SOME MEASURES OF AIRCRAFT PERFORMANCE ON THE AIRPORT SURFACE

WILLIAM JOHN SWEDISH

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DEPARTMENT
OF
AERONAUTICS
&
ASTRONAUTICS

FLIGHT TRANSPORTATION
LABORATORY
Cambridge, Mass. 02139

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

FLIGHT TRANSPORTATION LABORATORY

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WILLIAM JOHN SWEDISH

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ABSTRACT

During the month of January, a survey was conducted at Boston and Atlanta Airports to obtain input data for an interactive computer simulation of runway and taxiway traffic being developed by Lincln Laboratory. Data was collected for landings, takeoffs, and taxiing; included were such items as runway occupancy times, touchdown distances and times, liftoff distances and times, time over a given taxiway stretch, taxiway intersection delays and pre-takeoff delays.

This thesis presents the results of the analysis of that data. Sample means and deviations of various parameters are given. The results of further analysis, intended to disclose inherent patterns in the data, are also discussed.

First, it was found that there were few statistically significant differences in the speeds of different aircraft over the same taxiway stretch, regardless of the aircraft type or direction of travel. Also, length of the segment did not seem to have a uniform effect on speed. It is felt, though, that the location of the segment does have a substantial influence on taxiing speed.

Secondly, touchdown distance was not significantly different on runways equipped with VASI (Visual Approach Slope Indicator) systems, when compared with non-VASI runways. Both exhibit substantial variance in the distribution of touchdown points.

However, the distribution for VASI-runways presents a double peaking not otherwise noticed, which may indicate a difference between a VASI-assisted and an unguided landing.

Third, in analyzing runway occupancy times, it was found that the time to a given exit did not statistically vary, in general, regardless of the aircraft type involved. Overall differences between types were noted, with average occupancy times increasing with weight, but this is seen as being caused mainly by different patterns of exit use. On takeoffs, very few differences in occupancy times were found, regardless of type or runway.

Lastly, other analyses which could be performed on the collected data are discussed, and suggestions are made for the planning of future surveys. In particular, a more automated data gathering system, involving remote sensors on the runway, is strongly recommended for greater accuracy.

Thesis Supervisor: Amadeo R. Odoni

Title: Assistant Professor of Aeronautics and Astronautics

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Next, thanks are due to Mr. Joseph Connelley at Logan Airport and Mr. John Braden at Atlanta, for their cooperation, support, and hospitality to us during the survey. Their willingness to help went far beyond any limits of duty.

I would also like to thank Tom McKim and Ann Drumm for their help with the computer programs; Larry Giusti of Lincoln Lab for setting up the survey; Vic Dolat, also of Lincoln, for all of his help; and the fourteen MIT students who were such enthusiastic, hard-working observers.

Last but not least, sincere thanks to my good friend Mrs. Karyn Watson, for all the work she put into typing this thesis.

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Symbols

In using the computer to analyze the survey data, it was necessary to substitute numeric codes for the aircraft type, runway, taxiway, and heading. These codes are used in the following tables, and so this explanatory listing is provided.

Aircraft

1	BAC-111
3	DC-3
4	Martin 404
6	DHC-6 (Twin Otter)
7	B-707
8	DC-8
9	DC-9
10	VC-10
11	YS-11A
13	C-130
20	B-720
22	FH-227
27	B-727
37	B-737
47	B-747
58	CV-580
73	B-707-320
81	DC-8 stretch
88	CV-880
90	Electra
91	single engine light plane
92	twin engine light plane
93	business jet
94	heavy twin engine plane

Heading

0	outbound
1	inbound
2	outbound and inbound

Runways

1	4R
2	4L
3	9
4	15R
5	15L
6	22R
7	22L
8	27
9	33R
10	33L

Taxiways (Exits)

BOS:	1	North
	3	C
	4	D
	5	E
	6	F
	7	G
	8	H
	9	inner
	10	J
	14	N
	15	outer
	20	S (STOL)
	21	T
	30	33R
	31	33L
	40	4R
	41	4L
ATL:	12	12
	13	13
	90	10
	91	A
	92	B
	94	4
	99	9

CHAPTER I

INTRODUCTION

Few studies have been made to date on the performance of an aircraft on the airport surface during normal operations. The manufacturers provide data on approach speeds, takeoff and landing distances, etc. under test conditions, and the FAA has rules covering minimum aircraft separations and thus minumum interarrival times, but few people have actually gone into the field and taken measurements. There are some items, like takeoff and intersection delays which, to the knowledge of this author, have never been studied.

The lack of all this information became evident when Lincoln Laboratory received a contract from the FAA in August 1971 to produce computer simulations of different runway and taxiway configurations. This is but one of many projects attempting to model the activity on the air side of the airport, all of which require this type of data. For example, interest in our data has been shown to date by the Transportation Systems Center of the Department of Transportation, and the Massachusetts Port Authority. Assumptions could be made and estimates used in the programming, but that would leave the results open to doubt.

The published reports on previous studies were reviewed. The most complete of these studies actually comprises a series of reports published by the Airborne Instruments Laboratory at about 1960.[1,2] Here, use was made of the ASDE (Airport Surface Detection Equipment) at Idlewild (now Kennedy) Airport in New York, a short-range, high resolution radar display, to measure aircraft positions on the runway. From these, velocities and accelerations were calculated. A large amount of second-by-second data was gathered in this way.

Unfortunately, analysis of the data was not very thorough. For example, plotting the data as in Figure 1 reveals anomalous data points and positive accelerations on landing. These results might be explained by peculiarities of the data reduction process, but no explanation or description of the process is offered, even though the technique of using the ASDE is discussed at length. And since ASDE has been decommissioned at most airports, even this is no longer useful.

Lastly, most of the aircraft we would be interested in today did not exist in 1960. Those that did, like the 707 and DC-8, have been so changed by re-engining with fan jets that the AIL data is of little value.

At about the same time as the AIL reports were published, "A Report on Exit Taxiway Location" was produced by the University of California.[3] Here a model was developed that could specify the optimum locations of exit taxiways for given aircraft populations. The model requires information on the statistical distributions of times and speeds for the landing aircraft, which the authors obtained from, among other sources, the AIL reports. This does not affect the validity of the model itself, but it does not help us to obtain usable data either.

Finally, in a report published just this past year entitled, "Analysis of Runway Occupancy Time Data,"[4] an attempt was made to

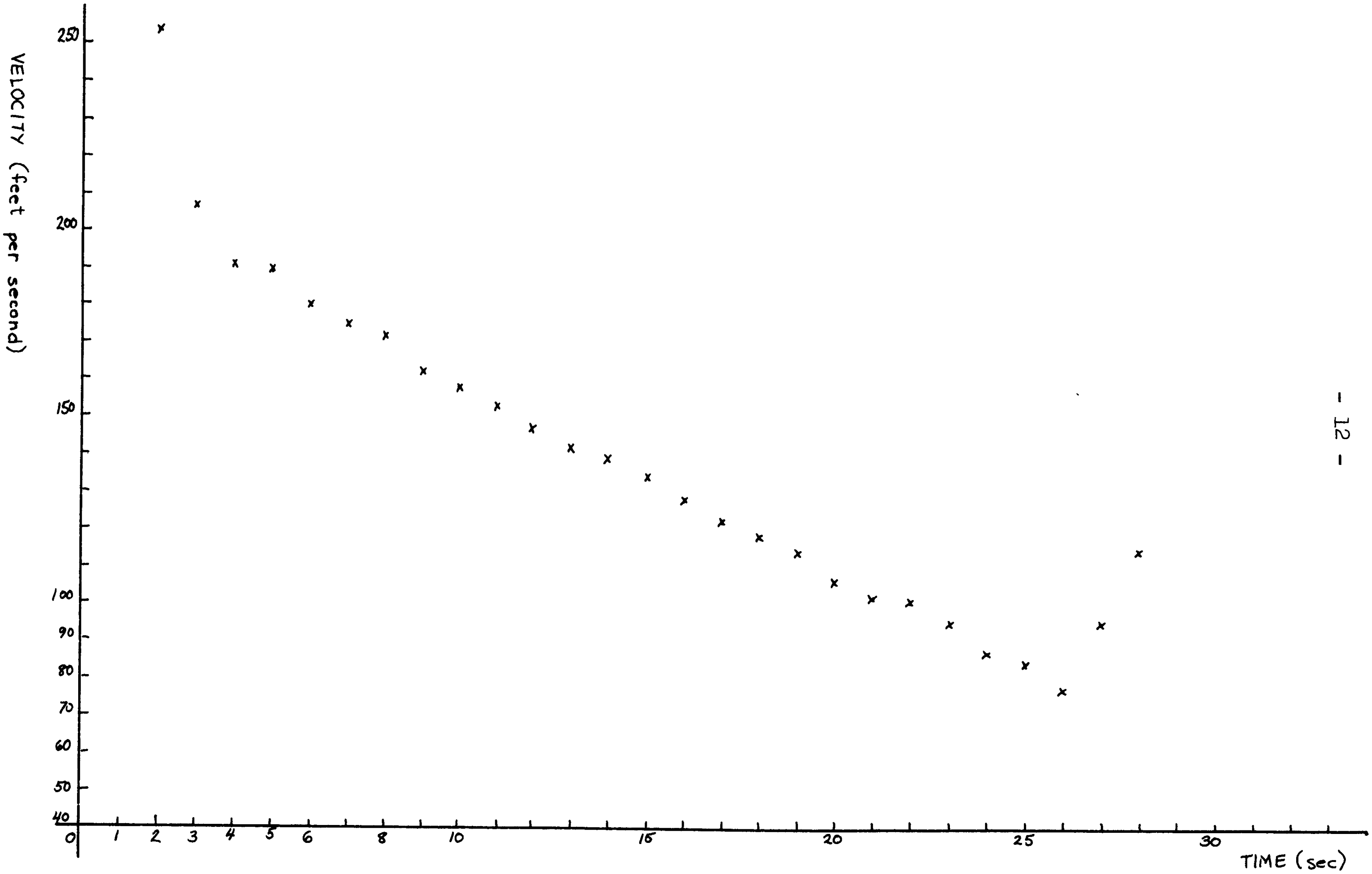


FIGURE 1. OBSERVED VELOCITY ON THE RUNWAY, PLANE NUMBER 34, REFERENCE 2.

study the runway occupancy times of modern jet equipment and to isolate some of the influential factors. Several interesting trends were observed, including the substantial effect of final gate position and physical airport layout on the pilot's choice of exits. The effect of congestion on occupancy times for arrivals-only runways was found to be insignificant (since times between arrivals were much greater than occupancy times, under all circumstances, there was never any pressure to reduce the occupancy times and exit more rapidly). However, the data sample itself is so small, consisting of only four hours of observations at each of three airports, that the statistical significance of the data is marginal and a truly detailed breakdown is impossible.

None of the above reports, which were the only pertinent documents to be found, included other information on taxiway speeds, intersection or takeoff delays, all of which were of interest to the Lincoln project. It was therefore decided to take our own survey, and to measure the aircraft's surface movements as completely as possible.

The Task of Measurement

After this decision was made, it was hard to limit the number of variables that we wanted to measure. An aircraft engages in a very complex, non-uniform series of maneuvers between the air and the gate, and there are many points of interest along the way. For a landing aircraft, its approach speed, landing distance, runway occupancy time, and velocity profile on the runway are all of interest. For departing aircraft we would have liked to look at occupancy times again, but also the various delays before takeoff - time spent in the queue, time between runway clearance and taking position on the centerline, time between takeoff clearance and the start of roll. And for all aircraft, data on their taxiing speeds, total taxi times, and delays at intersections would have been of great interest.

However, many of these items are interrelated. The presence of other aircraft on the field often forces a plane to speed up or slow down, turn or go straight, proceed or wait when the pilot would prefer to do otherwise.

The tower controller has a responsibility to direct the traffic, but in most cases the pilot has the final decision ("hold short of runway 4L for approaching traffic", for instance, is a mandatory - obedience command, while "take your first left-hand exit" is a request which can frequently be ignored). The result, therefore, is introduction of the human element which does not always proceed by the guidelines, but which adds variety and variance to both the events and the effects we want to measure.

Other significant factors that could be more easily quantified would include size of the aircraft, its performance specifications, weather (wind speed and direction, temperature and pressure), surface conditions (wet or dry), and physical layout of the airport (exit location and, as MITRE pointed out, gate position). Airline and flight number could be recorded. Another factor, congestion, can be gauged by proximity to the peak traffic periods and by the number of planes in the takeoff and landing queues.

Which of these variables and which of these factors could actually be measured was constrained by our choice of a measurement technique. Different alternatives with different capabilities were suggested and investigated, hybrid systems were discussed, and finally, one was selected. Despite some questions of accuracy, measurements were taken for most of the items of interest, and a large quantity of data was made available for further analysis.

CHAPTER II

SOME ALTERNATIVE TECHNIQUES

Unfortunately, there is no central station at airports where the ground speed and location of each aircraft in the vicinity is displayed. If there were, data collection would be much simpler. Few airports even have ASDE any longer, which just displayed the position of the aircraft, since it was not used often enough by the controllers to be justified. And so, unable to duplicate the procedures used by AIL, we were forced to investigate new methods of data collection.

Each method we considered needed to be fairly portable, since it was planned from the very beginning to conduct surveys at more than one airport. Of course, any of the standard ATC equipment at the airport could be used, if possible. And the technique had to be designed to have minimum interference with normal procedures, both to avoid unrealisitic data and to ensure cooperation from the local FAA and airport authorities.

The techniques studied fell into two categories: direct observation of traffic, with a large number of observers required, and indirect observation through radar or inertial devices. While each alternative had several disadvantages, the final decision was necessarily made on the basis of experimental practicality, rather than maximum accuracy.

Indirect Observation

The use of ATC surveillance devices in order to obtain some immediate interpretation of the data promised greater accuracy, but requires expensive equipment which might or might not be available at the airport site selected. There were other, operational drawbacks as well.

1. Radar Methods

a) ARTS III (Automated Radar Terminal System) - now in operation at several major hubs across the nation, this equipment provides an alphanumeric display of the aircraft's identity, ground speed and altitude while in the airport vicinity. However, the system does not extend to the runway threshold, and in fact it is programmed to automatically drop an approaching aircraft from the screen once it is within six miles of the airport. This programming could not be changed without extensive and expensive modifications; even if it were, the range of the display would be too great to permit detailed observations of runway movements.

b) ASDE - even though AIL used ASDE radar, as mentioned above, few airports possess it any more. In addition, although the ASDE gives quite accurate information on the location of the aircraft on the surface, it does not compute velocities, and so these would have to be calculated separately, after measuring displacements of aircraft from photographs of the display.

c) portable doppler radar - similar to that used by state highway police, this equipment can measure velocities directly. However, it measures only radial velocities, and would thus need to be set up almost immediately adjacent to the runway. This would be unacceptable to the FAA and the airport authorities we talked to, since they are concerned with maintaining a clear zone in this area.

We conducted some field tests of a doppler radar in November, to determine whether it would be useful for measuring taxiway speeds. It was discovered that steady readings were almost impossible to obtain. Apparently, this was due to false readings obtained from a) whirling propellor blades, and b) either the rotating compressor blades or high temperature exhaust gases of the jets. The radar was also confused by the vertical motions of the aircraft on the uneven taxiway surface. While it may have been possible to correct for these effects, the effort did not seem to be worthwhile, since many radar units would have been necessary to give adequate coverage of the entire taxiway system.

2. Inertial devices - located on board the aircraft, this class of equipment would include built-in inertial navigation systems (INS) as well as portable accelerometers installed just for this purpose. Since the pilot is too busy on takeoffs and landings to relay this information to the tower, a separate on-board observer would be required. This approach would seem to be completely impractical, not only for the expense involved, but also for the severe limitations on the number of flights per day which could be monitored.

Direct Visual Observations

Generally, information on speeds and accelerations can be obtained through analysis of the time elapsed over given known distances as recorded by observers. Some means of measuring these times would include:

1. Stopwatches - these would provide the most direct time measurements. There are several problems, however. It is difficult to take accurate times while the watch is running, which would be necessary under many different circumstances. Also, the number of aircraft which can be followed at any given time by one observer is limited. One possible solution is multiple stopwatches and multiple observers, but here it is necessary to correlate one observer's readings with another's, with possible loss of accuracy.

2. Tape recorder - a multi-track tape recorder, with pulses from a tone generator marking the events, can be used as a timing device. However, the problem of reducing the tape to usable form is severe. The tape could be run through a strip chart recorder, and the intervals between events measured directly from the chart. Or possibly an analog computer could be used to translate the pulses into specific events, and time the intervals between them. However, it is difficult to record, on the same tape, such additional desired data as aircraft type, airline, etc., without greatly complicating the analytic process.

3. Wide-angle camera with a built-in time diaplay - recording several events on a single or successive frames of film, use of a camera facilitates the observational procedure, although it still leaves much work to be done in data analysis. When equipped with a reticle or simple cross hair, the camera can also be used to measure distance between touchdown and threshold, for instance. This idea was investigated, but there proved to be several difficulties with

obtaining the proper equipment. A camera was available from Lincoln, which possessed the time display and which had been used to photograph ship traffic through the channel off Logan Airport. But this camera was deficient in several ways; mainly, it had a long fixed exposure time (about 1/30 of a second)and a poorly lighted time display which could not give the desired tenth-second accuracy.

These, then, were some of the general techniques which were considered and looked into prior to the start of the equipment. It was finally decided to use stopwatches as the basic measurement tools, for reasons of low cost, portability, and ease of use. Needless to say, the technique needed to be developed somewhat further than outlined above.

The Actual Technique

The observational procedure was separated into three separate sections: arrivals, departures, and taxiways. Each of these segments requires several observers to record all the items of interest, according to the following methods.

1. Arrival - for this segment, three observers per runway were needed to record the desired data on touchdown points, runway occupancy times, and intermediate velocities.

The first observer used a theodolite to measure the apparent angle between the plane's touchdown point and the runway threshold. This was later converted to a distance along the runway. He also recorded the type of aircraft, the airline, flight number (obtained from approach control radio), runway used, and weather data. Lastly, he called out when the aircraft was over the runway threshold and when it touched down, to provide common zero times for the other members of the approach team.

The second observer measured the time interval between the aircraft's being over threshold and its touchdown, and also between threshold and exit from the runway (aircraft completely clear). He used a double-event stopwatch, with two independent second hands. He also recorded the exit used.

The third observer recorded the real time of the aircraft over the threshold, and also used two stop watches to measure and record the time interval of the aircraft over successive distances. For this purpose, we tried to attach markers, squares of bright green cloth to the runway edge marker lights. The markers were limited to eight-inches square by request of the airport supervisor, and this proved to be too small to be seen. Therefore, runway intersections, lights, etc. were used instead as markers. (See Appendix B).

2. Departures - similar measurements were taken for takeoffs. Again, three observers comprised a team, although their individual functions changed.

The first observer again used the theodolite, this time to take the bearing of the lift-off point. He also recorded the airline, aircraft type, flight number, runway, and number of planes in the takeoff queue at the start of roll.

The second observer used two double event stopwatches to record the time intervals between 1) the plane reaching the stop line short of the takeoff runway; 2) receiving runway clearance from the controller; 3) lining up on the runway centerline; 4) receiving takeoff clearance; and 5) starting takeoff roll. He also indicated whether the plane stopped at the line or rolled through.

The third team member measured time intervals between 1) start of roll; 2) three intermediate points, a known distance apart, for the speed measurements; and 3) lift off, plus real time of liftoff.

3. Taxiways - Two men were needed to adequately measure taxiway times. One man used a stopwatch to measure time over a stretch of taxiway for an aircraft rolling at a uniform speed. Distances were measured beforehand from an airport survey map for the most often used taxiway segements. The airline, aircraft type, location of measured segment, and heading of the aircraft (in or outbound) were also recorded.

The other man took measurements of the delays at taxiway and runway intersections. He recorded the time between an aircraft stopping, the other aircraft passing through the intersection, and the first aircraft receiving crossing clearance, starting roll, and clearing the intersection, using two double event stopwatches.

Use of the Theodolite

Originally designed as a surveyor's instrument, a theodolite consists of a high-power (30X) telescope which can pivot both horizontally and vertically, connected to indicators which show the amount of deflection in either direction. The models which we used had internal scales which could be adjusted and read to the nearest second of arc.

The theodolite is mounted on a tripod, which, intended for outdoor use, has legs which end in sharp pointy tips. In order to use this same tripod indoors, it was necessary to have made a wooden base, shaped like a three-pointed star, which not only prevented the legs from gouging the floor but also prevented them from spreading apart.

After leveling the scope and zeroing it on a preselected landmark, all the observer had to do was track the aircraft with the theodolite and, when it touched down or lifted off, align the cross hairs of the scope with the point on the runway and read off the bearing as measured from the reference landmark. The bearings of the runway thresholds were also measured. Periodically the scope was again trained on the zero point and recalibrated if necessary.

The only modification to the theodolites was a small 5X scope mount to the top of the regular scope. This sighting scope had a much wider field of view than the higher power scope, and was of necessity the primary tool used by the observer.

CHAPTER III

OBSERVATIONS

By the middle of December, it had been decided that the survey would be conducted in two parts: first, one week at Logan Airport, in Boston, to test and adjust the techniques used, and then several days of data gathering at Atlanta Airport. Observations at another airport were desired to provide a contrast or a corroboration of our Boston data.

Atlanta was chosen for several reasons, all of which meant that we could get the largest amount of useful data in the short time available there. First, Altanta is an extremely busy airport (about third highest traffic volume in the country), and so would be operating at or near saturation most of the time. Secondly, the aircraft which we would observe would be mainly DC-9's and 727's for short to medium range flights, and so it would be possible to get a statistically large enough sample for at least these two types. Lastly, there was very little danger of snow to force an airport closing in Atlanta (however, it had snowed the week before we arrived, and at least rained during our survey).

Our operation at the airports were conducted with the cooperation of the FAA and airport authorities. In Boston, we received permission from Mr. Joseph Connelley, the FAA's chief controller at Logan, to conduct the survey from the controllers' ready room, located on the seventh floor of the control tower just beneath the cab, and affording an excellent view of the field. This seemed to be the best available location, since the cab itself was too small to hold more than one or two extra people.

