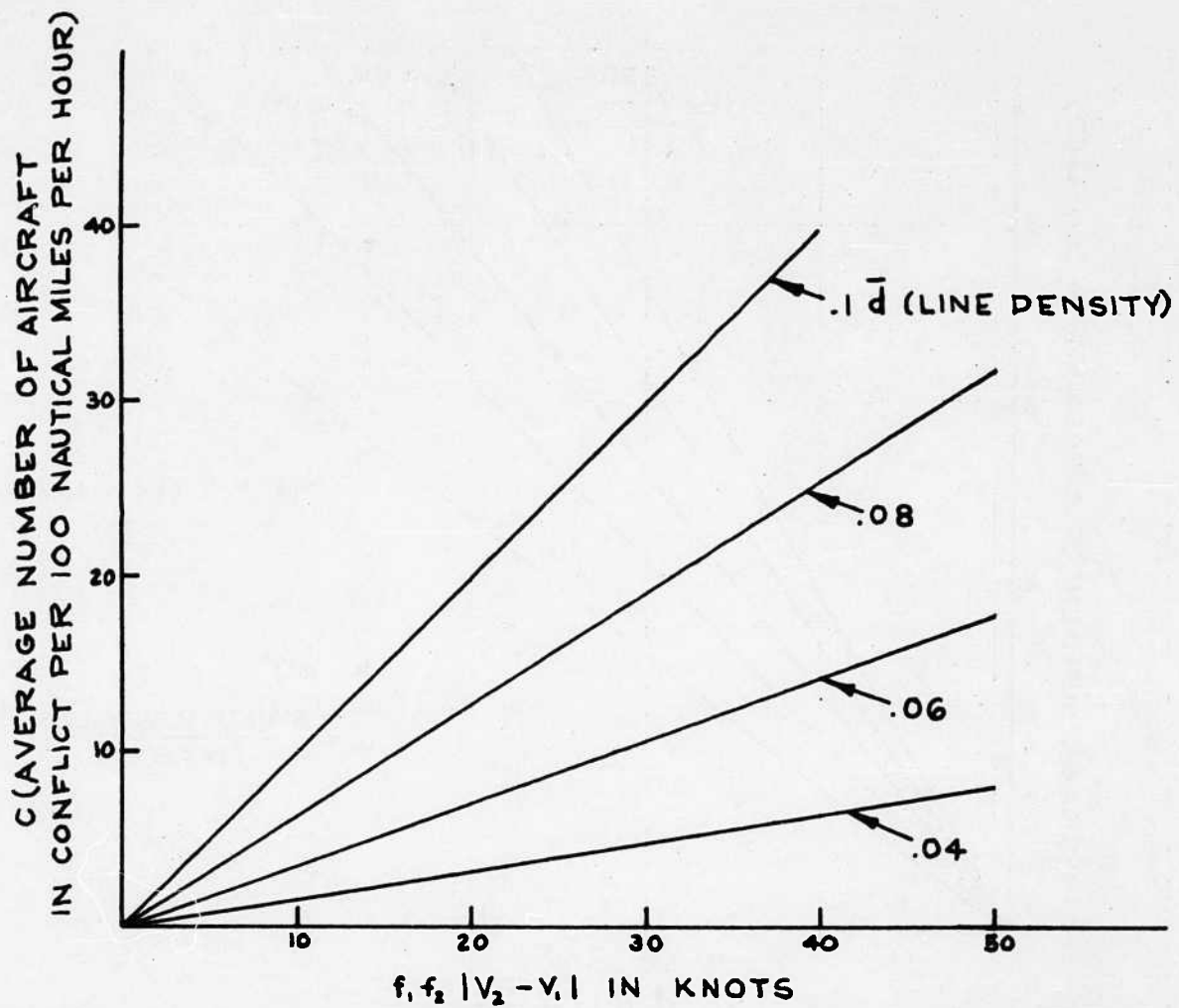NUMBER OF INTERSECTION CONFLICTS

FIG. 13 DETERMINATION OF THE AVERAGE NUMBER OF EXPECTED OVERTAKES.

CONCLUSIONS

Basically, the control load model attempts to explain in a rational way the phenomena of load as it is really experienced and observed by the operating personnel in the operating environment. The existing measures of load and manning planning standards do not explain the discrepancy that exists between the naive "traffic count"[1] and the experience of the operating personnel that are continuously subjected to the control load. This gap between the present criteria and the true load experience is further manifested in the maps shown in Appendix I where it is evident that no relationship exists between the "traffic count" and the sector size, shape and orientation. There are two possible explanations of this fact:

> (1) If the present "traffic count" criterion is correct then the actual load experienced varies considerably from one sector to another. Or,

> (2) If the experience of the field facilities differs considerably from the established criterion of traffic count, the actual method of sectorization does not follow the present count criterion but rather follows unspecified rules of trial and error based on the observation and experience of the field facilities.

In other words, a final test of the control load equation is its ability to explain in a rational way the experience and observation of the operating personnel. This means that no "absolute" proof is attainable and the scope of the model is limited by the sensitivity of the experience and observation of the operating personnel. The validity of the model will be determined by its ability to explain rationally and in each particular instance, the observed experience of the operating personnel.

In this context, the choice of psychometric techniques of measurements should be considered not as a method used in lack of any other method but rather as a fairly accurate quantification of the observation and experience of the operating personnel. The accuracy of this quantification is the limiting accuracy of the model in a sense that any additional accuracy is in effect meaningless in this realm.

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(1) In the sense of planning standard number 5 "traffic count" is equal to "2 times departures + overs"

The mathematical model, as such, does not specify any limits
to the load equation. Nevertheless it should be noted that our interest
lies within practical prescribed limits of traffic activity. The treat-
ment of very low traffic activity is of very little interest to us since the
loads imposed are below our sensitivity. On the other hand, very high
traffic activity, well beyond the control capacity of the sector might
generate additional and very complex load components unaccounted for
in the present control load equation. In particular, it is reasonable to
assume that some of the linear assumptions in the determination of k_1
(and k_2) will not hold true for very high traffic activity. However, this
is left for future development when and if the requirement to control
simultaneously 20-30 aircraft arises and we are able to observe the
effect of these high traffic activities on the control position. In the
following paragraphs the program to verify the basic model will be
explained in detail.

THE MEASUREMENT OF TRAFFIC

Before commencing any calculations of loads and sector design in
the real world environment special exercises will be conducted in order
to determine the required level of detail and fineness of real traffic
measurement. It should be noted that the traffic model is sensitive to
many variables (see Table 1) and change in any of the variables may
affect the total load calculations. On the other hand detailed and accurate
measurement might yield results appearing to have an order of accuracy
which is higher than the total validity of the model.

In addition, a simple method of traffic measurement should be devised
in a set format and in such a way that field personnel will be able to con-
duct measurements and apply them for the determination of load levels
and sector design. A special exercise is being planned where actual
measurements of the total traffic phenomena will be conducted in several
field facilities and finally a method of measurement will be established
for manual centers and computer equipped centers.

In particular, the problem of traffic speed distribution and weighted
traffic speed differential with altitude should be closely investigated in
order to determine the sensitivity of these measures to the locality. A
graphical method of data presentation should be established for the use
of the planning personnel in the field facilities.

The collected data of these exercises will be used in the real time
simulation and demonstration of the theory.

(52)

BRIEFING OF FIELD PERSONNEL

After the value of k_2 has been determined and a method for traffic measurement has been established, it is recommended that the method be presented to a selected group of planning officers in the field facilities. This presentation should be in a form of a 2-3 days seminar where the theory and its application will be explained and several complete exercises of traffic measurement, load calculation, and sector design will be conducted. This presentation will enable the field personnel to examine more closely the theory and its applications in the light of their experience.

FIELD MANUAL

As a final effort in the development of the theory and its application in the operating environment a field manual should be prepared that will treat the whole subject of traffic measurement, load calculations, and sector design from a practical point of view in order to enable field personnel to study the subject and apply it in their environment with discrimination. It is not suggested that this project include as one of its tasks a writing of an agency field manual, but rather that is should prepare the basic technical material that will be required for such a manual, if at any time the agency desires to implement this method. Undoubtedly the short seminar recommended above will give the project team the necessary clues for the preparation of this manual.

VALIDATION

The validation of the method of control load and sector design poses a serious problem. It should be noted that the sensitivity of the mathematical model is higher than any known independent judgment or measurement and therefore it will be difficult to validate the theory and the design method by independent measurement. On the other hand, if the method developed in this report is valid, it should be noted that a test of the model is possible in all real world instances where there exists an unexplained discrepancy between the aircraft count (as practiced today) and the load as experienced by the operating personnel in field facilities. We will try to use this fact in order to design a gross validation exercise of the theory.

Consider a given ARTCC where complete measurement exercises have been conducted in several of its sectors. We could determine the

load experienced during the busy hour of the busy watch and independently obtain a scale judgment regarding these sectors from supervisory personnel of the facility, provided they are familiar with all the sectors under consideration and can scale them in accordance with their gross operational experience in this environment.

In particular we are interested in all those sectors for which there is a discrepancy between the traffic count and the observed load. For instance, assume in a given facility four sectors have been measured and the load determined (see Table 10).

Table 10

Example of Sector Load Ranking

Sector	Traffic Count	Calculated Load	Ranking		By Traffic Count
			Load		
			Calc.	Obs.	
A	8	60	3	3	3
B	12	50	4	4	1
C	10	100	1	1	2
D	10	80	2	2	2

Very interesting information can be derived from the comparison of the calculated and the observed rankings. Sector B has the highest traffic count and yet both the observed and the calculated load agree on its lowest ranking. Sector C and D have equal traffic counts, yet both the observed and the calculated rankings agree that sector C imposes higher loads than Sector D. It is assumed that if enough samples of this nature can be determined and ranked by key operating personnel in the field facilities, a gross validation of the theory can be achieved. It is expected that the theory will explain rationally the real world phenomena and the observed experience.

DEMONSTRATION

The theory of sector design, unlike the basic load model, does not require special validation since it is based on the load equation and basic decisions concerning the optimization of the design (see equation 28). In other words, if the basic load model is verified, the theory of sector design will totally rely on this verification and does not require any independent test. On the other hand the theory and the proposed method of sector design needs demonstration in order to emphasize the importance of proper design procedures in any ATC environment.

