Analytical Methods of Research into Terminal Area Air Traffic Operations

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The application of mathematical models of various suboperations in the terminal area, and the use of fast time simulation on a digital computer to study the operation of a complete terminal area traffic control system, are briefly demonstrated. Mathematical models are used to analyze the capacity of race track holding patterns, the laddering operation, and the instrument landing system (ILS) funnel with time separations at the gate. The results of a fast time simulation on an IBM 7094, for an advanced method of providing sequencing and spacing for a single ILS runway are given. The landing system demonstrates a capacity of 32 landings/hr, along with runway availability for 20 takeoffs.

Introduction

THE effect of air traffic congestion in terminal areas is becoming increasingly important to commercial air transportation. To the traveling public, this congestion manifests itself in the form of delays at takeoff and landing causing late arrivals, missed connections, unplanned stopovers, delayed departures, etc., which give airline transportation a reputation for unreliability, and lend an aura of uncertainty or adventure to air trips. To the airline, this congestion causes increased fuel and crew costs, frequent changing of planned operations, and increased passenger service costs.

Future growth of air transportation and future improvements in travel convenience demand sustained research and development in these areas. The problem must be treated in full appreciation of all its operational, technical, legal, political, and social aspects. It is a systems engineering problem with improvements to come from better traffic procedures, newer traffic control equipment, improved transport aircraft navigation and guidance, and a broader understanding of terminal area traffic problems. This broad understanding must be based upon analytical and experimental work into the operation of newer and different traffic operations. The development of operations research for studying operational problems by mathematical methods, and the growth of experimental simulation tools, such as the digital computer, have given us the tools to provide a background of knowledge, based not upon our limited experience with the development of our present traffic system, but rather upon the experience of studying and working with a variety of other systems.

The objective of the research reported here was the development of quantitative analytical and simulation methods for investigating the operational procedures and performance capabilities for a variety of efficient high-performance terminal area traffic control schemes. The simulation scheme described later is not to be interpreted as a serious proposal for future terminal areas. It is an example of a study of a different type of system to find its performance in quantitative measures and to demonstrate the application of fast time simulation. The terminal area problems at the top five terminals are problems that require individual design solutions similar to the solutions in designing an aircraft. Just as analytical and experimental studies in the subject of aerodynamics contribute to the design solutions for transport aircraft, analytical and simulation studies in air traffic operations will contribute to the design of improved air traffic control systems for bad-weather operations.

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Definition of the Terminal Area Problem

Consider a single instrument runway used for both takeoff and landing operations, and define the terminal area as that area surrounding the runway where arriving and departing aircraft are climbing or descending. In Fig. 1, this area is represented by a circle of radius T_b centered on the outer marker of the ILS. T_b is a time boundary where inbound aircraft arrive in a random fashion. The random arrivals are subjected to landing control procedures within this area to give the desired landing intervals. Departing aircraft also arrive randomly at the runway ready for takeoff. A general definition of the terminal area problem can now be made. The traffic control problem in the terminal area is the derandomization of these random arrivals into an efficient arrangement of takeoffs and landings, such as to maximize the total operations rate and minimize the delays in both landing and takeoff processes, consistent with safety, passenger comfort, vehicle limitations, and other operational considerations arising from the environment.

The objective for any terminal area control system is the optimization of the product of (capacity × safety), or (capacity/collision risk), which may be defined as efficiency. The terminal area problem is one of providing efficient service to both arriving and departing traffic and is not the simple en route problem of maintaining safe separation.

Although the terminal area process must consider both the landing and takeoff flows, the emphasis is placed upon studying the landing flow process. Since landing aircraft cannot be controlled after they begin their approach at the ILS outer marker, and since they are airborne with a higher fuel con-

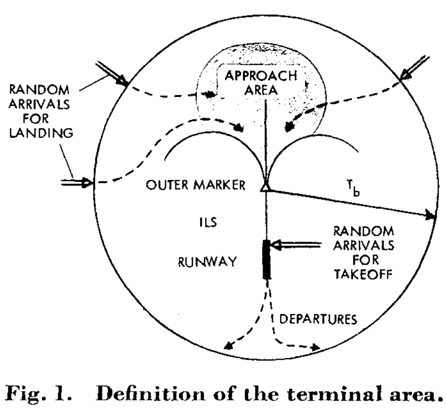

Fig. 1. Definition of the terminal area.

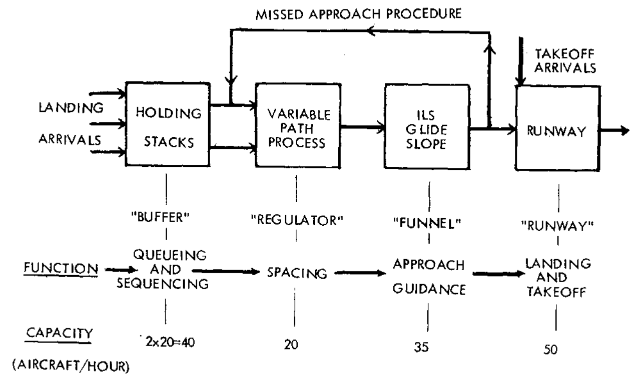

Fig. 2 Functional description of landing traffic control systems.

sumption in a high traffic density area, they are normally assigned priority over takeoff aircraft for usage of the runway. This priority assignment means that takeoff aircraft will be delayed more severely while awaiting gaps in the landing flow and insures that the landing flow process will dominate the design problems in any terminal area traffic control scheme. The key to improved terminal area performance is the ability to produce reliable, accurate landing intervals, and the emphasis in any study of terminal area performance must be placed upon the landing traffic control systems (LTCS).

A Functional Description of the LTCS

It is possible to isolate four general functional elements which are found in every landing control scheme (see Fig. 2).

The "buffer" element is a race track holding pattern at present, with aircraft stacked vertically at 1000-ft intervals. It is a storage element essential to any LTCS, acting as a reservoir to hold the random en route arrivals and to accommodate any delays or interruptions to landing service. As such, it isolates LTCS sector operations from the en route operations during busy periods. When the LTCS is not busy, en route arrivals pass through the holding area without any delay. Since the buffer is the first element of the LTCS, its position relative to the runway determines the size of the final control sector and the number of aircraft within the LTCS at any operating condition.