The survey was to be conducted in two shifts per day: in the morning, from 8:00 a.m. to 11:00 a.m., and the afternoon from 2:30 p.m. until dark (roughly at 5 o'clock). We intended to bracket the morning peak and catch as much of the evening peak as possible, our observational techniques limiting us to daylight conditions. Although it was intended to start on Monday, January 10, circumstances forced a one-day delay.

DAILY OPERATIONS

Tuesday, January 11

Although the weather the day before had been excellent, Tuesday morning was damp and extremely foggy. Visibility was too poor to zero the theodolites (the zeroing marker being a tall smokestack several miles away across the channel), and was soon down to one-half mile, where it stayed all morning. This was too low to see any but the nearest runways. As much information as possible was obtained from the radio.

Our observations were hampered, but not completely halted. There was still traffic on the field, and the taxiway crew, relatively untroubled by the fog, had little difficulty in timing aircraft over the near stretches of taxiway.

It was noticed at this time that few planes were forced to stop at intersections. When notified of crossing traffic, the pilot will ususally just slow down, hoping to avoid a full stop and the application of full breakaway thrust needed thereafter. In addition, tower clearance is usually phrased as "continue at your own discretion," leaving the final decision up to the pilot. Neither of these patterns were anticipated, and so our procedures had to be modified slightly.

By Tuesday afternoon, visibility was back to normal, and there were few problems in observing the arrivals and departures. That morning, small green flags had been attached to the runway light supports near the threshold of runway 4L, to mark off the distances over which the aircraft would be timed, in order to derive speeds. Despite the improved visibility, these were still extremely difficult to see, and so other landmarks were substituted. Appendix C contains a list of the intersections which were used, by both the arrivals and departures teams, for this purpose.

Wednesday, January 12

The weather on this day was clear and fair, with good visibility and a light wind. Observations for the day proceeded normally, with no significant incidents.

Thursday, January 13

As on Tuesday, a warm day has been followed by a very foggy morning. Runway Visual Range (RVR) was one mile at 8:00 a.m., and quickly dropped to a quarter mile. Once again the theodolite was useless, since it could not be zeroed, but this time even the taxiway crew had difficulty taking data. All traffic stopped at about 9:15; we left after an hour of waiting.

Weather had improved sufficiently by 1:30 that afternoon for us to take a chance and return to the airport. Visibility was up to four miles when we resumed observations. There was, however, a light drizzle which came down sporadically all afternoon.

Friday, January 14

This was another fair weather day, and observations proceeded uneventfully. It was discovered, however, that the two different theodolite teams, morning and afternoon, had been using two different landmarks to zero their readings. The bearings of one relative to the other was taken, in order to correct the previous readings and ensure consistency.

Sunday, January 16

Since observations had been restricted on two mornings, and one full day of the planned survey had been dropped, it was decided to extend the survey to Sunday afternoon. Data was taken from 2:30 p.m. until dark on arrivals, some departures, and taxiway activity.

Wednesday, January 19

Several observational problems arose on this, our first day in Atlanta. It was difficult to find a vantage point as optimal as our perch in the Logan control tower; we used the observation cab of a fire control tower located about midway between the two parallel runways 27R and 27L. As it turned out these were rather cramped quarters for the six of us, but worst of all, our view of the threshold and landing area of runway 27R was completely blocked by the hangers and maintenance facility of Delta Airlines at the end of the field. We did have a clear view of 27L, however, and most of the taxiway network, so we were still able to collect data.

Our theodolite readings for the day are of questionable accuracy, however. The wooden tripod base, which made it possible to use the outdoor surveying tripod indoors, was lost on the flight down from Boston. Since the tripod could not be used, the theodolite was rested on a window ledge - an insecure position, where it quite possibly was knocked out of alignment several times that afternoon. A replacement base was fabricated the next day.

Thursday, January 20

After consulting with Mr. John Braden, assistant airport manager at Atlanta, we set up our equipment on the roof of the terminal building itself, on a walkway just outside of and below the control cab. Needless to say, our view from this position was excellent. The only shortcomings of this location, as a matter of fact, were that it was completely exposed, and that there were no electrical outlets for our radios. Although they were both battery powered, they had to be played at low volume in order to conserve power; it was difficult for everyone to hear the transmissions then, and so most airline flight numbers were missed.

Although we had intended to record movements on both runways in use, 27R and 27L, traffic was so heavy that we were forced to choose only one. Both runways handled both takeoffs and landings, with 27L handling a greater ratio of arrivals to departures. Still, we decided to concentrate our attention on 27R, since it was closer and handled more traffic, as we had noticed the previous day.

In contrast to the previous day's excellent weather, it rained lightly later that afternoon. Observations became uncomfortable but not impossible, as we continued from the leeward side of the tower.

Friday, January 21

We returned to our position outside the control cab; the day was windy but clear. Wanting to gather as much data as possible, the six of us tried to cover all eight data gathering positions. One man took information for sheets D2 and A3, while another did D3 and A2; two others alternated positions, with one reading the theodolite while the other filled in sheets A1 and D1. Since each man handled one arrival and one departure sheet, and we were covering only one runway, there was no time when two tasks would have to be done simultaneously. The only compromise necessary to ease the work load slightly was to reduce the number of intermediate speed points from three or four to just one. At that time we had doubts about the accuracy of any data we could obtain on intermediate speeds, and thus were not hesitant about compromising this side of the observations.

That day finished our survey. No serious problems had been encountered, and no major changes were made in our initial operating plans. Although the work had not really been boring, it was repetitious and tiring, since it called for constant alertness and quick reactions. In terms of the effort required and the reactions of the observers themselves, the final observational technique upon which we decided was definitely acceptable.

CHAPTER IV

PRELIMINARY DATA ANALYSIS

After we had returned from Atlanta, the process of analyzing the data was begun. First the pages were ordered and numbered, and quickly scanned for obvious inconsistencies or undecipherable handwriting. In all, there were 264 pages of data. This included 99 on arrivals, 93 on departures, and 72 on taxiways.

By this time, the FAA flight strips for the days spent at Logan Airport had become available. (The strips are held for fifteen days, in the event they are needed for accident investigation or other legal purposes, and if not needed are then discarded.) Unfortunately, the strips for the first two survey days have been discarded by accident before we could collect them. The relevant strips were sorted out from the rest of the day's output, and compared to the survey sheets. In this way airline, aircraft type, and flight number were verified; aircraft over 300,000 pounds were identified by the "H" for "heavy" on the flight strips next to their type number; and destinations were obtained for the departing flights. Origins of arriving aircraft were found by using the Official Airline Guide and copies of the airline schedules.

There were many flights, however, which were not regularly scheduled into Boston, and these were a bit more difficult to trace. Some had been diverted from their original destinations, some were charter flights. In other cases, an unexplained flight number had undoubtedly been misunderstood over the radio or written down incorrectly.

At this same time, some rough calculations were performed on the data, and certain preliminary results were sent to Lincoln. These included average speeds over different taxiway segments for typical light, medium, and heavy jet aircraft, and an initial distribution of touchdown distances at Atlanta Airport.

Finding this distribution, and in general converting the theodolite readings into distances along the runway, was the cause of many headaches, and pointed to basic deficiencies in the data. Once a geometric formula was worked out for the conversion (see Appendix B), it was realized that the location of the observation point would be needed to within a few feet, in order that distances to the runway thresholds, and the angles formed at these thresholds, could be computed. Available airport survey maps could not give this information accurately, and so it was decided to use triangulation techniques to determine our exact location.

This method necessitated another trip to Logan, and using the theodolite once again to take bearings on the runway thresholds, intersections, and important runway exits. Once this data was available (similar data as needed for Atlanta had been obtained during the course of our observations there), it was possible to proceed, as outlined in the Appendix.

Unfortunately, consistent results could not be obtained. The computations apparently are extremely sensitive to the accuracy of the bearings used, and errors in these bearings produced variations of several hundred feet in the location of the tower when compared to each other and to the airport map.

It was eventually decided to use the approximate distance, as measured from the best available maps, between the control tower and the closest runway and the observed bearings of the runway thresholds, to compute the other distances and angles mentioned. These have been used in the calculations of touchdown and takeoff distances, and indirectly for approach speeds and average takeoff accelerations.

Computer programs were written to perform these calculations, and do other preliminary analyses of the recorded data. As a result of this stage of the analysis, computed values were obtained for taxiing speeds, approach speeds, touchdown and takeoff distances, and average takeoff acceleration, and various measures of takeoff and intersection delays (e.g. the time interval between receiving takeoff clearance and starting the takeoff roll, or between stopping at an intersection and receiving crossing clearance). A more complete discussion of these factors, and their potential significance, will start in the next chapter.

It was necessary to organize the data before punching it onto computer cards, and this provided an excellent opportunity to check for consistency between data sheets. Wherever possible, disagreements between data sheets were settled by reference to an outside source: either a third data sheet, the OAG, the FAA flight strips, or previous observations. Some errors in the calculated values turned out to be due to cardpunching errors, which were quickly corrected whenever found.

CHAPTER V

TAXIWAYS SPEEDS

Initial Hypothesis

Before we began the survey, it seemed reasonable to believe that some relation existed between an aircraft's size, weight, or performance, the distance over which it taxied, and its average speed. We expected to find that speed increased with both size and distance.

The influence of size would seem to come mainly from its effect on the pilot's perception of his speed. Until inertial navigation systems which could indicate ground speed were installed on board the wide-bodied jets, the pilot had no objective measure of taxiing speed, and was forced to rely on external cues.

One of these was visual. But as the height of the cockpit above pavement increased on the large jets, the pilot's field of view would change, and he would see less and less of the ground area immediately around his aircraft. This in turn means decreasing usefulness of such visual cues as centerline markings and taxiway lights.

Another cue would be the motion of the plane itself. No taxiway is perfectly smooth; some vibration and bouncing will always be transmitted to the pilot by the landing gear. As the size of the aircraft and its landing gear increases relative to the size of these surface irregularities, it would seem that the vibrations and the feeling of speed would decrease. The pilot would lose a seat-of-the-pants notion of his true speed.

We also believed that speed would increase with the taxiing distance. If the pilot wanted to avoid overusing his brakes, he would not be moving too fast when he approached an intersection, where he might be instructed by the tower to hold for crossing traffic. On a short stretch of taxiway, this would mean never attaining peak velocity; for a longer stretch, it would mean a period of constant velocity separated from the slower intersection-approach speed by periods of acceleration or braking.

The sections of taxiway over which velocities were measured during the survey were all chosen such that taxiing speed would be reasonably constant, except perhaps at the beginning and end. In other words, no measured section contained a turn, an intersection, or other cause for the plane to decelerate and then speed up again.

Lastly, if there was an effect on the aircraft's speed due to its weight, it was expected that this would mean a difference between inbound and outbound speeds on the same section of taxiway. Planes headed for the runway, carrying a full load of fuel, would be slower than inbound aircraft. Also, if there was a queue of aircraft waiting to takeoff, the pilot might prefer to taxi slowly rather than spend a long time in line. This situation would not present itself to inbound traffic.

Statistical Techniques

Comparisons were made between two different aircraft categories using a form of the standard t-test to compute means. The equation, found in Statistics Manual[5] by Crow, Davis, and Maxfield, is as follows:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{Q / n_1^2(n_1-1)}} \qquad (5.1)$$

$$\text{where} \quad Q = n_1 \sum_{i=1}^{n_1} (u_i - \bar{u})^2 = n_1 \sum_{i=1}^{n_1} \left(u_i^2\right) - \left(\sum_{i=1}^{n_1} u_i\right)^2 \qquad (5.2)$$

$$\text{and} \quad u_i = x_{1i} - x_{2i} \sqrt{\frac{n_1}{n_2}} \qquad (5.3)$$

for the i^{th} pair of observations

n_j is the number of events in the j^{th} sample $(n_1 \leq n_2)$

$\bar{x}_j$ is the mean speed of the j^{th} sample.

In a planned experiment, n_1 should equal n_2; they were rarely ever close in our survey. Only n_1 events out of the larger sample could be used for simplicity, the first n_1. This does not create problems if the events are perfectly random.

In our case, however, it meant that we could not be sure that the events we were comparing were truly comparable. For example, in comparing the average speed inbound of a particular aircraft type at Atlanta with its average speed outbound, we completely neglect the fact that inbound and outbound taxiing occurred on different taxiways. Only by carefully classifying the data, to ensure as closely as possible that only one significant variable differs between the two compared groups, can we hope to detect the true effect of that variable. Unfortunately, such classification sharply reduces the number of events in each sample group, limiting the usefulness of that sample.

For this comparison, we tested the hypothesis that the mean speed of the first sample equaled the mean speed of the second, at the 5% significance level (in other words, there is a 5% chance of accepting this null hypothesis when it should be rejected, or vice versa). Since this could be either a 2.5% chance of overestimating the true mean or a 2.5% chance of underestimating it (an equal-tails test), we compared the calculated value of t with the value from a table[6] of $t_{\alpha/2,n-1}$, where $\alpha/2 = .025$ and $n - 1$ is one less than the number of observations (n_1).

If, on the following tables, the absolute value of T(CALC) is less than T(.025), we accept the null hypothesis that $\bar{v}_1 = \bar{v}_2$. Otherwise, we reject the null hypothesis and state that there is a significant difference between the two samples. These cases are denoted by a star (*) in the left-hand margin.

Data Analysis

1. Heading

It was decided to first compare the inbound and outbound movements of each aircraft type, over all taxiways at a given airport (Tables I and II). No significant differences were found at Logan; at Atlanta, on the other hand, both the DC-9 and the 747 were found to be faster inbound than outbound.

To determine whether this was attributable to the aircraft or the taxiway, a comparison was next done between inbound and outbound

```
TYPE  V̄(IN)    NO  V̄(OUT)  NO   T(CALC)      T(.025)

   1  23.25    6  20.24   10   -1.2998         2.571
   3   8.88    1   0.0     0    0.0
   4   0.0     0   0.0     0    0.0
   6  22.87    7  21.72    4   -0.5154         3.182
   7  19.40   26  19.50   36    0.0477         2.060
   8  20.05   17  18.97   18   -0.6143         2.120
   9  21.01   82  20.30   75   -0.7002         1.990
  10   0.0     0  39.14    1    0.0
  11   0.0     0   0.0     0    0.0
  13  20.59    1   0.0     0    0.0
  20  21.05    4  12.06    1    0.0
  22  19.15    6  20.89    2    0.4087        12.406
  27  18.56   78  18.27   92   -0.3614         1.990
  37  18.51    3   0.0     0    0.0
  47  14.48    3  22.58    1    0.0
  58  22.26    6  19.57    5   -1.6776         2.776
  73   0.0     0   0.0     0    0.0
  81   0.0     0   0.0     0    0.0
  88  20.09    2   0.0     0    0.0
  90  21.18   10  20.70    4   -0.2253         3.182
  91  21.91    3   0.0     0    0.0
  92  30.70    1  25.60    2    0.0
  93  20.46    4   0.0     0    0.0
  94  11.84    1  21.24    2    0.0
T=70.18/84.44 14:21:50
```

Table I   Boston, inbound vs. outbound speeds, all taxiways, by aircraft type.

```
TYPE  V̄(IN)    NO   V̄(OUT)   NO    T(CALC)        T(.025)
   1  0.0      0    0.0      0     0.0
   3  0.0      0    0.0      0     0.0
   4  30.26    2    25.94    10   -1.4573         12.706
   6  0.0      0    0.0      0     0.0
   7  24.52    1    23.40    14    0.0
   8  26.69   16    22.12    21   -1.8133          2.131
*  9  26.16   55    23.12   139   -2.8872          2.005
  10  0.0      0    0.0      0     0.0
  11  34.42    3    25.72    4    -2.5528          4.303
  13  24.92    2    16.79    2    -1.6763         12.706
  20  0.0      0    20.72    1     0.0
  22  0.0      0    0.0      0     0.0
  27  25.22   32    23.68    60   -1.4846          2.041
  37  25.93    7    23.45    8    -0.9415          2.447
* 47  24.36    3    18.46    6   -10.0047          4.303
  58  0.0      0    0.0      0     0.0
  73  0.0      0    0.0      0     0.0
  81  0.0      0    17.14    3     0.0
  88  25.90    1    22.42    2     0.0
  90  0.0      0    0.0      0     0.0
  91  30.23    3    27.75    11   -0.5056          4.303
  92  24.52    1    25.93    11    0.0
  93  30.42    1    24.75    5     0.0
  94  0.0      0    0.0      0     0.0
T=59.05/71.17 14:28:35
```

Table II Atlanta, inbound vs. outbound speeds, all taxiways, by aircraft type.

```
EXECUTION BEGINS...
 TYPE =      9

 DIST    V̄(IN)    NO    V̄(OUT)  NO    T(CALC)       T(.025)
  725   21.63    10   17.63   12     1.5800        2.262
 1200   17.33    13   20.89    1     0.0
* 1400   21.14     6   14.79    6     7.4804        2.571
 1475    0.0      0    0.0     0     0.0
 1500    0.0      0    0.0     0     0.0
 2000   21.72    21    0.0     0     0.0
* 2325   23.48     6   15.97    9     2.7465        2.571
 2400   21.73    23   22.03   12    -0.2173        2.201
 2700    0.0      0   22.30    9     0.0
 2975    0.0      0   22.24   24     0.0
 1201   19.02     2    0.0     0     0.0
 1450   22.53    10   22.88    8    -0.1281        2.365
 1501    0.0      0   22.70   14     0.0
 1775   15.45     1   21.09    2     0.0
 1850   27.18     6   23.55   10     1.4553        2.571
 1900   22.48     3   26.67    2    -0.7975       12.706
 2001    0.0      0   20.34   27     0.0
 2500   18.05     1   23.03   45     0.0
 3475    0.0      0   29.08    3     0.0
 3500   28.48    32   25.25   29     1.6957        2.048
```

Table III   DC-9, inbound vs. outbound speeds by taxiway.

```
EXECUTION BEGINS...
 TYPE = 727

 DIST    V(IN)    NO   V(OUT)  NO    T(CALC)       T(.025)
  725   16.08    24   14.91    7     0.7494        2.447
 1200   16.35    12    0.0     0     0.0
* 1400  20.29    13   15.47   16     3.4761        2.179
 1475    0.0      0   19.18    4     0.0
 1500    0.0      0    0.0     0     0.0
 2000   19.85    10    0.0     0     0.0
* 2325  20.86     6   15.67   13     3.1753        2.571
 2400   21.67    12   21.69    8     0.0344        2.365
 2700    0.0      0   20.10   15     0.0
 2975    0.0      0   19.79   29     0.0
 1201   27.32     1   17.32    1     0.0
* 1450  19.91     3   22.41   10    -7.7816        4.303
 1501    0.0      0   30.37    5     0.0
 1775    0.0      0    0.0     0     0.0
 1850   27.72     5   33.64    3    -1.0780        4.303
 1900   27.74     3   15.62    1     0.0
 2001    0.0      0   18.49    9     0.0
 2500    0.0      0   23.21   21     0.0
 3475    0.0      0    0.0     0     0.0
 3500   24.91    20   25.70   10    -0.4596        2.262
```

Table IV 727, inbound vs. outbound speeds by taxiway.

```
TYPE =      7

DIST    V̄(IN)    NO   V̄(OUT)  NO     T(CALC)        T(.025)
 725   17.91     9   14.78    6      0.5999         2.571
1200   17.43     6    0.0     0      0.0
1400   15.35     1   11.91    4      0.0
1475    0.0      0   19.66    1      0.0
1500    0.0      0    0.0     0      0.0
2000   21.67     2    0.0     0      0.0
2325   19.03     2   20.64    7     -0.5841        12.706
2400   22.20     3    0.0     0      0.0
2700   25.08     3   25.85    3     -0.8994         4.303
2975    0.0      0   21.59   15      0.0
1201    0.0      0    0.0     0      0.0
1450   24.52     1   20.44    1      0.0
1501    0.0      0   25.11    3      0.0
1775    0.0      0   18.76    1      0.0
1850    0.0      0   35.33    1      0.0
1900    0.0      0   29.60    1      0.0
2001    0.0      0   22.84    3      0.0
2500    0.0      0   10.89    4      0.0
3475    0.0      0    0.0     0      0.0
3500    0.0      0    0.0     0      0.0
```

Table V 707, inbound vs. outbound speeds, by taxiways.

```
TYPE =      8

DIST   V̄(IN)   NO   V̄(OUT)  NO   T(CALC)      T(.025)
 725   14.12   5   16.51    1    0.0
1200   21.93   4    0.0     0    0.0
1400   22.30   5   15.41    1    0.0
1475    0.0    0    0.0     0    0.0
1500    0.0    0    0.0     0    0.0
2000    0.0    0    0.0     0    0.0
2325   23.43   2   16.81    3    0.8542      12.706
2400    0.0    0   19.38    3    0.0
2700    0.0    0   19.50    2    0.0
2975    0.0    0   20.24    8    0.0
1201    0.0    0    0.0     0    0.0
1450   21.92   4   15.60    1    0.0
1501    0.0    0   21.86    2    0.0
1775   28.16   3    0.0     0    0.0
1850    0.0    0   28.71    6    0.0
1900    0.0    0    0.0     0    0.0
2001    0.0    0   17.90    8    0.0
2500    0.0    0   19.61    2    0.0
3475    0.0    0    0.0     0    0.0
3500   28.32   9   25.26    2    1.9537      12.706
```

Table VI DC-8, inbound vs. outbound speeds by taxiways.

```
TYPE =     47

DIST   V̄(IN)   NO   V̄(OUT)  NO   T(CALC)      T(.025)
 725  13.84    1    0.0     0    0.0
1200  14.80    2    0.0     0    0.0
1400   0.0     0    0.0     0    0.0
1475   0.0     0    0.0     0    0.0
1500   0.0     0    0.0     0    0.0
2000   0.0     0    0.0     0    0.0
2325   0.0     0    0.0     0    0.0
2400   0.0     0    0.0     0    0.0
2700   0.0     0    0.0     0    0.0
2975   0.0     0   22.58    1    0.0
1201   0.0     0    0.0     0    0.0
1450  20.94    1    0.0     0    0.0
1501   0.0     0    0.0     0    0.0
1775   0.0     0    0.0     0    0.0
1850   0.0     0    0.0     0    0.0
1900   0.0     0    0.0     0    0.0
2001   0.0     0    0.0     0    0.0
2500   0.0     0   18.46    6    0.0
3475   0.0     0    0.0     0    0.0
3500  26.06    2    0.0     0    0.0
```

Table VII 747, inbound vs. outbound speeds by taxiway.

movements on each individual taxiway for selected aircraft types (Tables III - VII). These included the DC-9 and 747, of course, but also the 727, 707 and DC-8, because of the prevalence of these aircraft types.