After the validation of the model a field facility will be selected and by application of the theory and proposed method of sector design the facility will be resectorized. Using the same traffic, the resectorization will be tested in real time simulation against the present sectorization. Various measures will be conducted in order to demonstrate qualitatively (and if possible quantitatively) the gross results obtained by applying the method of sector design.

In particular the following measures will be conducted:

(1) Total time of delay
(2) Number of altitude and track changes
(3) Communication count
(4) Flight strip production

An improvement in these items (which is readily measurable) will be considered as a good demonstration of the method and an additional validation of the method.

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(4) Activity Analysis of Position in High Activity ARTCC; Prepared by
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    June 1962

(Part II)

(1) Green, Bert F., "Attitude Measurement". In: Lindzey, Gardner (Ed.)
    Handbook of Social Psychology. Cambridge, Mass.: Addison-Wesley,
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(2) MacCorquodale, K. and Meehl, P. E., On a distinction between
    hypothetical constructs and intervening variables, Psychol. Rev.,
    1948, 55, 95-107

APPENDICES

Table I-1

SECTOR STATISTICS

	TODAY	NAS GOALS
LOW ALTITUDE SECTORS	300	LOWER
HIGH ALTITUDE SECTORS	85	LOWER
ATC PERSONNEL PER SECTOR	2.03/11	APPROX. THE SAME
DESIGN STANDARDS:		
NO. OF A/C HANDLED	40 - 80	*
PER WATCH		
AVERAGE PEAK SECTOR TRAFFIC	15	INCREASE
(A/C PER HOUR)		
AVERAGE SIMUL. PEAK SECTOR	8	INCREASE
TRAFFIC (A/C)		

*NAS DESIGN IS BASED ON DIFFERENT MEASURES OF WORK & LOAD

FIG 1-1 SECTORS IN THE LOWER AIRSPACE
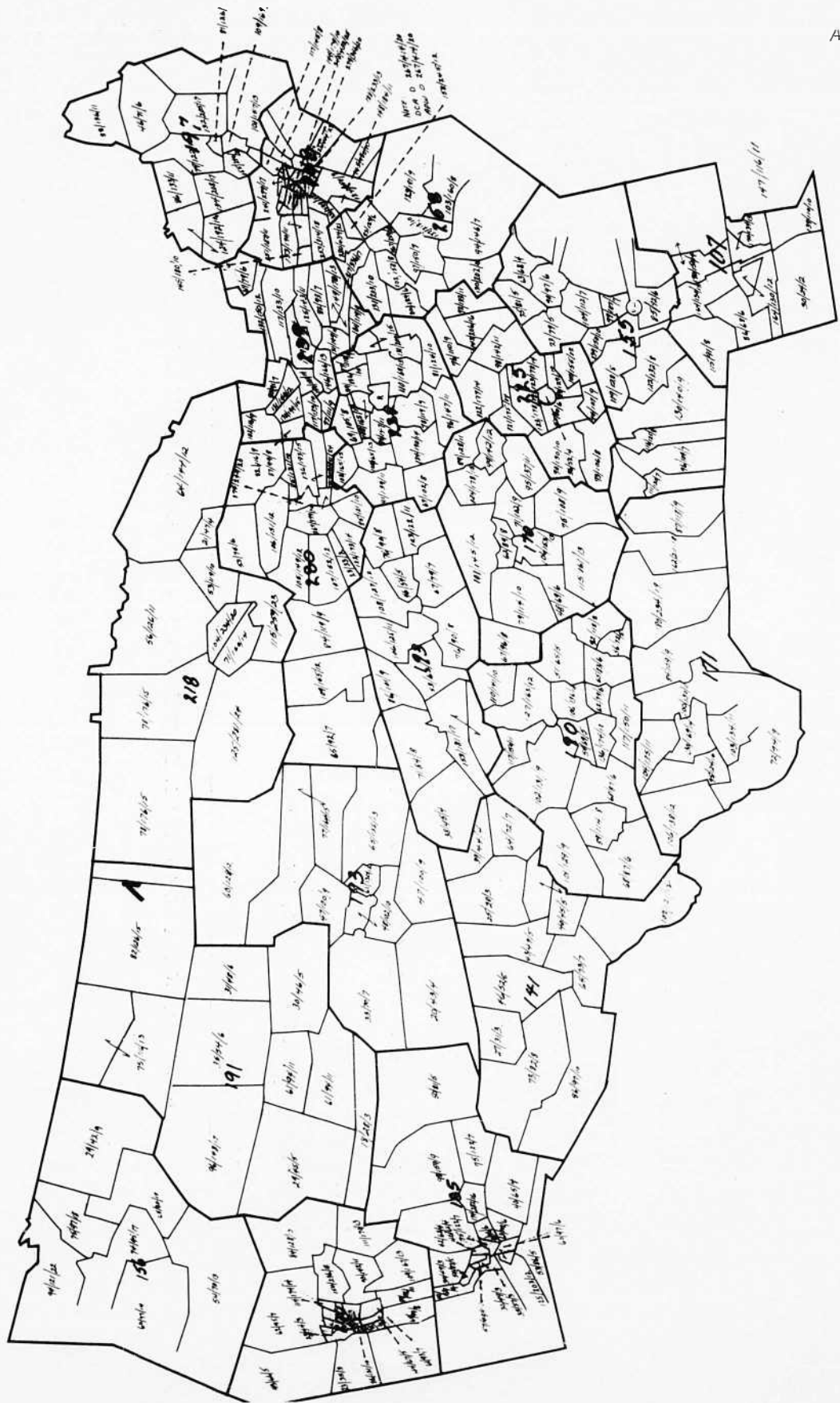
FIG I-2 SECTORS IN THE UPPER AIRSPACE

Fig. I-3   App. I-C
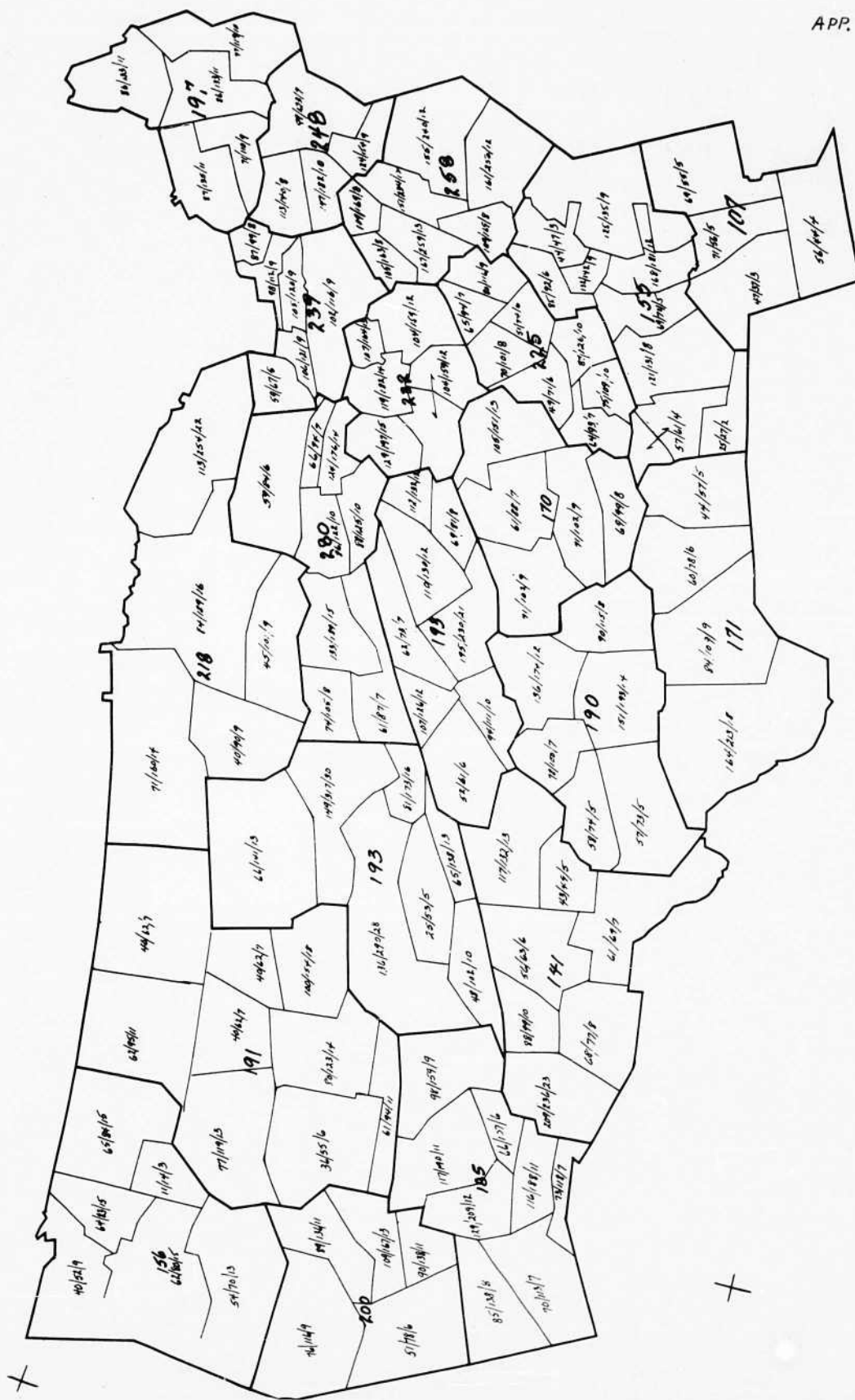
Figure I-3- ATC/NAV FACILITY COSTS BY COST CATEGORY, PRESENT MANUAL SYSTEM, FY 1963-1975

REPRODUCED FROM W. P. PROJECT No. 151-2S
FAA SRDS TRAFFIC AND ECONOMIC ANALYSIS BRANCH

(60)

FIGURE I-4 - ATC/NAV FACILITY COSTS BY FUNCTION, PRESENT MANUAL SYSTEM, FY 1963-1975

Millions of Dollars

Legend:
- Miscellaneous
- Navigation Facilities
- Flight Service Stations
- Terminal Area Control
- En route Control

