Summary of Joint FIL-TDC Simulation Activities in Air Traffic Control

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FOREWORD

This project was performed by the Civil Aeronautics Administration Technical Development Center under the sponsorship of the Air Navigation Development Board as a joint civil/military effort to meet stated operational requirements for a Common System of air navigation and traffic control.

SUMMARY

This report summarizes the joint air traffic control simulation activities performed at The Franklin Institute Laboratories (FIL) and the Technical Development Center (TDC) of the Civil Aeronautics Administration during a two-year contract period ending in June 1955. The general scope of the work specified that FIL continue to provide engineering services to TDC in the planning and execution of those simulation programs necessary to evaluate operational concepts of preliminary and finalized designs of equipments and techniques of the present and future, and that FIL devise and develop new and improved means of simulation.

Simulation processes included analytical, graphical, and dynamic techniques described in prior reports,[1,2,3] with the largest share of the actual simulation effort being conducted on the TDC dynamic air traffic control simulator at Indianapolis. Most of the statements contained in this report are based primarily on the experience gained to date during the joint FIL-TDC simulation studies. In addition, some of the opinions and conclusions were gleaned from subjective opinions of many CAA operational and planning personnel, TDC progress reports, as yet unpublished statements of Special Working Group 13 of the NAV Panel of the Air Coordinating Committee, and relevant technical and human engineering studies.

INTRODUCTION

The studies of this contract period continued and extended the prior joint simulation activities in accordance with the broad objectives of Air Navigation Development Board (ANDB) amended Project Specification 6.7, which specified a long-term program leading to "the solution of problems in the field of air traffic control."

It is axiomatic that any logical long-range program must have as its guideposts a strong systems team concept and a complete understanding of the problems in their most fundamental terms. It is recognized that the facilities of the dynamic simulator at TDC are somewhat limited, and that many of the complexities, interactions, and peculiar situations of actuality cannot be adequately duplicated or represented in simulation; therefore, the simulator cannot replace actual operational tests of new equipment and procedures. The simulation studies have yielded not only a wealth of needed fundamental and comparative information, however, but information as well concerning new operational procedures and facilities which have wide

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[1] Samuel M. Berkowitz and Ruth R. Doering, "Analytical and Simulation Studies of Several Radar-Vectoring Procedures in the Washington, D. C., Terminal Area," CAA Technical Development Report No. 222, April 1954.

[2] Samuel M. Berkowitz and Edward L. Fritz, "Analytical and Simulation Studies of Terminal-Area Air Traffic Control," CAA Technical Development Report No. 251, May 1955.

[3] Richard E. Baker, Arthur L. Grant, and Tirey K. Vickers, "Development of a Dynamic Air Traffic Control Simulator," CAA Technical Development Report No. 191, October 1953.

and immediate application in many of today's trouble spots. This information might have been either in bits and pieces and inconclusive, or impractical, impossible, unsafe, or even economically infeasible to obtain by any other means. Simulation is providing a powerful tool for rigorous and scientific planning of the interim and common systems of air traffic control with their many ramifications and rapidly changing operational requirements.

DISCUSSION

It is imperative that system planning and development stay at least a few years ahead of the industry's progress. Therefore, it should not be premature now to devote more intensive thought and some redirection of emphasis to what might be done toward realization of the full potentialities of facilities and equipment planned for all areas. Only in this way can tomorrow's problems be alleviated or eliminated properly before they become today's headaches. This should not be misinterpreted to mean that the authors endorse a so-called "continuous search for the ultimate." On the contrary, it is only after the many parameters are laid out and the requirements for each aspect and element of the system are specified in advance that adoption of incompatible and obviously poor setups can be avoided. Thus a reasonable degree of over-all system compatibility and capacity can be assured.

The authors firmly believe that for the next ten years or so, humans will play a large part in the control of both aircraft and air traffic, at least in the common system of peacetime air traffic control as it is known now. Although the navigation and control of aircraft and air traffic, of necessity, may be either partly or completely mechanized in the quite distant future, it is not intended to look that far ahead here. Rather, it is the intent to present realistically those requirements and possible solutions which can be applied in the near and not too distant future using today's equipment and techniques, with a minimum of confusion and revolutionary changes.

Terminal Area.

This section contains a summary of those findings gleaned to date concerning certain fundamental information, design requirements and criteria, and possible methods of satisfying them. Where pertinent and necessary for amplification, short qualifying statements follow each item, classified under the following headings. Although some items relate to several classifications, they are mentioned only once after the first applicable heading, listed in the following order:

Fundamental Information (Using Radar Control).
Airports.
Communications.
Equipment and Displays.
Controllers and the Human Element.
Location and Types of Navigational Facilities.
General Procedures.
Specific Jet Procedures.

Fundamental Information (Using Radar Control).

Contrary to popular belief, stacks are useful reservoirs. They serve as coarse filters for derandomizing traffic flow and for keeping the "hopper" full without periodically starving the system during one period and causing cumulative delays during another. Holding in stacks should be necessary only when system demands exceed the operating capacity. Stacks and associated fixed airways are extremely useful also as backups in the event of equipment failure.

With sustained demand rates of arrivals greater than 15 to 20 per hour, twin-feeding inner stacks should be used; the area should be divided cleanly into two approach sectors. The upper limit of 20 arrivals per hour is dictated mostly by the comparatively low rates of descent of nonpressurized aircraft and the variable descent rates of all aircraft.

Where the sustained demand rate of arrivals is less than 15 per hour, a single offset inner stack (offset from the localizer) should be used. Offsetting will allow final rough spacing variations and straight-in approaches without interference.

With the present radar-separation minimum of 3 miles and an outer-marker distance of about 5 miles, the maximum practical sustained landing rate (using twin-feeding inner stacks) is about 30 to 35 landings per hour per runway.[4] Force-feeding at higher rates will result in large percentages of separations of less than 3 miles; it may also cause a high number of runway wave-offs, even with high-speed exits properly spaced on the runway. Higher approach rates (with the 3-mile minimum), however, may be achieved with shorter glide-slope lengths, some degree of speed control, automatic approaches, and curved approach paths.

If, in the future, the radar-separation minimum is reduced as low as 2 miles, the maximum landing rate (using twin-feeding inner stacks) will be about 40 to 44 per hour. How to accommodate this many landings on a single runway is still a problem, however, unless runway-occupancy rules are changed.

If and when radar separations of less than 3 miles are contemplated, serious consideration must be given to the effects of propeller and/or jet turbulence created on a common path by the preceding aircraft of a sequence. Present data indicate that a good rule to use is a minimum of about 60 seconds separation; for example, the corresponding distance separation between a Constellation followed by a DC-7 approaching at about 150 mph (2 1/2 miles per minute) then would be a minimum of 2 1/2 miles.

When sustained landing rates above 40 to 44 per hour on a single runway are required, some sort of computing device will be required by the approach controllers; and, of course, radar separations will have to be less than 2 miles. This figure of 44 is about the upper limit for manual control, above which it is extremely difficult to maintain safe separations without causing a high workload and a large number of wave-offs.

An average of about 80 to 90 seconds of voice-communicating live time is required (air and ground) per aircraft when manual vectoring with close-in[5] feeder stacks is used. Therefore, the maximum number of aircraft which still can be handled fairly efficiently on a single party-line channel is about $\frac{3600}{90} \times 0.75 = 30$ per hour. This 75 per cent figure has been well validated and takes into account randomness of calls, deviations from the average, and channel busy times. Beyond 75 per cent channel density, the channel starts to saturate. This causes irritation, overconservatism, large delays, cumulative backups, and possible eventual breakdown.

For twin-feeding inner stacks located about 10 miles from the outer marker, the average communicating time per aircraft is about 2 minutes. Therefore, the maximum number of aircraft which can be handled efficiently on a single channel is about 22 per hour.

Airports.

Where multiple airports exist in the same terminal area, instrument runways should be in the same direction.

Crosswind components on the instrument runway should not exceed 15 mph for more than 5 per cent of the time under instrument flight rules (IFR) conditions.

Multiple airports should be avoided unless anticipated system demand exceeds the maximum potential capacity of the single airport.

With high-speed runway turnoffs located no more than 1000 feet apart (starting at about 1500 to 2000 feet from the threshold) and with present runway-occupancy rules, the maximum practical capacity of a single instrument runway is about 45 to 50 mixed landings and takeoffs per hour. With diverging intersecting runways,[6] one predominantly for landings and the other for takeoffs, the maximum practical capacity is about 55 to 60 operations per hour.

Under IFR conditions, where single or intersecting runways are used for intermixing landings and takeoffs, it is better by far (when aircraft are available and ready to go) to land one, take off one, and so forth, than to land a few, take off a few, and so forth. This is easily done by stretching and optimizing present arrival radar separations from an average of about four to five miles. This should be stretched even more, of course, where runway braking conditions are bad.

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[4] This is the average for sustained operations of more than 1 hour; peaks of 35 to 40 landings per hour can be attained for short periods of 15 minutes or so.

[5] "Close-in" is defined as being no more than about eight flying miles from the outer marker.

[6] The diverging configuration referred to here presumes that two runways intersect each other prior to each of their midpoints and then diverge. An example is the Washington National Airport with runway 3 intersecting runway 36 at about 2200 feet beyond the approach end of each runway.

Under present runway-occupancy rules, where sustained rates of about 60 to 80 operations per hour are anticipated, dual (either tandem or parallel) runways will be necessary.

Where simultaneous[7] use of dual runways is required, dual parallel runways should be separated by at least 3000 feet;[8] however, except for the relatively low percentage of instances in which the weather is very bad and the instrument runways cannot be seen (visually or with airport surface detection equipment), it should be mentioned that for parallel runways separated by less than 3000 feet, only a minimum of coordination between controllers would be required to use both runways at a rate close to their independent maximum capacities. The problem of coordinating the taxiing of aircraft from or to some dual parallel landing and takeoff runways is of concern, however, especially when the visibility and location of towers do not permit visual observation of aircraft position.

Adequate taxi strips, warmup pads located near the ends of the runways, and high-speed entrances to the runway takeoff positions should be provided. The warmup pads should be large enough to accommodate at least three large aircraft facing partly into the wind so that any of the aircraft cleared and ready to go can have ready access to the runway without interference from the others.

Communications.

Air/ground and ground/air control communications for vectoring operations should be primarily the direct, voice type, and they should provide for acknowledgment, preferably of the party-line, single-channel, simplex type. The redundancy, acknowledgment, and party-line features (along with voice) are considered essential in minimizing communication times, repeats, uncertainties, the possibility of issuing unsafe instructions (for example, accidentally assigning the same holding altitude to two different aircraft), or the possibility of aircraft pilots misinterpreting control instructions.

If the density of a voice channel is expected to exceed 75 per cent for sustained periods, the numbers and amounts of voice-communicating times can be reduced by transmitting certain static and less essential control information (such as fix clearances, expected approach-clearance time, weather, runway in use, and other data) over a signaling system or broadcast line. Provision should be made for acknowledgment via a private line; however, the voice channel should always be available for override, backup, and emergencies.