This further breakdown confirmed that the DC-9 was faster inbound than outbound over certain stretches of taxiway - but contrary to the first comparison, this occurred at Logan Airport and not in Atlanta. The reason for this is as follows: for over half the taxiways on which the DC-9 travelled, comparisons could not be made between inbound and outbound traffic, because traffic flows were entirely in one direction or the other. And yet the speeds over these segments influenced the overall average speed, discussed above. We were not really comparing equivalent samples; we were, instead, comparing inbound traffic on one segment with outbound traffic on another, completely different segment.

This comparison also turned up differences in taxiing speeds for the 727, at Boston the same as for the DC-9 (inbound faster than outbound, over the same sections of taxiway), but also at Atlanta (outbound faster than inbound, over the 1450 foot stretch of taxiway). None of this had appeared in the first comparison.

No differences were found over specific taxiway lengths for the 707, DC-8, or 747, mainly because of insufficient data. For the 747 in particular, there was no taxiway which handled traffic in both directions, and hence comparison was impossible.

Looking over the results for the DC-9 and 727 once again, it was noticed that the distances over which heading-dependent differences in speed occurred, did not actually apply to the same taxiway. At Logan, the distances of 1400 feet and 2325 feet each referred to parallel segments of the inner and outer taxiways (see map, Appendix A). Similarly, at Atlanta, the 1450 foot distance included two different taxiways - coded C and F on the same map. It was necessary to compare inbound and outbound traffic on these segments individually, therefore, before we could draw any conclusions.

The results are shown in Table VIII. For the DC-9, there was a significant difference between inbound and outbound traffic only for the 1400 foot segment of the inner taxiway with inbound traffic slower. There was no significant difference for the 2325 foot segment, or for either segment of the outer taxiway.

For the 727, inbound traffic was slower than outbound on both segments of the inner taxiway, but there was no significant difference on the outer taxiway. Analysis of the Atlanta data showed that one taxiway (C) was used only by outbound 727's, and the other was used only by inbound 727's. This made comparisons over the same taxiway impossible. However, it meant that the original comparison for this 1450 foot stretch of taxiway could be reinterpreted as follows: that inbound traffic or taxiway F is significantly faster than outbound traffic on the equally long, symmetrically located taxiway C.

2. Aircraft Type

Comparisons were also made between different aircraft types, to see if speed really did depend on size and weight of the aircraft.

If this were so, then it might be possible to speak realistically of three categories of commercial jet aircraft, based on gross weights-light: 40,000 - 80,000 pounds (e.g. DC-9, 737, and BAC-111), medium : 80,000 - 120,000 pounds (727, 720, 880), and heavy: 120,000 pounds and up (707, DC-8, 747).

As a first step, comparisons were made both within and between these hypothetical classes, for inbound traffic, outbound traffic, and both, over all taxiways at a particular airport. (Tables IX - X). The only differences found were between the DC-9 and the 727 at Logan Airport, the DC-9 being significantly faster inbound and outbound as well as overall.

Next, comparisons were made over specific taxiway distances, either inbound or outbound. Since no significant differences had appeared within our hypothetical groups, the comparisons were made between groups, using the aircraft type from each group for which the most data was available - DC-9, 727, 707 (Boston), and DC-8 (Atlanta).

Comparing the 727 and DC-9 shows no significant differences outbound over individual taxiway lengths. Once again, this conflicts with the original comparison made over all taxiways, and for the same reasons: the two samples are not really comparable, since the two aircraft showed different patterns of taxiway usage. (For instance, 50% more DC-9's used the 2400 foot length outbound than did 727's, but 167% more 727's than DC-9's used the 1400 foot segment.) Only one significant difference was found inbound, and that showed the DC-9

```
 TYPE =   9

 DIST    T/W   V̄(IN) NO V̄(OUT) NO T(CALC) T(.025)
*1400 INNER   13.62  4  22.96  4  4.5542  3.182
      OUTER   17.13  2  17.50  2  0.0700 12.706

 2325 INNER   15.51  7  23.92  5  2.6032  2.776
      OUTER   17.59  2  21.26  1  0.0


 TYPE = 27

 DIST    T/W   V̄(IN) NO V̄(OUT) NO T(CALC) T(.025)
*1400 INNER   15.56 12  20.19  6  3.2919  2.571
      OUTER   15.18  4  21.32  6  2.0397  3.182

*2325 INNER   14.69  7  22.31  4  3.3341  3.182
      OUTER   16.81  6  17.97  2  2.2926 12.706

 1450   C      0.0  0   19.91  3  0.0
        F     22.41 10   0.0   0  0.0
```

Table VIII   DC-9 and 727, inbound vs. outbound, specific runways.

```
EXECUTION BEGINS...
 LOCATION  BOSTON
 HEADING =  2

 TYPE1  TYPE2   V̄(1)   NO   V̄(2)   NO    T(CALC)      T(.025)
    9     37   20.67  157  18.51    3    0.7585       4.303
 *  9     27   20.67  157  18.40  170    3.7537       1.97
    9      7   20.67  157  19.46   62    1.1807       2.00
   27      7   18.40  170  19.46   62   -1.0472       2.00
    8      7   19.49   35  19.46   62    0.0205       2.04
   47      7   16.50    4  19.46   62   -1.1146       2.776
   22     58   19.59    8  21.04   11   -0.6957       2.365



 LOCATION  BOSTON
 HEADING =  1

 TYPE1  TYPE2   V̄(1)   NO   V̄(2)   NO    T(CALC)      T(.025)
    9     37   21.01   82  18.51    3    0.8729       4.303
 *  9     27   21.01   82  18.56   78    3.0375       1.99
    9      7   21.01   82  19.40   26    0.9132       2.060
   27      7   18.56   78  19.40   26   -0.4958       2.060
    8      7   20.05   17  19.40   26    0.3464       2.120
   47      7   14.48    3  19.40   26   -1.1154       4.303
   22     58   19.15    6  22.26    6   -0.9881       2.571



 LOCATION  BOSTON
 HEADING =  0

 TYPE1  TYPE2   V̄(1)   NO   V̄(2)   NO    T(CALC)      T(.025)
    9     37   20.30   75   0.0     0    0.0
 *  9     27   20.30   75  18.27   92    2.2786       1.99
    9      7   20.30   75  19.50   36    0.6750       2.04
   27      7   18.27   92  19.50   36   -1.2287       2.04
    8      7   18.97   18  19.50   36   -0.2376       2.110
   47      7   22.58    1  19.50   36    0.0
   22     58   20.89    2  19.57    5    0.8882      12.706
```

Table IX Boston, comparing certain types over all taxiways.

```
EXECUTION BEGINS...
 LOCATION  ATLANTA
 HEADING =  2

 TYPE1  TYPE2   V̄(1)  NO   V̄(2)  NO    T(CALC)      T(.025)
    9     37   23.98 195 24.60  15    -0.3928       2.145
    9     27   23.98 195 24.21  92    -0.3161       1.99
    9      8   23.98 195 24.10  37    -0.0959       2.04
   27      8   24.21  92 24.10  37     0.0983       2.04
    8     88   24.10  37 23.58   3     0.2300       4.303
   47      8   20.43   9 24.10  37    -1.8433       2.306
   11     58   29.45   7  0.0    0     0.0
   11      4   29.45   7 26.66  12     0.5787       2.447
   58      4    0.0    0 26.66  12     0.0


 LOCATION  ATLANTA
 HEADING =  1

 TYPE1  TYPE2   V̄(1)  NO   V̄(2)  NO    T(CALC)      T(.025)
    9     37   26.16  55 25.93   7     0.1028       2.447
    9     27   26.16  55 25.22  32     0.6365       2.041
    9      8   26.16  55 26.69  16    -0.2561       2.131
   27      8   25.22  32 26.69  16    -0.6685       2.131
    8     88   26.69  16 25.90   1     0.0
   47      8   24.36   3 26.69  16    -1.3314       4.303
   11     58   34.42   3  0.0    0     0.0
   11      4   34.42   3 30.26   2     0.8511      12.706
   58      4    0.0    0 30.26   2     0.0


 LOCATION  ATLANTA
 HEADING =  0

 TYPE1  TYPE2   V̄(1)  NO   V̄(2)  NO    T(CALC)      T(.025)
    9     37   23.12 140 23.45   8    -0.1152       2.365
    9     27   23.12 140 23.68  60    -0.6132       2.00
    9      8   23.12 140 22.12  21     0.6757       2.086
   27      8   23.68  60 22.12  21     0.9028       2.086
    8     88   22.12  21 22.42   2    -0.2227      12.706
   47      8   18.46   6 22.12  21    -1.9257       2.571
   11     58   25.72   4  0.0    0     0.0
   11      4   25.72   4 25.94  10    -0.0277       3.182
   58      4    0.0    0 25.94  10     0.0
```

Table X Atlanta, comparing certain types over all taxiways.

```
EXECUTION BEGINS...

 TYPE1 =  27
 TYPE2 =   9
 HEADING =    0

 DIST    V̄(1)     NO   V̄(2)     NO    T(CALC)       T(.025)
  725   14.91      7   17.63    12     0.9520        2.447
 1200    0.0       0   20.89     1     0.0
 1400   15.47     16   14.79     6    -0.6251        2.571
 1475   19.18      4    0.0      0     0.0
 1500    0.0       0    0.0      0     0.0
 2000    0.0       0    0.0      0     0.0
 2325   15.67     13   15.97     9     0.1204       2.306
 2400   21.60      8   22.03    12     0.1692       2.365
 2700   20.10     15   22.30     9     1.1010       2.306
 2975   19.79     29   22.24    24     1.1499        2.069
 1201   17.32      1    0.0      0     0.0
 1450   22.41     10   22.88     8     0.1987       2.365
 1501   30.37      5   22.70    14    -2.1490        2.776
 1775    0.0       0   21.09     2     0.0
 1850   33.64      3   23.55    10    -1.9446        4.303
 1900   15.62      1   26.67     2     0.0
 2001   18.49      9   20.34    27     1.0732        2.306
 2500   23.21     21   23.03    45    -0.1543       2.086
 3475    0.0       0   29.08     3     0.0
 3500   25.70     10   25.25    29    -0.2006        2.262
```

Table XI   727 vs. DC-9, outbound, by taxiways.

```
 TYPE1 =      27
 TYPE2 =       9
 HEADING =     1

 DIST    V̄(1)     NO   V̄(2)     NO    T(CALC)        T(.025)
* 725    16.08    24   21.63    10     2.5515         2.262
 1200    16.35    12   17.38    13     0.5806         2.201
 1400    20.29    13   21.14     6     0.2891         2.571
 1475     0.0      0    0.0      0     0.0
 1500     0.0      0    0.0      0     0.0
 2000    19.85    10   21.72    21     1.1524         2.262
 2325    20.86     6   23.48     6     1.1588         2.571
 2400    21.67    12   21.73    23     0.0334         2.201
 2700     0.0      0    0.0      0     0.0
 2975     0.0      0    0.0      0     0.0
 1201    27.32     1   19.02     2     0.0
 1450    19.91     3   22.53    10     2.6377         4.303
 1501     0.0      0    0.0      0     0.0
 1775     0.0      0   15.45     1     0.0
 1850    27.72     5   27.18     6    -0.3465         2.776
 1900    27.74     3   22.48     3    -2.9777         4.303
 2001     0.0      0    0.0      0     0.0
 2500     0.0      0   18.05     1     0.0
 3475     0.0      0    0.0      0     0.0
 3500    24.91    20   28.48    32     1.7691         2.093
T=54.47/66.04 13:56:10
```

Table XII   727 vs. DC-9, inbound, by taxiways.

```
 EXECUTION BEGINS...
  TYPE1 =     27
  TYPE2 =      7
  HEADING =    0

  DIST    V̄(1)     NO   V̄(2)     NO    T(CALC)       T(.025)
   725   14.91     7   14.78     6     0.0591        2.571
  1200    0.0      0    0.0      0     0.0
* 1400   15.47    16   11.91     4     3.7839        3.182
  1475   19.18     4   19.65     1     0.0
  1500    0.0      0    0.0      0     0.0
  2000    0.0      0    0.0      0     0.0
* 2325   15.67    13   20.64     7    -3.2772        2.447
  2400   21.60     8    0.0      0     0.0
  2700   20.10    15   25.85     3    -1.9666        4.303
  2975   19.79    29   21.59    15    -1.2610        2.145
  1201   17.32     1    0.0      0     0.0
  1450   22.41    10   20.44     1     0.0
  1501   30.37     5   25.11     3     0.7401        4.303
  1775    0.0      0   18.76     1     0.0
  1850   33.64     3   35.33     1     0.0
  1900   15.62     1   29.60     1     0.0
  2001   18.49     9   22.84     3    -1.9498        4.303
  2500   23.21    21   19.89     4     0.9542        3.182
  3475    0.0      0    0.0      0     0.0
  3500   25.70    10    0.0      0     0.0
```

Table XIII   727 vs. 707, outbound, by taxiway.

```
TYPE1 =    27
TYPE2 =     7
HEADING =   1

DIST   V̄(1)    NO   V̄(2)    NO   T(CALC)      T(.025)
 725  16.08    24  17.91    9    0.4653       2.306
1200  16.35    12  17.43    6    0.3623       2.571
1400  20.29    13  15.35    1    0.0
1475   0.0      0   0.0     0    0.0
1500   0.0      0   0.0     0    0.0
2000  19.85    10  21.67    2    0.3216      12.706
2325  20.86     6  19.03    2   -2.2152      12.706
2400  21.67    12  22.20    3    0.1362       4.303
2700   0.0      0  25.08    3    0.0
2975   0.0      0   0.0     0    0.0
1201  27.32     1   0.0     0    0.0
1450  19.91     3  24.52    1    0.0
1501   0.0      0   0.0     0    0.0
1775   0.0      0   0.0     0    0.0
1850  27.72     5   0.0     0    0.0
1900  27.74     3   0.0     0    0.0
2001   0.0      0   0.0     0    0.0
2500   0.0      0   0.0     0    0.0
3475   0.0      0   0.0     0    0.0
3500  24.91    20   0.0     0    0.0
```

Table XIV   727 vs. 707, inbound, by taxiway.

```
TYPE1 =     27
TYPE2 =      8
HEADING =    0

DIST   V̄(1)    NO   V̄(2)    NO   T(CALC)     T(.025)
 725   14.91    7   16.51    1     0.0
1200    0.0     0    0.0     0     0.0
1400   15.47   16   15.41    1     0.0
1475   19.18    4    0.0     0     0.0
1500    0.0     0    0.0     0     0.0
2000    0.0     0    0.0     0     0.0
2325   15.67   13   16.81    3   -0.2468       4.303
2400   21.60    3   19.38    3    0.8347       4.303
2700   20.10   15   19.50    2    0.1500      12.706
2975   19.79   29   20.24    8   -0.1132       2.365
1201   17.32    1    0.0     0    0.0
1450   22.41   10   15.60    1    0.0
1501   30.37    5   21.86    2    1.8732      12.706
1775    0.0     0    0.0     0    0.0
1850   33.64    3   28.71    6    0.8892       4.303
1900   15.62    1    0.0     0    0.0
2001   18.49    9   17.90    8    0.5336       2.365
2500   23.21   21   19.61    2    0.8665      12.706
3475    0.0     0    0.0     0    0.0
3500   25.70   10   25.26    2    0.1358      12.706
```

Table XV 727 vs. DC-8, outbound, by taxiway.

```
  TYPE1 =      27
  TYPE2 =       8
  HEADING =     1

  DIST    V̄(1)    NO    V̄(2)     NO    T(CALC)       T(.025)
   725   16.08    24   14.12     5     0.6116       2.776
  1200   16.35    12   21.93     4    -1.6167       3.182
  1400   20.29    13   22.30     5    -0.4932       2.776
  1475    0.0      0    0.0      0     0.0
  1500    0.0      0    0.0      0     0.0
  2000   19.85    10    0.0      0     0.0
  2325   20.86     6   23.43     2    -0.6287      12.706
  2400   21.67    12    0.0      0     0.0
  2700    0.0      0    0.0      0     0.0
  2975    0.0      0    0.0      0     0.0
  1201   27.32     1    0.0      0     0.0
* 1450   19.91     3   21.92     4    -4.3600       4.303
  1501    0.0      0    0.0      0     0.0
  1775    0.0      0   28.16     3     0.0
  1850   27.72     5    0.0      0     0.0
  1900   27.74     3    0.0      0     0.0
  2001    0.0      0    0.0      0     0.0
  2500    0.0      0    0.0      0     0.0
  3475    0.0      0    0.0      0     0.0
* 3500   24.91    20   28.32     9    -2.5208       2.306
```

Table XVI 727 vs. DC-8, inbound, by taxiways.

```
EXECUTION BEGINS...                _
 TYPE   DIST   TW   HEAD     V     NO   T(CALC)     T(.025)
 * 27    725    9      1 16.42  14
    9    725    9      1 20.41   8  -2.9710       2.365


   27    725   15      1 15.60  10
    9    725   15      1 26.49   2  -1.0041      12.706


   27   1400    9      0 15.56  12
    7   1400    9      0 11.28   3   2.1426       4.303


   27   1400   15      0 15.18   4
    7   1400   15      0 13.81   1   0.0


   27   2325    9      0 14.69   7
    7   2325    9      0 18.25   3  -1.9858       4.303


 * 27   2325   15      0 16.81   6
    7   2325   15      0 22.43   4  -6.8533       3.182
```

Table XVII   Comparing Types over Different Taxiways with the same Length.

TYPE	MEANSPEED	STD. DEV.	NO. OF EVENTS
1	21.14	4.25	14
3	8.88	0.0	1
4	26.66	7.06	12
6	22.46	4.06	11
7	20.20	7.48	75
8	21.83	7.17	71
9	22.56	6.48	329
10	39.14	0.0	1
11	29.45	10.15	7
13	20.80	4.80	5
20	19.49	5.14	6
22	21.43	3.58	6
27	20.48	6.08	251
37	24.05	6.35	16
47	19.22	5.15	13
58	20.87	4.54	9
81	17.14	3.15	3
88	22.19	2.90	5
90	21.04	6.36	14
91	27.16	8.79	17
92	26.11	6.01	15
93	23.83	8.32	9
94	18.11	5.98	3

Table XVIII   Taxiing speed, mean and deviation, by type, all taxiways.

TYPE	DIST (FT)	AV SPEED(KT)	STD DEV(KT)	NO OF OBS	IN/OUT
1	725	19.25	3.12	2	IN
1	725	24.70	0.77	2	OUT
1	1400	31.88	0.0	1	IN
1	2325	23.17	0.0	1	IN
1	2325	20.54	0.0	1	OUT
1	2400	17.75	1.49	5	OUT
1	2700	21.83	2.07	2	OUT
3	1200	8.88	0.0	1	IN
6	725	22.83	3.00	2	IN
6	725	17.17	0.0	1	OUT
6	1400	21.03	5.76	2	IN
6	1400	27.63	0.0	1	OUT
6	2325	22.67	4.46	2	IN
6	2975	27.04	0.0	1	IN
6	2975	21.05	4.36	2	OUT
7	725	17.91	12.35	9	IN
7	725	14.78	2.48	6	OUT
7	1200	17.43	8.89	6	IN
7	1400	15.35	0.0	1	IN
7	1400	11.91	2.73	4	OUT
7	1475	19.66	0.0	1	OUT
7	2325	19.03	1.30	2	IN
7	2325	20.64	3.84	7	OUT
7	2400	22.20	6.21	3	IN
7	2700	25.08	3.49	3	IN
7	2700	25.85	4.76	3	OUT
7	2975	21.59	5.07	15	OUT
8	725	14.12	6.23	5	IN
8	725	16.51	0.0	1	OUT
8	1200	21.93	3.95	4	IN
8	1400	22.30	5.95	5	IN
8	1400	15.41	0.0	1	OUT
8	2325	23.43	5.64	2	IN
8	2325	16.81	7.03	3	OUT
8	2400	19.38	4.14	3	OUT
8	2700	19.50	6.17	2	OUT
8	2975	20.24	10.30	8	OUT
9	725	21.63	5.67	10	IN
9	725	17.63	6.48	12	OUT
9	1200	17.38	2.73	13	IN
9	1200	20.89	0.0	1	OUT
9	1400	21.14	3.88	6	IN
9	1400	14.79	3.23	6	OUT
9	1800	15.44	0.0	1	IN
9	1800	29.46	4.00	2	OUT
9	2325	23.48	2.12	6	IN
9	2325	15.97	5.09	9	OUT
9	2400	21.73	5.21	23	IN

Table XIX   Boston, taxi speeds, by type and distance.

9	2400	22.03	4.78	12	OUT
9	2700	22.30	4.49	9	OUT
9	2975	22.24	8.75	24	OUT
10	2975	39.14	0.0	1	OUT
13	2400	20.59	0.0	1	IN
20	725	16.60	0.0	1	IN
20	1200	20.91	1.24	2	IN
20	2325	27.56	0.0	1	IN
20	2325	12.06	0.0	1	OUT
22	725	17.88	0.0	1	IN
22	1400	26.92	0.0	1	IN
22	2325	22.28	0.0	1	IN
22	2400	19.72	0.0	1	IN
22	2400	17.98	0.0	1	OUT
22	2975	23.80	0.0	1	OUT
27	725	16.08	5.57	24	IN
27	725	14.91	3.96	7	OUT
27	1200	16.35	5.65	12	IN
27	1400	20.29	4.23	13	IN
27	1400	15.47	2.97	16	OUT
27	1475	19.18	3.32	4	OUT
27	2325	20.86	4.26	6	IN
27	2325	15.67	3.95	13	OUT
27	2400	21.67	5.26	12	IN
27	2400	21.60	5.85	8	OUT
27	2700	20.10	3.37	15	OUT
27	2975	19.79	4.17	29	OUT
28	2400	16.52	0.0	1	IN
37	725	15.76	0.0	1	IN
47	725	13.84	0.0	1	IN
47	1200	14.80	0.02	2	IN
47	2975	22.58	0.0	1	OUT
58	725	16.51	0.0	1	IN
58	725	22.59	0.0	1	OUT
58	2325	25.97	0.0	1	IN
58	2400	23.72	1.73	2	IN
58	2400	19.06	6.32	3	OUT
58	2975	18.08	0.0	1	OUT
88	1200	19.46	0.0	1	IN
88	1400	20.72	0.0	1	IN
90	725	19.86	7.10	3	IN
90	1200	16.71	0.0	1	IN
90	2325	22.54	1.32	2	IN
90	2325	18.11	0.0	1	OUT
90	2400	26.50	9.86	3	IN
90	2400	21.79	0.0	1	OUT
90	2700	21.46	0.61	2	OUT
90	2975	10.94	0.0	1	IN

Table XIX .continued.