Fiscal Year
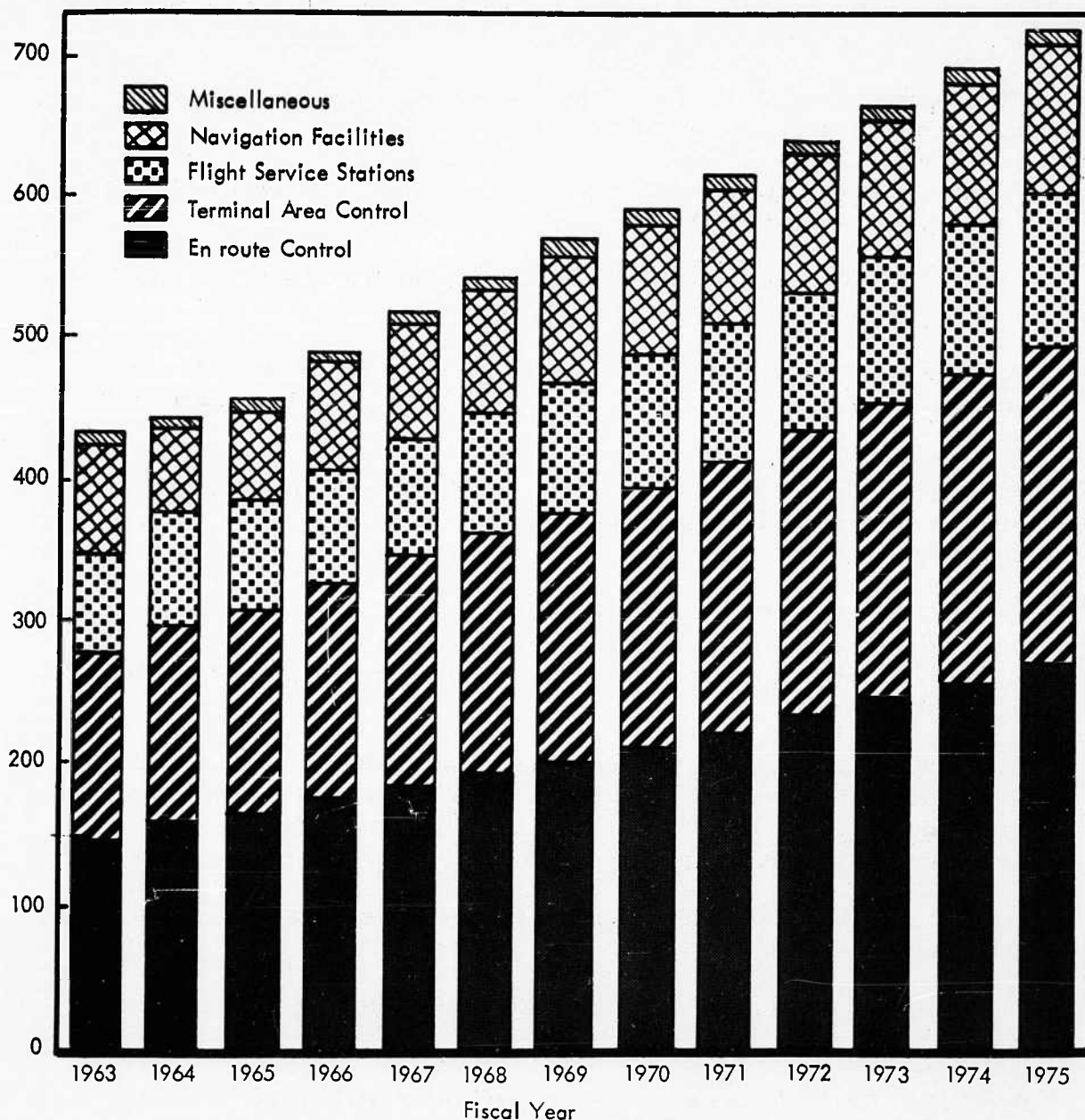
REPRODUCED FROM W. P. PROJECT No. 151-2S
FAA SRDS TRAFFIC AND ECONOMIC ANALYSIS BRANCH

DEFINITIONS

The following terms have been used in the body of the report. It is not suggested here that these definitions have any validity beyond the limited scope of the report.

AIRCRAFT, NUMBER OF (N): The instantaneous number of aircraft under the control of the control position.

AIRSPACE VARIABLES: A group of variables which defines the geometry of the sector (see Table 4).

CAPACITY, CONTROL (C_p): A measured capability of a control position to control traffic-expressed in units of load.

COEFFICIENT OF AIRSPACE LOAD (k_2): The work generated by a single aircraft due to its participation in a conflict. Expressed in DEW per aircraft.

COEFFICIENT OF ROUTINE LOAD (k_1): The work generated by routine handling of a "typical" aircraft in the sector. (See page 7.) Expressed in DEW per aircraft.

COMPARISONS, PAIRED, METHOD OF: A psychometric scaling technique in which each item to be judged is compaired once with every other item to be judged. The judgement is made as to which item is greater on the judged dimension.

CONFLICT (C): Predicted convergence of aircraft in space and time which constitutes a violation of a given set of separation minima. In this study the conflict is expressed by C = the number of aircraft participating in a conflict per unit time.

CONFLICT, INTERSECTION (C_I): A conflict generated at the convergence of two or more airways.

CONFLICT, OVERTAKE (C_O): A conflict generated by the action of overtaking aircraft along an airway.

DESIGN CAPACITY: An agreed upon level of capacity used for sector design purposes. Expressed in units of load.

DESIGN LOAD (L_D):   An agreed upon level of load used for design purposes. (e.g. the average load imposed during the busiest hour of the 37th busiest day of the year.)

DENSITY, AIRWAY ($\bar{d}$):   The average number of aircraft per unit length of airway. Expressed as aircraft per nautical mile.

DENSITY, AREA (D):   The average number of aircraft per unit of area. Expressed as aircraft per square nautical mile.

DISTRIBUTION, ALTITUDE (Q_h):   The distribution of aircraft in altitude. Expressed in percent of total traffic per altitude layer.

DISTRIBUTION, SPEED (Q_v):   The distribution of average traffic speed per altitude layer. Expressed in knots.

DYNAMIC ELEMENT OF LOAD (DEL):   The basic unit for measuring load. Work per unit time. Expressed in DEW per hour.

DYNAMIC ELEMENT OF WORK (DEW):   The basic unit for measuring work. The work generated for the control position by one standard aircraft flying across a sector on the straight and level without regard to interactions with other aircraft.

EFFECTIVENESS, AREA (ES):   A sector design concept in which the sector is designed for area coverage. Expressed in percent of maximum possible area coverage for a given load level.

EFFECTIVENESS, LOAD (E_L):   A sector design concept. The ratio between the airspace load and the sum of routine and airspace loads.

$$\left(\frac{L_2}{L_1 + L_2} \right)$$

EFFECTIVENESS, SECTOR (E):   A sector design concept.   The product of the load, area, and track effectiveness.   ($E_L \times E_S \times E_S$)

EFFECTIVENESS, TRACK (E_S):   A sector design concept in which the sector is designed for track coverage. Expressed as a percentage of the maximum possible track coverage for a given level of load.

EFFECIENCY, DESIGN (E):   A sector design concept. The ratio of the cumulative load to the cumulative design capacity.

EFFORT, CONTROL: The total activity required at the control position for maintaining a given level of service and safety.

FLOW ORGANIZATION FACTOR (g_o):   A non-dimensional number which quantifies the geometry of aircraft flow in the sector where the entire sector area constitutes the traffic field.

FLOW ORGANIZATION FACTOR, EQUIVALENT (g_e):   A transformation of g_o for a given geometry of airway structure.

FLOW ORGANIZATION FACTOR, EQUIVALENT VOLUMETRIC (g_{eh}):   A transformation of g_e for a given Q_h and a given Q_v.

FLOW ORGANIZATION FACTOR, VOLUMETRIC (Q_h):   A transformation of g_o for a given Q_h and a given Q_v.

FLUX (F):   The rate of change in number of aircraft populating a sector or passing a point on an airway in a given time.   Expressed as aircraft per hour.   Equal to DENSITY times SPEED.

HANDOFF: The control procedure associated with the movement of aircraft from one jurisdiction to another.

HANDOFF, TERMINAL: Handoff to or from a terminal area.

HANDOFF, VERTICAL: Handoff vertically between high and low altitude sectors.

LOAD (L):   The average control work per unit of time imposed on the control position expressed in DEL.

LOAD, AIRSPACE (L_2):   That component of total load due to the interaction between aircraft (i. e. potential conflict).   Expressed in DEL.

LOAD, BACKGROUND (L_o):   The component of total control load which is independent of the traffic.   It results from those administrative and technical functions required simply because the control position exists and must remain functional.

LOAD, ROUTINE (L_1):   The component of total load associa ed with the handling of the individual aircraft without regard to their interactions. Expressed in DEL.

LOAD, INDUCED ($L_3 + \ldots + L_n$):   Those components of load resulting from interactions between sectors.

POPUP: An aircraft requesting admission to the IFR system while in flight.

POSITION, CONTROL: That part of the ground environment that exercises jurisdiction and control of all aircraft under control in an enroute sector.

PSYCHOMETRIC METHOD: Any scaling technique designed to convert judgements into quantitative expressions on some defined dimension.

RADAR SNAPSHOT: A printed display representing the face of a radar scope at a particular instant of time, and showing either a real or simulated air traffic control situation.   May include alpha numerics or other symbols.

RELIABILITY: An indication of the extent to which a measurement will change from time to time or sample to sample.   Depends both upon the constancy of the thing measured and the constancy of the measuring method.

ROUTINE TRAFFIC VARIABLE (P_i):   The i th characteristic of the controlled traffic contributing to the routine load.   Expressed in percent of the total traffic.

ROUTINE WEIGHT (γ_i):   A weight assigned to the i th routine traffic variable to establish its contribution to routine load.   Expressed in work per aircraft (DEW per Aircraft).