The "regulator" accepts random arrivals from en route control, or sequences aircraft from the holding stacks. In bad weather, it provides correct spacing intervals between each pair of aircraft in the landing sequence by controlling the path and speed (i.e., the velocity vector) of all aircraft between the holding areas and the ILS outer marker. After this point, the fixed approach speeds of present aircraft determine landing times, and so the accuracy of landing intervals is a function of spacing intervals achieved by the regulator at the outer marker. Since runway occupancy times are variable with aircraft operations, it is impossible to establish a rigid schedule of arrival times for the outer marker. Instead an efficient regulator will respond to runway variations and reschedule or respace outer marker arrivals.

Controlling an aircraft target along a three-dimensional continuous path using discrete control commands and attempting to achieve a specified arrival time at the outer marker poses the most difficult problem in achieving a high-performance LTCS and makes stringent demands upon aircraft guidance methods for the terminal sector.

The "funnel" is formed by the common path required to provide ILS guidance during present aircraft approach to landings. In bad weather, the minimum common path is from the outer marker to the runway (about 5 miles in length), although normally, aircraft are funneled onto the ILS localizer in the few miles previous to the outer marker. Radar separations presently require 3 miles separation in the approach area outside the outer marker and safe runway intervals are of the order of 1 min. When a stream of landing aircraft with varying approach speeds occurs, the slower aircraft are left behind at the outer marker causing large runway intervals and consequent reduced landing rates.

The "runway" is the most obvious element of the LTCS, and its operations have received the most attention. The basic operating rule is to avoid having two aircraft simultaneously on the runway, and runway capacity is therefore determined by the occupancy times for takeoffs and landings. These occupancy times vary with runway surface conditions exit configuration, the flying speeds of the traffic mix, the wind conditions, day or night operations, visibility conditions, etc. Measured data exist giving average and standard deviation of occupancy times for normal operation and are documented in Ref. 4.

Of these four elements, only the regulator is not presently standardized in bad-weather operation. In order to clearly identify these functional elements, it is of interest to describe the operation of the present clear weather and bad-weather landing traffic systems.

An Example of an Instrument Flight Rules (IFR) Landing System

The present LTCS for Kennedy Airport is shown in Fig. 3. The four functional elements are clearly identified: ILS runway 04R; a common path funnel 7 miles long; a radar vectoring regulator where the arrival traffic is sequenced and spaced before joining the ILS localizer; and dual holding stacks, Tomlin (about 28 naut miles from the runway), and Deer Park (about 62 naut miles from the runway, and joined to the regulator by an approach routing underneath the departure routings). There is a holding pattern directly overhead the airport (above 5000 ft), which is used solely for the LTCS for La Guardia airport.

Whereas visual flight rules (VFR) landing patterns are within 5 miles of the airport, the IFR patterns extend out to 35 miles. Traffic from the west is diverted around the air-

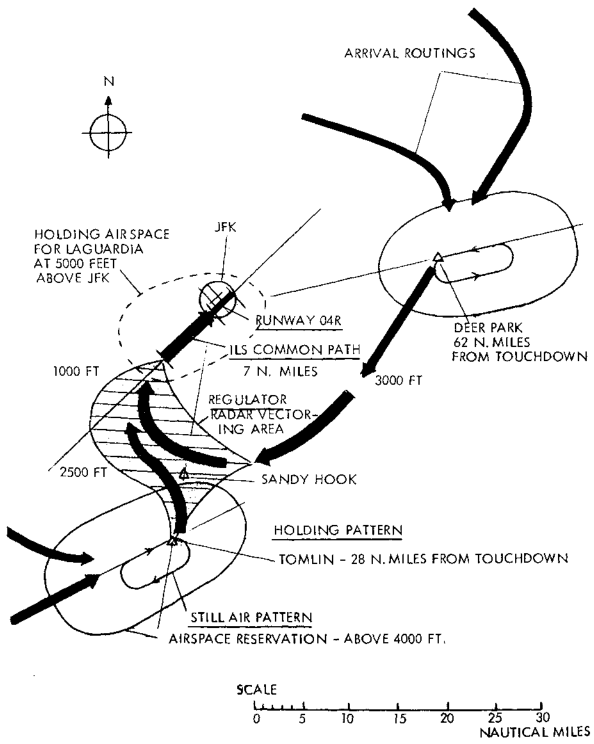

Fig. 3 IFR landing traffic control system for Kennedy Airport.

port traveling, for instance, an extra 80 miles via Deer Park. There has been almost an order-of-magnitude increase in the size of the landing process. Similarly, the number of aircraft involved in the landing flow process has increased. If aircraft with 120-knot ground speeds were being landed at a rate of 30/hr (2-min spacings), then there would be eight aircraft between Sandy Hook in the regulator area and the runway. If 15 aircraft/hr were being drawn from Deer Park, there would be another five aircraft along the arrival routing to the regulator. The complexity of such an operation requires the use of simulation tools with adequate representation of the human controllers, the radio channels and their usage, the piloting response to commands, etc., in order to perform any analytical study that would determine the effects of various traffic factors.

In the IFR patterns, the ground controllers supply the guidance necessary to achieve safe intervals in the landing stream, and the pilot is steering his aircraft according to various radar vectors without any knowledge of the desired path or the previous aircraft's progress. As the landing flow rate is increased, more precise spacing becomes necessary. The controller must pay closer attention to guidance of each target and issue more radar vectors via the radio channel. The regulator capacity is determined by the number of aircraft which can be supported in the flows between stacks and runway as limited by the number of controllers or radio channel congestion.

Role of Operations Research Mathematical Models

Certain suboperations, which occur in the terminal area, can be studied using the methods of present operations research mathematics. These suboperations are usually simple processes, which are made into well defined mathematical problems through some idealization of the real world. However, these models are extremely useful for determining relationships between various operational parameters, establishing an upper bound on capacities, estimating delay measures, and increasing our understanding of the real processes. The theoretical models provide a complementary tool to the experimental counterpart of the fast time simulation discussed later. A number of mathematical models describing typical suboperations are described in the following sections.