91	1200	20.30	0.0	1	IN
91	1400	22.71	0.44	2	IN
92	725	25.60	4.26	2	OUT
92	1400	30.70	0.0	1	IN
93	1200	19.73	0.0	1	IN
93	1400	20.29	4.79	2	IN
94	1400	11.84	0.0	1	IN
94	2975	21.24	3.56	2	OUT

Table XIX continued.

TYPE	DIST(FT)	AV SPEED(KT)	STD DEV(KT)	NO OF OBS	IN/OUT
4	1450	8.94	0.0	1	OUT
4	2001	25.19	0.0	1	OUT
4	2500	28.42	5.03	4	OUT
4	3500	30.26	0.94	2	IN
4	3500	27.89	6.07	4	OUT
7	1450	24.52	0.0	1	IN
7	1450	20.44	0.0	1	OUT
7	1501	25.11	16.72	3	OUT
7	1775	18.76	0.0	1	OUT
7	1850	35.33	0.0	1	OUT
7	1900	29.60	0.0	1	OUT
7	2001	22.84	5.39	3	OUT
7	2500	19.89	4.01	4	OUT
8	1450	21.92	6.32	4	IN
8	1450	15.60	0.0	1	OUT
8	1501	21.86	3.02	2	OUT
8	1775	28.16	12.01	3	IN
8	1850	28.71	5.37	6	OUT
8	2001	17.90	2.78	8	OUT
8	2500	19.61	5.48	2	OUT
8	3500	28.32	4.59	9	IN
8	3500	25.26	3.87	2	OUT
9	1450	22.53	4.68	10	IN
9	1450	22.88	7.01	8	OUT
9	1501	22.70	6.13	14	OUT
9	1775	15.45	0.0	1	IN
9	1775	21.09	1.80	2	OUT
9	1850	27.18	3.23	6	IN
9	1850	23.55	6.70	10	OUT
9	1900	22.48	2.18	3	IN
9	1900	26.67	5.27	2	OUT
9	2001	20.34	4.99	27	OUT
9	2500	18.05	0.0	1	IN
9	2500	23.03	5.40	45	OUT
9	3475	29.08	4.82	3	OUT
9	3500	28.48	7.26	32	IN
9	3500	25.25	6.46	29	OUT
11	1850	21.47	0.0	1	IN
11	2001	20.41	0.02	2	OUT
11	2500	31.04	8.43	2	OUT
11	3500	40.89	7.30	2	IN
13	2500	16.79	4.54	2	OUT
13	3500	24.92	2.32	2	IN
15	2500	9.86	0.0	1	OUT
20	3500	20.72	0.0	1	OUT
27	1450	19.91	3.32	3	IN

Table XX Atlanta, taxi speeds, by type and distance.

```
27   1450      22.41      4.60     10    OUT
27   1501      30.37      7.47      5    OUT
27   1850      27.72      1.55      5    IN
27   1850      33.64      9.54      3    OUT
27   1900      27.74      4.61      3    IN
27   1900      15.62      0.0       1    OUT
27   2001      18.49      4.68      9    OUT
27   2500      23.21      5.19     21    OUT
27   3500      24.91      5.05     20    IN
27   3500      25.70      5.89     10    OUT
37   1450      26.49      9.23      2    IN
37   1850      27.38      0.0       1    IN
37   2500      24.91      6.74      7    OUT
37   3500      25.28      2.94      4    IN
37   3500      13.19      0.0       1    OUT
47   1450      20.94      0.0       1    IN
47   2500      18.46      5.27      6    OUT
47   3500      26.06      0.23      2    IN
81   1450      15.33      0.0       1    OUT
81   1501      15.31      0.0       1    OUT
81   2001      20.77      0.0       1    OUT
88   1501      20.18      0.0       1    OUT
88   2001      24.67      0.0       1    OUT
88   3500      25.90      0.0       1    IN
91   1450      34.09      5.98      3    OUT
91   1850      36.51     12.91      2    IN
91   2001      17.67      0.0       1    IN
91   2001      23.63      5.52      2    OUT
91   2500      26.27     12.85      3    OUT
91   3500      25.65      7.36      3    OUT
92   1450      24.52      0.0       1    IN
92   1450      39.02      0.0       1    OUT
92   1501      22.77      0.0       1    OUT
92   1850      29.60      0.0       1    OUT
92   2001      20.22      3.39      3    OUT
92   2500      26.97      5.45      2    OUT
92   3500      26.41      7.56      3    OUT
93   1850      30.42      0.0       1    IN
93   2001      20.77      0.0       2    OUT
93   2500      12.33      0.0       1    OUT
93   3500      34.94      6.94      2    OUT
T=4.83/9.91 10:55:56
```

Table XX continued.

faster than the 727 over the 725 foot section at Logan.

This distance refers to two separate sections of taxiway, the inner and outer taxiways again. Further analysis shows that the DC-9 was still faster over the inner taxiway, with no significant difference on the outer. (See Table XVII).

For the other case studied, comparing a medium jet (727) with a heavy jet (707/DC-8), only a few differences were noted. Outbound at Logan, the 727 was faster over the 1400 foot lenth, and slower over the 2325 foot length; while inbound at Atlanta, it was slower over both 1450 feet and 3500 feet. Each of these distances refers to two distinct sections of taxiway, and once again further analysis was necessary to separate the effect of a section's length from that of its location.

For the Atlanta data, this was simple. There the complete separation of inbound and outbound traffic meant that only one of each pair of equal length taxiways handled the inbound traffic. Thus the results from Atlanta truly were significant.

A breakdown of the data at Logan indicated only one significant difference, and that was over 2325 feet of the outer taxiway. For the other segment in question, the results of the t-test lead us to accept the null hypothesis that the true mean speeds were equal for the two types.

Conclusions

Overall, taxiing speeds were fairly consistent, and were generally about 20-25 knots. Speeds did range, however, from a minimum of three knots to a maximum of fifty knots. Average speeds, and standard deviations, are presented in Table XVIII.

In the majority of cases, as we have seen, taxiing speed did not seem to vary between aircraft types, nor was there a difference between inbound and outbound directions (using the t-test, at the 5% significance level). Speeds did vary over different taxiway sections, but looking at Table XIX which gives average speeds for all aircraft types over individual sections, there does not seem to be any consistent increase with length.

Obviously, then, there must be other factors besides distance to explain this variation. It is worth noting that the section over which differences consistently occurred was the inner taxiway at Logan; location of the section would therefore seem to be critical. In this case, it can be suggested that the taxiing behavior of aircraft changes sharply in the proximity of the terminal, and in particular on the apron itself. Here, the inbound pilot must be watchful for ground vehicles as well as other aircraft, and also be preparing to maneuver into his gate.

At the other end of the taxiway system, the plane which had just exited from the runway might be expected to be travelling at its maximum taxiway velocity. As it approached the terminal, it would slow down until it was on the apron. Taxiing speeds would thus be related to distance from the terminal, and this effect should be investigated.

Another possible factor is the extent to which aircraft follow each other on the taxiway. Just as a chain is only as strong as its weakest link, so a queue can move only as fast as its leader. Any unique factor affecting the leader would also affect the other planes in the queue, therefore, and its effect would be masked.

More data would be needed to investigate other possible relations, such as differences between airlines or speed differences as a function of congestion or time of day, a reasonable substitute.

Taxiway Intersections

During the survey, times were recorded for intersection delays, when one aircraft was instructed by the tower to stop or slow down to allow another aircraft to cross in front of it. Means and standard deviations for these times are presented in Table XXI.

The first part of the table gives time intervals from the moment when the first aircraft reached the stopline (STOP) or, if it did not stop, when it received notice from the tower and started to slow down. PASS gives the time when the second aircraft cleared the intersection. CLEARANCE recorded the time when the first aircraft received radio clearance from the ground controller to proceed through the intersection. START is the time when the aircraft crossed the stopline; CLEAR is the time when it touched the stopline on the other side of the intersection, and had cleared the intersection.

The second part of the table gives the time intervals between events. First is the time delay for the first plane to be given clearance to proceed, after the intersection has been cleared. The small mean is accounted for by the fact that these times were often negative, as provisional clearance was granted ("Clear to cross at your discretion after this DC-9") before either plane reached the intersection.

START to CLEAR is also an interesting measure, since it gives the average time required to fully clear the intersection by the stopped plane. Comparing this with the STOP to PASS time, we can see how cautious the ground controller is: the aircraft which was requested to stop could probably have gotten through the intersection long before the other plane reached it. But, when the intersection is a taxiway crossing a runway, and the other plane is an arrival, it definitely has priority for the use of the entire runway.

It is not known how priorities are assigned at a taxiway-taxiway intersection. If it is done on a first-come, first-serve basis, then presumably STOP to PASS time will be less, as will be the overall delay. However, a taxiway intersection could also cause longer delays, as there is the possibility of waiting for a long queue of aircraft to pass through the intersection. It would never be necessary to wait for more than one plane to cross at a runway intersection. Comparing the two different types of intersections could reveal other interesting operational patterns.

Some differences were noticed between operations at Boston and Atlanta, although no statistical analysis was performed. In general, the delays at Boston were greater, and the range of the delay times was also greater. But on the other hand, intersection delays at Logan were less frequent than at Atlanta. This is primarily due to Atlanta's taxiway-runway configuration, which requires crossing one of the active runways to reach the terminal. Therefore most observations for Atlanta were for runway intersections, which might also explain the lower average times.

Time interval	BOSTON			ATLANTA		
	m	s	no.	m	s	no.
Stop to: pass	52.7	78.1	63	43.4	33.4	101
Clearance	60.0	82.5	60	44.7	34.6	78
Start	67.2	77.8	67	51.8	36.1	101
Clear	92.1	85.3	67	71.2	39.2	101
Pass to clearance	3.7	9.6	58	0.6	12.2	98
Clearance to start	7.8	8.5	60	7.9	7.1	98
Start to clear	25.1	14.4	66	19.3	7.7	101
Clearance to clear	32.7	14.7	59	27.2	10.5	98

Table XXI Taxiway intersection delay data.

CHAPTER VI

LANDINGS

As a result of previous work done on measuring runway occupancy times,[7] it was known that occupancy time tended to increase with aircraft size. We hoped to confirm this, and also possibly derive a formula which would enable us to predict which runway exit an arriving aircraft was likely to use. In addition, it was hoped that some information could be derived from the distribution of touchdown distances, i.e. from runway threshold to touchdown point.

Runway Occupancy Time

Runway occupancy time is measured from the moment the plane is over threshold to the time it has turned off the runway and its tail has crossed the runway edge. It is the time over which that runway is effectively blocked to any and all other traffic. As such, it has a large potential effect on the total traffic-handling capacity of that runway.

When the runway is used for arrivals only, occupancy time is of little consequence to the capacity, because the time between arrivals, as limited by the three-mile separation standard, is almost always greater than the occupancy time. It is then necessary to reduce interarrival times before capacity can be increased.

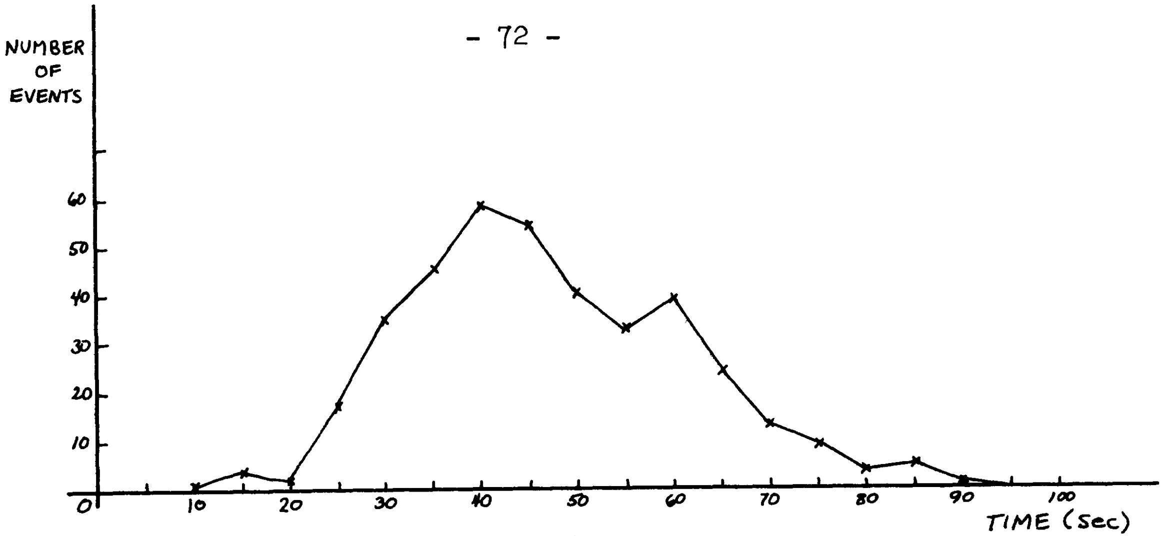
On the other hand, when the same runway is used for both arrivals and departures, occupancy time becomes more critical. The usual mode of operation here is to increase the separation between arrivals, so that there is enough time to allow a takeoff between the landings. However, there is less excess time available in this case. If a landing aircraft stays on the runway too long, and there may not be enough time to insert a takeoff before the next landing, the controller will refuse permission to the departing aircraft rather than take the risk of waving off the next arrival. Because of the operational problems and risk of guiding a wave off back into the approach path, not to mention the great amount of fuel consumed by such an operation, arrivals have priority over departures for use of the same runway.

Figures 2 - 3 are graphs of the runway occupancy times which we observed, for all aircraft and for specific types, over all runways. Next, the observed times are broken down by type, runway, and exit (Figures 4 -7).

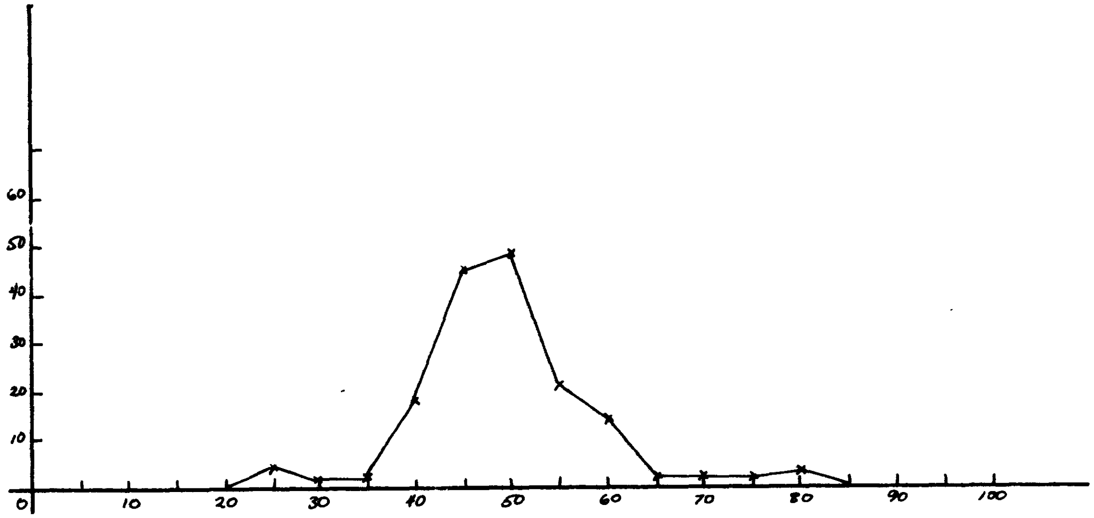
Use of the t-test to analyze the data (see Chapter 5) demonstrated something which was suggested by the graph: that most aircraft which use a particular exit have similar occupancy times.

A comparison was first done between certain aircraft types (Table XXV) using all observed landings. These results showed some significant differences between our hypothetical classes (light, medium and heavy jets), but no significant differences within each class. It can be seen that there does seem to be a relationship between weight and occupancy time: the DC-9 is marginally quicker to exit than the 727, which in turn is substantially quicker than either the 707 or the DC-8.

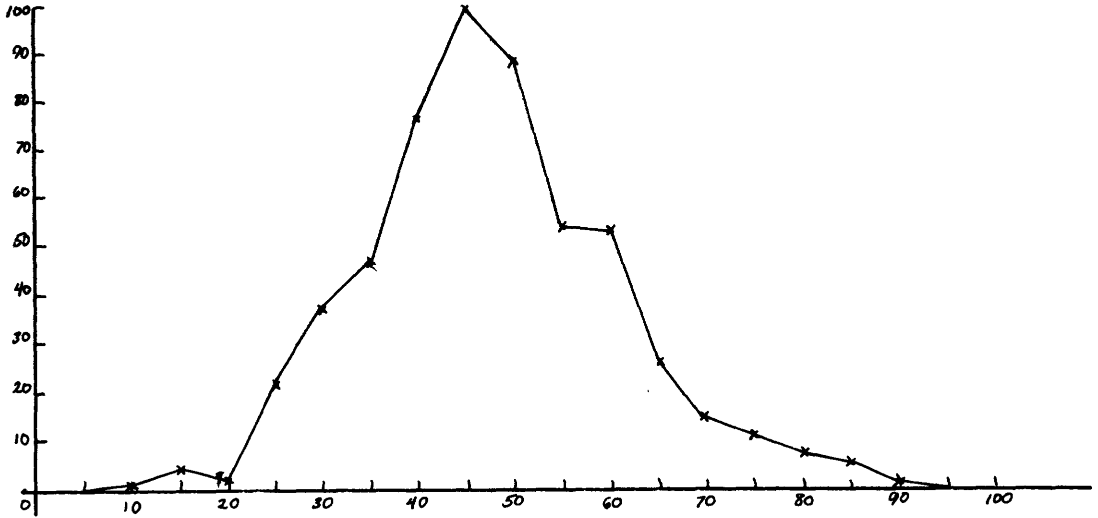
However, when operations are broken down by runway and exit,