Each sector or control function should have at least one discrete frequency.

Significant reductions in communicating time and intercontroller coordination and associated equipment may be realized by the use of a standard flight-numbering system. For example, a general five-digit identification could be coded for air traffic control purposes only to give airline, airplane-type discrete identification and direction; in this way misinterpretations of duplicate flight numbers of the same or different airlines could be avoided.

The system should not require a pilot to monitor more than one voice channel at one time. The number of frequency changes should be held to a minimum.

Equipment and Displays.

For high-density areas using twin-feeding inner stacks, 10- to 12-inch slant radar scopes are adequate for use in vectoring.

Ground-based radar should be one of the primary traffic-control tools in congested terminal areas.

Spacing references at two-, three-, four-, and five-mile radii from the outer marker should be made on a map overlay. This aids the controller in establishing and maintaining proper radar separations. Similarly, a mark should be made two miles from the runway to aid in checking the present two-mile minimum specified for a takeoff followed by a landing.

Radar trail is desirable to give an indication of speed, direction, drift, and relative motion.

Airport surveillance radar (ASR) rotation rates as slow as 15 rpm seem adequate for traffic-control vectoring and identification purposes on uncluttered scopes. As a matter of fact, the number of "hits" per aircraft per scan at 15 rpm is almost double that at 26 to 28 rpm.

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[7] "Simultaneous" means without coordination between controllers handling landing and takeoff aircraft.

[8] Separations are as yet unresolved; Special Working Group 13 of NAV Panel of ACC now is establishing this figure.

For high-density radar-vectoring systems in single major airport areas, only a momentary bloomer code of the secondary radar seems necessary for identification purposes, and then only at the request of the controller.

Radar blips should be as short and narrow as possible to avoid conservatism in establishing the prescribed separations.

Controllers' radar and symbolic displays should be close together to permit rapid integration of the complete traffic picture.

Precision approach radar (PAR) should be used as the primary monitor facility for final-approach functions. An automatic rate-of-closure conflict-warning device would be desirable, and it should be capable of being fed any desired advance-warning time, distance separation, or time separation.

For conventional aircraft operations in the terminal area, good radar coverage up to 10,000 feet altitude is adequate. For jet approaches within a 30-mile radius, coverage up to approximately 30,000 feet would be desirable.

A high degree of efficiency can be effected by locating close-in en route and terminal area approach operations side by side.

Insofar as practicable, the facilities and procedures used to meet the demands of major terminal areas should be uniform and compatible with those meeting the lesser demands of the large majority of relatively minor terminal areas.

Controllers and the Human Element.

A controller should not be required to vector more than three aircraft manually at one time. Beyond three aircraft the channel starts to saturate, with an attendant decrease in safety, a high percentage of separation violations, and resulting "go-arounds."

There should be a clear division of authority between controllers and assistants.

Outer-marker-to-runway distances should be as short as practicable to avoid unnecessary controller conservatism in allowing for performance variations on final approach. Shorter approaches will allow closer spacing, and consequently, higher peak efficiencies.

The use of radars in dark rooms should be avoided. The use of suitable ambient lighting such as the TDC-developed trichromatic white lighting, the U. S. Air Force broadband blue lighting (BBBL), and an FIL-developed "minus-green" system should be evaluated for radar rooms. The illumination should be sufficient to allow normal reading and writing without attendant eyestrain, it should not cause significant reflectivity from the radar scopes or loss of contrast, and it should not cause sudden shocks or strains for a person entering or leaving the radar room.

Locations and Types of Navigational Facilities.

Twin-feeding inner stacks, if used, should be offset and symmetrical about the outer marker and as close to the minimum flight paths of all the entry airways as possible. For maximum efficiency and minimum communications, they should be no farther than about eight to nine statute miles from the outer marker. This distance will allow sufficient flexibility in path-stretching to establish the prescribed radar separations; and it will minimize workload, coordination, and variability. It also will preclude the possibility of requiring a controller to vector more than three aircraft manually at one time when using three-mile minimum radar separations.

Inner fixes should be offset sufficiently from the outer marker and final approach to avoid disruption of normal holding procedures when accommodating a straight-in jet approach or an emergency descent through the holding altitudes.

A minimum offset distance of about 3 1/2 miles should be adequate with reliable radar returns. This still allows sufficient distance for reasonably fine path-stretching (vectoring) operations. Furthermore, it should be stated that the shorter flying distances from the inner fix to the outer marker (down to the minimum of about 3 1/2 miles) result in less controller workload, and consequently, in higher system efficiency and safety.

Altitudes at close-in inner fixes should be no lower than 2500 feet above the airport elevation. This will leave at least 1500 feet open for departures and refeeding possible missed approaches; it also will allow an altitude cushion in the event of radar failure. Altitude separations of 1000 feet should be maintained in the holding patterns.

When traffic demands are heavy for sustained periods, and to allow for periods of airport shutdown, blocked runways, or for similar reasons, there should be a sufficient number of outer stacks to provide cushions for traffic backups and proper feeding of the inner stacks. Locations and prescribed altitudes of these outer fixes should not block en route and departure airways and altitudes.

General Procedures.

Where practicable, airways should be arranged to avoid normal clutter areas on radar scopes.

Inbound and outbound traffic routes should be as independent of each other as practicable. Where crossovers occur, blocked (reserved) altitudes should be used; however, sufficient flexibility should be provided to allow turning these altitudes over to either function as the need arises.

Similarly, in multiairport terminal areas, traffic routes for each airport and for inbound and outbound traffic at each airport should be independent. This makes for a minimum of data transfer, coordination, and resulting conservatism.

Maximum speeds, specified holding speeds, and a mild degree of speed control should be prescribed in high-density areas.

System flexibility should be such that during periods of light traffic or when gaps occur during heavier periods, aircraft can fly from outer fixes directly to the outer marker. Thus they can bypass the inner fixes and avoid unnecessary extra mileage, effort, and possible cumulative backups later.

When demand is greater than capacity for sustained periods, flow control should be exercised. The amount and type of flow control should take into account all pertinent factors without being arbitrary. Some type of traffic-delay predictor or computer should be more dependable than the unpredictable and sometimes overconservative human controller.

Provision should be made for feeding aircraft on a first-come, first-served basis, with delays (if any) averaged out on an impartial and equal basis to suit maximum over-all capacity. Provision also should be made to reverse sequences where necessary in the event of emergencies, weather minimums for various aircraft types and pilots, refeeding missed approaches, and similar situations.

Where traffic includes some beacon-equipped aircraft, arbitrary assignment of priorities to these aircraft at the expense of the non-beacon-equipped aircraft should not be practiced as a general rule. Instead, each individual case should be treated on the basis of the over-all benefit to all of the traffic involved.

Insofar as practicable, aircraft should descend at certain established standard rates; that is, about 500 feet per minute (fpm) for unpressurized types, 1000 fpm for conventional pressurized types, and about 2000 fpm for commercial jets. This procedure will aid the controller in timing and coordinating the approach sequences.

Variable outer-marker separations[9] should be used for the different sequences of slow, medium, fast, and jet aircraft. These separations take into account the airspeeds of the different types of aircraft and their variability in performance, different glide-slope lengths, the particular radar minimums being used, and headwinds. Turbulence on common paths also should be considered. Compatibility of landing rate with runway capacity also should be taken into account to minimize the number of probable wave-offs.

Where practicable, all path-stretching operations should be conducted in the control sector of the controller who is directing the maneuver to minimize workload, coordination, and conservatism; however, there are times when "spill-over" may be necessary to provide a final safe separation adjustment.

Provision should be made for refeeding a missed approach into gaps available in the inner feeding stack or stacks or directly back into the vectoring area. This will avoid making aircraft go all the way around or to the top of the stack via a roundabout route. Provision still should be made for a fixed missed-approach procedure and blocked altitude, however, in the event of equipment failure (radar, communications, or other equipment) or possible conflict with outbound routes and altitudes.

Distance sufficient to allow necessary bracketing between interception of the localizer to the outer marker should be provided; approximately one to two miles should be sufficient in most cases for conventional aircraft.

Inbound and outbound patterns should be arranged so that little confusion and delay should result when a wind shift dictates the use of another runway.

Patterns should be arranged to minimize ground noise. A bare minimum of 1200 feet altitude should be maintained until final descent for landing.

The major part of the navigation to the inner feeder fixes is performed by the pilot and is monitored by the controller. This practice should be continued.

Provision should be made for handling overtraffic without adversely affecting inbound and outbound traffic.

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[9] Berkowitz and Fritz, op. cit.

Laddering inbound aircraft in altitude is undesirable. All altitude changes should be held to a minimum.

Turns on passenger airliners should not require angles of bank exceeding 30° for passenger comfort.

If approach-control computers are used, safety should not be compromised by use of computers which work on a probability basis unless sufficient altitude separation or manual override and warning times are provided.

For maximum efficiency and safety in any approach-vectoring system (manual, semiautomatic, or completely automatic), the prescribed procedures and associated separations should provide for:

1. Allowing for speed differences within and between various aircraft types.
2. Rescheduling gate times by stretching the path or slowing down the No. 2 aircraft of a sequence if the No. 1 aircraft is late, or vice versa. Likewise, adjustments should be made for No. 3, No. 4, and so forth.
3. Handling multiairport areas.
4. Handling missed approaches.
5. Clearing obstructions.
6. Bypassing airspace reservations.
7. Integration with either all beacon-equipped or partially beacon-equipped aircraft.

The system arrangement should be flexible enough to allow radar vectoring of beacon-equipped aircraft through cluttered areas on the scope while simultaneously using Air Force-Navy-CAA (ANC) and timed procedures for nonequipped aircraft. This is not meant to imply favoritism; on the contrary, this should increase over-all system capacity and decrease delays. To put it another way, beacon-equipped aircraft then would encounter less delay than usual, without radar assistance, and nonequipped aircraft probably would be better off; in no case should they be worse off. Average separations of 2 1/2 to 3 minutes for sequences of beacon-equipped and non-beacon-equipped aircraft can be effected while maintaining average separations of 1 1/2 to 2 minutes between sequences of beacon-equipped aircraft and average separations of 3 1/2 to 4 minutes between sequences of non-beacon-equipped aircraft.

The width, thickness, and number of secondary radar blips displayed on the radar scope should not clutter the radar-vectoring area between the inner feeder fix or fixes and the outer marker; otherwise, peak proficiencies would be difficult to maintain due to conservatism, uncertainties, confusion, possible creation of false targets, and even cancellation of targets at certain separations.

Helicopter flight paths should avoid interference with fixed-wing traffic and should avoid flights in the vicinity of active landing runways where practicable. Helicopter approaches at 90° to the runway can be effected if separation with fixed-wing traffic is coordinated.

Specific Jet Procedures.[10]

Jet departure clearances should be available before or immediately after the jet leaves the parking ramp. Upon reaching their warmup pad, approximately 1 1/2 minutes should be allowed for warmup, checkout, and runway occupancy.

If possible, any anticipated departure delays of more than a few minutes should be absorbed on the ground prior to starting the engines.