A. Number of Aircraft Within the Terminal Area

Because the controller workload and radio communications congestion are directly related to the instantaneous number of aircraft within the terminal area, it is necessary to describe the number of aircraft which will be found in the terminal area as a function of its size, the arrival rate of aircraft, and operational capabilities of the terminal area traffic control system. With the terminal area defined as a circular time bounded area,

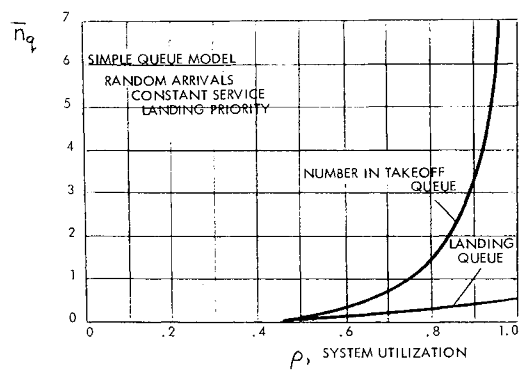

Fig. 4 Average number of aircraft delayed in terminal area.

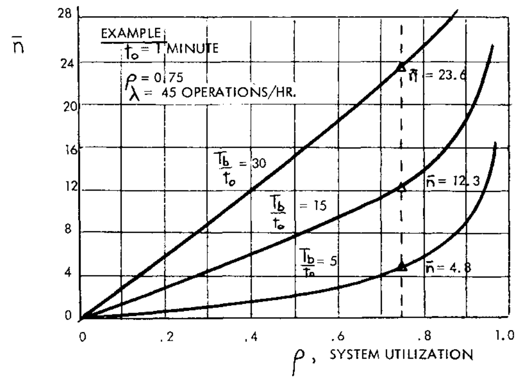

Fig. 5 Total number of aircraft in terminal area.

as in Fig. 1, it is an easy task to develop mathematical models that describe the number of aircraft. The aircraft can be placed in two categories: those that are flying inbound or outbound, without delay, and those that are in the area waiting for takeoff or landing.

The average number of flow aircraft $\bar{n}_F$ flowing through the terminal area is $\bar{n}_F = \bar{n}_L + \bar{n}_T = \lambda \cdot T_b$ where λ = arrival rate (aircraft per hour), and T_b = extent of the terminal area in hours of flying time. The average number of inbound, landing aircraft is $\bar{n}_L = \lambda_L \cdot T_b$ where λ_L = arrival rate for inbound aircraft, and the average number of outbound take off aircraft is $\bar{n}_T = \lambda_T \cdot T_b$ where λ_T = arrival rate for outbound aircraft. For example, at 60 operations/hr, $\bar{n}_F = 30$ aircraft, if $T_b = 0.5$ hr, and $\bar{n}_F = 5$ aircraft if $T_b = 5$ min. These are average values, and at peak times the instantaneous number of aircraft in the terminal area will exceed these values. If we assume random arrivals, the probability distribution for these numbers of aircraft will be Poisson. This would indicate, for example, that there is a 3.3% chance of having 40 or more aircraft in the terminal area for $T_b = 0.5$ and $\lambda = 60$/hr.

When delay is occurring in the terminal area, these estimates of the average number of flow aircraft will be augmented by the average number of aircraft $\bar{n}_q$ which are waiting for runway service. The inbound aircraft will be delayed by holding at some point, or by following an extended flight plan. The departure queue consists of aircraft lined up at the threshold of the runway. For random arrivals, with $\lambda_T = \lambda_L$ and a constant runway service interval t_0, it is possible to use simple queueing theory to estimate the average number of aircraft in the takeoff and landing queues. Normally, priority will be given to landing aircraft, which reduces the average number awaiting landing and increases the number awaiting takeoff as shown in Fig. 4.

The average total number of aircraft in the terminal area due to terminal area size and delay is given as

$$\bar{n} = \bar{n}_F + \bar{n}_q = \rho^2/2(1 - \rho) + \rho(T_b/t_0)$$

where ρ = runway or system utilization or loading

$$\rho = \lambda \cdot t_0 = \frac{\lambda}{(1/t_0)} = \frac{\text{arrival rate (aircraft/hr)}}{\text{service rate (capacity operations/hr)}}$$

This result is shown in Fig. 5, where curves of $\bar{n}$ for various terminal area sizes (T_b/t_0) are plotted against system utilization. For example, if the system is operating at 75% capacity ($\rho = 0.75$), with t_0 = 1-min intervals at the runway, and 45 arrivals/hr, then the average number of aircraft in the terminal area will be 23.6 for $T_b = 0.5$ hr, 12.3 for $T_b = 0.25$ and 4.8, if $T_b = 5$ min. The size of the terminal area is dominant in determining the number of aircraft. If we wish to keep terminal area operations within one control sector of the air traffic organization to avoid handoffs, radio channel changes, and problems in coordination, then the

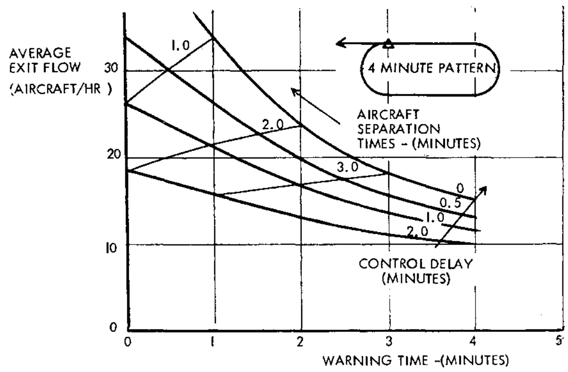

Fig. 6 Holding pattern capacity.

extent of the terminal area must be kept small to reduce the control sector workloads and radio congestion.

B. Standard Holding Pattern Models

The standard holding pattern is a racetrack pattern with 1-min turns, and 1-, 1.5- or 2-min straight legs (see Fig. 6). It is flown with respect to a given fix point and a straight leg defined by a radio navaid. Apart from tracking the holding leg up to the fix point, no guidance is available to pilots flying the pattern. With the effects of wind, the actual pattern flown is quite distorted, and large airspace reservations surround present holding patterns (see Fig. 3).

During busy periods, the holding stacks are likely to be in use. It is important to know the pattern exit capacity and to be able to analyze the effects of controller variables, different pattern sizes or geometries, operating policies, etc., on the pattern exit flows. The problem under study here is that of getting an aircraft out of its pattern and through the fix point in a preferred exit direction. The vertical control process, laddering, is discussed in the next model.