RULES OF OPERATION (a):   See SEPARATION MINIMUM

SECTOR ORIENTATION: The position of the sector with reference to the normal flow of traffic.

SECTOR SIZE: The land area in square nautical miles, which, by projection, defines a sector.

SEPARATION MINIMUM (a):   The volume of airspace reserved by the rules for each aircraft in flight.   In the load model this volume is quantified into a linear measure (a).   Expressed in nautical miles per aircraft. (In radar, the value of a is $\bar{5}$ nautical miles.)

SIGMA - UNIT (σ):   A unit of measurement equal to the standard deviation of the distribution of measurements.

SIMULATION, DYNAMIC: Any form of simulation of an air traffic situation which permits the controller to alter the planned movements of aircraft.

SIMULATION, REAL TIME: Any form of simulation of an air traffic control situation in which the situation develops at the same rate as in an operational environment.

SCALE, EQUAL INTERVAL: Any scale of measurement which has additive properties.

SCALE, LINEAR: Same as EQUAL INTERVAL SCALE (above).

SECTOR: Jurisdictional unit for the exercise of control in the enroute environment.

SECTOR GEOMETRY: The shape of the sector (e.g. round, square, rectangular etc.)

SPEED, AVERAGE TRAFFIC ($\overline{V}$):   The mean speed of the traffic under control within the sector.   A constant for a given sector.   Expressed in knots.

STANDARD AIRCRAFT: Any aircraft that does not require special handling in terms of frequencies and procedures in general, an air carrier but may include some non-air carriers.

TIME OF TRAVERSE, AVERAGE ($\overline{T}$):   The mean time required for controlled aircraft to cross the sector.   A constant for a given sector. Expressed in hours.

TRACK LENGTH, AVERAGE ($\overline{s}$):   The mean lengths of the intrasector flight paths of controlled aircraft.   A constant for a given sector.   Expressed in nautical miles.

TRAFFIC ACTIVITY: The amount, behavior, and characteristics of the traffic flow.

TRAFFIC CHARACTERISTICS: See TRAFFIC FEATURES (below).

TRAFFIC FEATURES: Those aspects of traffic contributing to routine load.   Includes routine weights and routine traffic variables.

TRAFFIC PHENOMENA, TOTAL: See TRAFFIC ACTIVITY.

TRAFFIC VARIABLES: The number speed and the distribution of aircraft.

VALIDITY: An indication of the extent to which a measuring procedure in fact measures the variable it is designed to measure.

VELOCITY DIFFERENTIAL ($|V_2 - V_1|$):   The absolute difference between two aircraft flying along the same airway at the same altitude.

VELOCITY DIFFERENTIAL, WEIGHTED $(f_i f_j \mid V_j - V_i \mid)$: The velocity differential weighted in accordance with the velocity distribution. Where $0 < f_{ij} < 1$ and $\Sigma f_{ij} = 1.0$

SYMBOLS

List of Symbols

a	=	Separation Minima = Rules of operation
C	=	Conflict
C_I	=	Conflict, Intersection
C_p	=	Capacity, Control
C_o	=	Conflict, Overtake
D	=	Density, Area
d	=	Density, Airway
DEL	=	Dynamic Element of Load
DEW	=	Dynamic Element of Work
E	=	Effectiveness, Sector
ES	=	Effectiveness, Area
E_L	=	Effectiveness, Load
E_S	=	Effectiveness, Track
F	=	Flux
g_e	=	Flow Organization Factor, Equivalent
g_{eh}	=	Flow Organization Factor, Equivalent Volumetric
g_h	=	Flow Organization Factor, Volumetric
g_o	=	Flow Organization Factor
k_1	=	Coefficient of Routine Load
k_2	=	Coefficient of Airspace Load
L	=	Load (Total)
L_o	=	Load, Background
L_1	=	Load, Routine
L_2	=	Load, Airspace
$L_3 + \ldots + L_n$	=	Load, Induced
N	=	Aircraft, Number of
P_i	=	Routine Traffic Variable
Q_h	=	Distribution, Altitude
Q_n	=	Distribution, Area
Q_v	=	Distribution, Area
S	=	Sector Area
$\bar{s}$	=	Track Length, Average
$\bar{T}$	=	Time of Traverse, Average
$\bar{V}$	=	Speed, Average Traffic
W	=	Work (Total) or Control Work
γ_i	=	Routine weight
μ	=	Design Efficiency (also used as a conversion factor in $\sigma = \mu$ DEW)
σ	=	Sigma - Unit

Following is the introduction and the instruction given to all the participants of the scaling study of k_1.

INTRODUCTION

1. This exercise, in which you are asked to participate, is part of a study to determine quantatively the loads that are imposed on any control position in the enroute environment. It is important that you understand what it is that we are trying to achieve in this particular exercise and therefore you are asked to read this introduction carefully.

2. We assume that the load imposed on the control position is a sum of three components:

   L_o The "background load" of the system which is generated internally in the facility represents the administrative functions and duties of the controllers. This load is completely independent of any traffic circumstances and therefore we will not concern ourselves with it.

   L_1 The "routine load" which is directly proportional to the number of aircraft under control at any given time provided no interaction (or conflict) between the aircraft is considered.

   L_2 The "airspace load" which is directly related to the average number of conflicts that are expected to develop in the airspace or, in other words, the load which is inversly related to the available - conflict free - airspace.

3. In this exercise we will concern ourselves only with the routine load (L_1). In particular, we will try, with your help, to evaluate the relative amount of "work" which is involved in the control of an aircraft traversing an enroute sector where no interaction (conflict) between the aircraft is considered.

If the routine work generated by all aircraft was the same our problem would have been much simpler and the routine work (W_1) would be:

$$W. = KN$$

where N is the number of aircraft and K is the amount of work which is generated by one aircraft traversing an enroute sector.

Unfortunately not all aircraft generate the same amount of work, and it is reasonable to assume that the average amount of work per aircraft depends on the user classification and the function of the aircraft in the sector.

4.   In particular we will concern ourselves with the following factors and their relative contribution to the amount of routine work.

(1)   number of airliners vs number of non airliners
(2)   number of vertical hand-offs to or from a higher control strata
(3)   number of aircraft coming from or going to a terminal area
(4)   number of aircraft climbing and descending in the sector
(5)   number of aircraft requesting IFR clearance while in the sector ("Pop ups")

Your judgment will help us to evaluate the relative work associated with these factors and determine the value of k_1.

> Remember - This is not a test of your capability.
> You are acting as a judge to help us in the
> determination of the control load.
>
> Please read the instructions carefully.

INSTRUCTIONS

The object of this exercise is to develop a measuring stick for determining the amount of work involved in enroute traffic control.

We are trying to determine the relative contribution of a number of factors to the total control work. In this part of the study we are examining the routine work, that is the amount of work generated just by having aircraft traverse the sector without any consideration of their inter-actions, (i. e. the conflictions which might arise.)

Even a single aircraft flying across a sector generates some work for the controller, although there may be no other aircraft in the system. The controller communicates with the pilot, posts flight strips, etc. Your help is needed to determine the total work involved in a number of enroute traffic situations. If you will look at the first page you will see that the situation is printed as a radar display. Each display shows six identified aircraft under radar control as well as a number of unidentified aircraft not in the system. Shrimp boats indi-cate the identified aircraft, and carry the information required to make a judgment of the amount of work required. The key to this information is given at the bottom of the page.

Your task in each case will to compare two such sector displays and decide which member of the pair involves the more work in getting the aircraft across the sector. This will include first, accepting the planes in a hand-off, second, everything the control team does in connection with them while they are in the sector, and finally, their hand-off to an adjacent control position.

Each and every one of these displays is identical with respect to sector design, and the location, speed, and performance characteristics of the aircraft. They differ only with respect to aircraft identification and the past or future history of the aircraft within the sector. Thus you will find in one display an aircraft may be a commercial air carrier but in another display it will be identified as a military aircraft of the same type. Some aircraft are identified as being hand-offs to or from a terminal area. It will be noted in these cases that all adjacent terminal areas lie to the north (NE or NW). Thus a north bound aircraft designated as a terminal area hand-off is going to a terminal area, whereas a southbound aircraft with the same designation has been handed off from a terminal area.

Other features which may vary from display are: altitude changes (as opposed to straight and level flight), vertical hand-offs which occur sometime during the aircraft's traverse of the sector, but not necessarily at the moment of display, and Popups, i.e. aircraft which have just asked to be admitted to the IFR system. You must accept the Popups.

Remember that despite these differences, the displays are all the same as of the instant of display. All differences between displays appear in connection with the shrimp boats which tag the identified aircraft. Your task will require that you examine these shrimp boats for the required information. You should also keep in mind that your judgments should be of:

    (a) ALL THE WORK of
    (b) ALL THE MEN involved in controlling
    (c) ALL THE AIRCRAFT in the system for
    (d) THE FULL DURATION OF THEIR FLIGHTS across the sector

Several other things need to be kept in mind while you are performing this task:

    1. All the displays represent a full IFR environment.
    2. Aircraft identifications are given primarily to differentiate between air carrier and non-air carrier aircraft.
    3. No immediate conflictions are present in any of the displays.
    4. The displayed sector is south of, and adjacent to a terminal area.
   5. All hand-offs are radar hand-offs.

It should be pointed out again that what we are trying to do here is to separate out, and measure different parts of the work generated in air traffic control. The situations you will be judging involve only a part of the controllers' task. We are interested in discovering how large a part that is, and this is our reason for asking your help. This is a test of the system, and not of the controller.

In the books before you the displays to be compared lie on facing pages which have been numbered at the top center. You are to decide which member of the pair involves the more total work and indicate your choice on the answer sheet by placing a check in the appropriate box. Alternative "A" is always on the left hand side, alternative "B" on the right. Place your check in the correspondingly labeled column. You must make a choice for every pair of displays even though the alternatives are equal or nearly so. Data processing depends upon a complete set of answers.

> Remember - The instant of display is identical in all 380 displays. Your judgment will involve the total work which is generated for the facility by the aircraft throughout their flights across the sector.

> Always check the situation which represents the greater amount of total work.