BOSTON

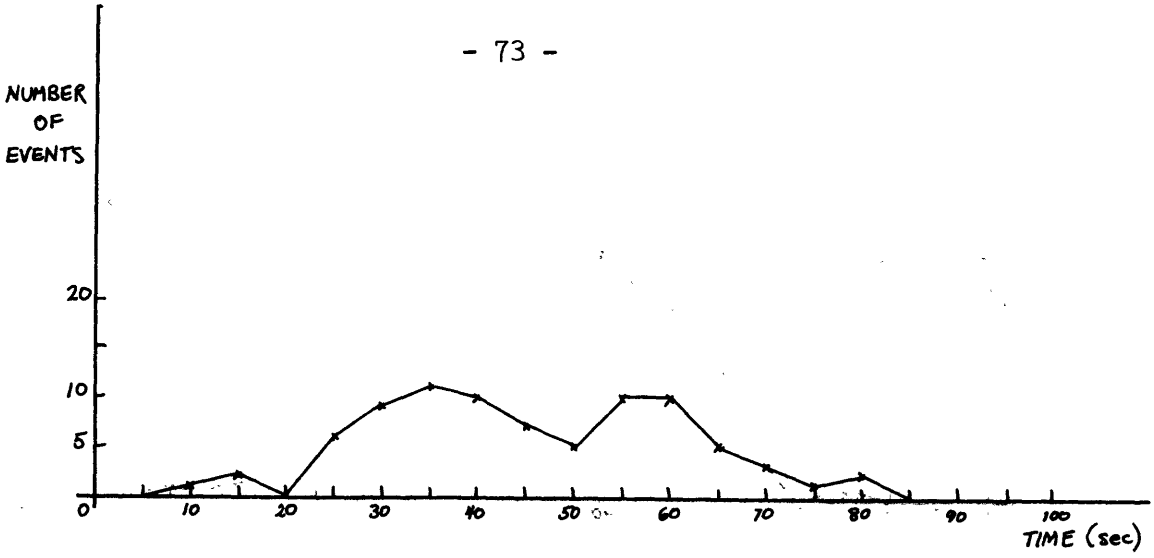


ATLANTA

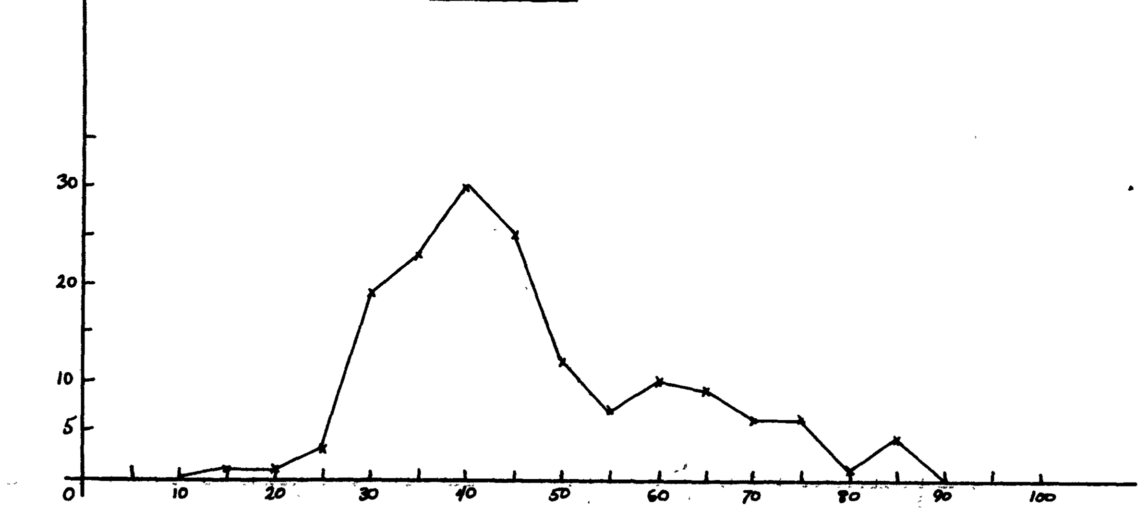


TOTAL

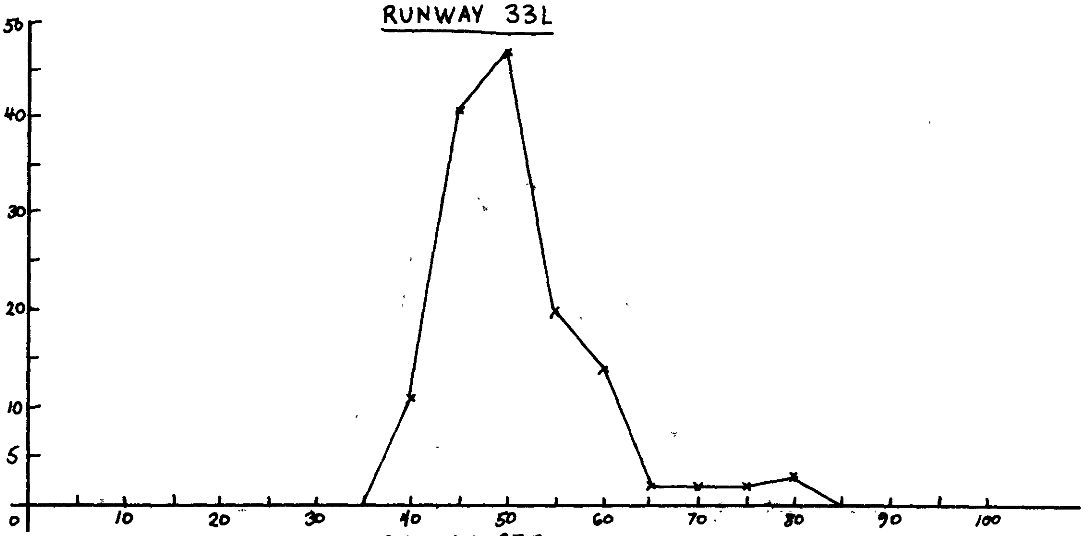
FIGURE 2 LANDING OCCUPANCY TIMES, ALL TYPES, ALL RUNWAYS



RUNWAY 27

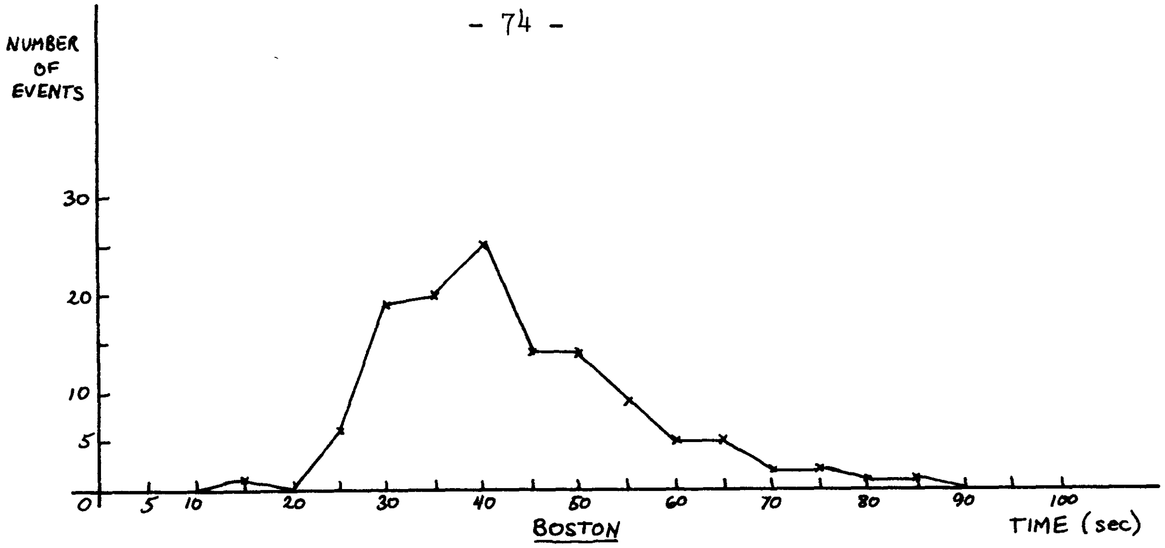


RUNWAY 33L

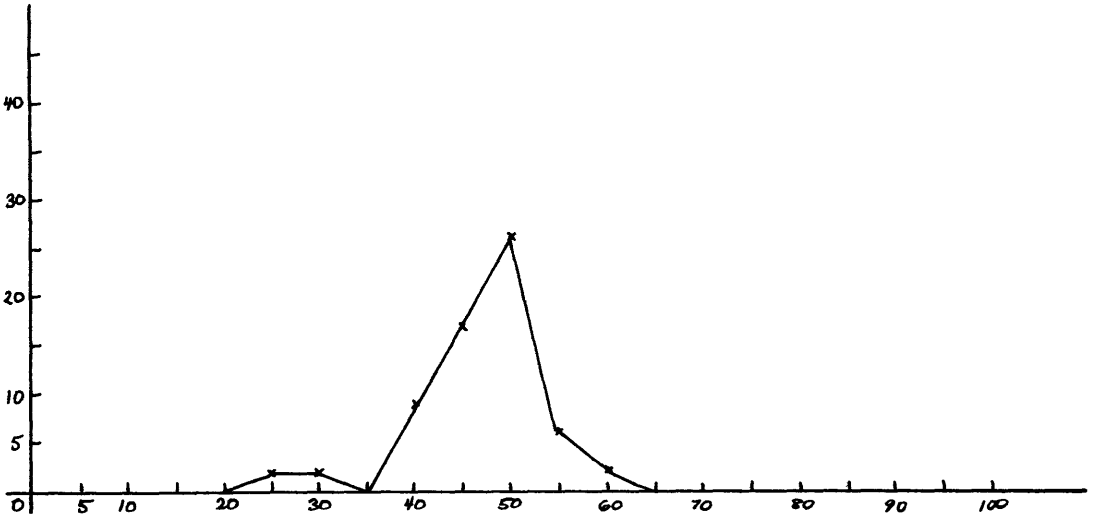


RUNWAY 27R

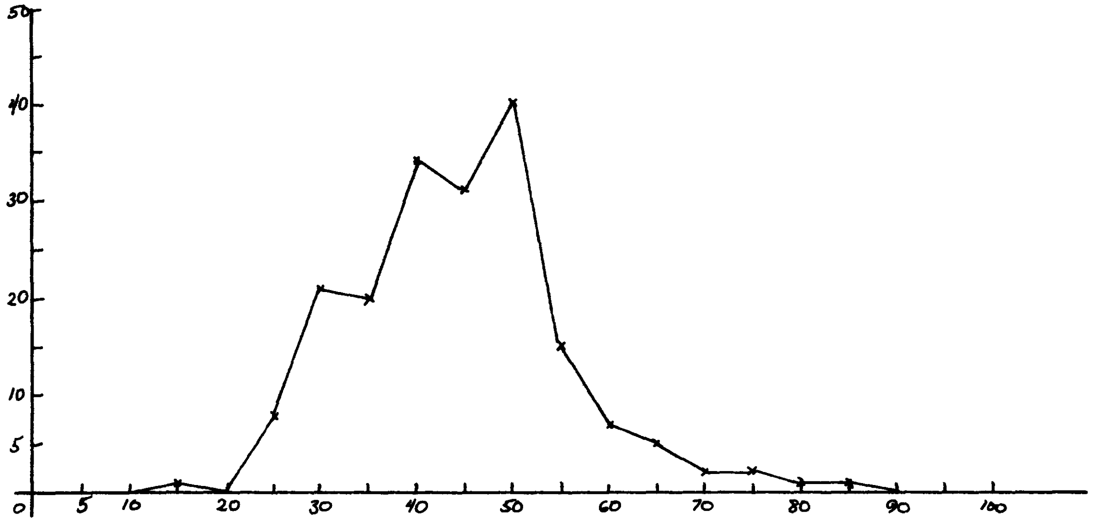
FIGURE 3 - LANDING OCCUPANCY TIMES, ALL TYPES, SELECTED RUNWAYS



BOSTON

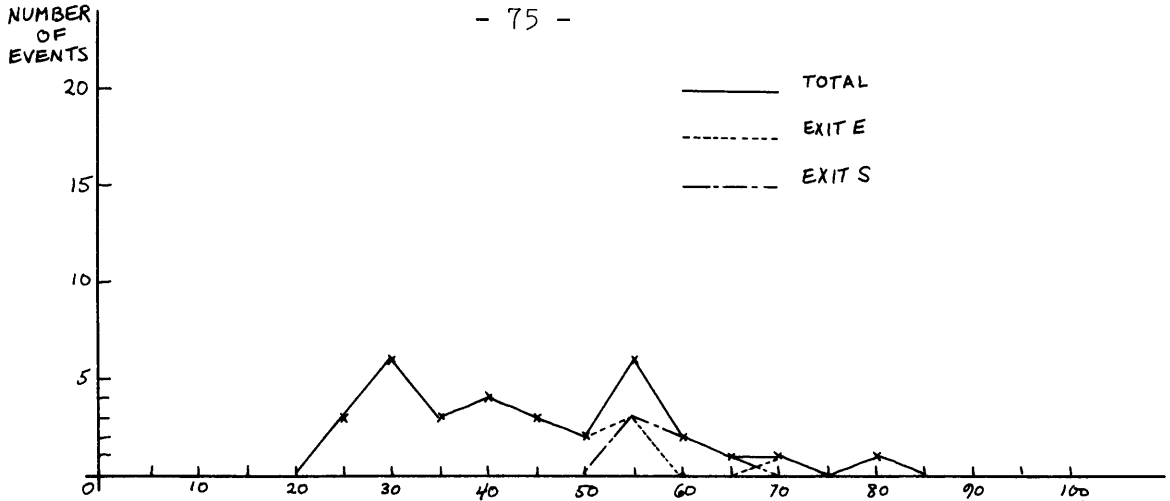


ATLANTA

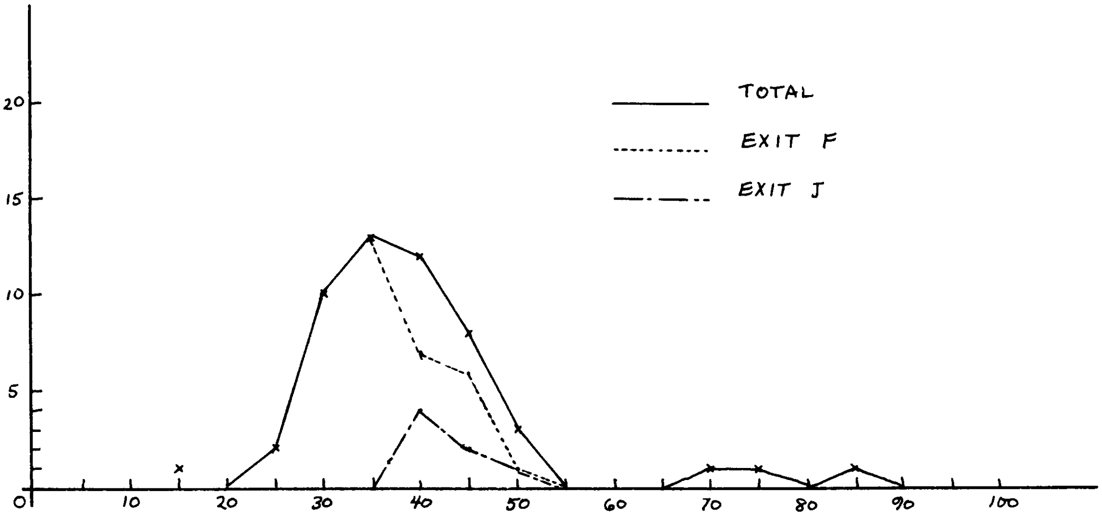


TOTAL

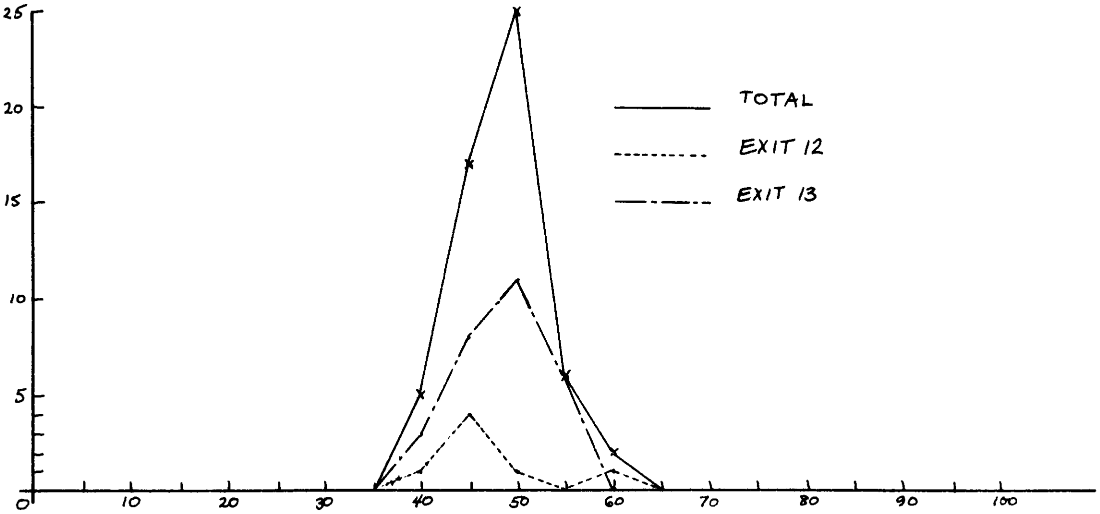
FIGURE 4 - DC-9 LANDING OCCUPANCY TIMES, ALL RUNWAYS



RUNWAY 27



RUNWAY 33L



RUNWAY 27R

FIGURE 5- DC-9 LANDING OCCUPANCY TIMES, SELECTED RUNWAYS

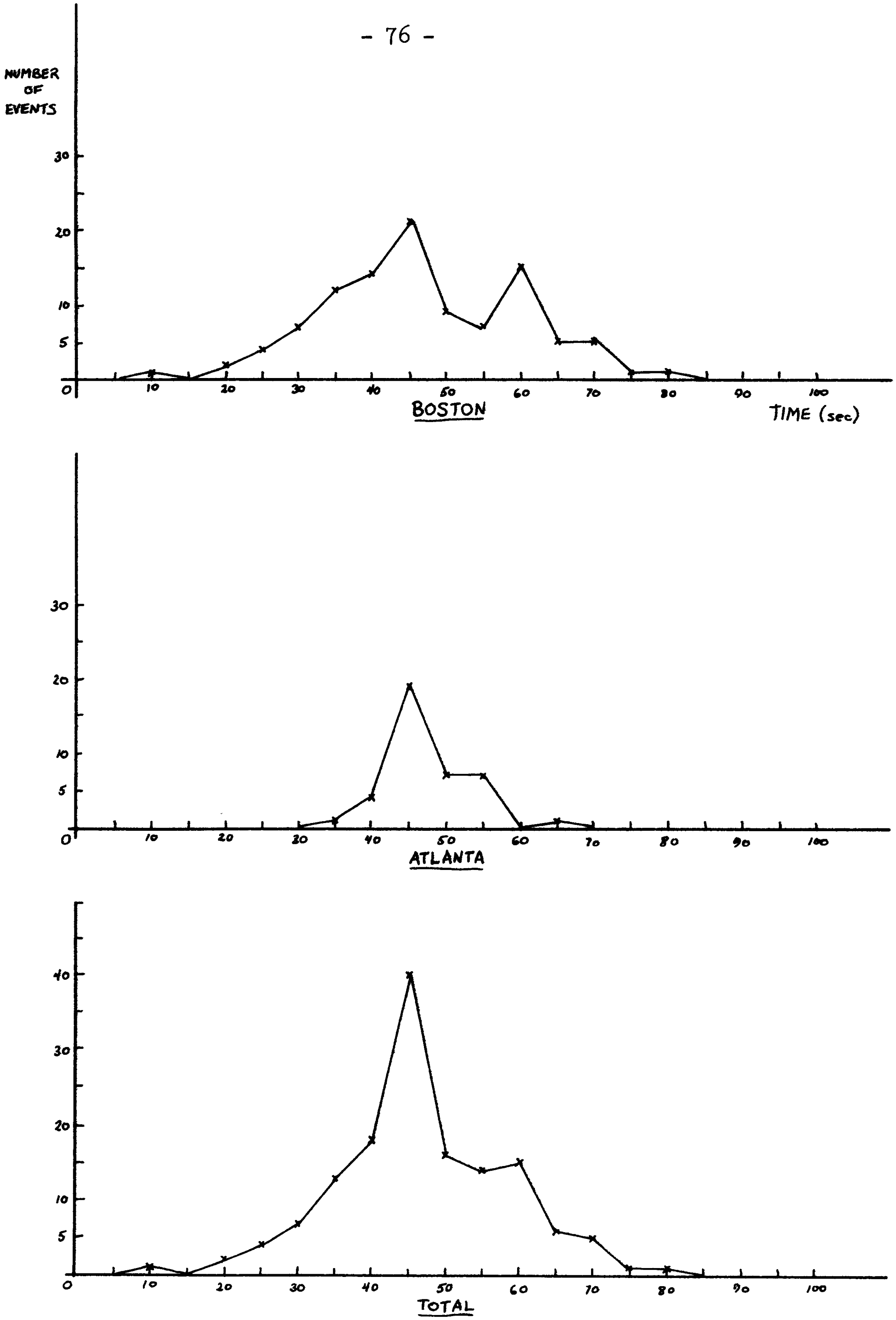


FIGURE 6 - 727 LANDING OCCUPANCY TIMES, ALL RUNWAYS

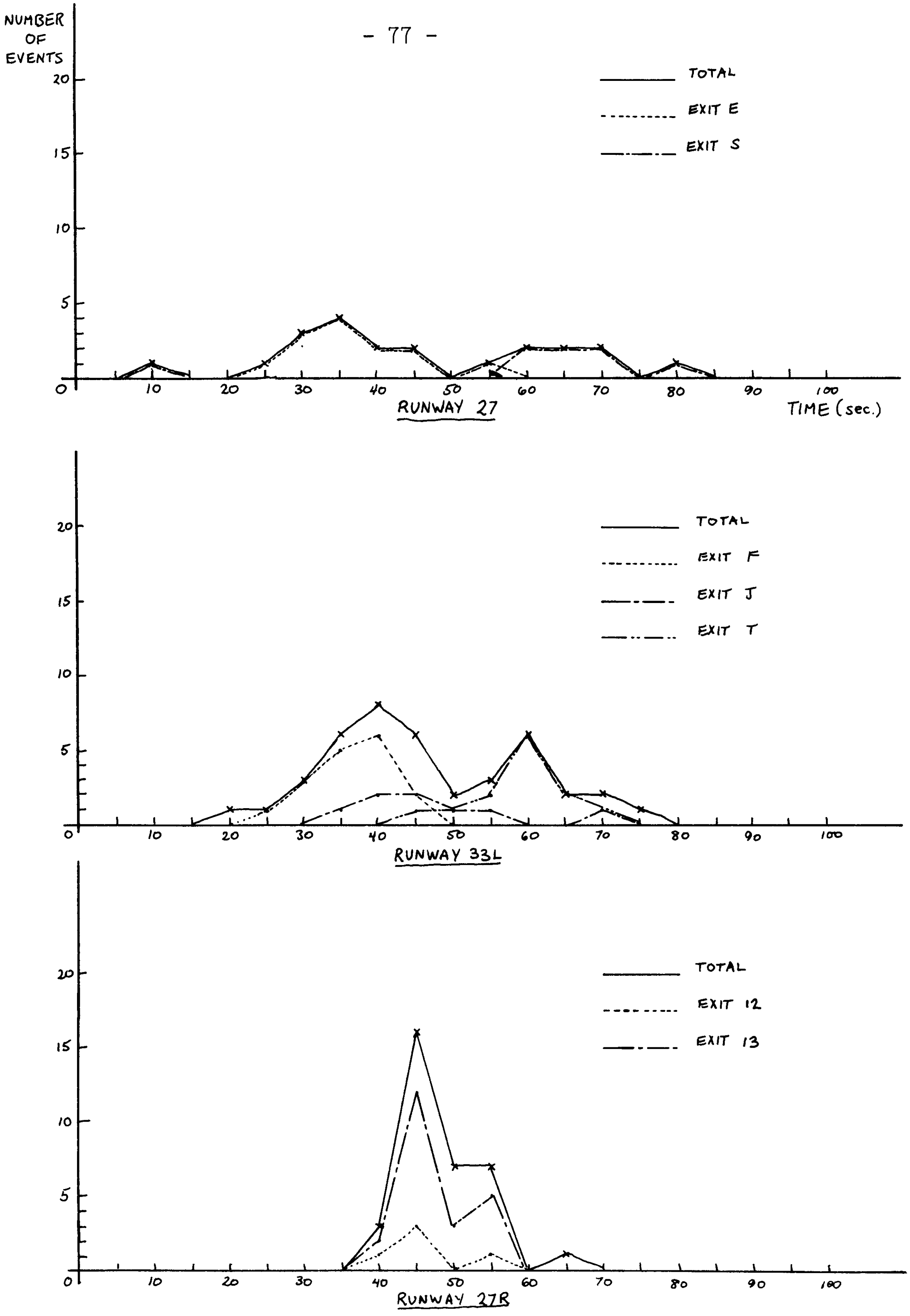


FIGURE 7 - 727 LANDING OCCUPANCY TIMES, SELECTED RUNWAYS

```
 RUNWAY OCCUPANCY TIME,BY TYPE, ALL EXITS
 TYPE   MEANTIME  STD DEV  NO OF EVENTS
    1      46.22    10.65          10
    3      66.05    14.07           2
    4      55.50     5.58           6
    6      48.04    15.37           7
    7      59.02    16.26          33
    8      57.99     9.11          22
    9      47.59    11.11         177
   10      39.50    17.84           3
   11      61.75     0.64           2
   13      53.13     4.35           3
   20      65.83     1.61           3
   22      48.06    14.39          14
   27      49.98    11.96         138
   37      50.71     7.25          12
   47      70.53    19.01           7
   58      49.62     6.55           5
   73      61.97    15.35          12
   81      54.23    12.90          10
   88      54.40    10.19          15
   90      47.21    14.65          12
   91      51.00    20.76           5
   92      46.85    13.67          12
   93      54.86     9.98           5
   94      66.85    19.29           4
T=5.30/18.12 10:46:28
```

Table XXII.