The holding pattern is defined in "time space," which eliminates the effects of a mix of differing aircraft holding speeds. The pattern geometry of Fig. 6, for example, consists of 1-min turns, 1-min straight legs, and a preferred exit direction along the specified holding leg. Fig. 6 indicates the pattern capacity (maximum average exit flow in aircraft per hour) as a function of three control variables; aircraft separation times for safe spacing of the exit flow; control delay times in passing controller messages to the pilot as a result of controller decision times, message lengths, etc.; and warning times where the pilot is notified in advance of an expected exit clearance by the controller such that he may cut across the holding pattern and reduce some exit delays. The model assumes zero wind effects, ideal piloting, and random aircraft position in the pattern when called. The average of exit intervals is easily calculated and serves as an upper bound on pattern capacity.

The capacity of various standard holding patterns can be established by operational models similar to those studied here. For the normal exit direction and size of present terminal area patterns, these capacities are below 30 aircraft/hr. Similar models, which use a preferred exit direction of 90° to that indicated in Fig. 6, and models that study a scheduled operation of the holding pattern using different exit altitudes, show pattern capacities of the order of 60 aircraft/hr. Holding patterns of different shapes such as orbital or semiorbital also promise increased capacity and show significantly less variance in exit intervals. The analytical models indicate that a single holding pattern is not a source of delay in the terminal area, if improved control procedures are adopted.

C. Laddering Models

The process of controlling the descent of traffic within a holding pattern stack has become known as "laddering," since each pressure level or 1000-ft step of the ladder is vacated before the next aircraft is cleared to descend. The capacity of this process, particularly when nonpressurized aircraft descending at 500 fpm are mixed with faster aircraft, has been found to be a flow restrictive element in past terminal areas.

Various analytical models of the laddering process are useful in explaining the reasons underlying capacities of the order of 20 aircraft/hr. The process is very dependent upon communications procedures, and the delays can be explained in terms of average message length and radio channel congestion with increasing numbers of aircraft in the stack. If the message time and aircraft descent time are added to define a "ladder time," then the variability of ladder times causes a blocking effect from the slow descent aircraft which depends upon the sequence of aircraft in the stack. Figure 7 shows this blocking effect as a function of the stack size H and the fraction of slow descent aircraft in a random sequence of fast and slow descent aircraft. For a large stack, a small fraction of nonpressurized, slow aircraft quickly blocks the laddering process, causing it to operate as though all aircraft were slow descenders. Conversely, for small fractions of slow aircraft and small stack sizes, the capacity increases substantially. This indicates that the laddering process has sufficient capacity to be used within the terminal area for supplying vertical separation between landing aircraft particularly where pressurized jet transport aircraft form a large percentage of the traffic.

D. ILS Funnel Models

Blumstein[2] first showed that, with certain operational assumptions, the effect of a distance separation S_0 at the beginning of a common approach path of length m and a desired time separation t_0 at the runway clearly defined a theoretical capacity restriction on the landing flow. The assumptions are that 1) arrivals arrive randomly and are not resequenced; 2) aircraft maintain a constant groundspeed, and that a mix of traffic speeds can be represented by a mean speed $\bar{V}$ and a range of speeds R; 3) aircraft maintain given separation standards at the beginning and end of the common path, and sufficient aircraft are available and can be controlled in such a way as to meet exactly these separation standards. Figure 8 shows the funnel geometry.

With these assumptions, the funnel operating policies, separation standards, common path length, traffic mix, etc. become operational parameters defining funnel capacity. In studying higher IFR landing rates where funnel capacity is an important restriction, the analytical funnel models are valuable in evaluating the potential performance of various proposals for changing separation standards and operating policies.

Current Federal Aviation Agency (FAA) regulations require that a radar separation S_0 of 3 naut miles be maintained along the complete length of the common path. Figure 9 shows the theoretical capacity for this operating policy for common paths up to 10 miles in length for an example repre-

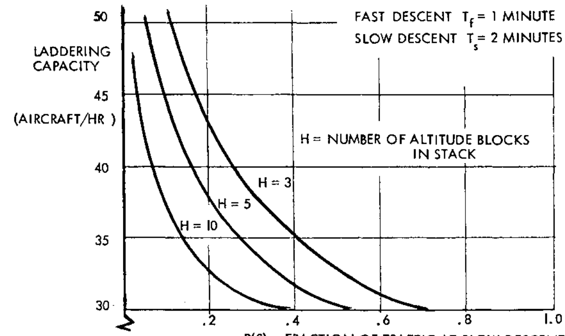

Fig. 7 Effect of slow descent aircraft on stacking outflow.

sentative of current traffic conditions. Path lengths are normally in excess of 5 naut miles, and the upper bound on landing rates is less than 30 landings/hr. Blumstein, in recognition of current practice, relaxed the S_0 separation along the common path which allows an increase in some cases. For the example of Fig. 9, this increase is very slight.

Recognizing that the critical separation in the funnel operation occurs at the runway where a faster, overtaking aircraft is planned to be a given distance or time behind the previous aircraft, it is possible to specify a lower separation for slow aircraft in the vicinity of the ILS outer marker and thus reduce the penalties of funnel operation. A natural form for this outer marker or gate separation is a time separation T_0 that makes distance separations at the gate proportional to the second aircraft's speed. For instance, if the time separations at the gate and runway are equal, the case where a slow aircraft is placed 1.5 min behind a faster aircraft at the gate is obviously less critical than the case where a faster aircraft is 1.5 min behind an aircraft on the runway. Figure 9 indicates the increased capacity from adopting such funnel operation policies. To implement such timed separations, it would be necessary to know the planned approach speed of every aircraft and supply the pilot and traffic controller with the guidance equipment necessary to achieve accurate time intervals at the ILS outer marker. Figure 9 shows the effect of further reducing the T_0 separation to 1 min at the gate. Funnel capacity for a common path of 5 naut miles has been increased to almost 38 landings/hr.

The approach funnel models define an upper limit for the landing capacity of a single ILS instrument runway. For minimal time separations $T_0 = t_0 = 1$ min, and the present radar separation of 3 naut miles, the funnel capacity is below 35 landings/hr for present procedures and would be below 45 landings/hr even if the T_0 separation procedures were applied. The need for simultaneous dual ILS runway operations to match peak traffic requirements at major airports is quite clear.