Unrestricted climbs from takeoff to optimum altitudes are desired. Lateral separation can be provided either by multiple navigational tracks, radar vectoring, or both. Present information reveals that allowance should be made for rates of climb averaging about 2000 fpm during the first 10,000 feet.

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[10] An excellent presentation of jet problems, requirements, and possible solutions may be found in the work by C. J. Stock and W. S. Ridenour, "Turbo-Powered Aircraft and Air Traffic Control," CAA Airways Operation Division, Region 1, November 1954. It should be stated, however, that nothing in this section should be interpreted to imply that commercial jet aircraft should be given special handling or priorities. On the contrary, it is believed that commercial jets should be able to operate compatibly with their older counterparts; however, each jet flight should be given every judicious consideration (at least in their infancy) without being considered an emergency.

Any appreciable jet holding should be at high altitudes, 20,000 feet or higher. Sufficient airspace should be provided to account for high winds and turns at one-half the standard rate (1 1/2° per second).

Jet approaches should be handled in high-altitude feeding stacks offset from the final-approach course.

Upon being cleared from their high-altitude feeding stacks, jets should be given irrevocable outer-marker times. Their high rates of descent (up to 2000 fpm and higher) should be taken into account. It would be desirable if jets could maintain some standard descent rates to reduce uncertainties and resulting conservatism.

The straight-in approach distance to the outer marker should be at least 10 miles long. An additional radio fix on the localizer course should be established at this intercept distance. This will serve as an aid to the pilots, as an emergency low-altitude holding fix, as a checkpoint for radar identification, and as a close-in checkpoint for refining controller estimates of gate times. It also will permit some path-stretching via radar vectoring to suit more precise approach intervals between this fix and the outer marker.[11]

En Route Area.

Parts of five Air Route Traffic Control (ARTC) areas were simulated. Controllers from the corresponding ARTC Centers participated in many of the simulation runs, although members of the TDC staff served as controllers in most of them. Emphasis was placed mostly upon (a) the Indianapolis ARTC area, in order to study preliminary arrangements for the Airways Operations Evaluation Center (AOEC); and (b) the New York ARTC area, in order to study some of the high-density traffic problems which exist there. In some cases traffic samples were constructed directly from actual flight strips provided by the various ARTC Centers. All traffic samples included the major en route control problems such as crossing, overtake, and altitude change.

Four 12-inch sloping-panel radar displays were used during the simulation program, as well as a 30-inch horizontal radar-plotting scope. Recently some interesting tests have been conducted with television-projection equipment which was used to project a radar picture down on the panoramic horizontal display board.

Communications, both radio and interphone, were simulated on simplified phone circuits, with clocks and counters used for communication measurements. In the later stages of the simulation program, the limited data-transfer device (LDTD) was used for center-tower communications.

Radar Control.

The objective of the first series of en route simulation runs was to provide a preliminary evaluation of those concepts under consideration for the first arrangement of facilities for the AOEC. The initial plan for the AOEC called for implementation of a complete radar air traffic control system in both en route and terminal areas. Therefore, a radar simulation program was outlined jointly by representatives of TDC, Bell Telephone Laboratories, and FIL. This section deals with the conclusions reached during the radar simulation runs. These conclusions will be discussed as they relate to displays, communications, and procedures.

1. Displays. The 30-inch horizontal plotting scope is preferred to the 12-inch sloping-panel radar scope because a much better scale factor can be used for a given area of coverage and radar targets can be followed with cardboard target markers on the horizontal scope (see Fig. 1). The radar pips could be seen below the target markers when viewed on a slant from the normal control positions due to separation between the scope overlay and the scope face.

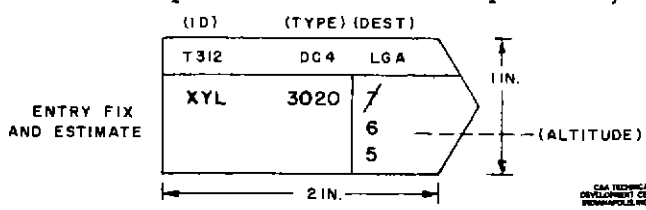

Fig. 1 Radar Target Marker

[11] Figure 3 in CAA Technical Development Report No. 191 shows a terminal-area configuration used successfully in recent simulation studies for integration, without special handling, of jet and reciprocating-engine operations.

Essential radar control information consists of:

A. Aircraft identification.
B. Type of aircraft (for speed, rate-of-climb, and descent information).
C. Altitude (including altitude to which aircraft is cleared and critical altitudes to be passed through in climb or descent).
D. Entry point into sector.
E. Estimated time of entry.
F. Desired route through sector (usually destination and entry point into sector determine route).

Target markers should carry all of the essential control information. This is much more desirable than having some of the information on target markers and the remainder on a supplementary display because the latter arrangement causes an inefficient division of the controller's attention. For reference purposes, less essential information can be written on the backs of the target markers or carried in a supplementary file.

During periods of radar failure, time estimates are needed for control purposes. In simulated radar-failure tests, estimates were added to the cardboard markers and the markers were moved on a block-to-block basis as fix reports were received from the aircraft. This display proved adequate for control purposes and led to development of the panoramic display for control in nonradar areas.

In areas of high-density traffic the scale factor of the radar display should be no greater than 2 miles to the inch, particularly when target markers are used. If circumstances necessitate a higher scale factor (for example, 5 miles to the inch), a supplementary display is needed for the posting of control information. In simulation tests the panoramic display was found to be a better supplementary display than the flight strip. Correlation of information on two pictorial displays (radar and panoramic) proved to be easier than correlation of information on a pictorial display (radar) and a symbolic display (flight strip). A scale factor of 2 miles to the inch for the panoramic display also was found to be optimum generally, regardless of the scale factor of the radar. It appears, however, that it might be necessary to use a 1 1/2- or 1-mile-per-inch scale in certain very-high-density areas owing to the large number of target markers involved.

Simulation tests also showed that the panoramic display is better than the flight strip for the control of aircraft in areas adjacent to radar-coverage areas. In some tests the horizontal scope was mounted in a hole in the panoramic display so that radar and nonradar areas were united. In more recent simulation tests it was found that the television-projection equipment was particularly well suited for use with the panoramic display. The radar picture was projected down onto the panoramic display, and the target markers were aligned periodically with their associated radar pips. Contrary to expectations, the controllers' heads and arms did not interfere with the projected radar picture often enough to cause troublesome obscurement of the picture. As in the case of the horizontal scope, the transition to nonradar control, if the radar fails, is an easy one. The possibility of combining radar pictures of adjacent areas by projecting them on a single panoramic board is being investigated at TDC presently.

2. Communications. A large majority of aircraft should be in direct radio contact with the controller if radar control is to be effective. A simplified one-bay data-transfer board with electromechanical indicators should be satisfactory for the transfer of essential control information (simplified flight plans) between radar controllers; however, an interphone line still would be needed for unusual coordination messages and as a backup in case of equipment failure. The data transfer board was simulated with flight strips and pencil (Fig. 2); further tests were postponed pending the availability of the actual Type C equipment.

ENTRY FIX	ID	TYPE	DEST.	ALT.	ENTRY TIME
LAF	A507	DC 6	MIA	18	1012
MTN	E 712	DC 4	CHI	11	1013
GFD	T57	CON	STL	12	1003
FLD	T378	404	IND	5	0958

Fig. 2 Data-Transfer Display for Radar Control

Interphone communication procedures during radar control are much simpler than they are during nonradar control. During most of the simulation program interphone was used for intercontroller communications.

The actual LDTD was used in simulation runs of the New York area for tower-center coordination. Data for inbound aircraft were transferred from center to tower in the manner in which the LDTD was intended. In other runs data were transferred in reverse (tower to center) in order to investigate the possible use of the equipment for departure aircraft. In both cases there was no doubt that the LDTD performed a useful function in relating aircraft with specific altitude slots under joint tower-center control. There still is some question, however, as to whether the equipment is flexible enough to handle mixed IFR-VFR arrivals, altitude-inversion problems, and other complicated problems which occur in the en route terminal area transition zone. In any event, interphone still will be necessary as a communications backup.

3. Procedures. Tower-center coordination is reduced when the terminal-area controller and the en route controller work together on a common horizontal plotting scope with target markers. During simulation runs flights en route to the terminal area within the simulated sector were stepped down to a reasonable altitude by the en route controller and then were instructed to change frequencies to the terminal-area controller. By pointing to the target marker the en route controller indicated to the terminal-area controller that the flight was changing over to his control. Similar procedures were used for departing aircraft. This arrangement worked flexibly and the workload was distributed evenly. Traffic densities up to 45 aircraft per hour were handled in this manner. En route sector controllers also worked well together on a common horizontal display.

The use of target markers with an enlarged radar picture, in conjunction with complete radio coverage by the controller, provides a desirable division of duties between the controller and his assistant. The controller can concentrate his attention on the radar display and communications with the aircraft while his assistant handles routine communications with the adjacent sectors, makes up target markers, and computes estimates.

The transfer of aircraft control between remotely located radar sectors controlling adjacent areas is simple and straightforward, provided that:

A. Flight-plan information precedes the aircraft by about five minutes.
B. There is from 10 to 15 miles overlap in the coverage of the radars.
C. Aircraft report upon entering a sector for radar-identification purposes.
D. There are adequate rules for aircraft changing altitude near the common sector boundary; for example, climbing or descending aircraft should fly well to the right of the airways or on very-high-frequency omnirange (VOR) alternate airways.
E. There are no major crossing routes on or immediately adjacent to the sector boundaries.

When radar sectors are stratified and the scopes are remotely located, vertical coordination can be accomplished by establishing transfer altitudes at the boundary between the sectors.

In general, controllers are very conservative in maintaining separations between aircraft in cases of crossing and overtake. During simulation, when estimates showed that aircraft would be less than 15 or 20 miles apart at the same altitude, altitude separation usually was initiated. Present radar-separation standards call for a minimum of 3 or 5 miles, depending on the range of the aircraft from the radar site.

Panoramic Display, Without Radar.

In this section the simulation studies of the panoramic display are discussed with respect to its advantages and disadvantages in areas where radar is not available; that is, using ANC procedures.

The basic operation of the panoramic display is quite simple and straightforward. Each aircraft is represented by a target marker (Fig. 3) which contains relevant control information. The target markers, or "shrimp boats," are placed on a horizontal map display and are moved on a block-to-block basis. When an aircraft makes a fix (position) report, the corresponding marker is moved so that it occupies a position between that fix and the next fix on its route. If fix reports reach the controller promptly, the panoramic display provides the controller with an up-to-date, two-dimensional picture of the aircraft in and around the area which he controls; the altitude information written on the marker provides the third dimension.