RUNWAY OCCUPANCY TIMES,ALL TYPES BY EXIT

RUNWAY	EXIT	MEANTIME	STD DEV	NO OF EVENTS
1	3	30.00	0.0	1
1	6	39.02	11.12	6
1	10	37.50	3.54	2
1	12	50.00	0.0	1
1	14	63.73	6.04	12
1	30	45.61	7.42	22
1	31	54.00	0.0	1
2	3	32.40	3.39	2
2	6	26.80	1.13	2
2	14	55.50	0.0	1
2	21	38.50	6.02	5
2	30	50.99	5.54	17
2	31	39.58	8.21	6
6	10	53.50	2.12	2
6	20	27.00	0.0	1
7	3	64.36	12.25	28
7	5	65.56	7.66	8
7	6	54.33	10.41	3
7	10	47.91	8.30	19
7	20	36.00	0.0	1
8	4	19.00	0.0	1
8	5	42.90	9.82	53
8	20	61.60	17.43	25
8	40	57.50	2.12	2
9	1	44.00	0.0	1
10	1	67.68	20.15	12
10	4	39.60	6.51	2
10	6	41.88	10.66	82
10	7	46.83	12.29	3
10	10	50.92	11.81	28
10	21	61.35	8.20	30
11	12	51.60	6.47	19
11	13	53.74	8.57	83
11	14	74.60	5.37	2
11	90	51.30	0.0	1
11	91	52.05	5.07	11
11	92	58.25	7.35	6
11	94	51.03	3.69	18

Table XXIII.

```
EXECUTION BEGINS...

 RUNWAY OCCUPANCY TIME, ALL TYPES, GIVEN RUNWAY AND EXIT
 TYPE  RUNWAY   EXIT  MEANTIME   STD DEV  NO OF EVENTS
    1       1     30     43.20     0.0              1
    1       2     30     47.00     0.0              1
    1       7      5     73.20     0.0              1
    1       8      5     36.00     0.0              1
    1      10      6     41.70     4.94             4
    1      10     10     48.00     4.24             2
    3      10      6     76.00     0.0              1
    3      11     12     56.10     0.0              1
    4      11     12     55.07     1.10             3
    4      11     13     55.93     8.72             3
    6       2      3     30.00     0.0              1
    6       6     20     27.00     0.0              1
    6       7      5     60.00     0.0              1
    6       9      1     44.00     0.0              1
    6      10      6     58.43     9.10             3
    7       1     14     61.50     7.81             4
    7       1     30     57.00     0.0              1
    7       2     30     51.50     9.19             2
    7       2     31     43.50     0.0              1
    7       7      3     76.90    13.90             5
    7       7      5     62.00     0.0              1
    7       7      6     66.00     0.0              1
    7       7     20     36.00     0.0              1
    7       8      5     42.63     6.68             4
    7       8     20     65.02     3.23             4
    7      10      1     83.67     3.37             3
    7      10      6     38.50     0.0              1
    7      10     10     41.17     5.38             3
    7      10     21     51.20     4.53             2
    8       2     30     54.00     0.0              1
    8       7      3     62.70     0.0              1
    8       8     20     65.00     0.0              1
    8      10      1     66.45     3.18             2
    8      10      6     31.00     0.0              1
    8      10     10     62.50     0.0              1
    8      10     21     61.00     0.0              1
    8      11     12     45.10     0.0              1
    8      11     13     56.99     6.27             9
    8      11     14     70.80     0.0              1
    8      11     92     59.30     6.51             3
    9       1      6     30.60     0.0              1
    9       1     10     40.00     0.0              1
    9       1     12     50.00     0.0              1
    9       1     14     67.30     0.71             2
    9       1     30     44.67     6.80             8
```

Table XXIV.

9	2	21	40.63	4.27	4
9	2	30	49.03	5.40	6
9	2	31	31.00	1.41	2
9	6	10	52.00	0.0	1
9	7	3	62.32	2.96	4
9	7	5	66.32	10.06	4
9	7	10	51.22	4.26	6
9	8	5	42.91	11.52	24
9	8	20	65.95	8.26	6
9	8	40	56.00	0.0	1
9	10	1	64.65	33.73	2
9	10	6	38.23	6.48	40
9	10	10	45.43	3.46	7
9	10	21	68.17	11.73	3
9	11	12	49.69	6.86	7
9	11	13	51.19	4.98	28
9	11	91	51.35	6.74	6
9	11	92	53.20	0.0	1
9	11	94	51.08	2.75	12
10	1	30	48.00	0.0	1
10	8	4	19.00	0.0	1
10	10	10	51.50	0.0	1
11	11	13	61.75	0.64	2
13	8	5	50.00	0.0	1
13	11	90	51.30	0.0	1
13	11	94	58.10	0.0	1
20	7	3	64.00	0.0	1
20	10	21	66.75	0.35	2
22	1	30	45.75	9.55	2
22	2	6	27.60	0.0	1
22	7	10	19.60	0.0	1
22	8	5	51.27	5.80	3
22	8	20	59.50	0.0	1
22	10	6	53.67	17.29	4
22	10	7	58.50	0.0	1
22	11	13	47.70	0.0	1
27	1	3	30.00	0.0	1
27	1	6	36.50	19.09	2
27	1	14	64.00	2.83	2
27	1	30	44.47	6.63	7
27	1	31	54.00	0.0	1
27	2	6	26.00	0.0	1
27	2	30	52.60	6.22	6
27	2	31	52.00	0.0	1
27	7	3	60.40	7.27	10
27	7	6	48.50	3.54	2
27	7	10	46.96	4.43	9
27	8	5	39.83	7.68	13

Table XXIV continued.

27	8	20	63.45	21.63	8
27	10	1	50.00	26.63	3
27	10	6	38.88	5.23	17
27	10	10	51.11	11.10	8
27	10	21	62.15	5.97	13
27	11	12	48.94	5.93	5
27	11	13	50.27	4.58	22
27	11	91	53.95	3.61	2
27	11	92	59.20	12.45	2
27	11	94	51.37	3.44	3
37	1	14	57.20	0.0	1
37	10	6	40.25	8.84	2
37	11	12	60.80	0.0	1
37	11	13	50.70	5.59	5
37	11	91	52.17	1.80	3
47	7	3	56.50	37.48	2
47	10	10	80.20	0.0	1
47	11	13	75.12	8.02	4
58	1	6	38.50	0.0	1
58	7	10	54.40	0.0	1
58	8	5	50.60	1.98	2
58	10	6	54.00	0.0	1
73	1	14	69.50	6.36	2
73	7	10	50.00	0.0	1
73	8	20	56.17	26.63	3
73	8	40	59.00	0.0	1
73	10	1	80.00	0.0	1
73	10	10	77.50	0.0	1
73	10	21	56.57	7.47	3
81	2	14	55.50	0.0	1
81	7	3	73.30	6.36	2
81	8	5	44.20	0.0	1
81	10	6	37.50	0.0	1
81	10	10	45.60	1.98	2
81	10	21	59.40	10.47	2
81	11	13	48.50	0.0	1
88	2	30	53.00	0.0	1
88	7	5	64.00	0.0	1
88	8	20	62.00	0.0	1
88	10	1	69.00	0.0	1
88	10	10	58.30	19.37	2
88	10	21	55.83	10.98	3
88	11	13	47.62	5.65	4
88	11	94	46.70	6.08	2
90	1	10	35.00	0.0	1
90	1	14	60.00	0.0	1
90	2	21	30.00	0.0	1
90	2	31	40.00	4.24	2
90	7	3	59.80	0.0	1

Table XXIV continued.

90	7	10	56.30	0.0	1
90	8	5	45.10	21.35	2
90	10	4	35.00	0.0	1
90	10	6	45.20	0.0	1
90	10	21	75.00	0.0	1
91	1	30	60.00	0.0	1
91	6	10	55.00	0.0	1
91	8	20	18.00	0.0	1
91	10	7	48.00	0.0	1
91	11	13	74.00	0.0	1
92	1	6	46.00	8.49	2
92	1	30	35.00	0.0	1
92	2	3	34.80	0.0	1
92	10	4	44.20	0.0	1
92	10	6	45.02	6.46	4
92	10	7	34.00	0.0	1
92	11	12	60.70	0.0	1
92	11	13	81.40	0.0	1
93	7	3	59.05	2.47	2
93	8	5	37.20	0.0	1
93	10	6	58.40	0.0	1
93	11	13	60.60	0.0	1
94	8	5	43.00	0.0	1
94	10	6	86.00	0.0	1
94	11	13	60.00	0.0	1
94	11	14	78.40	0.0	1

Table XXIV continued.

```
EXECUTION BEGINS...
 TYPE1  TYPE2     T̄(1)    NO    T̄(2)    NO    T(CALC)      T(.025)
  *  9     27    47.25   188   49.79   143   -2.0156        1.97
     9     37    47.25   188   50.71    12   -1.6718        2.201
     9      1    47.25   188   46.22    10    0.3363        2.262
  * 27      7    49.79   143   58.53    35   -2.7392        2.04
     7      8    58.53    35   57.48    24    0.2885        2.069
     7     73    58.53    35   60.28    13   -0.4574        2.179
     7     47    58.53    35   70.53     7   -1.4431        2.447
     8     88    57.48    24   54.40    15    0.9879        2.145
  * 27      8    49.79   143   57.48    24   -3.5048        2.069
     8     81    57.48    24   54.23    10    0.8383        2.262
     8     47    57.48    24   70.53     7   -1.5606        2.447
    22     58    47.26    15   49.62     5   -0.6240        2.776
    11     58    61.75     2   49.62     5    9.0836       12.706
T=18.93/24.05 13:19:40
```

Table XXV Landing occupancy times, t-test of selected types, all exits.

```
EXECUTION BEGINS...
 TYPE1    9
 TYPE2    27

  R/W   T/W   DIST    T(1)   NO    T(2)   NO    T(CALC)      T(.025)
 33L     F    4100   38.05   41   38.95   22   -0.4795        2.080
  4R   33R    4500   46.54   14   48.64   14   -0.8967        2.160
 27      E    4500   46.26   28   39.83   13    1.6375        2.179
 33L     J    5200   47.96   16   48.91   17   -0.5641        2.131
*22L     C    6100   62.32    4   57.64   11    5.6963        3.182
 33L     T    6800   52.43    7   62.15   13   -1.6158        2.447
 27      S    7000   65.95    6   63.45    8    0.2778        2.571
  4R     N    7500   67.30    2   64.00    2    2.2000       12.706
 33L   NO.    7500   64.65    2   50.00    3    0.4462       12.706

 27R     A    5500   51.35    6   53.95    2   -0.4183       12.706
 27R    12    5900   49.69    7   48.94    5    0.2207        2.776
 27R     D    5900   51.08   12   51.37    3   -0.1369        4.303
 27R    13    6700   51.19   28   50.27   22    0.7585        2.080


 TYPE1    9
 TYPE2     1

  R/W   T/W   DIST    T(1)   NO    T(2)   NO    T(CALC)      T(.025)
 33L     F    4100   38.05   41   41.70    4   -1.3061        3.182
  4R   33R    4500   46.54   14   45.10    2    0.4909       12.706
 27      E    4500   46.26   28   54.60    2   -0.4534       12.706
 33L     J    5200   47.96   16   48.00    2   -0.0165       12.706



 TYPE1    9
 TYPE2     8

  R/W   T/W   DIST    T(1)   NO    T(2)   NO    T(CALC)      T(.025)
 33L   NO.    7500   64.65    2   66.45    2   -0.0833       12.706

*27R    13    6700   51.19   28   56.99    9   -2.5515        2.306
```

Table XXVI DC-9 vs. 727, BAC-111, DC-8, by exits.

```
TYPE1    9
TYPE2   37

 R/W   T/W   DIST    T̄(1)   NO    T̄(2)   NO    T(CALC)      T(.025)
33L     F    4100   38.23   40   40.25    2   -0.2820      12.706
27R     A    5500   51.35    6   52.17    3   -0.1754       4.303
27R    13    6700   51.19   28   50.70    5    0.2351       2.776



TYPE1    9
TYPE2    7

 R/W   T/W   DIST    T̄(1)   NO    T̄(2)   NO    T(CALC)      T(.025)
27      E    4500   46.26   28   46.50    5   -0.0487       2.776
33L     J    5200   47.96   16   41.17    3    1.8226       4.303
 4L   33R    5700   49.03    6   51.50    2   -0.2711      12.706
22L     C    6100   62.32    4   76.90    5   -2.5370       3.182
* 33L   T    6800   68.17    3   51.20    2   17.7730      12.706
27      S    7000   65.95    6   59.94    5    0.6111       2.776
 4R     N    7500   67.30    2   61.50    4    1.2075      12.706
33L   NO.    7500   64.65    2   83.67    3   -0.8920      12.706
```

Table XXVII DC-9 vs. 737, 707, by exits.

```
TYPE1  27
TYPE2    7

 R/W   T/W   DIST    T(1)   NO    T(2)   NO   T(CALC)      T(.025)
33L     F    4100   38.95   22   52.25    2   -0.9465      12.706
 4R   33R    4500   48.64   14   53.33    3   -0.7196       4.303
27      E    4500   39.83   13   46.50    5   -1.0376       2.776
33L     J    5200   48.91   17   41.17    3    1.4527       4.303
22L     C    6100   57.64   11   76.90    5   -2.4725       2.776
33L     T    6800   62.15   13   51.20    2    3.3017      12.706
27      S    7000   63.45    8   59.94    5    0.2802       2.776
 4R     W    7500   64.00    2   61.50    4    0.7568      12.706
33L   NO.    7500   50.00    3   83.67    3   -2.1669       4.303



TYPE1  27
TYPE2    8

 R/W   T/W   DIST    T(1)   NO    T(2)   NO   T(CALC)      T(.025)
33L   NO.    7500   50.00    3   66.45    2   -1.4646      12.706

*27R   13    6700   50.27   22   56.99    9   -3.5058       2.306
 27R    B    7450   59.20    2   59.30    3   -0.0076      12.706
```

Table XXVIII 727 vs. 707, DC-8, by exits.

```
 TYPE1    7
 TYPE2     8

  R/W  T/W  DIST    T(1)   NO    T(2)   NO    T(CALC)     T(.025)
*33L  NO.   7500   83.67    3   66.45    2  61.2382       12.706



 TYPE1    7
 TYPE2    73

  R/W  T/W  DIST    T(1)   NO    T(2)   NO    T(CALC)     T(.025)
 33L    J   5200   41.17    3   63.75    2  -2.3262       12.706
 33L    T   6800   51.20    2   56.57    3  -4.6315       12.706
 27     S   7000   59.94    5   56.17    3   0.2634        4.303
  4R    H   7500   61.50    4   69.50    2  -0.8161       12.706



 TYPE1    7
 TYPE2    47

  R/W  T/W  DIST    T(1)   NO    T(2)   NO    T(CALC)     T(.025)
 22L    C   6100   76.90    5   56.50    2    0.9048      12.706



 TYPE1    8
 TYPE2    47

  R/W  T/W  DIST    T(1)   NO    T(2)   NO    T(CALC)     T(.025)
*27R   13   6700   56.99    9   75.12    4  -3.4394        3.182



 TYPE1   22
 TYPE2    58

  R/W  T/W  DIST    T(1)   NO    T(2)   NO    T(CALC)     T(.025)
 33L    F   4100   48.46    5   46.25    2    0.4234      12.706
 27     E   4500   51.27    3   50.60    2    0.1116      12.706
LOGOFF IN 5 MINUTES
LOGOUT AT 14:50:17 ON 05/22/72 *** BY SYSTEM ***
```

Table XXIX Other comparisons by exits.

				DC-9		727		707	
r/w	exit	dist.	type	time	f	time	f	time	f
4R	33R	4300	1	44.67	.667	45.66	.572	57.00	.2
	N	7500	2	67.30	.133	64.00	.143	61.50	.8
4L	33R	5655	1	49.03	.5	52.60	.667	51.50	.667
22L	C	6000	2	62.32	.285	60.40	.476	76.90	.625
27	E	4500	1	46.26	.781	39.83	.636	46.50	.5
	S	7000	1	65.95	.188	63.45	.364	59.94	.5
33L	F	4150	1	38.23	.746	38.88	.41	38.50	.2
	J	5200	1	47.96	.164	48.91	.204	41.17	.3
	T	6800	1	68.17	.055	62.15	.318	51.20	.2
	No	7650	1	64.65	.035	50.00	.068	83.67	.3
								DC-8	
27R	A	5500	3	51.35	.118	53.95	.059		
	D	5900	3	51.08	.218	51.37	.088		
	12	5950	1	49.69	.128	48.64	.147	45.10	.072
	13	6700	1	51.19	.510	50.27	.646	56.99	.642
	B	7450	1	53.20	.018	59.20	.059	59.30	.214

Table XXX Observed frequency of exit use, selected types.

these differences largely disappear (Tables XXVI-XXIX). Aircraft using a given exit generally have the same occupancy times; the observed overall differences lie in the fact that all aircraft do not have the same exit use patterns. Probability of exit use is related to type.

It is possible that this probability could be derived from the known characteristics of the aircraft and of the exit. These could include weight and thrust, distance to the exit from the threshold, the distances from the exit to the previous exit and to the next exit, and some measure of the difficulty of using each exit (based perhaps on the turning angle-acute, right, or obtuse -required of the aircraft). Other factors such as approved speed and touchdown point undoubtedly affect exit -use, but they cannot be realistically specified beforehand for each aircraft, and hence were not considered as part of a general formula.

Although an attempt was made to obtain such an equation by regression analysis, it was not very successful. Available data was too scattered among different types and exits for any clear pattern to emerge. Often, one type had only one arrival on a given runway, and there was thus a unit probability assigned to that type for using that exit. This tended to bias the input data for the regression.

A possible alternative approach would be to group exits by distance from the threshold, for all runways, and calculate probabilities. Another regression could then be attempted for this data. Or these probabilities could be modified by empirical factors to account for the actual exit configuration, and then used directly to predict exit-use patterns.

Table XXX gives the observed exit-use probabilities and mean times for several aircraft types.

Touchdown Distances

Next, the distribution of touchdown distances was investigated. The most noticeable feature of the distribution is the considerable variance involved. This is apparent both in the frequency distribution curves (Figures 8 - 10) and in the table of mean and standard deviations of distances, Tables XXXI - XXXIII).

The original reason for recording touchdown distances was to study the influence of VASI (Visual Approach Slope Indicator) systems on the touchdown points. Presumably, installation of the VASI on a runway would, by providing a pilot with better guidance, decrease the variance in the touchdown distance.

Of the seven runways on which arrivals were observed, three had VASI's. These are indicated on the following table by a star (*).

```
EXECUTION BEGINS...
 RUNWAY      VARIANCE     NUMBER
     1      41827.89        19
     2      43163.85        31
     6           0.0         1
     7*     45170.76        49
     8      49319.46        85
    10      57329.97       150
    11*     56118.88       141
    12*     46769.66        63
T=2.06/3.25 15:53:07
```

Table XXXIIIa Variance of touchdown distances, all types, by runway.

A standard F-test was used to test the null hypothesis that different runways exhibit the same variance in touchdown distance:

$$F = S_1^2/S_2^2 \tag{6.1}$$

$$S_1^2 > S_2^2$$

where S_i^2 = sample variance of sample i

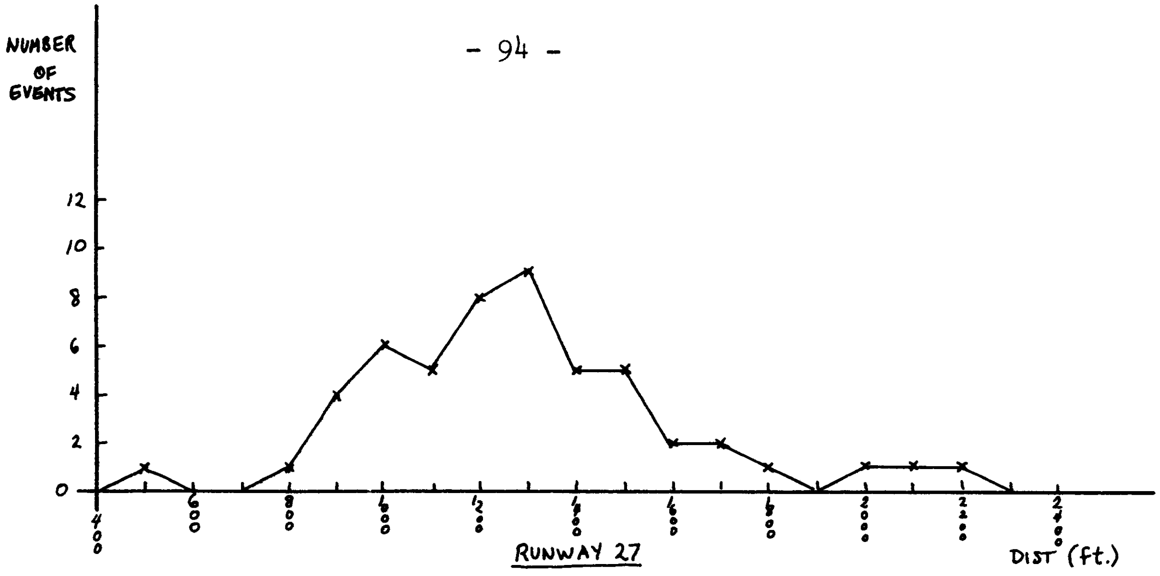
and evaluated by comparison with the tabled value[8] of $F_{\alpha/2,n_1-1,n_2-1}$. No significant differences were found between any of the runways, whether or not VASI-equipped, at the 5% significance level.

The other noticeable feature of the distributions is that each curve appears to peak twice. One possible explanation for this is that two different references were being used by pilots on landing; one being the VASI, the other being the threshold, the 500 foot mark, or some other point on the runway. It is hard to tell what point the pilot was aiming for from his touchdown point, however, because he must flare his approach path before he gets to his target. This maneuver, through its imprecise nature, can be presumed to be an important cause of the observed variance.