E. Runway Operations Models

The final element of the LTCS can be used for both takeoff and landing operations and has received much attention in measuring the occupancy times in good weather, studying the location and shape of runway exits, and determining the operational capacity of various runway combinations.[3,4] The capacity of a single runway is determined not only by the average of occupancy times, but also by the variance, and both of these values are affected by bad weather, runway surface conditions, night operations, aircraft vortices, poor visibility, and the particular runway geometry.

The variance of runway times determines a safe spacing between successive operations in order to prevent two aircraft from being on the runway simultaneously or to prevent a high missed approach rate. This variance affects the design of the whole LTCS, since rigidly scheduled time slots cannot be applied efficiently to the runway operations. The LTCS will have errors in its delivery of aircraft to the runway, and these errors combine with the runway variance to produce a missed approach rate at any given runway operations rate. If we assume the LTCS errors and runway occupancy times are normally distributed, then the allowable runway operations

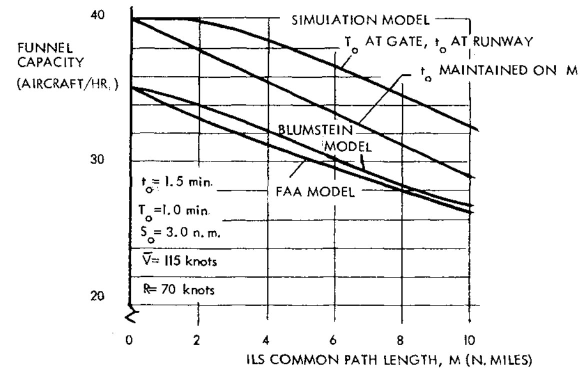

Fig. 9 Comparison of gate separation policies-ILS funnel.

rate for a 1% missed approach rate can be plotted versus LTCS accuracy as shown in Fig. 10. For scheduled operations, where time slots are reserved at the runway, the runway interval t_0 is given by

$$t_0 = t_L + K(2\sigma_a{}^2 + \sigma_L{}^2)^{0.5}$$

where t_L = average runway occupancy, σ_L = variance of runway occupancies, $\sigma_a{}^2$ = variance of arrival errors of LTCS, and K = the factor chosen to insure a 1% probability of missed approach. For this case, the arrival error of each aircraft in a given pair contributes to the missed approach rate. If the LTCS is rescheduled on the basis of the actual arrival time of the first aircraft of each pair, then the runway interval

$$t_0 = t_L + K(\sigma_a{}^2 + \sigma_L{}^2)^{0.5}$$

and the improvement resulting from this rescheduling or interval operation is indicated in Fig. 10. This simple example demonstrates that the accuracy the LTCS must achieve is of the order of σ_a = 10 sec, in order to have single runway operations rates (landings and takeoffs) of the order of 50 operations/hr, and indicates the improvement in adopting rescheduling or interval approach control schemes.

Accurate control over navigation in the terminal area and good information on aircraft position and ground speed will be needed in order to insure such small arrival errors. Since arrival errors grow with time of prediction, it is desirable to estimate or reschedule arrival times from as close to landing as possible, except that it becomes increasingly difficult to accomplish the rescheduled traffic flow since they are close to the final approach. This forms the essential problem in designing a workable high flow rate approach regulator.

Role of Fast Time Simulation

In order to study the complete operation of a given terminal area, it is necessary to construct a complex working model of the operation which is complete in sufficient detail for the purposes of the investigation. The construction and operation of the working model is called simulation, and it

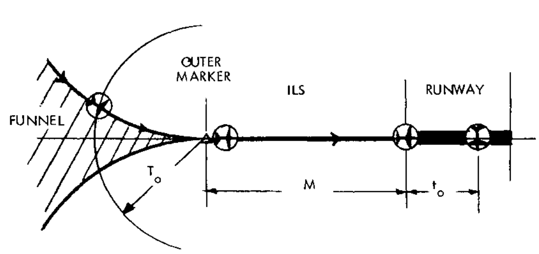

Fig. 8 The ILS approach funnel model.

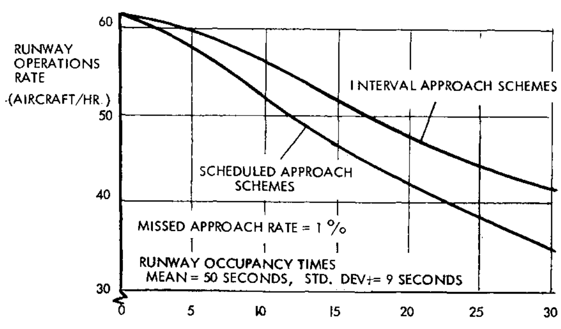

Fig. 10 Runway operations rate vs LTCS accuracy.

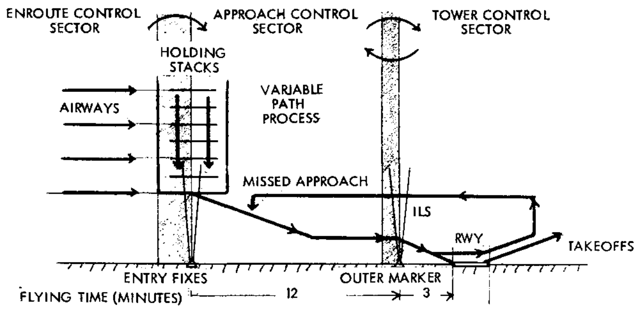

Fig. 11a Landing traffic control system (present scheme).

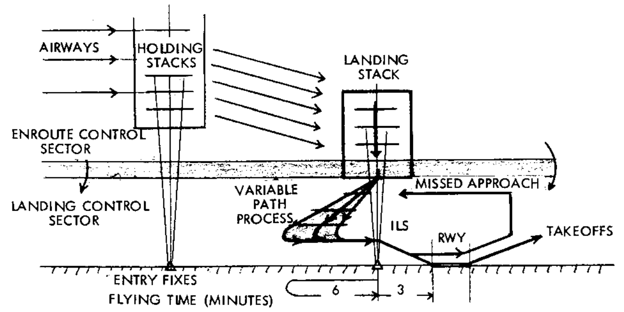

Fig. 11b Landing traffic control system (simulation scheme).

forms the experimental counterpart of the mathematical analysis methods. In contrast with the mathematical models, which study suboperations that have general applicability to various traffic systems, the simulation model provides a working model of a particular, specific traffic system and gives results applicable solely to this system.