FIG. III - 1   SAMPLE PAIRED COMPARISON DISPLAY
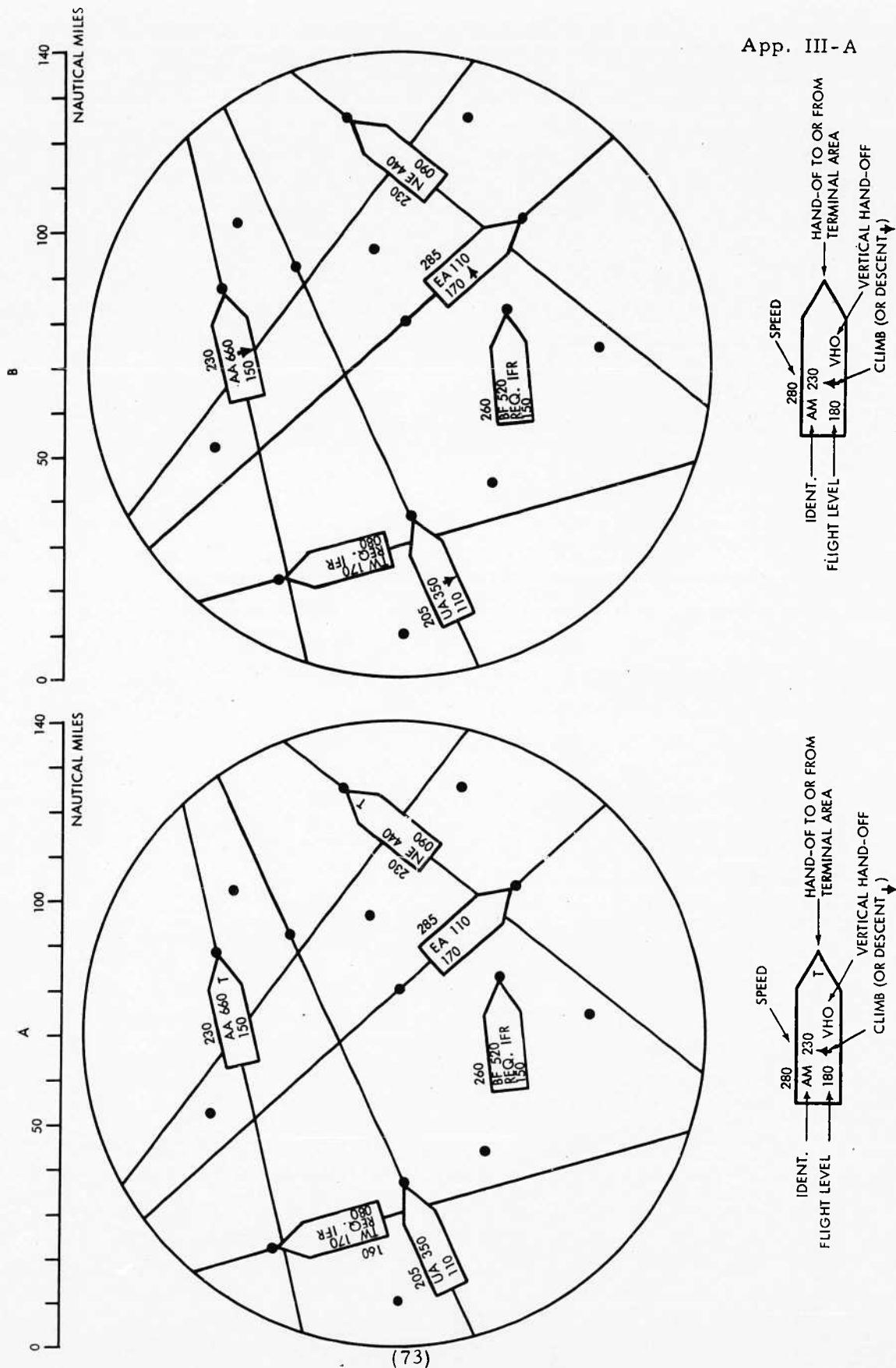
FIG III - 2 SAMPLE PAIRED COMPARISON ANSWER SHEETS

ANSWER SHEET

Remember: Check the situation which represents the greater amount of total work.

(1)

(2)

Table III - 1

ANALYSIS OF PSYCHOMETRIC DATA BY METHOD OF PAIRED COMPARISONS

PREFERENCE MATRIX (%)

ALL SUBJECTS 179

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1		89	90	86	92	52	78	91	98	96	89	97	90	77	82	98	95	94	97	95
2	11		40	24	37	13	2	63	88	65	62	78	24	28	52	93	73	63	82	73
3	10	60		34	42	18	20	72	95	74	72	88	37	33	66	98	88	85	95	83
4	14	76	66		71	11	50	74	91	93	78	94	36	54	68	98	77	84	95	78
5	8	63	58	29		12	15	67	93	83	70	89	18	36	61	94	68	72	95	82
6	48	87	82	89	88		74	96	99	94	96	98	80	83	92	100	89	96	99	93
7	22	98	80	50	85	26		81	94	89	75	93	50	55	72	98	91	88	96	95
8	9	37	28	26	33	4	19		71	58	73	91	23	3	14	92	45	49	77	52
9	2	12	5	9	7	1	6	29		27	33	51	6	5	8	91	12	20	44	16
10	4	35	26	7	17	6	11	42	73		42	59	8	6	30	96	40	40	66	34
11	11	38	28	22	30	4	25	27	33	58		92	21	4	15	88	46	46	62	40
12	3	22	12	6	11	2	7	9	51	41	8		7	4	6	83	24	18	49	24
13	10	76	63	64	82	20	50	77	94	92	79	93		59	73	99	80	85	96	88
14	23	72	67	46	64	17	45	97	95	94	96	96	41		83	97	76	87	92	78
15	18	48	34	32	39	8	28	86	92	70	85	94	27	17		95	60	76	85	59
16	2	7	2	2	6		2	8	9	4	12	17	1	3	5		7	4	15	6
17	5	27	12	23	32	11	9	55	88	60	54	76	20	24	40	93		56	85	59
18	6	37	15	16	28	4	12	51	80	60	54	82	15	13	24	96	44		88	41
19	3	18	5	5	5	1	4	23	56	34	38	51	4	8	15	85	15	12		90
20	5	27	17	22	18	7	5	48	84	66	60	76	12	22	41	94	41	59	10	

Table III - 2 ANALYSIS OF PSYCHOMETRIC DATA BY METHOD OF PAIRED COMPARISONS

MATRIX OF SUCCESSIVE DIFFERENCES

ALL SUBJECTS 179

	2-1	3-2	4-3	5-4	6-5	7-6	8-7	9-8	10-9	11-10	12-11	13-12	14-13	15-14	16-15	17-16	18-17	19-18	20-19
1	1.25	0.03	-0.20	0.34	-1.37	0.71	0.55	0.85	-0.81	-0.54	0.61	-0.55	-0.55	0.20	1.41	-0.85	-0.05	0.24	-0.19
2	1.25	-0.26	-0.44	0.39	-0.81	0.04	1.43	1.07	-0.99	-0.07	0.47	-1.48	0.14	0.62	1.31	-1.13	-0.28	0.60	-0.30
3	1.54	-0.26	-0.41	0.22	-0.71	1.21	0.66	0.69	0.15	-0.07	0.58	-1.48	-0.12	0.85	2.46	-1.50	-0.10	0.59	-0.70
4	1.79	-0.30	-0.41	0.55	-1.77	0.10	1.50	1.06	-0.56	-0.74	0.83	-1.96	0.46	0.37	2.73	-2.50	0.27	0.63	-0.88
5	1.74	-0.13	-0.74	0.55	-1.16	0.65	1.05	0.71	-0.37	-0.42	0.70	-2.14	0.57	0.63	2.22	-1.95	0.11	1.07	-0.72
6	1.18	-0.23	-0.32	-0.06	-1.16	0.82	1.05	0.55		0.17	0.77		0.13	0.42	2.48	-1.28	0.48	0.51	-0.06
7			-0.85	1.05	-1.71	0.37	0.88	0.55	-0.35	-0.53	0.69	-1.45	-0.13	0.43	0.95	-1.65	-0.12	0.76	-0.67
8	0.98	-0.23	-0.08	0.21	-1.26	1.07	0.88	0.82	-0.62	0.41	0.48	-2.03	-1.11	0.75	1.64	-1.21	0.08	0.69	-0.84
9		-0.45	0.30	-0.15		0.83	1.04	1.06	-0.62	0.18	0.44	-1.58	-0.10	0.22	1.64	-1.39	0.35	0.66	-0.82
10	1.38	-0.27	-0.85	0.56	-0.65	0.83	1.01	1.28	-0.24	-0.20	1.42	-1.61	-0.16	1.02	1.75	-1.50	0.	0.41	-0.55
11	0.91	-0.28	-0.18	0.24	-1.24	0.81	0.07	0.82	-0.20	-1.18	1.42	-2.24	-0.94	0.73	2.40	-1.85	-0.01	0.90	-0.68
12	1.05	-0.38	-0.43	0.37		-0.09	0.15	-0.19	-0.16	-0.56	0.68	-1.50	-0.26	0.22	2.09	-2.11	-0.21	0.64	-0.54
13	1.98	-0.39	0.04	0.56	-1.76	0.51	0.73	0.34	-0.10	0.22	0.	-1.98	0.22	0.40	1.81	-1.81	0.20	0.31	-0.64
14	1.29	-0.13	-0.53	0.44	-1.31	-0.14	1.96	0.07	-0.90	0.51	0.51	-2.16	0.22	0.96			0.40	0.33	-0.81
15	0.87	-0.36	-0.05	0.18	-1.10		1.65	0.34	-0.39	-0.51	0.25		-0.35	0.96			0.46	0.64	-0.53
16								0.07	-0.51					0.27			-0.20	0.91	-0.84
17	1.04	-0.56	0.42	0.29	-0.76		1.43	1.07	-0.94	-0.16	0.61	-1.56	0.15	0.46			0.15	1.16	-1.38
18	1.27	-0.74	0.05	0.44	-1.13		1.22	0.80	-0.59	-0.14	0.81	-1.98	-0.05	0.40			0.15	1.16	-1.28
19	0.91	-0.72	0.	0.	-0.58		0.98	0.87	-0.56	-0.13	0.33	-1.72	0.28	0.38			-0.10	1.06	-1.28
20	1.02	-0.32	0.18	-0.16	-0.14		1.59	1.04	-0.58	-0.16	0.46	-1.97	0.38	0.56			0.44		