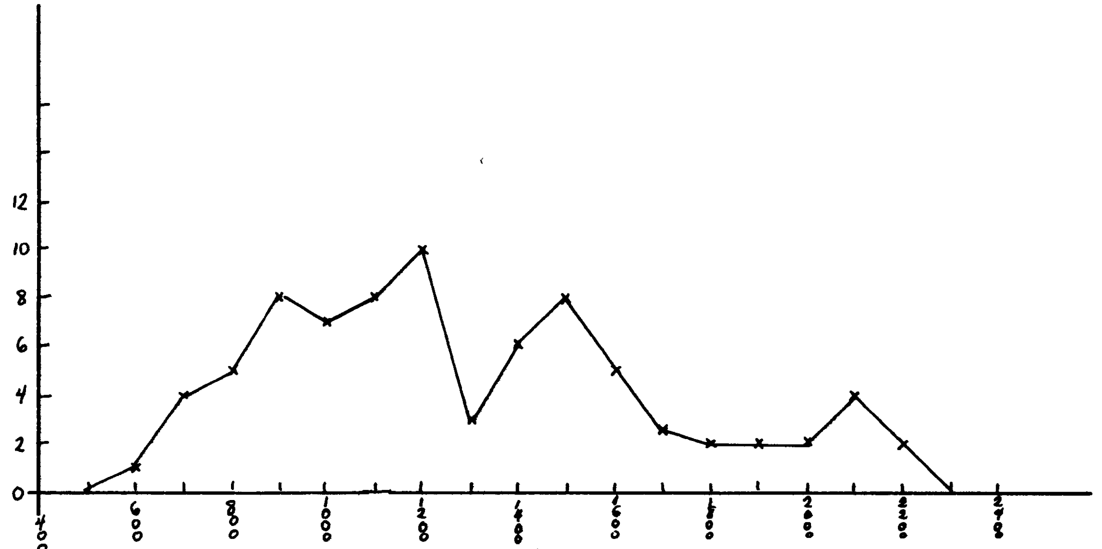
If the double peaking does have a cause, then presumably it would make sense to treat each peak as part of a separate distribution. Unfortunately, the curves overlap, and it is next to impossible to separate them using present data. Having two separate distribution means that it does not make sense to measure the variance over the runway as a whole, or to compare these variances as was done above.

Variance should be computed for each distribution above; if one was due to use of the VASI, then these two variances could be compared to measure the effect of VASI on touchdown distance.

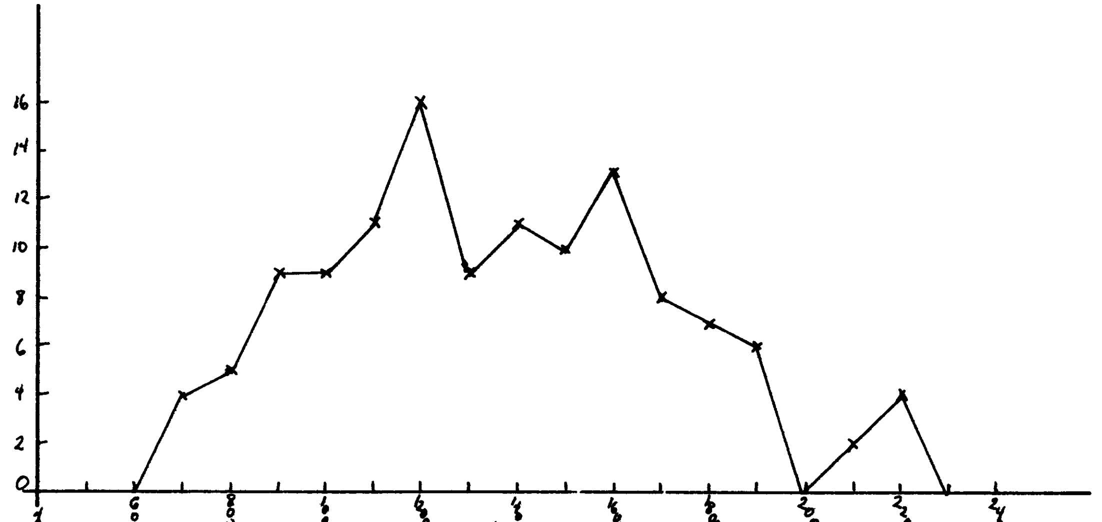
The touchdown point is another possible factor governing the choice of runway exits, since it influences the distance which the aircraft travels on the runway surface before it turns off and over which it can use brakes and thrust reverses. Just scanning the data, it seems that the standard deviation associated with given exits and given aircraft types is less than for the runway or the aircraft types as a whole. This is another possible relation which bears investigation.



RUNWAY 27

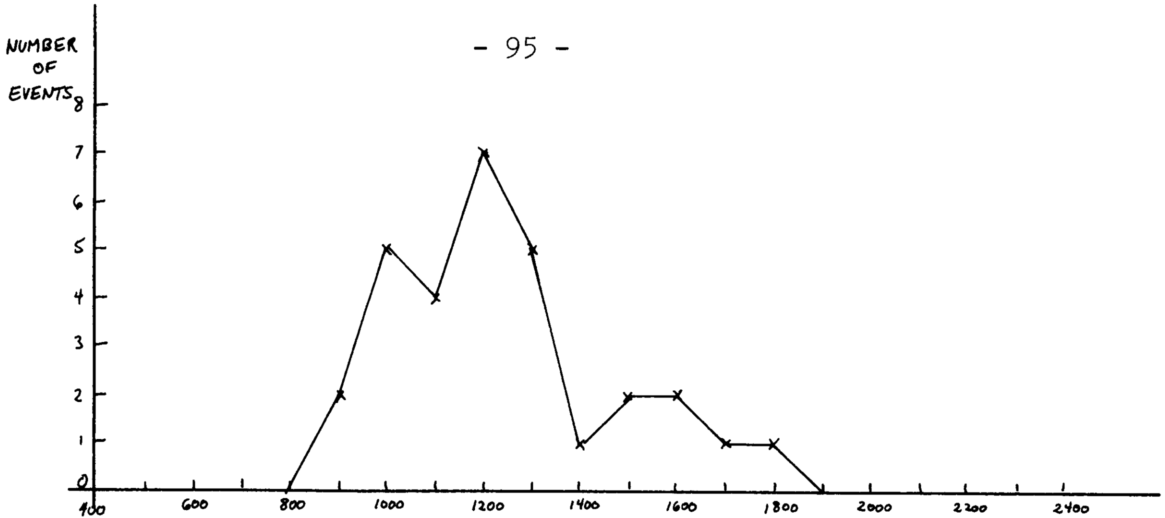


RUNWAY 33L

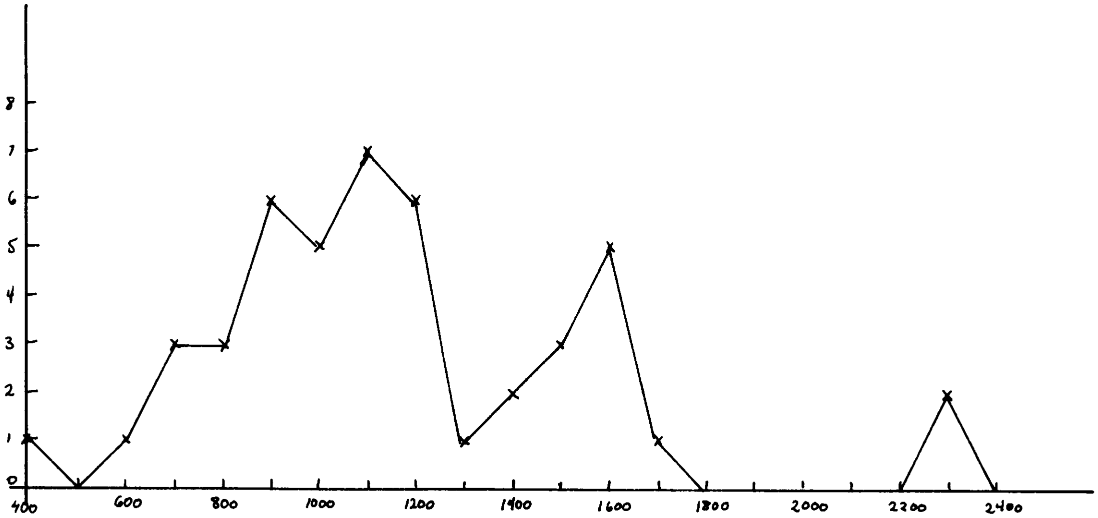


RUNWAY 27R

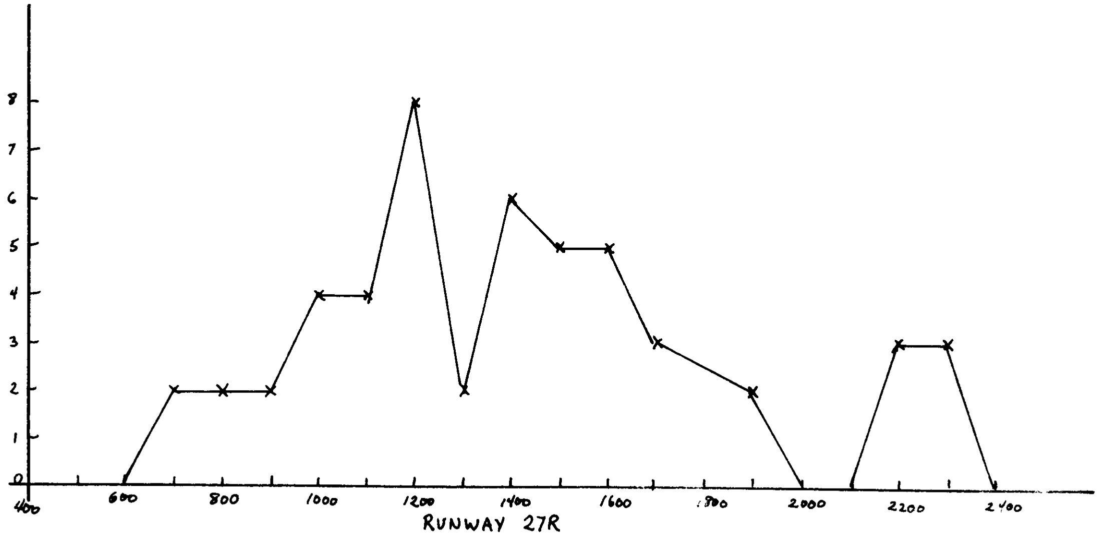
FIGURE 8 - TOUCHDOWN DISTANCES, ALL AIRCRAFT, SELECTED RUNWAYS



RUNWAY 27

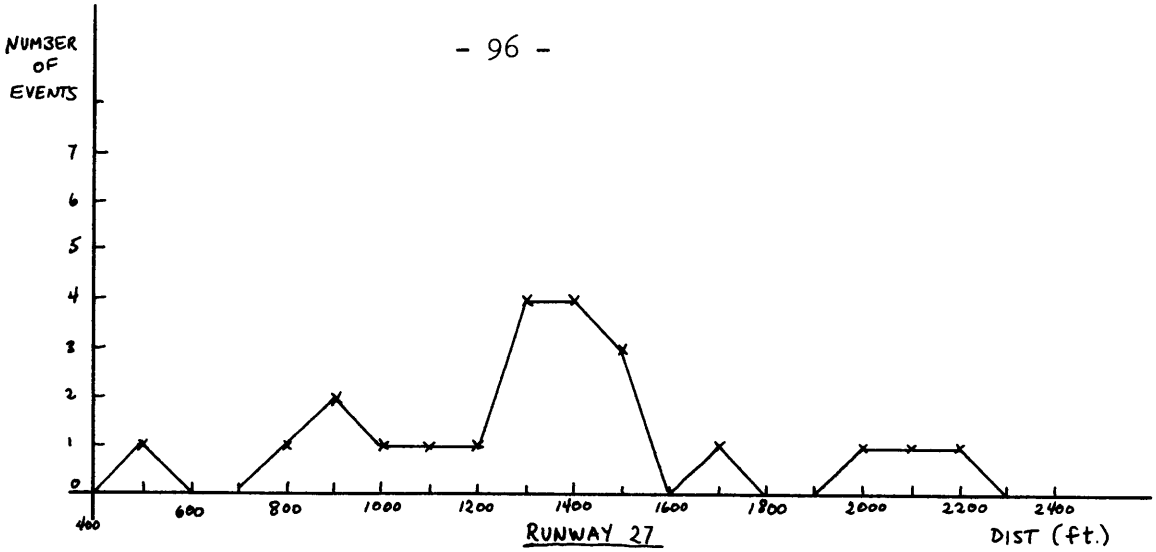


RUNWAY 33L

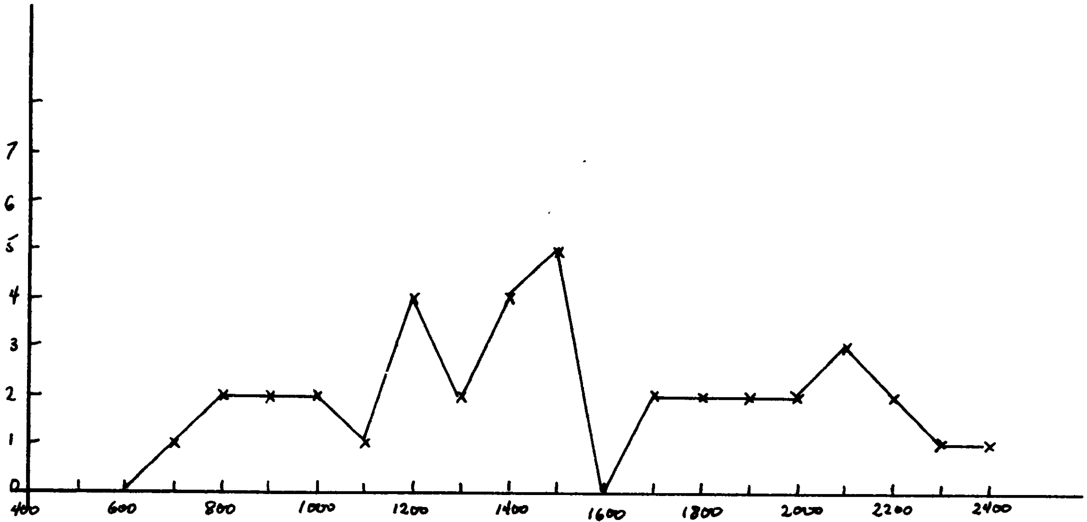


RUNWAY 27R

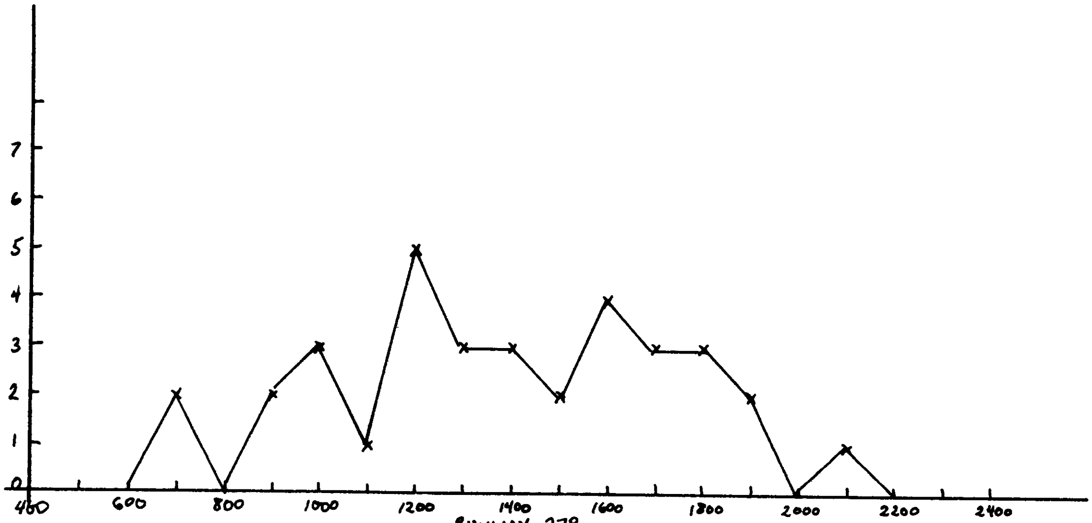
FIGURE 9 - DC9 TOUCHDOWN DISTANCES, SELECTED RUNWAYS



RUNWAY 27



RUNWAY 33L



RUNWAY 27R

FIGURE 10 - 727 TOUCHDOWN DISTANCES, SELECTED RUNWAYS

```
 RUNWAY TOUCHDOWN DISTS,BY TYPE, ALL EXITS
 TYPE MEANDIST  STD DEV  NO OF EVENTS
    1   1332.08    567.97      8
    3   1282.55      0.0       1
    4   3016.09   2021.55      6
    6   2264.87   1331.90      6
    7   1427.87    491.88     24
    8   1617.02    571.74     21
    9   1360.79    469.40    149
   10   1077.58    909.26      3
   11   1751.46    294.53      2
   13   1165.06    280.15      2
   20    961.74    311.04      3
   22   1514.04    869.06      8
   27   1509.26    452.76    116
   37   1166.85    557.97     11
   47   1685.54    878.72      6
   58    981.61     94.07      4
   73   1731.37    401.56      7
   81   1602.34    595.30     10
   88   1687.17    693.02     14
   90   1106.39    455.39      8
   91   2511.39   1109.84      2
   92   1753.79    945.87      7
   93   1189.80    389.94      5
   94   2836.24   3870.46      3
T=5.15/14.47 14:17:42
```

Table XXXI.

```
RUNWAY TOUCHDOWN DISTS,ALL TYPES BY EXIT
UNWAY  EXIT  MEANDIST   STD DEV   NO OF EVENTS
    1   10    915.16     0.0           1
    1   12   2018.37     0.0           1
    1   14   1088.64   264.73          4
    1   30    691.97   629.00          8
    1   31   2478.28     0.0           1
    2   14   2131.63     0.0           1
    2   31   1281.99   367.55          6
    6   20   2963.70     0.0           1
    7    3   1427.73   465.31         22
    7    5   2450.23  1172.84          7
    7   10   1206.15   217.84         18
    7   20   3143.78     0.0           1
    8    4   1548.82     0.0           1
    8    5   1263.29   271.81         42
    8   20   1510.81   476.98         22
    8   40   1595.55   352.18          2
   10    1   1949.99   683.63         12
   10    4    495.31    66.00          2
   10    6   1209.50   403.08         77
   10    7   1821.64     0.0           1
   10   10   1613.55   513.88         28
   10   21   1656.74   515.38         29
   11   12   1772.32  1307.54         19
   11   13   1653.02   592.71         83
   11   14   4557.12  3859.98          2
   11   91   1035.69   314.85         11
   11   92   1809.35   657.09          6
   11   94   1424.76   446.88         18
```

Table XXXII.

```
EXECUTION BEGINS...


 RUNWAY TOUCHDOWN DIST, ALL TYPES, GIVEN RUNWAY AND EXIT
 YPE  RUNWAY  EXIT    MEANDIST    STD DEV  NO OF EVENTS
   1      7     5     2616.75       0.0              1
   1      8     5     1616.38       0.0              1
   1     10     6     1086.80     175.96             4
   1     10    10     1038.13     143.49             2
   3     11    12     1282.55       0.0              1
   4     11    12     3656.81    2853.99             3
   4     11    13     2375.38     916.44             3
   6      6    20     2963.70       0.0              1
   6      7     5     4686.00       0.0              1
   6     10     6     1484.88     169.30             4
   7      1    14     1088.64     264.73             4
   7      2    31     1040.33       0.0              1
   7      7     3     1180.76     403.13             2
   7      7     5     1691.68       0.0              1
   7      7    20     3143.78       0.0              1
   7      8     5     1153.16     211.92             3
   7      8    20     1494.28     352.64             4
   7     10     1     1709.57     126.37             3
   7     10     6     1406.23       0.0              1
   7     10    10     1262.40     269.73             3
   7     10    21     1918.16       0.0              1
   8      7     3      878.46       0.0              1
   8      8    20      939.64       0.0              1
   8     10     1     2596.14     489.57             2
   8     10     6     1550.22       0.0              1
   8     10    10     1654.50       0.0              1
   8     10    21     2376.56       0.0              1
   8     11    12      812.16       0.0              1
   8     11    13     1443.25     322.23             9
   8     11    14     1827.70       0.0              1
   8     11    92     1912.25     607.26             3
   9      1    10      915.16       0.0              1
   9      1    12     2018.37       0.0              1
   9      1    30      491.61     495.59             4
   9      2    31     1645.33      40.73             2
   9      7     3     1418.62     315.37             4
   9      7     5     1641.87     200.95             3
   9      7    10     1113.88     185.72             6
   9      8     5     1291.58     247.74            19
   9      8    20     1341.96     268.15             5
```

Table XXXIII.

9	8	40	1346.52	0.0	1
9	10	1	1227.37	652.24	2
9	10	6	1086.91	272.41	37
9	10	10	1934.20	505.16	7
9	10	21	1853.54	466.18	3
9	11	12	1539.03	317.16	7
9	11	13	1624.14	496.68	28
9	11	91	1065.44	421.05	6
9	11	92	2357.98	0.0	1
9	11	94	1493.09	472.64	12
10	1	30	29.43	0.0	1
10	8	4	1548.82	0.0	1
10	10	10	1654.50	0.0	1
11	11	13	1751.46	294.53	2
13	8	5	1363.16	0.0	1
13	11	94	966.96	0.0	1
20	7	3	912.87	0.0	1
20	10	21	986.17	435.79	2
22	7	10	997.45	0.0	1
22	8	5	1315.44	0.0	1
22	8	20	1093.89	0.0	1
22	10	6	1364.94	756.32	4
22	11	13	3245.81	0.0	1
27	1	30	1179.97	599.46	3
27	1	31	2478.28	0.0	1
27	2	31	1501.40	0.0	1
27	7	3	1606.22	431.29	9
27	7	10	1323.54	195.93	9
27	8	5	1310.09	295.39	11
27	8	20	1664.15	652.04	8
27	10	1	1999.21	1027.58	3
27	10	6	1417.09	378.99	16
27	10	10	1775.83	483.94	8
27	10	21	1674.40	488.72	13
27	11	12	1394.84	277.11	5
27	11	13	1488.68	318.99	22
27	11	91	1039.85	146.04	2
27	11	92	1380.70	849.15	2
27	11	94	1417.18	553.55	3
37	10	6	541.05	618.12	2
37	11	12	966.96	0.0	1
37	11	13	1573.21	475.26	5
37	11	91	973.43	182.49	3
47	7	3	895.71	0.0	1
47	10	10	1256.25	0.0	1

Table XXXIII continued.