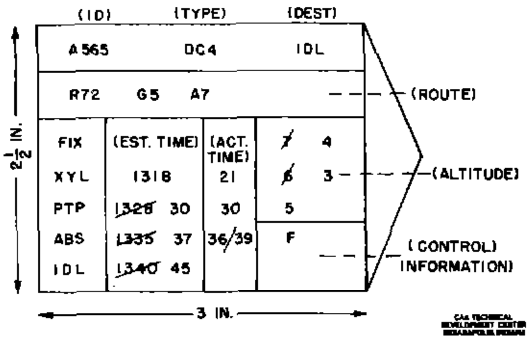

Fig. 3 Panoramic Display Target Marker

Although simulation studies have not proved conclusively that 100 per cent direct air/ground center communications are vital to the nonradar operation of the panoramic display, they indicate that it is very desirable that a large percentage of aircraft be in direct radio contact with the controller.

1. **Developments in the Panoramic Display During Simulation.** At first, clearances were issued on a fix-to-fix basis. It soon was found, however, that many of these short clearances were unnecessary, and eventually clearances to destination could be issued in most cases. Other developments during simulation included the use of small racks on which the target markers of aircraft which had not yet entered the panoramic-board area were mounted for easy inspection by the controller, and the use of buff and green shrimp boats to show direction of flight. It was found that about two miles per inch generally was the most satisfactory scale factor.

2. **Advantages of the Present Panoramic Display.** The following list outlines some of the advantages of the panoramic display and summarizes the opinions of many controllers who made the dynamic-simulation runs:

A. The amount of data which the controller must scan to follow traffic is much less than that required by the flight-strip display.

B. The pictorial presentation of relationships between aircraft requires less mental visualization of problems by the controller than does the flight-strip display.

C. Controllers found that they needed less time to learn to control traffic in an area with which they were unfamiliar than they did with flight strips. It is believed that panoramic displays also will reduce the time required to train new controllers.

D. Coordination between controllers is reduced when two or three sectors are controlled on the same display.

E. The assistant controller's writing load is relatively light. This enables him to assume a larger part of the controller's communication load and to post information on new aircraft more rapidly.

3. **Disadvantages of the Present Panoramic Display.** Some disadvantages of the present panoramic display are listed below. These also are based on controllers' opinions.

A. The area of the surface which the controller must scan in order to see all pertinent traffic usually is larger than that of flight-progress boards.

B. In some cases critical crossing problems were not recognized by controllers soon enough to take the most effective measures to solve them.

C. It was difficult to coordinate and issue clearances for large altitude changes such as those occurring near terminal areas because the target markers for the aircraft involved often were many feet apart on the panoramic board.

D. The target markers show the present positions of aircraft; whereas, data needed for the solution of problems involving future positions often are on several target markers at various positions on the display instead of in one central location as on the flight-progress board. This sometimes make prediction and problem solution difficult.

E. In scanning the panoramic display, controllers had some difficulty in determining which aircraft eventually would enter their sectors and which would not.

F. Controllers and assistant controllers sometimes had difficulty reading the shrimp boats because of their distance from the eye or because of their position on the display (sideways or upside down).

En Route Quantitative-Measurement Program.

Operation of the panoramic display was compared quantitatively with that of the standard flight-progress board, and no radar was used. A third system employing full radar control also was tested.[12] The highlights of this program are discussed in the following paragraphs.

The 3 displays and their associated systems were tested with 5 different traffic samples, each 1 hour in length, which varied in density from 20 to 40 aircraft per hour. The sample construction was based on actual traffic in the area simulated, the Indianapolis air-route and approach-control sectors. Direct controller-pilot radio communications were simulated in all runs. Data were obtained on unsafe traffic separations (or conflicts), delays to aircraft, altitude changes, and communications loadings.

The radar system, which included the small minimum separation standards used in radar control, was superior to the other systems in all respects. With one important exception, no significant differences were found between the flight-strip display and the panoramic display. In the panoramic runs, however, the assistant controller was able to assume a larger share of the interphone load than in the flight-strip runs because he had much less writing to do.

Subsequently, in some short tests designed exclusively for the study of display functions, it was found that the panoramic display was superior to the flight-strip display with respect to the time needed to spot conflicts and to make decisions regarding altitude changes. This short test technique shows promise for future quantitative comparisons because the experimental design is relatively simple and a large amount of data may be obtained in a relatively short time.

SOME MATHEMATICAL METHODS FOR MEASURING CAPACITY, CONGESTION, AND DELAYS

The purpose of this section is to summarize some of the mathematical analogs which can best describe certain air traffic control problems. They are included in this report because the mathematical model, or analog, is the basic tool for simulation. Once the model itself is derived, it is simple to introduce changes and to evaluate them, thus providing first-order approximations at virtually no cost.

For purposes of this report, three basic models have been developed covering three major aspects of air traffic control. They are: departures, en route operations, and terminal-area arrivals.

Departures.

Before each aircraft leaves the runway, the pilot is assigned a path through the terminal area. This path is determined essentially by the destination of the flight and its direction. In addition, the pilot is given an altitude assignment which may be his final altitude; in the case of high-density airports, it is an interim altitude which applies only in the terminal area. It is apparent that an aircraft can be sent along any path so long as there is an available altitude and that delays will occur when all of the altitudes along any given path are blocked.

This situation is analogous mathematically to a telephone system with several trunks; therefore, it is possible to apply the model for that system to this one, with some modifications. The main purpose of the model, of course, is to predict delays for a variety of conditions. Thus, if m aircraft per hour request a given path which has c available altitudes, with a separation of t minutes between successive aircraft at the same altitude, the congestion factor ϵ can be calculated:

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[12] R. S. Miller, "Enroute Quantitative Simulation Studies," Franklin Institute Laboratories Working Paper No. 8, Project No. 2384-1 (Limited Distribution), August 1955.

$$\epsilon = \frac{mt}{60\ c} \tag{1}$$

Using this result, enter Fig. 4 and read the expected average delays directly on the appropriate curve. Because the delays are given in units of separation times, they can be converted to minutes by multiplying the length of the separation.

Such a model, of course, has many uses because it is possible to vary any or all of the three major variables (m for traffic, t for separation, and c for altitudes) and to assess the delay results very quickly. As an illustration of some of these effects, Table I shows the average delays for 6 different conditions of separation and number of altitudes for a constant traffic load of 8 aircraft per hour. A drastic increase in delays occurs for the change in separation from 15 minutes to 20 minutes for 3 available altitudes as contrasted with 4 available altitudes.

The En Route Area.

Altitude-Distribution Problem

When a pilot files his flight plan prior to departure, he specifies the route and altitude he desires. Whenever possible, after the aircraft has passed the terminal area, it is assigned to that altitude if it is open. By definition, an altitude is open to an aircraft if no other flight has preceded it by less than the accepted separation.[13] Because of the bunching effect of

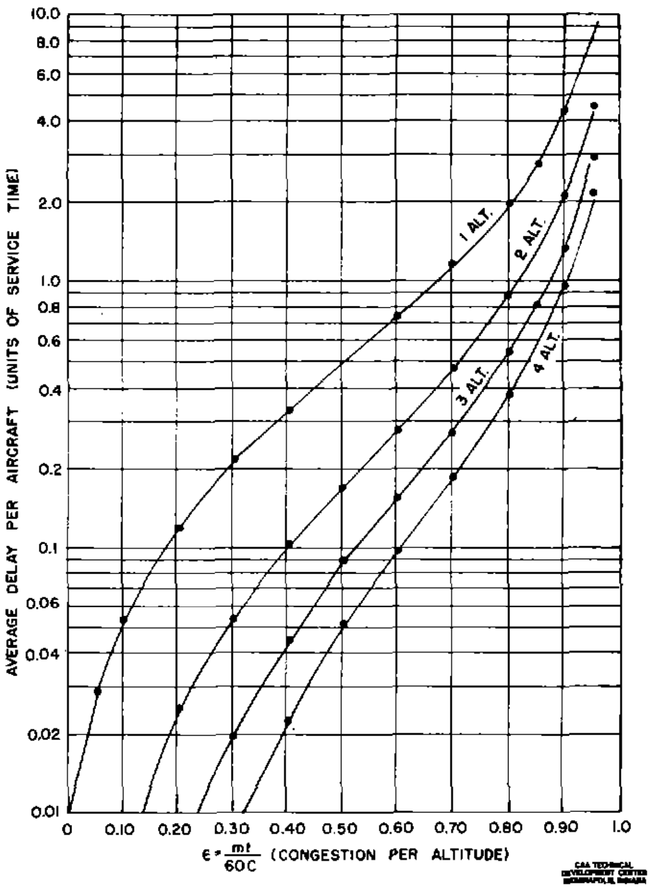

Fig. 4 Average Delay per Aircraft for One, Two, Three, and Four Available Altitudes

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[13] ARTC Centers also must consider overtakes. Frequently a faster aircraft 20 to 30 minutes behind a slower aircraft will be assigned a different altitude to eliminate the necessity for additional control later.

TABLE I

AVERAGE DELAYS IN MINUTES PER ROUTE*

Number of Available Altitudes	Effective Separation In Minutes		
	10.0	15.0	20.0
3	0.6	3.4	24.0
4	0.1	0.8	3.0

*Eight aircraft per hour.

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random traffic, altitudes frequently are not open; therefore, some aircraft must be sent to altitudes other than those requested. Such action, of course, replaces the alternative of delaying the flights in question; in a sense, this creates a "refugee" problem at the other altitudes. This results in a peculiar distribution of intervals between flights at each altitude because the final flow of traffic is composed of some of the aircraft which requested the altitude plus some which were displaced from other altitudes. Mathematically, this can be written:

$$a = me^{-mt} + d \tag{2}$$

where

a = actual number of aircraft observed.

m = the number of aircraft which originally asked for the altitude.

e = the mathematical constant 2.718.

t = the average separation between aircraft.

d = the number of displaced aircraft.

Several actual distributions of intervals from the heavy New York and Washington traffic areas were tested against this model. The agreement between theory and the actual data was very close.

One of the functions of this model is to provide insight into the internal transformations which take place under present-day conservative rules. Using the most frequently observed average en route separation in use today (15 minutes), therefore, some of these characteristics for several observed traffic rates have been calculated. They are shown in Table II. It should be remembered that these figures are applicable only when the observed rate persists for several hours; that is, steady state.

From Table II it is readily seen that the number of refugees amounts to about half the number sent away. In other words, for every two aircraft sent to other altitudes, there remains a gap large enough to allow one airplane to slip in from another altitude. Although this condition is tolerable for one or two busy altitudes along a route, it is obvious that as the number of busy altitudes increases, there exists less and less room to which the refugees can go. At that point delays become inevitable. A survey of the busier en route fixes in the New York and Washington areas disclosed only two altitudes over two fixes which actually averaged two aircraft per hour over an eight-hour period, with individual peak periods of three and four per hour, maximum.

TABLE II

SINGLE ALTITUDE CHARACTERISTICS
IN THE MULTIALTITUDE EN ROUTE AREA*

Average Observed Number of Aircraft	Number of Original Requests	Number of Requests Granted	Number of Refugees to This Altitude	Number Sent to Other Altitudes
0.5	0.54	0.47	0.03	0.07
1.0	1.14	0.86	0.14	0.28
1.5	1.84	1.17	0.33	0.68
2.0	2.66	1.36	0.64	1.30
2.5	3.63	1.47	1.03	2.16

*Hourly averages.