COLUMN SUM

	2-1	3-2	4-3	5-4	6-5	7-6	8-7	9-8	10-9	11-10	12-11	13-12	14-13	15-14	16-15	17-16	18-17	19-18	20-19
COLUMN SUM	21.455	12.051	-5.987	-30.785	-3.859	-0.978	6.009	10.854	-18.482	27.118	8.384	-22.728	18.770	1.996	13.464	13.271	-8.806	-13.722	-2.883

COLUMN AVERAGE

	2-1	3-2	4-3	5-4	6-5	7-6	8-7	9-8	10-9	11-10	12-11	13-12	14-13	15-14	16-15	17-16	18-17	19-18	20-19
COLUMN AVERAGE	1.262	0.634	-0.333	-1.710	-0.203	-0.051	0.316	0.543	-1.155	1.937	0.559	-1.588	1.043	0.100	0.748	0.698	-0.489	-0.722	-0.144

K VALUES

	U.	1.262	0.929	0.726	1.043	-0.113	0.446	1.489	2.237	1.748
	1.604	2.238	0.528	0.476	1.019	2.956	1.368	1.468	2.167	1.444

NO. OF SUBJECTS 179

PAIRED COMPARISONS TECHNIQUE

The paired comparisons technique was originally selected to minimize the difficulty in making the judgment required of the controller. While it is recognized that this method yields relatively little information for the amount of work done by the subject, nevertheless the redundancy results in greatly increased reliability of the information obtained.

The paired comparisons method can be reduced to quantitative form in a variety of ways. These are summarized in Guilford's Psychometric Methods* as Case 1 to Case 5 inclusive. Case 5, the simplest, also makes the greatest number of assumptions. In particular, it makes the assumption that the dispersions of the difference distributions in the judgmental tests are all equal and that these differences are all normally distributed. If these assumptions are valid, then a linear scale should result. Even if they are not valid, near linearity can generally be expected in the central part of the range. It should be noted that the more extreme scale values are less reliable. This is because of the assumption of normality of the distribution of the differences. In the middle of the normal curve, a change in the opinion of one judge as to which of two displays represents more work will do very little to shift the scale value of either of the displays involved. But toward the extremes, the alteration of opinion of one judge will make a very material difference in the positions or the scale value of the display. It is for this reason that we discard all displays having scale values of more than ± 2 sigma from the mean in the paired comparison analysis. The 2 sigma is a purely arbitrary value which could well be set at some other level. The discard of those differences having sigma values over ± 2 results in extreme scale being determined by a smaller number of judgments than is the case with scale values more centrally located and hence an additional reduction in the reliability of these values. Accordingly, since we have an excess of information (20 scale values and but 5 unknown χ's) we elect to use only those scale values toward the center of the distribution. For purposes of this exercise we used only scale values between $\pm 1/2$ sigma.

*Guilford, J. P., Psychometric Methods, New York: McGraw-Hill, 1936

PAIRED COMPARISON INTRA-SCALE RELATIONSHIPS

The calculation of scale relationships for the sigma scale of the paired comparisons study are illustrated in the following:

Let P_{ij} be any member of a set S, where i = 1, 2, 3, 4, 5, and j = 1, 2, 3. The set of all P_{ij} consists of 243 (3^5) members, where each member consists of 5 digits and every digit can have the value of 1, 2, or 3.

We have considered a subset $\overline{S}$ of all P_{ij} where the numerical sum of the j values is equal to 8. This means that the 20 members of $\overline{S}$ shown in Table 6, Part II, (p. 39) are considered.

Each member of S represents a group of 6 aircraft and the values of i represent the classification and function of the aircraft in the group.

The values of j now represent the actual number of aircraft having the specified classification and function, and the subset $\overline{S}$ of the selected P_{ij} can be transformed in a one-to-one manner to the subset $\overline{R}$ of all selected P_{ij} as shown in Table 6.

If each member of the subset $\overline{R}$ is assigned a numerical value, we can add and subtract these values. It should be remembered that a sum of two members will represent a group of 12 aircraft, a sum of 3 members, 18 aircraft, and so on. Examples:

(1) (a) + (b) = 00032 + 00051 = 00083
      The number 00083 represents:
            12 aircraft, all airlines
                  no vertical handoffs
                  no handoffs to a terminal area
                  8 descending or climbing aircraft
                  3 popups.

(2) (g) + (f) - (i) = 00032 = (a)
(3) (c) + (d) - (e) = 00051 = (b)
(4) (m) + (o) - (c) = 40200 = (s)

As long as the number of members with a plus sign is equal to one more than the number of members with a minus sign, we get a new member which can be a member of R, or in particular cases a member of $\overline{R}$.

We are interested in the value of the member R (00000); which represents 6 aircraft and involves all airlines, no vertical handoffs, no handoffs to a terminal area, no climbing or descending aircraft, and no popups. The

value of R (00000) thus corresponds, by definition, to 6 DEW.

CALCULATIONS OF R (00000)

The value of R (00000) may be calculated by combining members of the subset $\overline{R}$ in various ways such that they represent R (00000). We are interested in obtaining at least two independent determinations of R (00000).

A.
$\quad$ $(2g + t - j - q)$

$\quad$ I $\quad$ $(2g + i - j - e)$ $\qquad$ = $\quad$ 00002

$\quad$ $(2g + h - j - b)$

$(q + g - t)$	,	$(j + c - l)$
$(q + c - s)$	,	$(j + a - k)$
II $(q + a - r)$	,	$(g + b - h)$ = $\quad$ 00003
$(m + j - p)$	,	$(g + e - i)$
$(m + e - o)$	,	$(e + a - f)$
$(m + b - n)$	,	$(c + b - d)$

$\quad$ III $\quad$ $(5a + 4q - 5m - 3n)$ = 00004

B. $\quad$ (1) $\quad$ $3(I) - 2(II) = R (00000)$

$\quad$ (2) $\quad$ $4(II) - 3(III) = R (00000)$

C. $\quad$ Example of two independent determinations of R (00000):

$\quad$ (1) $\quad$ $3(2g + i - j - e) - 2 (g + e - i) = R (00000)$

$\quad$ (2) $\quad$ $4(m + b - n) - 3 (5a + 4q - 5m - 3n) = R (00000)$.

INTERNAL CONSISTENCY

The linearity and hence the additive character of our scale of work can be tested by the $A + B - C = D$ paradigm. If, in fact, our units on the scale of work are equal at all points on the scale, then this paradigm should hold true. The possibility that errors in judging scale values might not in fact be random, but might in some way be associated with the scale value itself is refuted by plotting observed values against the calculated values of the 20 displays, where the calculated values are the average of the scale values obtained from the $A + B - C$ formula. If the errors had in fact been correlated with the scale values in a systematic manner, the effect should be uniformly noticeable on such a graph over most of the points.

Table IV - 1 shows the alternative ways the separate scale values can be calculated using the A + B - C paradigm. The letter entries are the coded display identifications as given in Table 6 (p. 39).

Table C shows the distributions of these calculated scale values. Tabulated values are derived from the combination occupying the comparable position in Table IV - 1. The striking fact about this table is the remarkable consistency of the values which clearly justifies the linearity assumption.

Table IV - 3 summarizes these results by showing the mean and standard deviation of these calculated values. It also examines the significance of the difference between calculated and observed values, using the standard deviation of the calculated values to establish the probability that the observed value is a member of the same distribution. Only one of the twenty observed values lies outside the 5% confidence interval, and since one out of twenty such instances would be expected to occur by chance, even this may be considered a chance variation.

Theoretically, it should be possible to reduce the error by means of an iteration procedure in which the means of the calculated values are substituted for the observed values in the equations represented by Table IV - 1, and new values calculated for the twenty displays. Iterations of this procedure should result in a convergence of the values upon the straight 45° line of Figure IV - 1. This procedure has been completed for 50 iterations with the results shown in Table IV - 4. Here the 3rd column represents the mean of the 49th and 50th iterations. These values have been plotted against the observed values in Figure IV - 2 which confirms the linear relationship and further demonstrates the absence of errors correlated with the scale values.

Table IV - 1

Alternative Ways of Computing Scale Values

of Each Display from Known Scale Values of

Three Other Displays

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
CKL	CDE	ALK	BEC	BIH	AIG	AIF	BIE	EHB	BLD	ALC	CKA	AOF	BOE	CSM	JNB	BSD	ASC	CRA	GRA
CRS	DJL	ASR	BLJ	BON	AOM	ATR	BTQ	ETQ	BPN	APM	CPM	APK	BPJ	DSN	JOE	BTH	ATG	CTG	GSC
FGI	DQS	BED	BSQ	CDB	EKJ	CHD	DGC	FGA	CLE	FJE	DJB	BQN	BQM	ENB	JQM	CSE	FQE	DQB	HQB
FMO	EHI	DBH	CHG	CLJ	ERQ	CTS	DTS	FTR	EKF	FPO	DPN	CND	DMC	EPJ	KMA	ERF	FTI	DTH	HSD
GRT	ENO	DMN	CNM	CSQ	IRT	HMN	GNM	GOM	EPO	JRQ	EJC	CPL	DPL	EQM	KOF	ETI	KQJ	EQC	IQE
KMP	HQT	EJL	HST	FJK	KOP	IMO	INO	HON	KQR	LRS	KSR	CSO	HMG	FMA	LMC	JRK	KSL	LQJ	IRF
	JNP	EQS	LNP	FQR					LQS		OPS	EQO	HOI	FPK	LND	MNB		LRK	
	MNQ	GST	NOS	IQT					MPQ		JSQ	GNH	DSO	IMG	LSO	MOE		MOC	
		MLP		JOP								GOI		INH		MPJ		NOD	
		MOS		MOQ								JQP		LSP		JSL		OPL	

The sum of scale values for the first two lettered displays, less the scale value of the third, yields an estimate of the scale value of the display identified by the letter in the column heading.