Particularly in the terminal area, there is a need for investigations into various traffic systems, which use different approach procedures, assume improved navigation and guidance for aircraft, study communications congestion, and introduce the digital computer for both decision making and information processing. Fast time simulation on a digital computer provides a useful analytical and design tool for such investigations.

Fast time simulation of air traffic systems has not received as much attention as real time simulation for two main reasons: there has been doubt that faster or more useful testing could be achieved; and it is necessary to replace the human controller by an automatic, decision-making control logic, which could be difficult to construct. The size and speed of present computers allow as much realistic detail as the investigator cares to include, and statistically significant results can be obtained about 15 times faster than from real time simulation. The speed and the controlled testing (which results from the ability to repeat exactly the test run with only one factor changed) allows the design of a testing program to study the operational performance of any proposed control scheme and its sensitivity to factors such as wind, human errors, equipment accuracies, communications congestion, etc. Fast time simulation is very well suited to basic research in air traffic control (ATC) operations and to preliminary design investigations of any particular scheme where the easy changes to system procedures and quick test results allow the design process to proceed more rapidly.

It becomes especially appropriate when traffic control schemes that use the digital computer itself are being considered, since much care must be taken in testing the computer logic against all possible traffic situations. It is interesting to compare the programing development of the computer controller with the learning process of the human controller. The results of early test runs, where unforeseen traffic situations occur, causes reprograming of the computer logic until an efficient and flexible decision-making process is developed. All the experience of the human controller can be incorporated into the computer controller, and the ability of the computer to make instantaneous calculations, its reliability, and the quality of its memory make the computer a potentially more effective controller than the human. The problems of realizing this potential and of finding ways to integrate the computer with the monitoring of human controllers and with other ATC equipment will require considerable research and development and fast time simulation.

Description of the Simulation LTCS

A comparison of the geometry of the present terminal area and the simulation scheme chosen for investigation is shown in Fig. 11. In both schemes, the four functional elements of the general LTCS shown in Fig. 2 may be identified.

The present traffic scheme directs traffic through the surrounding airways network to twin holding stacks downwind from the ILS runway. The handoff from en route control sectors to approach control is made at these stacks. Approach control ladders aircraft in these stacks, coordinates their exits to form a landing sequence, and spaces aircraft by means of path stretching using radar vectoring in the area before the ILS outer marker. At the ILS, aircraft are cleared from approach control and handed off to tower control. In the event of a missed approach, the aircraft flies a published procedure, which takes it back into the radar vectoring area and returns it to the jurisdiction of approach control.

The simulation terminal area scheme changes these traffic flow patterns. En route sectors maintain control over all IFR traffic above 5000 ft in the terminal area, and meter the traffic arrivals from the entry fix holding patterns to a single landing stack located at the ILS outer marker. No radar vectoring is necessary as altitude separation is maintained, and, in the event of an interruption of landing service, inbound aircraft are collected in the holding pattern at the ILS outer marker. The metering by en route controllers insures that the landing stack is normally occupied by only a few aircraft, which are temporarily delayed awaiting entry into the variable path process. The landing stack pattern is not the normal race track pattern, but an orbital pattern for which analytical models indicate more efficient operations.

Therefore, the LTCS begins at the ILS outer marker with a single, orbital pattern landing stack. The landing controller draws aircraft from this stack into the variable path process that uses a control pattern to obtain spacing intervals. This pattern is called an "orbital fan" pattern and the controller assigns an outbound radial and orbit radius to bring aircraft around to join the ILS. Altitude separation is maintained, and there will be three aircraft in the spacing pattern during busy periods. The accuracy of the spacing intervals depend upon the pilot or autopilot's ability to fly the assigned orbit with accuracies of less than ± 0.5 mile. These orbit radii are of the order of 5 miles, and the angle of bank for all aircraft is less than 5°. Various equipment exists or has been proposed for flying orbital patterns either manually or automatically.[9] As each aircraft passes the ILS outer marker inbound, the following aircraft should be on its orbit the correct flying time from the outer marker and 1000 ft higher. It is then cleared by the landing controller to leave the orbit and begin its approach. For a missed approach, the aircraft returns to the outer marker and can be fitted smoothly into the landing pattern. No handoffs or radio channel changes are necessary in the complete landing process.

This simulation scheme represents a complete antithesis of present thinking with regard to terminal area control systems. It uses a single stack and applies altitude separation throughout the terminal area instead of using radar separations in the geographical plane. It reduces the size of the final control sector by moving a holding pattern inward to the ILS outer marker and delaying any attempt to provide spacing until the immediate vicinity of the ILS outer marker. It returns the guidance responsibility to the pilot, who is asked to fly a landing pattern selected by the landing controller, which is adjustable to accommodate traffic errors as they occur.

The objective of this particular scheme is to produce a high degree of landing interval accuracy and reliability and to achieve safe operation using current separation standards at landing rates of the order of 35/hr and operation rates (take-off and landing) of 50/hr. It assumes a typical traffic mix of aircraft and the provision of some form of navigation system such as very high-frequency omnidirectional range/distance measuring equipment (VOR-DME) to give orbital guidance. It was selected from a variety of control schemes equally deserving of consideration because it reduced the size of the final control sector, which reduced the average number of aircraft being controlled and avoided communications congestion. This scheme delays the sequencing and spacing control functions until they become more effective because of reduced uncertainties and smaller estimation errors in the traffic operations. Its successful simulation operation indicates that consideration should be given to a class of terminal area systems, which use spacing control patterns (IFR landing patterns) in the vicinity of the outer marker. The methods of fast time simulation give us the means to develop working models of these schemes and investigate the details of their operation.

Traffic Factors in the Terminal Area

A description of the programing of the simulation is given in Ref. 1. It is necessary to represent every pertinent system of operation such as aircraft target navigation, target dynamics of response to controller commands, the communications channels, the traffic information available to the controller logic (and its accuracy), the meteorological effects on target groundspeeds, etc. There is no limitation to the detail that can be included in present fast time simulations. There is a need for some detailed traffic data to be measured in our present system such as the distribution of message lengths, the dynamic characteristics of aircraft targets in horizontal and vertical maneuvers, etc.