Altitude-Change Problem.

Aircraft in flight are often required to change altitudes either because of unfavorable weather or because of the exigencies of the traffic-control picture. At present, the large ANC separations required for one airplane to pass through the altitude of another going in the same direction create complications which restrict the free flow of aircraft.

The mathematical model is highly adaptable to showing the degree of complexity. Because an altitude-changing flight must be separated from both aircraft in front and those behind it, the problem resolves itself into finding how much free time[14] is available at the altitude being crossed. From the model, this proportion of free time is:

$$P_{FT} = \frac{e^{-KB}}{e^{-Kt}} \quad (1-at) \qquad (3)$$

where

a = actual number of flights observed at an altitude.

t = minimum longitudinal separation.

B = the sum of the front and rear separations required for crossing.

$K = \frac{a}{e^{-at}}$ = total number of aircraft demanding an altitude.

For example, the case may be considered of an average of 2 aircraft per hour flying at an altitude with a minimum separation of 15 minutes; with B, the total required separation for aircraft going in the same direction, equaling 20 minutes. From the formula the proportion of free time is found to be 0.38; or, only about 4 out of 10 aircraft which want to cross the altitude can do so without delay under the assumed conditions.

This example may be considered to be fairly representative of the crossing problem for same direction traffic. Turning to the opposite direction problem for altitude-changing aircraft, however, a much more serious situation exists. According to present ANC rules, an

[14] In this illustration and those following, only time separation is considered. It is true that controllers sometimes use lateral (right-side) separation, fix separation, and geographical separation. In most cases, however, time separation is the basic separation employed.

aircraft cannot cross through an altitude unless it has a given number of minutes separation f from all opposite direction aircraft at that altitude. Therefore, an altitude is blocked to opposite direction traffic by two aircraft if they are closer than some minimum distance S, according to:

$$S = 2f\,(V_L + V_C) \tag{4}$$

where

V_L = the speed of the two level flights.

V_C = the speed of the crossing flight.

To show the magnitude of the problem, the data in Table III were computed with the assumption that f, the separation, is ten minutes.

TABLE III

MINIMUM BLOCKING DISTANCES IN MILES
FOR ALTITUDE-CROSSING AIRCRAFT

Speed of Altitude-Changing Aircraft (mph)	Speed of Aircraft in Level Flight (mph)			
	180	240	300	360
	Blocking Distances (miles)			
360	180	200	220	240
300	160	180	200	220
240	140	160	180	200
180	120	140	160	180

For an aircraft traveling at 240 mph, crossing an altitude at which flights are traveling at 360 mph, the minimum permissible distance between the two level flights is 200 miles.

These figures take on a more vivid meaning when it is realized that the distance from Washington to Philadelphia is about 120 miles, from Washington to New York is 215 miles, and from New York to Boston is 192 miles. It is no surprise, then, to find so many one-way airways between these cities because the whole problem is eliminated in this manner.

Another interesting figure in connection with this problem is the minimum time separation B between two level flights at the same altitude which will permit another aircraft to cross their altitude between them. The formula is:

$$B = \frac{S}{V_L} = \frac{2f\,(V_L + V_C)}{V_L} \tag{5}$$

Table IV was constructed for the same conditions as Table III.

When these values for B are inserted into Equation (3) it becomes apparent that the chance for an aircraft to change altitude through the altitude of opposite direction traffic is not far from zero.

TABLE IV

MINIMUM TIME SEPARATIONS IN MINUTES
WHICH PERMIT ALTITUDE-CROSSING

Speed of Altitude-Changing Aircraft (mph)	Speed of Aircraft in Level Flight (mph)			
	180	240	300	360
	Minimum Time Separations (minutes)			
360	60	50	44	40
300	53	45	40	37
240	47	40	36	33
180	40	35	32	30

En Route Intersections.

Because of the nature of the airway structure, it is inevitable that aircraft on converging courses must pass points of intersection. As a result, each such point becomes a troublesome spot where proper separations must be maintained not only between successive aircraft but between crossing flights as well. If the valid assumption is made that the average separation between the two classes of traffic is the same, then the en route model yields the following formula for the probability that one route blocks a fix:

$$P_B = 1 - e^{-Kt} (1 - at) \qquad (6)$$

where

$$K = \frac{a}{e^{-at}}$$

Then, to combine the activities of two routes over one fix, the following expression may be used which gives the probability of conflict at the intersection of two routes:

$$P_e = \frac{a_1 P_{B_1} + a_2 P_{B_2}}{a_1 + a_2} \qquad (7)$$

This formula has been evaluated for several conditions, and the results are given in Table V.

TABLE V

PROBABILITY OF CONFLICT AT THE INTERSECTION OF
TWO MAJOR ROUTES AT ONE ALTITUDE

	Average Separation, 10 Minutes; Aircraft per Hour, Route 1			Average Separation, 15 Minutes; Aircraft per Hour, Route 1		
Aircraft per Hour, Route 2	1	2	3	1	2	3
1	0.32	0.40	0.43	0.46	0.56	0.58
2	0.40	0.58	0.66	0.56	0.78	0.85
3	0.43	0.66	0.78	0.58	0.85	0.95

It is obvious from Table V that the probability of conflict is quite high with present ANC separations. It should be emphasized, however, that these figures would hold only if the controller did not intercede. These figures point up a very serious problem and lead to one or more of three solutions. First, whenever possible, intersecting aircraft should be given altitude separation, thus completely removing the problem. Second, in areas where altitudes are at a premium and must be used for intersecting flights, the use of radar to reduce separations at these points to a reasonable but safe figure would remove a large part of the difficulty. Another solution would be the use of a simple electronic computer which always would generate the optimum answer for any given problem. Even the best of controllers may not always make optimum decisions when under the strain of heavy traffic loads.

One or more of these solutions must be adopted in the near future as traffic increases. Probably the most easily implemented, and also the most fruitful, would be the use of radar vectoring.

Terminal-Area Arrivals.

Aircraft arrive in a terminal area from many directions and many altitudes at random times. It then is the function of approach control to marshal all of these aircraft into an orderly array, properly sequenced and spaced, through the outer marker and down the glide slope. In this process of funneling aircraft from many paths into one single line in which there is a large spacing between successive flights, it is inevitable that some delay will occur. Of course, the total delay increases as the traffic density increases.

A mathematical model for this aspect of air traffic control was developed at The Franklin Institute sometime ago.[15] Essentially, that model incorporates not only the capacity and the traffic load, but the duration of the traffic as well. The basic results are given in Figs. 5 and 6 which show delays for various values of congestion, defined as the arrival rate divided by the effective acceptance rate. More practically, it is the same as Equation (1) where c is equal to unity. Both the time t and the delays are measured in units of average separation (service) times. Figs. 8 and 9 of Technical Development Report No. 251[15] show examples of their use.

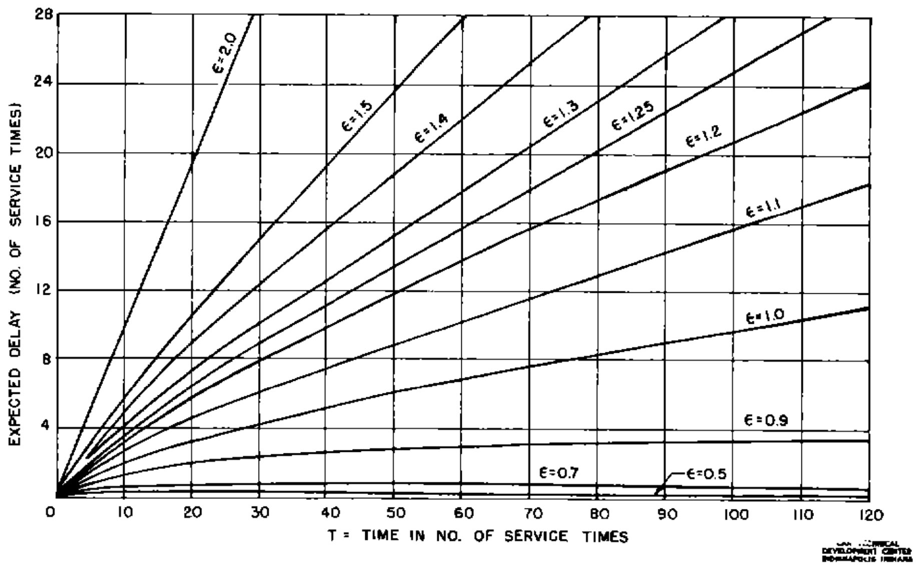

Fig. 5 Expected Delay of Aircraft Arriving at Time (t) for Several System Loadings

[15]Berkowitz and Fritz, op. cit.

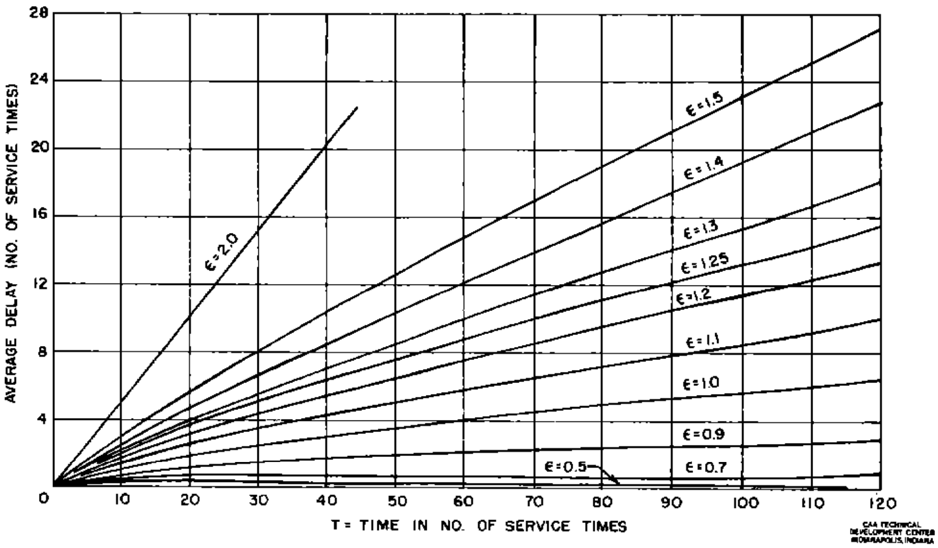

Fig. 6 Average Delay of All Aircraft During the Time From 0 to t for Several System Loadings

NEW AND IMPROVED SIMULATION FACILITIES

Under this contract, three projects leading to new and improved simulator facilities were completed. Two of these projects, the development of an electronic-target generator and the development of a synchro-target repeater, resulted in equipment which was constructed for evaluation at TDC. The third project was a study program resulting in the establishment of functional requirements and characteristics for a new universal air traffic control simulator.[16, 17, 18]

The development and construction of the electronic-target generator was undertaken for several reasons. It was believed that an electronic generator would possess higher accuracy than the TDC optical-target generators. Also, an increase in the number of target generators was contemplated, and it was desirable to explore the qualities and compatibility of an electronic generator before embarking on any expansion program. Because it was not necessary that electronic generators be located in the same room, it was believed that with respect to housing requirements they might offer greater flexibility than would optical generators.