Table IV - 2

Distributions of $(X + Y - Z = \overline{R})$ Scale Values

A	B	C	D	E	F	G	H	I	J
2.93	2.38	3.09	2.03	2.70	2.33	2.74	1.66	1.49	2.05
2.95	2.34	3.07	2.08	2.72	2.43	2.35	1.27	1.30	1.92
2.76	2.43	3.05	1.99	2.41	2.08	2.49	1.41	1.38	1.96
2.67	2.28	2.89	1.99	2.55	2.02	2.24	1.22	1.30	1.97
3.15	2.27	2.81	2.08	2.46	2.41	2.34	1.56	1.79	1.71
2.93	2.67	2.91	2.18	2.45	2.28	2.34	1.46	1.70	1.98
	2.48	2.99	2.07	2.52					2.00
	2.37	3.15	2.22	2.90					1.81
		2.95		2.71					
		3.09		2.60					

K	L	M	N	O	P	Q	R	S	T
1.62	1.37	2.63	1.56	1.44	.78	1.26	.83	.60	.08
1.63	1.66	2.37	1.35	1.30	.99	1.01	.64	.53	.19
1.43	1.51	2.34	1.46	1.38	.89	1.16	.73	.67	.19
1.23	1.37	2.37	1.21	1.39	.65	1.2	.33	.47	.25
1.42	1.37	2.23	1.21	1.48	1.05	.82	.78	.76	.39
1.51	1.47	2.09	1.07	1.19	.79	1.14	.69	.81	.39
	1.42	2.13	1.27	1.33	.93	1.11		.74	
	1.49	2.31	1.36	1.49	.64	1.10		.86	
		2.32		1.58		1.31		1.00	
		2.33		1.44		1.11		.86	

Table IV - 3

Means and Standard Deviations of Calculated Scale Values

Display	N	Calculated from First Iteration		Observed V	M - V	$\dfrac{M - V}{\sigma}$
		M	σ			
A	6	2.90	0.15	3.07	0.17	1.13
B	8	2.40	0.12	2.48	0.08	0.67
C	10	3.00	0.10	2.96	0.04	0.40
D	8	2.08	0.08	1.94	0.14	1.75
E	10	2.60	0.14	2.51	0.09	1.36
F	6	2.26	0.16	2.03	0.23	1.44
G	6	2.42	0.16	2.43	0.01	0.06
H	6	1.43	0.15	1.47	0.04	0.27
I	6	1.50	0.19	1.69	0.19	1.00
J	8	1.92	0.10	1.91	0.01	0.20
K	6	1.47	0.14	1.49	0.02	0.14
L	8	1.46	0.09	1.51	0.05	0.56
M	10	2.31	0.14	2.23	0.08	0.57
N	8	1.31	0.15	1.35	0.04	0.27
O	10	1.40	0.10	1.59	0.19	1.90
P	8	0.84	0.14	0.79	0.05	0.36
Q	10	1.12	0.13	1.21	0.09	0.69
R	6	0.67	0.15	0.72	0.05	0.33
S	10	0.73	0.16	0.72	0.01	0.66
T	6	0.23	0.11	0.0	0.23	2.09* Sig. 5%

$$\sqrt{\overline{\sigma^2}} = 0.14 \qquad \overline{M-V} = 0.09 \qquad \frac{\overline{M-V}}{\sqrt{\overline{\sigma^2}}} = 0.64$$

Table IV - 4

Display Scale Values - σ Units

	Observed	1st Iteration	49-50 Iteration Avg.
A	3.069	2.899	2.966
B	2.480	2.404	2.442
C	2.956	3.004	2.992
D	1.937	2.082	2.031
E	2.510	2.605	2.580
F	2.027	2.261	2.143
G	2.428	2.415	2.402
H	1.467	1.428	1.442
I	1.694	1.497	1.580
J	1.913	1.925	1.920
K	1.488	1.474	1.481
L	1.512	1.459	1.507
M	2.230	2.312	2.277
N	1.352	1.312	1.315
O	1.588	1.404	1.453
P	0.789	0.840	0.793
Q	1.208	1.124	1.150
R	0.718	0.668	0.712
S	0.719	0.731	0.738
T	0.0	0.224	0.147
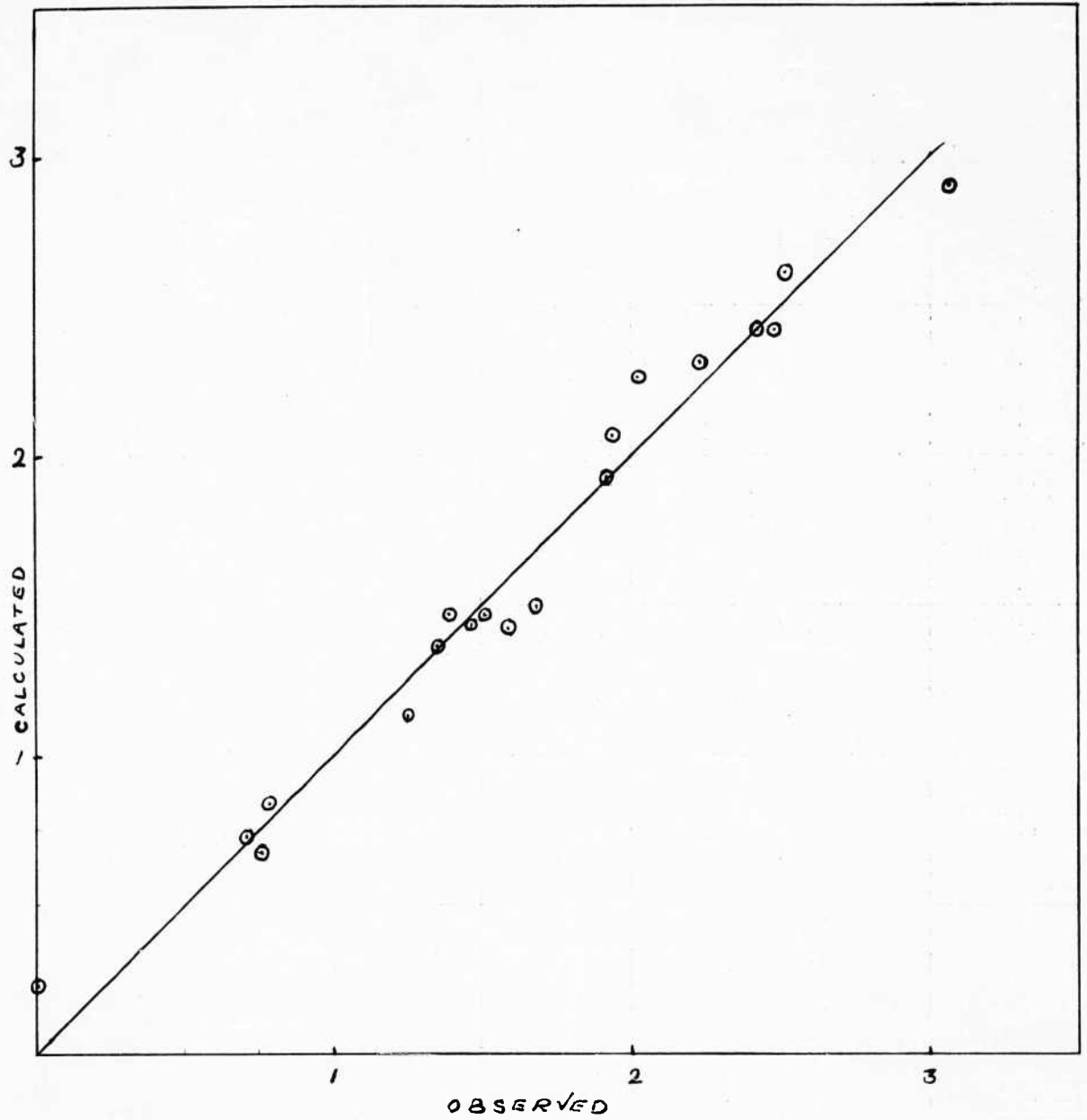
Fig. IV-1   Calculated Versus Observed Values
After 1st Iteration

Fig. IV-2   App. IV-C
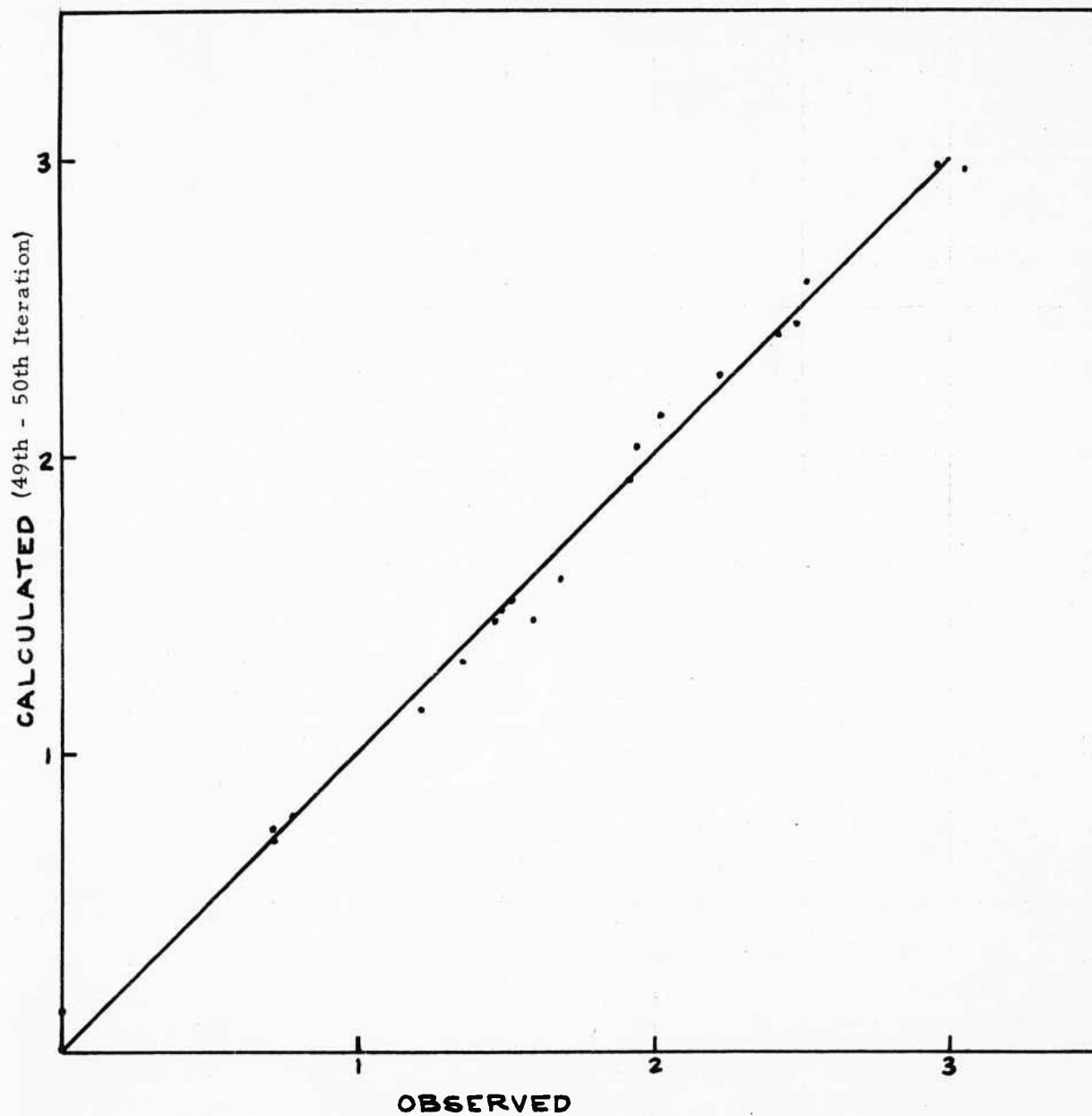
DISPLAY SCALE VALUES - σ UNITS