In the preparation of a testing program for a terminal area simulation, it is important to consider a number of traffic factors which define the system environment and which have a strong effect on operations.

1) Service rate: At some point in every LTCS, there is a bottleneck element that limits the landing or operations rate. An important test for every scheme is the capacity test, which determines the service rate at which the system would run if it were kept busy and locates the limiting element.

2) Arrival rate: The arrival rate (aircraft per hour) describes the flow of aircraft entering the system. Since the arrival rate will be less than the service rate for unsaturated steady-state operation, the system operating rate will always equal the arrival rate.

3) System utilization, ρ: the ratio of arrival rate/service rate is called utilization in queuing theory. It is a parameter relating directly to the amount of delay occurring in the system. At low utilizations, delays are minimal. As utilization increases beyond 0.75, average delay values increase very rapidly until, at $\rho \geqslant 1.0$, the average delay becomes infinite as it is growing without bound. In using average delay as a measure of system effectiveness in comparing simulation results, one must insure $\rho < 1.0$.

4) Distribution of arrival times: Another queuing factor that affects average delays is the degree of randomness of the arrivals. A Poisson distribution describes completely random arrivals, as would be expected from a large number of sources in the absence of any flow control process. The arrival times of aircraft at a large airport can be Poisson distributed, even where airline schedules are in effect. The other extreme of regularly spaced arrivals results in minimum terminal area delays in the terminal area system, since the delays have occurred outside the area to achieve these well spaced arrivals. It is important when stating average delay measures to describe the traffic arrival input. If arrival times are not Poisson or uniformly distributed, it is difficult to find a common basis of comparison.

5) Traffic entry altitudes: Although aircraft may be considered to arrive at the terminal area system when they reach the entry fixes, they may be at different altitudes. Another important characteristic of traffic input is the distribution of arrival altitudes, and this should be specified in describing the simulation tests.

6) Traffic mix: The range of target speeds in both the horizontal and vertical is a prime factor in determining the complexity of the traffic problem. If all traffic targets had the same speeds in the terminal area, the spacing problems would

Table 1 Tabulation of results

Run	Traffic parameter	Runway separation t_0, sec	Nominal arrival rate, aircraft/hr	Mean landing interval, sec	Estimated operations rate, aircraft/hr	No. of landings	No. of missed approach	Mean delay, min	Mean system error, error, sec
Min. runway interval									
A1	$t_0 = 120$, $\rho = 0.87$	120	25.2	156.2	47.2	88	0	5.22	12.2
A2	Descent, 500 ft/min	120	25.5	167.9	50.5	78	0	11.98[a]	−1.8
A3	$t_0 = 105$, $\rho = 0.85$	105	26.1	150.4	47.5	101	2	6.48	5.2
A4	$t_0 = 90$, $\rho = 0.86$	90	29.7	133.1	44.9	97	0	4.99	3.1
Wind tests									
B2	Wind 1, headwind	90	31.5	126.4	47.7	96	0	6.17	3.3
B3	Wind 2, crosswind	90	31.5	125.1	47.0	110	0	5.09	0.9
Utilization tests									
C1	$\rho = 0.92$	90	31.5	126.2	45.7	107	1	6.20	8.7
C2	$\rho = 0.76$	90	26.2	149.7	43.5	90	0	3.79	−0.2
C3	$\rho = 0.66$	90	22.7	168.2	37.2	99	0	3.04	−1.7
Traffic input									
D1	Regular input, no mix	90	36.0	101.8	55.5	131	1	2.32	0.2
D2	Regular with mix capacity test	90	34.0	113.1	50.0	106	0	6.93[a]	2.2
D3	Poisson, no mix	90	36.0	108.2	47.2	118	3	6.67	17.7
Navigation error									
D4	$\sigma = 0.25$ naut miles	90	31.5	129.2	50.4	104	3	6.33	8.8

[a] Unsteady state.

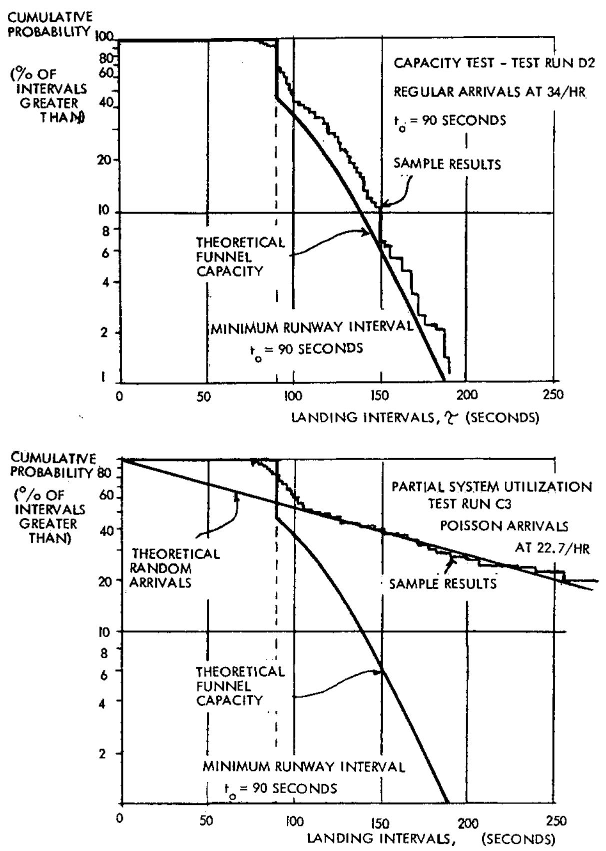

Fig. 12 Sample results, cumulative distribution of landing intervals.

be simplified, and different types of traffic control schemes would result.

7) Aircraft piloting, navigation, and guidance: An important factor in the terminal area is the level of piloting ability. Here we are interested in the dynamic response of aircraft to traffic control commands and the accuracy of aircraft tracking in carrying out navigational tasks. The static accuracy of the short range navaid-pilot display, the pilot or autopilot tracking capability, the accuracy and quality of information available to the control system, and the effects of varying winds and heights are all factors that determine the dynamic behavior of the aircraft targets and their accuracy in attaining correct spacing intervals. Once again, assumptions made in this area will result in different traffic control schemes and different separation standards to maintain safe, efficient operations.