The synchro-target tracker was developed to provide an inexpensive device which would make readily available another entire radar sector to be used in conjunction with the TDC electromechanical simulator in the study of multisector problems. It was believed that this device might be useful also for radar-control training, and that experience with it also would indicate its possible advantages or disadvantages as a manual method for remoting radar information.

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[16] I. Glassman, "An Electronic Target Generator for Use in TDEC's Electromechanical ATC Simulator," Franklin Institute Laboratories Working Paper No. 5, Project No. 2384-1 (Limited Distribution), June 1955.

[17] J. C. Price and R. S. Grubmeyer, "A Synchro Target Repeater," Franklin Institute Laboratories Working Paper No. 6, Project No. 2384-1 (Limited Distribution), June 1955.

[18] R. S. Grubmeyer, "A New Air Traffic Control Simulator," Franklin Institute Laboratories Working Paper No. 3, Project No. 2384-1 (Limited Distribution), May 1955.

In line with simulator expansion plans, the universal simulator study was performed to pinpoint and highlight those characteristics desired in an air traffic control simulator capable of exploring traffic problems as far ahead possibly as 1975. Should funds become available for the construction of such a simulator in the near future, this study could be used as a starting point for the development of detailed specifications. On the other hand, if future simulator requirements are to be met by expanding and modifying the present TDC simulator, this study could be used as a guidepost for the expansion program.

CONCLUSIONS

1. The results of the joint FIL-TDC program have continued to yield a wealth of information which, in spite of the recognized limitations of being unable to duplicate fully or to anticipate all of the peculiar situations and interactions of actual conditions, might have been in bits and pieces, inconclusive, impossible, unsafe, or even economically infeasible to obtain by any other means. Although some of the information obtained to date might be considered merely to be of a fundamental and long-range nature, much of this information concerns new operational procedures, techniques, equipment, and facilities which have wide and immediate application in many of today's trouble spots.
2. It is believed that for the next ten years or so, human operators probably will continue to play a large part in the control of both aircraft and air traffic in the common system of peacetime air traffic control as it is known at the present time.
3. With present radar-separation and runway-occupancy rules, the maximum practical sustained approach-vectoring and landing capacity on a single runway averages about 30 aircraft per hour. The maximum practical number of manually vectored approaches which can be handled on a single, voice, air/ground channel also is about 30 per hour.
4. Further reductions in communicating time and in controller and pilot workload can be made by using cockpit pictorial Rho/Theta computers in conjunction with controllers' approach-control computers.
5. In terminal areas, ASR rotation rates as low as 15 rpm seem adequate for traffic control vectoring and identification purposes on uncluttered radar scopes.
6. For high-density radar-vectoring systems in single airport terminal areas, only a momentary bloomer code of the radar safety beacon seems necessary for identification.
7. Even when only a relatively small percentage of aircraft are beacon-equipped, the advantages (in the form of reduced over-all delays and of safety) of having a simple beacon system to provide almost continuous tracking through heavily cluttered terminal areas are significant.
8. Where traffic consists of some beacon-equipped and some non-beacon-equipped aircraft, arbitrarily giving beacon-equipped aircraft preferential treatment does not appear to be significantly beneficial over-all, or even justifiable.
9. For terminal areas having high sustained traffic densities, inner feeder stacks offset a minimum of 3 1/2 miles and a maximum of 8 to 9 miles from the outer marker should be adequate with reliable radar returns.
10. Assuming the radar separation of 3 miles can be reduced to 2 miles in the future, the maximum sustained practical capacity for manual vectoring of approaches is about 40 to 44 per hour. Beyond this figure some form of computing device to aid or replace most or all of the functions of the approach controllers will be necessary.
11. Automatic or semiautomatic approach computers should allow for simple refeeding of missed approaches, rescheduling gate times in the event of early or late arrivals, handling multiairport areas, clearing obstructions, bypassing airspace reservations, and variations in speeds between the different aircraft types; and they should be capable of being integrated with all traffic without regard to whether it is or is not beacon-equipped.
12. Large horizontal plotting scopes are preferred over small (10- to 12-inch) slant scopes for en route radar control. A scale factor of about 2 miles to the inch is desirable.
13. Target markers used on horizontal radar scopes should contain all essential control information. Supplementary tabular posting-strip displays cause inefficient division of the controllers' attention.
14. Panoramic displays using shrimp-boat target markers have certain advantages for controlling en route traffic in nonradar areas. Furthermore, correlation of information and coordination between panoramic displays (for nonradar areas) and horizontal radar displays is relatively simple. Certain disadvantages in the panoramic display itself, however, and in the manner in which it is used, must be overcome in order that it may be adequate for a wider variety of traffic situations.

15. Overhead radar-projection displays show excellent promise, especially when used with the panoramic displays. As in the case of the horizontal radar scopes, if the radar fails, the transition to nonradar control is an easy one.
16. The limited-data-transfer device performs a useful function in transferring flight data and control jurisdiction of inbound aircraft from center to tower control. There is some doubt, however, as to its flexibility in handling mixed IFR-VFR traffic, altitude-inversion problems, priorities, and resequencing. Interphone still is necessary as a backup, however.
17. Tower-center coordination and uncertainties are reduced considerably when the approach and en route transition controllers work side by side on a common horizontal plotting scope.
18. Measuring the actual physical activities of a controller does not appear to yield realistic indices of his total workload. The mental rather than the physical aspects of the controller's workload contribute more to his own conservatism and appraisal of workload, or the converse, to his degree of relaxation.
19. Drastic reductions in delays during peak traffic loads can be effected by relatively small changes in separations and number of paths and altitudes available.
20. Due to the random nature of traffic and to en route controllers' conservatism, the theoretical maximum capacity of 6 aircraft per airway per altitude (using a minimum en route separation of 10 minutes) is reduced to a maximum no-delay capacity of about 3 per hour in actual practice.
21. En route intersections create serious problems and losses in system efficiency. These problems can be alleviated most directly by providing altitude separation, or, better still, by using radar vectoring.
22. The high conflict potential in the ANC en route system in use today creates conservatism, great mental strain, and often, very poor decisions. A computer which could carry out such diverse controller activities as prediction, conflict search, vacancy search, and similar functions, should be extremely valuable.
23. The study of a new universal simulator for long-range military and civil use should serve as a good starting point for the development of detailed specifications and as a guide for expanding and modifying the present TDC simulator.

RECOMMENDATIONS

Future Simulation Activity.

In accordance with the broad framework and objectives of the AOEC at Indianapolis, of ANDB's newly formed systems engineering group, and of ANDB's Simulation Project Specification 6.7, short- and long-range simulation programs should be undertaken (not necessarily in the order shown) for purposes of:

1. Investigating those aspects of safety and efficiency associated with various configurations, techniques, systems, and the like, which are of a generalized nature, the results of which can be useful not only for certain fundamental investigations but for certain specific applications and geographical arrangements as well.
2. Isolating and evaluating those specific equipments and concepts under consideration for implementation in AOEC prior to their final adoption.
3. Determining the optimum procedures, selection, and arrangement of navigational and control facilities for near future alleviation of critical areas such as New York, Chicago, and Washington.
4. Integrating civil requirements and procedures with those of the military, not only for peacetime use but slanted toward joint civil/military situations peculiar to those strategic, defense, and tactical requirements planned in the event of emergencies.

In addition to and/or in conjunction with the broadly stated problem areas, further systematic evaluations should be made to include such related and interrelated aspects and operational uses of each which are considered pertinent to the development and smooth transition from the present to the interim and common systems of air traffic control, such as:

1. Various traffic rates, distributions, and populations, including increasingly higher percentages of jet, helicopter, vertical takeoff (VTO), and supersonic types.
2. Combinations of route structures, control coordination, and control techniques, including:

A. Fixed airways, with off-airway flights.
B. Complete area control.
C. Rho/Theta fixes, with or without automatic reporting, or both.
D. Altitude sectorization, including very-high-altitude control.
E. Centralized radar control, with or without adjacent ANC control.
F. Decentralized radar control, with or without adjacent ANC control.

3. Various rules, procedures, and separation criteria.
4. Displays, such as:

A. Horizontal direct-view and projection radars; size, scale factor, altitude coverage, integration of several radars on a common display such as Vidicon, Iatron, and others; and best methods for symbolizing, organizing, and displaying control data.

B. Intracenter, intercenter, and center-tower data-display, storage, and transfer devices.

C. Charactron, Mink, Kenyon, and three-dimensional displays.

D. Those under consideration for secondary radar replies, including the use and number of codes necessary.

E. Various arrangements and types of flight strips as radar backups, including the use of color-coding for altitude, speed class, destination, and so forth.

F. Panoramic displays with shrimp-boat target markers; determination of optimum area, coordination, and overlap area between displays; best use of tabular displays at critical points; possibility of revising ANC separations; problems in handling jets; and feasibility of incorporating certain automatic plug-in shrimp-boat target markers.

5. Private-line, automatic data-link, and aural communications.
6. Automatic computers, flight-path planning, and conflict-warning devices.
7. Others, as the need arises.

Continue the exploratory quantitative program of en route static and dynamic-simulation tests, to include:

1. Determination of significant criteria for making quantitative comparisons of en route systems and their components.
2. Investigations of methods of designing and conducting en route dynamic-simulation tests which can yield statistically stable data within a reasonable length of time without too many replications and without significantly compromising realistic environment.
3. Additional static tests with other areas, types of traffic conflicts, and other display functions; and determination of the validity of the static-test technique.
4. Determination of the feasibility of short dynamic and static-dynamic tests (5 to 10 minutes) in order to reach a compromise between a realistic situation and experimental control.

New and Expanded Simulation Facilities.

The electromechanical optical simulator at TDC should be expanded from its present complement of 18 radar targets to a minimum of 24, or preferably to 30. Space limitations in the TDC simulator building almost dictate that any additional target generators and their consoles be the electronic, compatible type which can be located remotely from the present optical projectors.

Steps also should be taken to prepare detailed specifications for the design and procurement of a new universal traffic-control simulator which can best meet, where practicable, the broad and futuristic requirements of all elements of the armed forces and the CAA.

Consideration also should be given to the possibility of redesigning and constructing a similar target-synchro type of device for the manual remoting of filtered radar information to the AOEC.

APPENDIX A

COMPARATIVE RESULTS AND DISCUSSION OF SOME TERMINAL-AREA STUDIES

Use of the Radar Safety Beacon.

In order to explore the comparative effects on average delays, by being able to "see" through heavy clutter when aircraft are equipped with simple beacons which enable continuous radar tracking in a high-density terminal area employing twin-feeding inner stacks, a paper analysis was undertaken for the assumed conditions of:

1. The proposed independent LaGuardia Airport configuration, with twin-feeding inner stacks located at Jersey and Idlewild Airports.[19]
2. Zero wind.
3. Random traffic samples of 1 1/2 hours, arrivals only, with peak hours of 18, 24, or 30 arrivals. These are considerably higher than present IFR rates.
4. None, 33, 50, 67, or 100 per cent of the beacon-equipped aircraft.
5. No special priorities given to beacon-equipped aircraft; that is, on a first-come, first-served basis.
6. Very heavy scope clutter.
7. No identification codes.
8. Average separations of two minutes between sequences of beacon-equipped aircraft, three minutes between sequences of beacon-equipped and non-beacon-equipped, and four minutes between sequences of non-beacon-equipped aircraft.