Fig. IV-2   Calculated Versus Observed Values

After 50 Iterations

Selection of Displays for Calculation of γ_i Values

The observed values resulting from our paired comparisons are shown in Table IV - 4. From this table it can be clearly seen that the displays occupying the middle of the distribution are: k, i, j, k, l, n, and o. Because of their position on the normal distribution of differences, these display values are considered to be more reliable than more extreme display values, and thus they are the ones of choice for computing the γ_i's.

Figure 9 (page 44) represents the relationship between the position of the display, the value in units of DEW and the values in units of sigma. It can be seen that a general formula for the DEW value of each display R $(Z_1 Z_2 Z_3 Z_4 Z_5)$ can be expressed as follows:

$$R_j(Z_1 Z_2 Z_3 Z_4 Z_5) = (6 - Z_1) + \sum_{i=1}^{5} Z_i \gamma_i = \left[(P_j) - (x) \right] \mu \text{ DEW}$$

where Z_i is the number of aircraft participating in an i manner

R $(Z_1 Z_2 Z_3 Z_4 Z_5)$ is the value of the display in DEW units
(P_j) is the position of the display with respect to the position of $P(t)$.
(x) is the position of the absolute zero of the scale with respect to $P(t)$.
and μ is the ratio between the linear DEW scale and the sigma scale

$$\mu = \frac{\sigma}{\text{DEW}}$$

$P(t)$ is the position on the DEW scale of the zero point on the σ scale. The following equations have been used to extract the γ_i values.

I H L K	to extract γ_3 and γ_4
J K	to extract γ_5
I L	to extract γ_2
L O	to extract γ_1

Table 9 (page 43) shows the values of γ_i. The values obtained include the conversion factor μ. In particular the value of γ_i includes both a free number (DEW) and a multiplier of the conversion factor μ. In effect the results obtained are a ratio scale and not, at this stage, an absolute scale.

RELIABILITY

Internal consistency has been demonstrated by means of the iteration process using the A + B - C paradigm. Reliability can also be demonstrated by recalculating our display values from the obtained γ_i's. In making this calculation, it must be noted that the calculated values will be based upon deviations from R (00000) rather than from (t), the arbitrary zero of our scale. This is clearly shown in Figure 10 (page 45) which shows the distance from R (00000) to (t) to be - 0.385 sigma units. This value is the X at the right hand side of Table 8 (page 44).

The line of least squares has been fitted to the display values for varying numbers of displays, based upon the obtained γ_i's. Figure IV - 3 shows this line for all 9 displays lying within $\pm$ 1/2 sigma from the mean. In the same figure is shown the line based upon 8 of these displays, Q having been omitted because of its marked deviation from the line.

Figure IV - 4 shows the line of least squares for all 20 displays, for 18 (A and T having been eliminated) and for 16 (A, C, S, and T having been eliminated). The equations for the best fitting lines are:

20	$Y = .486 + .755X$
18	$Y = .393 + .808X$
16	$Y = .369 + .814X$
9	$Y = .528 + .681X$
8	$Y = .161 + .894X$

The significant fact about these groups is the relative constriction of the calculated values when compared to the observed values. This constriction suggests that toward the extremes of the scale, units judged equal are not in fact equal to similarly judged units in the middle of the scale. Thus we are on safest ground when we restrict ourselves to those displays toward the middle of the scale.
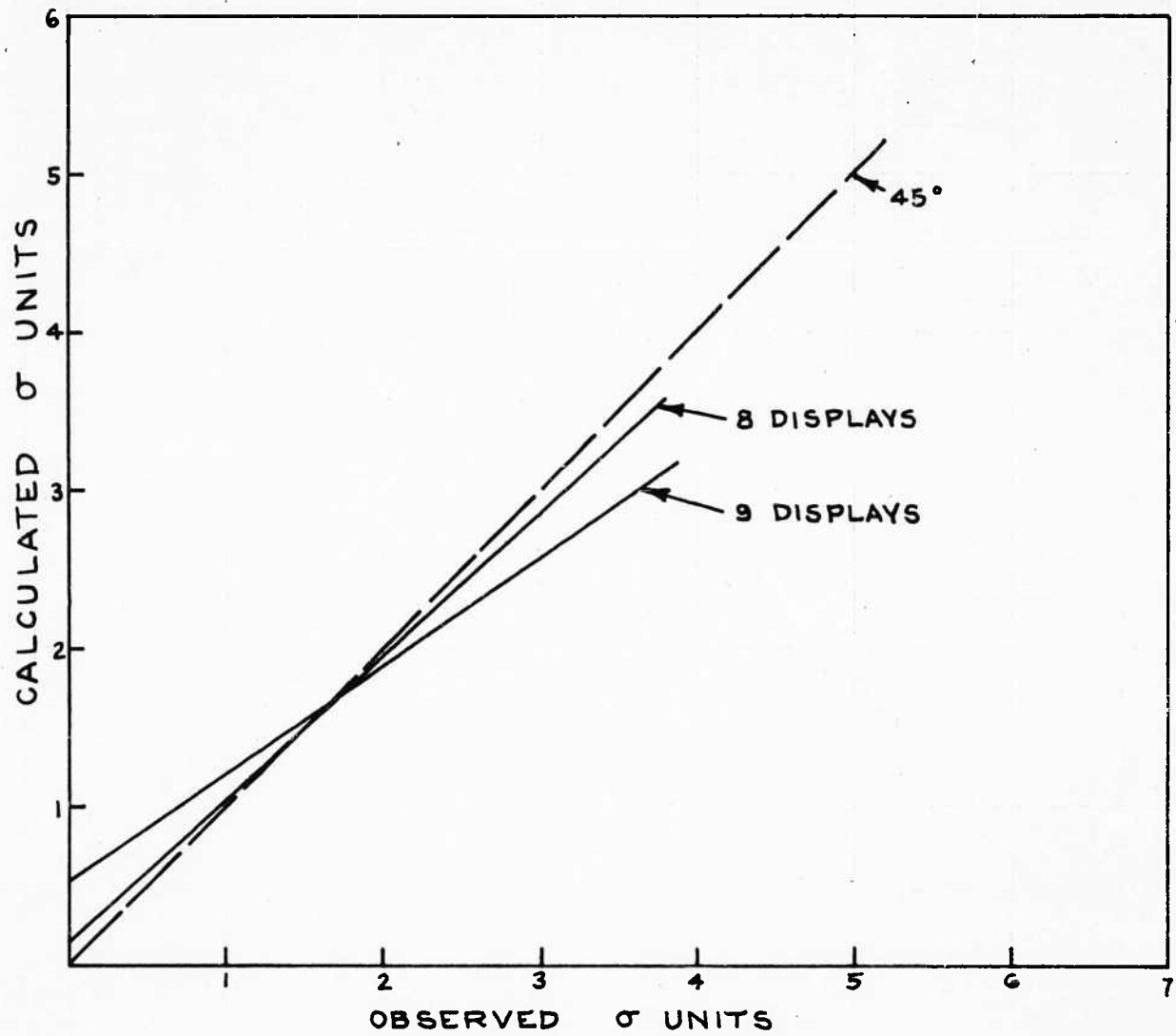
LINE OF LEAST SQUARES

Fig. IV-3

LINE OF LEAST SQUARES

Fig. IV-4

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System Design Team, Washington, D. C. and Research Division, Atlantic City, New Jersey, Systems Research and Development Service, Federal Aviation Agency. THE CONTROL LOAD, CONTROL CAPACITY AND OPTIMAL SECTOR DESIGN by B. A. Arad*, C. E. Mayfield**, and others, Interim Report, December 1963, 90 pp.
(Project 102-11R, Report No. RD-64-16)

Unclassified Report

The complexity of total traffic phenomena in a controlled airspace is described by a model that relates the variables of the traffic (number of aircraft, distribution, speed), the rules of operation (separation minima) and the airspace (volume and flow organization) to the load which is imposed on the control position of the sector. Basic units of control load and control work are defined and used for quantification of the control effort required. The relationship between the load imposed on the control position and the geometry and the orientation of the sector is demonstrated and a method for optimizing the design of the sector is analyzed and described in a numerical example. The control
(over)

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I. Arad, B. A.
   Mayfield, C. E.
II. Project No. 102-11R
III. Report No. RD-64-16

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