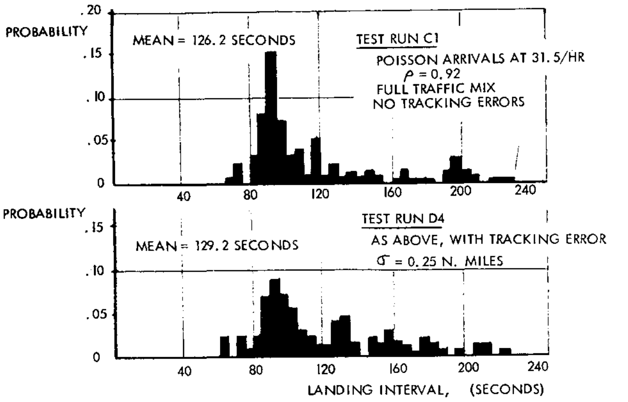

Fig. 13 Effect of tracking errors on landing interval distribution.

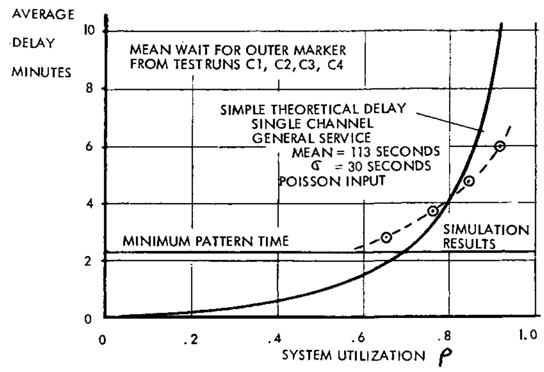

Fig. 14 Variation of average delay with utilization.

8) Meteorological factors: The effect of wind velocities in terminal area control schemes can be of major importance. Unfortunately, the variations of wind speeds with time and altitude prevent time averaging compensations to be applied in attempting accurate spacing intervals. Wind must be regarded as unknown and variable, i.e., a source of "noise" affecting system operation, and the system should be designed to minimize the noise effects.

9) Communications factors: A serious barrier to the operation of any high-performance terminal area scheme is the congestion or message delay that may occur on communication channels. The exchange of information by secondary radar will relieve radio channels for future systems, but radio is likely to remain the main means of communication between the control system and the pilots. The number of channels required and the controller functions on each channel form an integral part of the design of any system, and it is desirable to minimize both the communications workload and the number of channels used. An estimate of average message delays on any communications channel can be made if the specific message count (the number of messages per aircraft handled), the average message length and its variance, and the systems operating rate are known. Care must be taken in designing radio procedures, since radio channel congestion can easily be the limiting factor in achieving higher operational rates.

All of these traffic factors define the operating environment for any traffic control scheme and form the basis of investigating control system performance. A detailed description of the traffic mix, traffic input characteristics, wind models, target dynamics, etc., for this simulation is given in Ref. 1.

Simulation Test Results

Unlike previous ATC simulation tests, which compare the effects of system changes for a fixed environment, this testing program examines the effect of different operating environments on a fixed LTCS (which was developed by preliminary testing). There are many measures of system performance which can be easily collected by the computer during the simulation run and processed afterward. For this particular scheme, the landing interval distribution, outer marker interval distribution, outer marker heights, delay distributions, system errors at gate delivery, landing stack occupancy, radio channel utilizations, radio channel gap time or idle time distributions, and other data were collected and are fully reported in Ref. 1. Results are tabulated in Table 1. Typical results are plotted in Figs. 12–14. The capacity test run Fig. 12a shows that the cumulative distribution of landing intervals follows the theoretical model of funnel capacity, which indicates that ILS funnel is the capacity restrictive element for this simulation. At lower utilizations, the landing distribution for random arrivals will follow the theoretical random arrivals line for large landing intervals as shown in Fig. 12b.

A histogram of landing intervals is shown in Fig. 13. There is a small probability of runway intervals less than the minimum runway separation $t_0 = 90$ sec arising from system errors. The distribution is well skewed to the right because of the funnel effect causing larger landing intervals. Figure 13 also indicates that random orbit tracking errors will not affect this distribution very strongly. The probability of achieving exactly a 90-sec landing interval is reduced, but the mean value is approximately the same, and the distribution remains well skewed to the right.

The average delay to landing arrivals is plotted against system utilization in Fig. 14 and compared to the theoretical delay from a single channel service system with the same service characteristics. As expected at low utilizations, the delay to arriving aircraft approaches the minimum time spent in flying the landing pattern. However, at higher utilization, the average delay does not increase as rapidly as the theoretical single channel delay. The terminal area system is a multichannel, correlated service, stochastic system, and it is difficult to apply any useful models from present queuing theory to form a general policy about its operation.

Conclusions

The future growth of traffic at our major terminals demands sustained research on the broadest terms to gain quantitative knowledge about advanced, high-performance terminal area air traffic control systems. In particular, the regular all-weather operation of our air transportation system will require extensive development of traffic control systems, which can sustain high operational rates during blind landing operations.

The mathematical methods of present operations research can be usefully applied to certain operations that occur within complete terminal area systems. Although necessarily describing idealized operations, useful estimates of delay measures or capacities can be made, and the relationships between various traffic variables clearly defined. The ability to work with stochastic operational models is very important to the designer of future traffic systems.

Fast time simulation of working operational models of terminal area control schemes is a very useful research tool in investigating traffic system performance and specifying the procedures and equipment capabilities which are required. The size and speed of newer computers and their availability to a wide number of investigators makes fast time simulation a very promising means of carrying out these basic research efforts.

The use of control spacing patterns for IFR landing procedures is a feasible method of obtaining the landing interval accuracy required for high-performance systems. Advanced means of giving accurate navigational data to the pilot or autopilot would be required, but the avoidance of radio congestion resulting from radar vectoring and the establishment of regular flight procedures can produce a smaller, higher-performance terminal area system. There are many such systems which should be investigated.

The computer can be used as a decision-making control element in the terminal area. It will require extensive research and development to accomplish its integration into future systems, but the computer does promise to be a more effective controller than the human.

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