The theoretical average delays for the 18, 24, or 30 arrivals of the peak hour are shown in Figs. 7 and 8. Figure 7 is a plot of the average delays versus arrival rate for the various

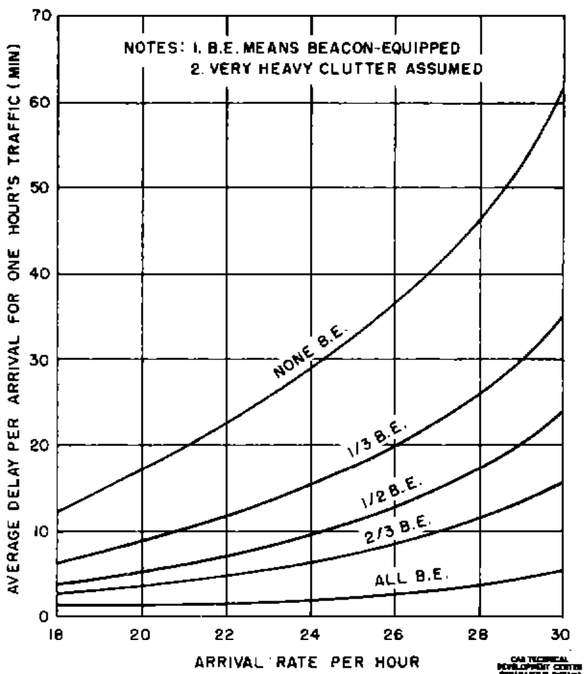

Fig. 7 Theoretical Average Delay per Arrival as a Function of Arrival Rate for Various Percentages of Beacon-Equipped Aircraft

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[19] Clair M. Anderson and Charles E. Dowling, "Evaluation by Simulation Techniques of a Proposed Traffic Control Procedure for the New York Metropolitan Area," CAA Technical Development Report No. 245, August 1954, Fig. 11.

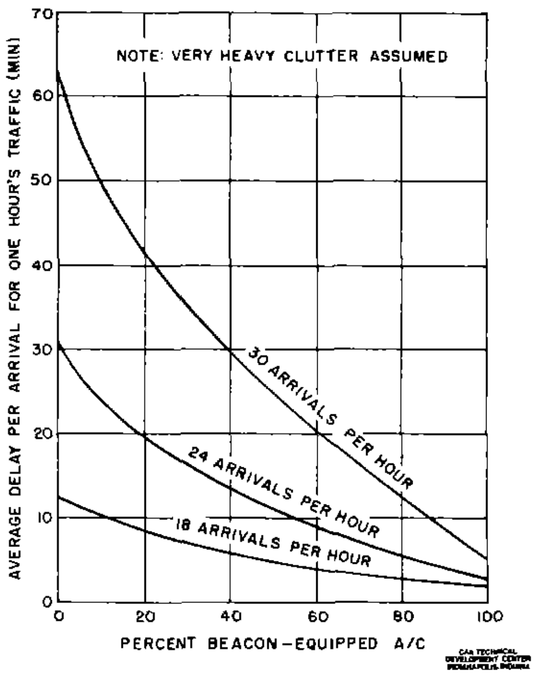

Fig. 8 Theoretical Average Delay per Arrival as a Function of Percentage of Beacon-Equipped Aircraft for Various Arrival Rates

percentages of beacon-equipped aircraft. Figure 8 shows the same average delays cross-plotted against the percentage of beacon-equipped aircraft, with the arrival rate per hour as the independent parameter. The appreciable decreases in delays at successively increasing arrival rates, even when only a relatively small percentage of aircraft are beacon-equipped, should be noted.

A somewhat cursory analysis also was made to determine significant trends if beacon-equipped aircraft were given preferential treatment when some of the aircraft in a sample of arrival traffic are beacon-equipped. The conditions assumed were those stated previously, except that only a single random sample of 24 arrivals per hour was used for just one case of 50 per cent of the aircraft being beacon-equipped. It was found that there was a slight but statistically insignificant over-all decrease in average delays in contrast with the results of the comparable case on the first-come, first-served basis. When individual delays to the non-beacon-equipped aircraft were examined, however, it appeared that they could become excessive and possibly intolerable when beacon-equipped aircraft were given priorities arbitrarily. More studies are needed under a wide variety of conditions, rules, and code uses before any firm conclusions can be drawn, however.

The Use of Diverging Intersecting Runways, Intermixing Landings and Takeoffs.

In previous simulation tests,[20,21] mixed landings and takeoffs were presumed to use only the single instrument runway. It was found best by far to stretch the separations of landing aircraft by 25 to 30 per cent in order to intermix takeoffs than to land a few, take off a few, and so forth. Here, the sustained rate was found to average about 50 mixed operations per hour. This was approaching the limit of capacity, however, and the degree of coordination required was found to be very high, with the attendant risk of lowering safety standards and/or efficiency during really bad weather.

Six dynamic-simulation runs were made to determine the effects of handling a demand of 66 IFR operations (35 arrivals, 31 departures) per peak hour on diverging intersecting

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[20] Berkowitz and Doering, op. cit.

[21] Berkowitz and Fritz, op. cit.

runways, assuming uncluttered radar scopes. The runway layout was assumed to correspond to Washington National Airport's instrument runway 36 and intersecting runway 3, with the intersection at about 2250 feet beyond the threshold of runway 36. All landings were made on runway 36 so that when the landing aircraft cleared this 2250-foot intersection, takeoffs on runway 3 were clear to go. In 5 of the 6 runs, departures used either runway 36 or 3, depending on the direction of their destinations. In the sixth run, all takeoffs used runway 3 only. A twin-feeding inner-stack system was assumed for radar manual-approach control.

The radar-separation rules observed included a 3-mile minimum between successive landings, either a 2- or 2 1/2-mile minimum separation between a takeoff followed by a landing, and the rule of no 2 aircraft on or over the same runway at the same time. A landing aircraft was presumed to occupy the landing runway when it was still 1000 feet from the runway threshold, the assumed wave-off point. Separations used were those described in previous reports[22,23] as optimum separations. No military aircraft were involved.

Highlights of the results of these simulation runs are shown in Table VI. It should be pointed out that these quantitative results are inconclusive statistically because an insufficient number of runs were made for each variable used (separations, samples, number of approach controllers, and takeoff runways). The trends were very significant and evident, however, in: (a) the reductions in over-all average landing and departure delays when the 2 1/2-mile radar separation between a takeoff and a landing was reduced to 2 miles, and the trends became even more pronounced when only intersecting runway 3 was used for all takeoffs; (b) the larger number of actual operations moved per hour (56 to 64) in contrast with the theoretical maximums (58 to 72, depending on the separations and takeoff runways used) and the prior comparable single-runway runs (50 to 53 per hour); (c) the low number of TILTAMS;[24] and (d) the comparative ease and efficiency with which one approach controller could handle both east and west sectors while coordinating with the departure controller at the same time.

The subjective opinions of the various controllers further showed that the use of diverging intersecting runways was a highly efficient and relaxed operation. Much less coordination, mental strain, and physical workload were involved than with the single runway, or even with other dual-runway configurations where operation of the dual runways is not completely independent. Of course, the higher theoretical capacity of dual parallel or tandem runway layouts (80 to 90 per hour) is very desirable; but the economics, the problem of taxiing aircraft crossing active runways, and the potential traffic demands also must be taken into account.

Some High- and Very-High-Density Tests of Various Approach-Control Configurations.

In previous simulation tests,[23] the approach configuration featured twin-feeding inner stacks located symmetrically about 6 miles from the outer marker; and all traffic samples averaged 35 arrivals per hour, with theoretical acceptance rates (using optimum separations) ranging from about 29 per hour in a 20-mph headwind to about 38 per hour in zero wind conditions. In all runs two approach controllers vectored inbound aircraft manually within the east and west sectors. Reliable target returns and uncluttered radar scopes were employed.

During this contract period, some dynamic-simulation runs were made with assumed uncluttered radar scopes to explore the effects of: (a) reducing the communications load by lowering the transfer altitude for transition to approach control from 4500 feet to 3500 feet and by eliminating the broadcasting of weather information by approach controllers; (b) using one approach controller to handle the work of both sectors; (c) using close-in twin stacks to reduce workload and variability; (d) using a 4-stack feeder layout to shorten the approach interval when feeding both pressurized and low-rate-of-descent (unpressurized) aircraft; (e) using very-high-density rates of 50 arrivals per hour; (f) using optimum outer-marker separations yielding a theoretical maximum acceptance rate of 51.7 per hour (assuming possible future minimum radar separations of 2 miles); (g) using an orbiting layout along with the 30-inch bright-tube horizontal radar display; (h) using an approach-control computer (electronic multitrack approach computer known as EMTAC) to reduce controller workload;

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[22] Berkowitz and Doering, op. cit.

[23] Berkowitz and Fritz, op. cit.

[24] TILTAM means time interval less than assigned minimum.

TABLE VI

DYNAMIC-SIMULATOR RESULTS OF MIXED ARRIVAL AND DEPARTURE RUNS*

Run No.	Sample No.	Number of Approach Controllers, East and West Sectors	Takeoff Runways Used	Minimum Separation Between Takeoffs Followed by Landings (miles)	Theoretical Operations Capacity/Hour	Actual Operation/Hour for Peak 45-Minute Period	Average Delay per Arrival for 35 Arrivals of Peak Hour (minutes)	Average Delay per Departure for 31 Departures of Peak Hour (minutes)	Average Delay per Operation for 66 Operations of Peak Hour (minutes)	Number of TILTAMS During Peak Hour		East and West Approach Control Communication Density for Entire Run (per cent)
										(> 15 seconds)	(> 30 seconds)	
IA 11	1	1	3 and 36	2 1/2	58	56	11.9	6.[illegible]	9.2	0	0	44 (Both)
IA 12	1	2	3 and 36	2 1/2	58	57	11.8	3.0	7.7	1	0	23 East 25 West
IA 21	2	1	3 and 36	2 1/2	58	56	10.2	4.8	7.9	0	0	42 (Both)
IA 31	3	2	3 and 36	2	63	58	9.3	1.9	5.8	1	1	30 East 24 West
IA 32	3	1	3 and 36	2	63	58	8.8	1.4	5.3	0	0	47 (Both)
IA 22	2	2	3 only	2	72	64	4.4	2.1	3.3	2	0	29 East 26 West

*Test Conditions: Zero wind, manual vectoring, Type IA samples of arrivals and departures, single or intersecting runways.

Note: 1. All arrivals landed on WNA runway 36.
2. In all runs except IA 22, departures destined to proceed N, NE, and E took off on WNA intersecting runway 3; all others took off on runway 36.
3. Traffic samples consisted of 1/2-hour loading period (11 arrivals and 11 departures), 1-hour peak period (35 arrivals and 31 departures), and 1/2-hour unloading period (12 arrivals and 13 departures).
4. Transfer altitude to approach control was 4500 feet.
5. A TILTAM is a Time Interval Less Than Assigned Minimums.
6. The two-digit data-transfer device and aircraft identification were employed in all runs.

(i) integrating jets within the assumed 40-mile diameter of the terminal area; and (j) using full aircraft identification with the actual LDTD instead of a 2-digit identification with the experimental data-transfer device.

In the EMTAC and jet runs it was assumed that aircraft were equipped with pictorial (Rho/Theta) computers and that aircraft were assigned tracks via EMTAC which they would navigate themselves.[25] Controllers then would monitor and manually vector their paths only when necessary to maintain the prescribed separations.

Tables VII and VIII contain a summary of the quantitative results. Highlights of the examination and comparison of the detailed data and the subjective opinions of the controllers are as follows:

1. The four-stack arrangement of inner-feeder fixes was rejected after one run because it was much too cumbersome to handle manually.
2. The orbiting approach with concentric paths also was abandoned after three runs owing to the abnormally high mental and physical workload imposed on controllers. This high workload was typical of any all-radar, manually controlled system where no fixed tracks or holding fixes were employed.
3. Lowering the en route transition-to-approach transfer altitude from 4500 to 3500 feet and eliminating the weather-broadcast information by approach control reduced the total average communicating time per aircraft by about 10 seconds; however, the effects on delays and capacity were negligible.
4. The use of full identification for all aircraft as opposed to a 2-digit code had a surprisingly large effect on the voice communications load; the average total communicating time per aircraft jumped from about 55 to 80 seconds, or almost 50 per cent.
5. Controllers believed that close-in, angled feeder stacks were the easiest to handle of all arrangements tested to date; however, the results showed no operational advantages.
6. Except for the relatively high physical workload involved, it was found that one good controller could maintain control of both sectors of close-in, twin-stack systems with no loss of efficiency in any respect as compared to a two-controller operation.
7. The approach-control computer (EMTAC) fulfilled its purpose of reducing controller workload. Communicating time was reduced by 20 per cent, and control procedures were very simple. These EMTAC runs showed their average delays to be slightly but insignificantly higher than comparable manual runs, however.
8. No data are shown for the EMTAC runs involving the integration of jets due to equipment malfunctions; however, it was concluded that the delay results, the system capacity, and the total communication workload were the same as or slightly better than comparable EMTAC runs involving only conventional aircraft.
9. Using 2-mile minimum radar separations, the theoretical maximum approach capacity with manual vectoring is about 52 approaches per hour in zero wind conditions, with a practical capacity of about 40 to 44 sustained landings per hour, or about 80 per cent efficiency. In practice this probably would be less, about 70 to 75 per cent efficiency under sustained conditions, even with uncluttered scopes. It is believed that some sort of approach computer or computer aid will be necessary to attain efficiencies higher than 70 to 80 per cent.

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[25] The layout for the EMTAC and mixed jet-conventional aircraft runs, known as Phase 2A or Map 2J, was shown in Fig. 3 of CAA Technical Development Report No. 251.

TABLE VII

TERMINAL-AREA DYNAMIC-SIMULATION RESULTS*

Run No.	Map Used	Transfer Altitude	Arrival Rate/Hour	Theoretical Maximum Acceptance Rate/Hour	Number of Approach Controllers	Average and Maximum Delay for All Aircraft in Sample		Number of TILTAMS for Entire Run		Average of TIGTAMS for Entire Run	Maximum Effective Acceptance Rate for Peak One-Hour Period	Number of TILTAMS During Peak One-Hour Periods		Average East and West Communication Channel Density for Entire Run Air and Ground	Average Communication Time per Aircraft for Entire Run
		(feet)				Average (minutes)	Maximum (minutes)	(> 15 seconds)	(> 30 seconds)	(seconds)		(> 15 seconds)	(> 30 seconds)	(per cent)	(seconds)
1	2D	3500	35	36.1	1	8.1	23.0	9.0	2.0	13.7	35.1	3.0	0.0	52 (Both)	48.0
2	2D	3500	35	36.1	1	15.1	32.4	4.0	0.0	19.9	32.4	2.0	0.0	50 (Both)	57.0
3	2D	3500	35	36.1	1	12.4	23.1	15.0	1.0	15.5	34.3	7.0	1.0	48 (Both)	47.0
Average	2D	3500	35	36.1	-	11.9	32.4	9.3	1.0	16.4	33.9	4.0	0.3	50 (Both)	50.7
1	2D	3500	50	51.7	1	16.9	35.4	7.0	0.0	19.7	42.9	4.0	0.0	62 (Both)	54.0
2	2D	3500	50	51.7	1	20.7	41.1	4.0	2.0	20.2	42.3	3.0	1.0	63 (Both)	57.0
3	2D	4500	50	51.7	1	16.6	39.4	1.0	0.0	18.3	44.2	1.0	0.0	76 (Both)	65.0
Average	2D	N.A.	50	51.7	-	18.1	41.1	4.0	0.7	19.4	43.1	2.7	0.3	N.A.	N.A.
1	2D	3500	50	51.7	2	17.2	38.7	4.0	0.0	19.0	41.7	0.0	0.0	36 East 32 West	53 East 70 West
2	2D	4500	50	51.7	2	19.3	39.9	2.0	0.0	18.1	43.5	0.0	0.0	40 East 32 West	62 East 62 West
3	2D	4500	50	51.7	2	25.9	51.4	1.0	0.0	23.0	43.2	1.0	0.0	35 East 39 West	60 East 81 West
Average	2D	N.A.	50	51.7	-	21.3	51.4	2.3	0.0	20.0	42.8	0.3	0.0	N.A.	N.A.
1	2D	3500	35	51.7	1	2.9	13.4	1.0	0.0	32.7	35.5	0.0	0.0	52 (Both)	54.0
2	2D	3500	35	51.7	1	1.8	8.8	0.0	0.0	31.8	35.9	0.0	0.0	54 (Both)	57.0
Average	2D	3500	35	51.7	-	2.3	13.4	0.5	0.0	32.2	35.7	0.0	0.0	53 (Both)	55.0
1	2F	6000	35	51.7	1	2.4	11.6	6.0	0.0	34.7	35.7	1.0	0.0	N.A.	N.A.
1	2F	6000	50	51.7	1	12.0	25.3	14.0	4.0	17.7	43.2	7.0	3.0	N.A.	N.A.
2	2F	6000	50	51.7	2	13.4	25.7	8.0	1.0	18.1	43.8	2.0	0.0	N.A.	N.A.
1	2E	4500	50	51.7	1	15.0	32.4	3.0	0.0	18.4	42.9	1.0	0.0	60 (Both)	52
2	2E	4500	50	51.7	1	24.4	54.8	5.0	3.0	24.9	41.4	2.0	2.0	62 (Both)	59
Average	2E	4500	50	51.7	-	19.7	54.8	4.0	1.5	21.6	42.2	1.5	1.0	61 (Both)	55

*Test Conditions: Zero wind, manual vectoring runs only, using two-digit data-transfer device.

Note:
1. N.A. means not available or not applicable; maximum delays are not averaged.
2. A TILTAM is a Time Interval Less than Assigned Minimums; a TIGTAM is a Time Interval Greater than Assigned Minimums.
3. No weather data were given by approach controller; it is assumed that the en route terminal transition controller broadcasts this information.
4. The 2D and 2E maps are close-in twin-stack layouts, approach controllers used the sloping panel radar scopes.
5. The 2F map is an orbiting layout, approach controllers used the 30-inch horizontal bright-tube scope.
6. 2 1/2-hour samples of arrivals and zero wind used in all runs.

TABLE VIII

TERMINAL-AREA DYNAMIC-SIMULATION RESULTS*

Run No.	Manual or EMTAC	Map Used	Arrival Rate/Hour	Theoretical Maximum Acceptance Rate/Hour	Number of Approach Controllers	Average and Maximum Delay for all Aircraft (minutes)		Number of TILTAMS for Entire Run		Average of TIGTAMS for Entire Run (seconds)	Average Landing Rate/Hour for Entire Run	Maximum Landing Rate for Peak Hour	Total Communication Density East and West (per cent)	Average Communication Time per Aircraft Air and Ground (seconds)	Average Number of Messages per Aircraft Air and Ground
						Average	Maximum	(> 15 seconds)	(> 30 seconds)						
211 LD	Manual	2D	35	36.0	1	6.2	18.0	4.0	2.0	12.4	33.5	34.5	70	74	26
212 LD	Manual	2D	35	36.0	2	10.4	25.8	6.0	0.0	16.7	32.0	34.0	Average of 35 each	79	27
222 LD	Manual	2D	35	36.0	2	15.8	34.9	4.0	1.0	20.9	31.0	32.5	Average of 31 each	74	25
231 LD	Manual	2D	35	36.0	1	18.4	34.2	6.0	0.0	19.3	31.0	33.0	75	87	31
232 LD	Manual	2D	35	36.0	2	16.6	30.2	2.0	0.0	14.1	31.5	33.5	Average of 36 each	85	26
Average of 5 runs	-	-	35	36.0	N.A.	13.5	34.9	4.4	0.6	16.7	32.0	33.5	70 if all on 1 channel	80	27
211 EM	EMTAC	2J	35	36.0	1	9.5	24.6	5.0	1.0	17.8	31.5	34.0	53	63	25
221 EM	EMTAC	2J	35	36.0	1	20.6	39.7	5.0	0.0	25.9	29.0	32.0	52	65	25
231 EM	EMTAC	2J	35	36.0	1	19.9	43.0	5.0	2.0	22.8	30.0	32.0	50	62	26
Average of 3 runs	-	-	35	36.0	-	16.7	43.0	5.0	1.0	22.2	30.0	32.5	51	63	25
242 LD	Manual	2D	50	51.7	2	17.1	35.8	0.0	0.0	20.4	40.5	44.0	Average of 42 each	75	24
252 LD	Manual	2D	50	51.7	2	25.2	47.9	3.0	0.0	20.1	40.5	43.0	Average of 38 each	68	22
262 LD	Manual	2D	50	51.7	2	9.6	24.1	1.0	0.0	9.8	46.0	48.0	Average of 46 each	72	21
Average of 3 runs	-	-	50	51.7	-	17.3	47.9	1.3	0.0	16.8	42.5	45.0	Average of 42 each 84 if all on 1 channel	72	22

*Test Conditions: Manual vectoring and EMTAC runs, using actual limited-data-transfer device.

Note:
1. N. A. means not applicable.
2. Maximum delays are not averaged.
3. Transfer altitude to approach control was 3500 feet in all runs.
4. No weather data were broadcast by approach controllers.
5. Uncluttered scopes were assumed in all runs.
6. 2 1/2-hour samples of arrivals only and zero wind used in all runs.