47	11	13	1990.32	945.34	4
58	7	10	878.46	0.0	1
58	8	5	1055.66	54.06	2
58	10	6	936.67	0.0	1
73	8	20	1457.00	0.0	1
73	8	40	1844.58	0.0	1
73	10	1	2249.97	0.0	1
73	10	10	1788.86	0.0	1
73	10	21	1593.05	524.28	3
81	2	14	2131.63	0.0	1
81	7	3	1727.33	892.37	2
81	8	5	1339.36	0.0	1
81	10	6	1550.22	0.0	1
81	10	10	1008.33	404.45	2
81	10	21	2208.23	410.24	2
81	11	13	1114.46	0.0	1
88	7	5	3231.56	0.0	1
88	8	20	2020.50	0.0	1
88	10	1	2376.56	0.0	1
88	10	10	1599.64	878.95	2
88	10	21	1223.22	465.36	3
88	11	13	1653.20	584.76	4
88	11	94	1255.04	38.90	2
90	2	31	929.77	234.76	2
90	7	10	1239.57	0.0	1
90	8	5	968.05	625.50	2
90	10	4	541.98	0.0	1
90	10	6	1688.58	0.0	1
90	10	21	1585.32	0.0	1
91	8	20	1726.62	0.0	1
91	11	13	3296.17	0.0	1
92	10	4	448.64	0.0	1
92	10	6	1564.83	618.78	3
92	10	7	1821.64	0.0	1
92	11	12	1894.51	0.0	1
92	11	13	3417.29	0.0	1
93	7	3	1388.13	600.01	2
93	8	5	965.72	0.0	1
93	10	6	1332.01	0.0	1
93	11	13	874.99	0.0	1
94	10	6	255.23	0.0	1
94	11	13	966.96	0.0	1
94	11	14	7286.54	0.0	1

Table XXXIII continued.

CHAPTER VII

TAKEOFFS

Occupancy Times

Fewer differences were expected to be found among takeoff occupancy times, because there are fewer variables involved. (Takeoff occupancy time is defined as the interval between the start of the aircraft's roll and the moment it lifts off from the runway). The curves of occupancy time versus frequency do show less variance than the similar curves for arriving aircraft. One main reason for this is greater operational uniformity: all aircraft start from the same point. No choice, such as for runway exits, is involved. The only significant factor, other than aircraft type, would seem to be the wind speed and direction, since this affects the ground speed required by the plane to become airborne.

The mean and standard deviation of takeoff times appear in Table XXXIV. It can be seen that, for the commercial jet, these times are all of the order of 25-35 seconds, and 20-25 seconds for propellor-driven planes.

Comparisons between aircraft types are made in Table XXXV, combining data for all runways and Tables XXXVI-XXXVIII, comparing the same aircraft over specific runways when possible. Once again, the t-test was used at the 5% significance level. The only significant difference between occupancy times was found when the DC-9 and the BAC-111 were compared, and this was confined to only one runway. Since both aircraft have similar performance characteristics, only two possible explanations can be offered at this time: first, that the BAC-111's operated at a much lower load factor than the DC-9's, and hence had a much better thrust-weight ratio, or secondly, that it was simply a difference in pilot technique. The BAC-111 had the lowest overall mean occupancy time of any commercial jet observed.

However, the similarities between types are more striking than the differences. It was known that the larger aircraft require greater takeoff distances, and this led to the expectation of greater takeoff times as well. But the final liftoff speed is greater as well, and this reduces the time it takes for the larger aircraft to traverse the longer distance. The effects of the two factors, distance and speed, would thus seem to cancel out, resulting in similar occupancy times for all jet aircraft.

Delay Times

During the survey, times were also recorded for various maneuvers by the departing aircraft as they prepared to takeoff. These are also listed in Table XXXIV.

The first time listed, CL-RCLR, is the time elapsed between an aircraft receiving clearance from the tower to enter the runway (RCLR) and the instant when he is aligned on the centerline (CL). One source of the variance of this measure is that the planes are not all in the same location when they receive tower clearance. They might be holding just off the runway, or they might be still taxiing out from the terminal. Although for most aircraft these times were between thirty and forty seconds, a range of 227 seconds was also observed between the minimum, ten seconds, and the maximum, 237 seconds.

The next column shows the time between reaching the centerline and receiving takeoff clearance. These times were often negative, which would explain the small means. This is because an aircraft taxiing out to the runway would often receive his runway clearance and takeoff clearance simultaneously, before he reached the runway, if there was no queue.

Finally, the delay between reception of takeoff clearance from the tower and actually starting takeoff roll is listed. There was a wide variance on this measure as well, and it is suspected that this might be due to different check list procedures employed by different airlines. There is usually a short delay due to this safety check, and also a short time before breakaway thrust is built up by the engines, and the aircraft will start to move. Generally, the delay was less than ten seconds, although the larger jets averaged longer delays.

Once again, the variance was largely due to some aircraft which received takeoff clearance before they reached the runway. This effect was partially counteracted, however, because these aircraft were already rolling when they hit the runway centerline; there was no need to bring the engines up to breakaway thrust, and the pre-takeoff check list could be covered while the plane was still on the taxiway.

Takeoff Dynamics

Information is given in the last four columns of Table XXXIV on the average takeoff times, average takeoff distances, average speed at liftoff, and average acceleration, for the different aircraft types. The speed and acceleration were calculated from the recorded time and distance, assuming a constant acceleration, by use of the following standard equations

$$S = 1/2\ at^2 + v_o t + S_o \qquad (7.1)$$

and

$$(v - v_o) = at \qquad (7.2)$$

where S = distance of liftoff point from runway threshold

a = acceleration

t = takeoff occupancy time

v_o = initial velocity = 0.0

S_o = initial displacement from threshold = 200 feet

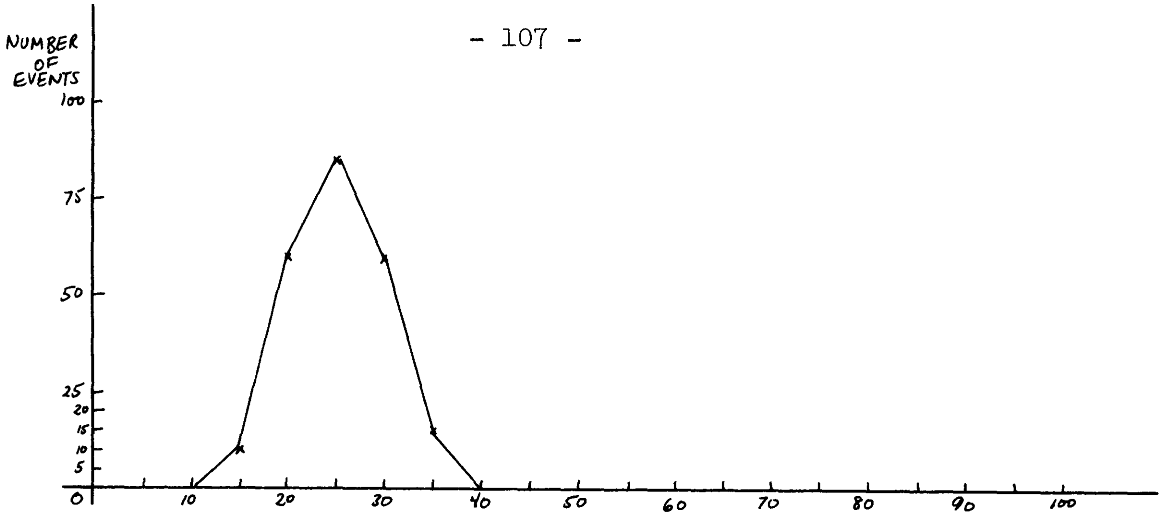
v = final takeoff velocity

The accuracy of these calculations is questionable, however. Although the average velocities are in more or less correct relative order, the magnitudes are almost always too great. For example, the 707 had a calculated mean takeoff speed of 204 knots; this is in contrast to the expected value of about 165 knots.[9]

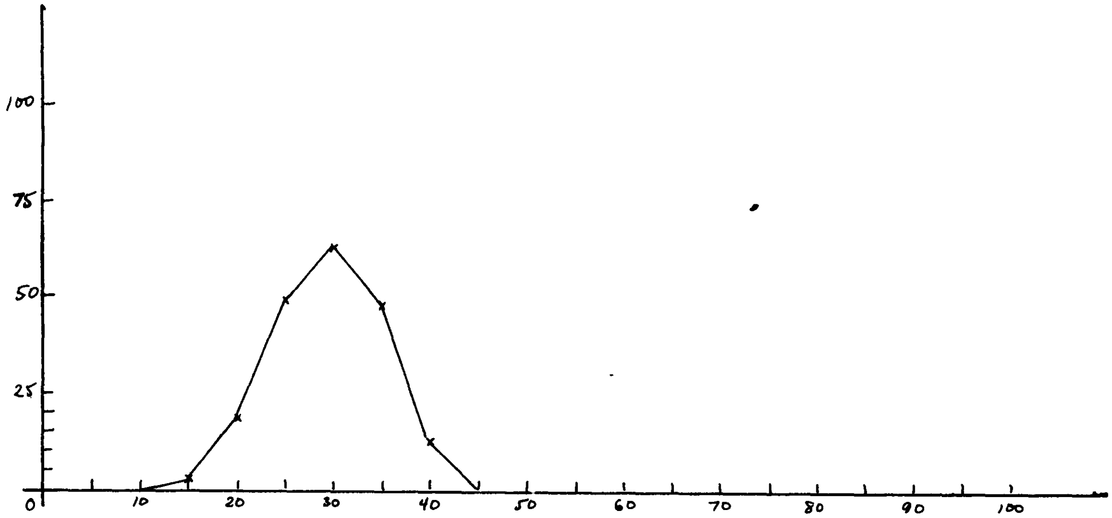
Possibly, the assumption of constant acceleration used to calculate the speeds was not justified. When the aircraft starts to roll, engine thrust is still increasing from breakaway thrust to full takeoff power. And then, as speed increases, so does drag; this would decrease net thrust and therefore acceleration as well.

It may have been noticed before now that nothing has been mentioned about the times elapsed from start of roll to intermediate points along the runway. These were originally intended to give us a velocity profile for the departures. Unfortunately, no usable results were obtained from this data. Once again the assumption of constant acceleration was made, which could explain the unrealistic velocities calculated.

In order to obtain an accurate velocity profile, up to and including takeoff speeds, it is probably necessary to use many small segments of runway over which acceleration could reasonably be assumed to be constant. This was done by AIL[10], which measured aircraft distance along the runway every second.



BOSTON



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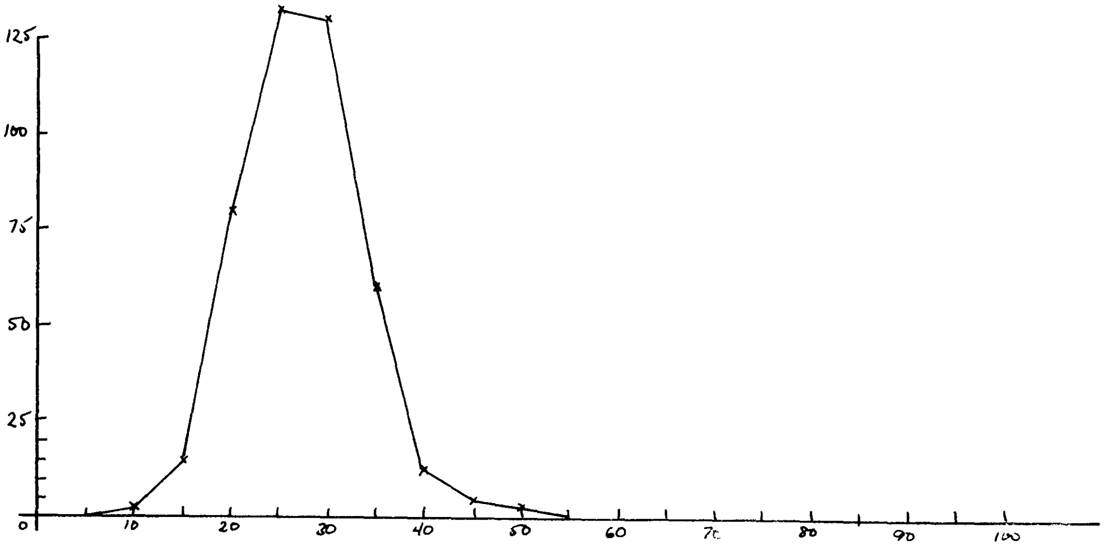
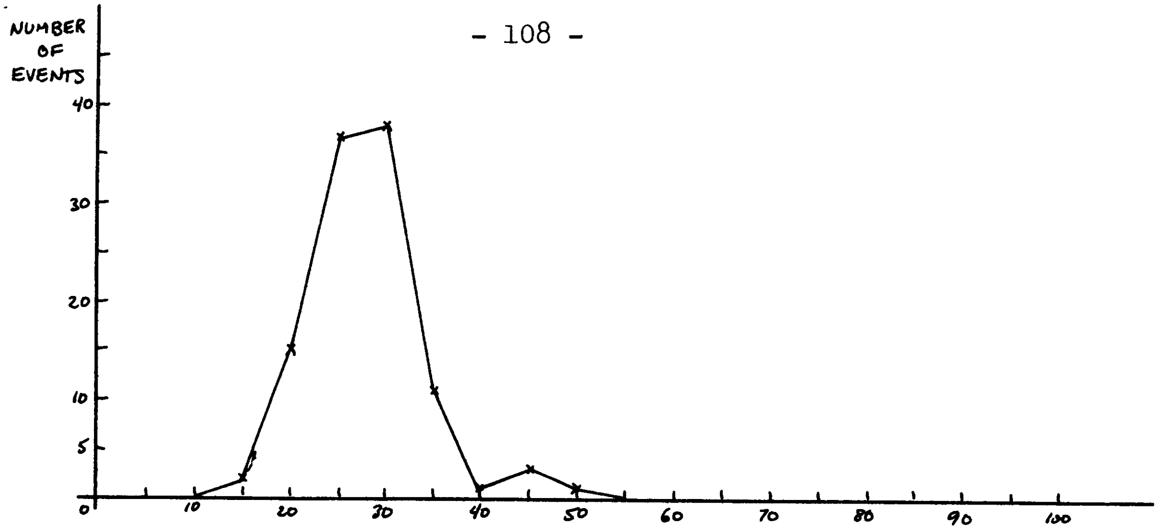
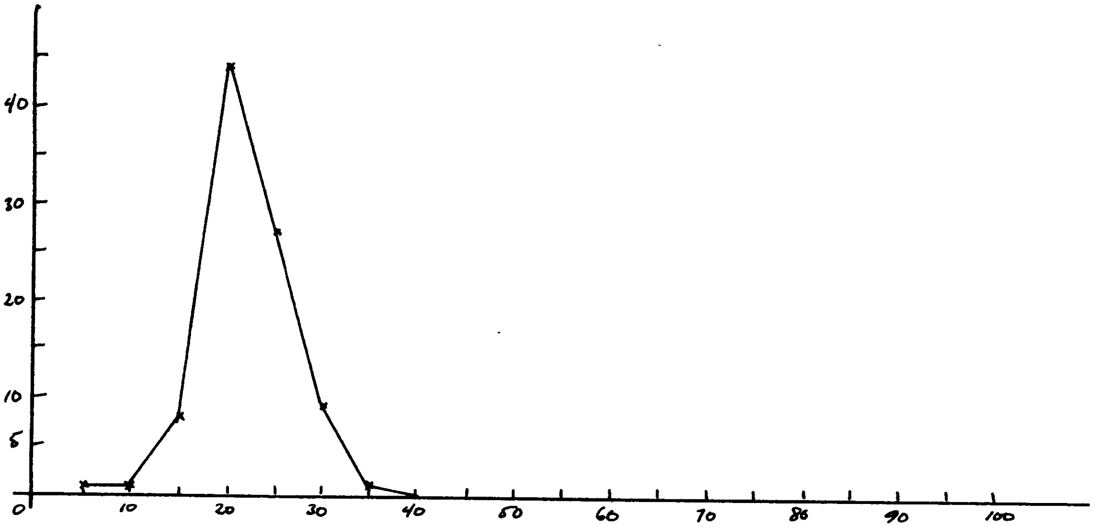


TOTAL

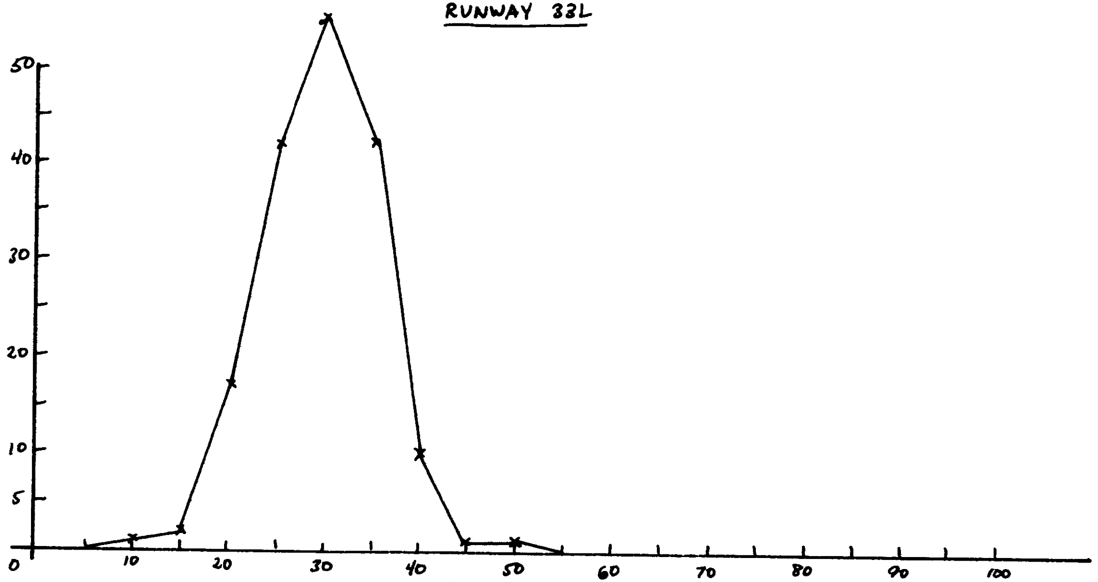
FIGURE 11 - TAKEOFF OCCUPANCY TIMES, ALL TYPES, ALL RUNWAYS



RUNWAY 22R



RUNWAY 33L



RUNWAY 27R

FIGURE 12 - TAKEOFF OCCUPANCY TIMES, ALL TYPES, SELECTED RUNWAYS

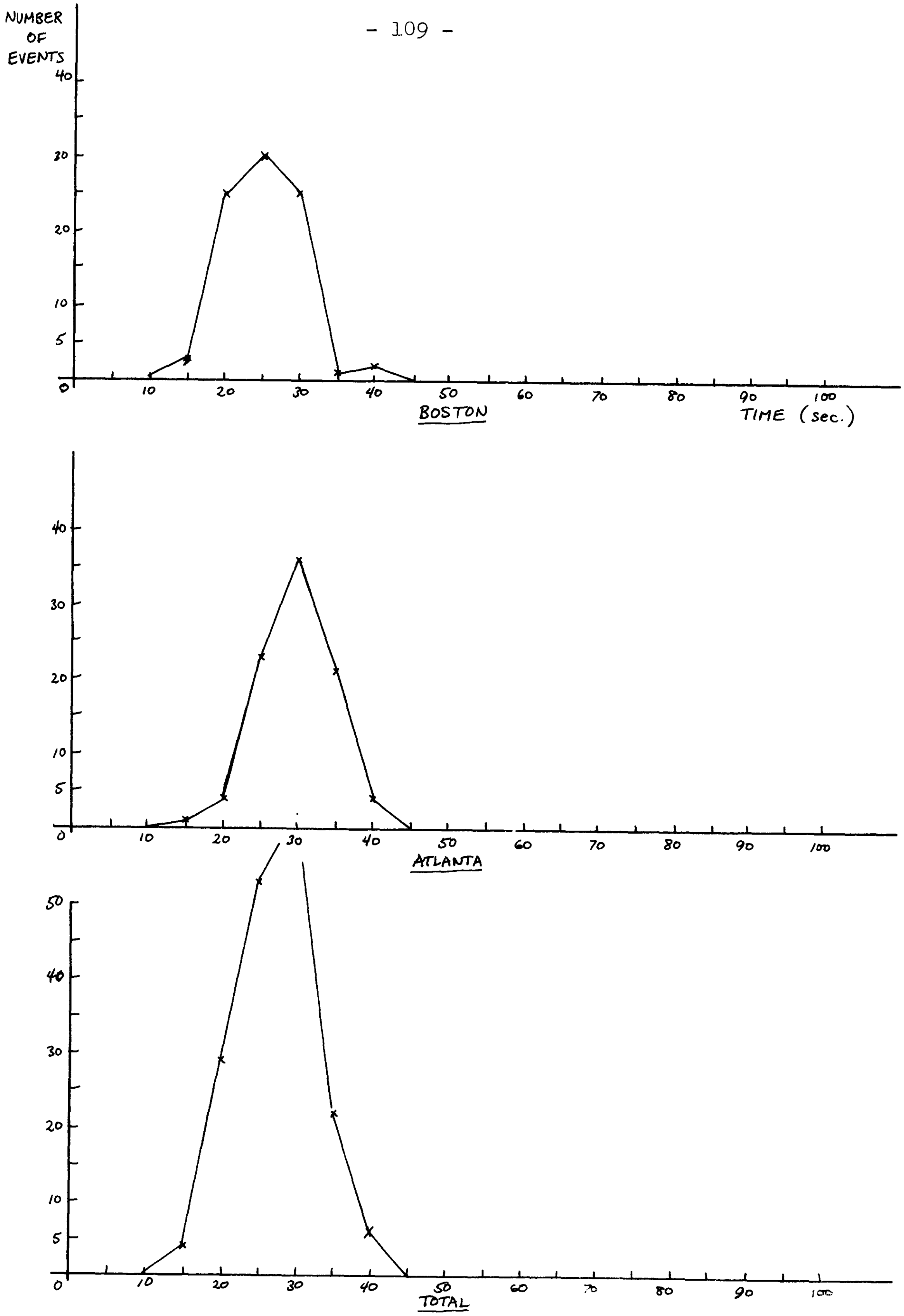
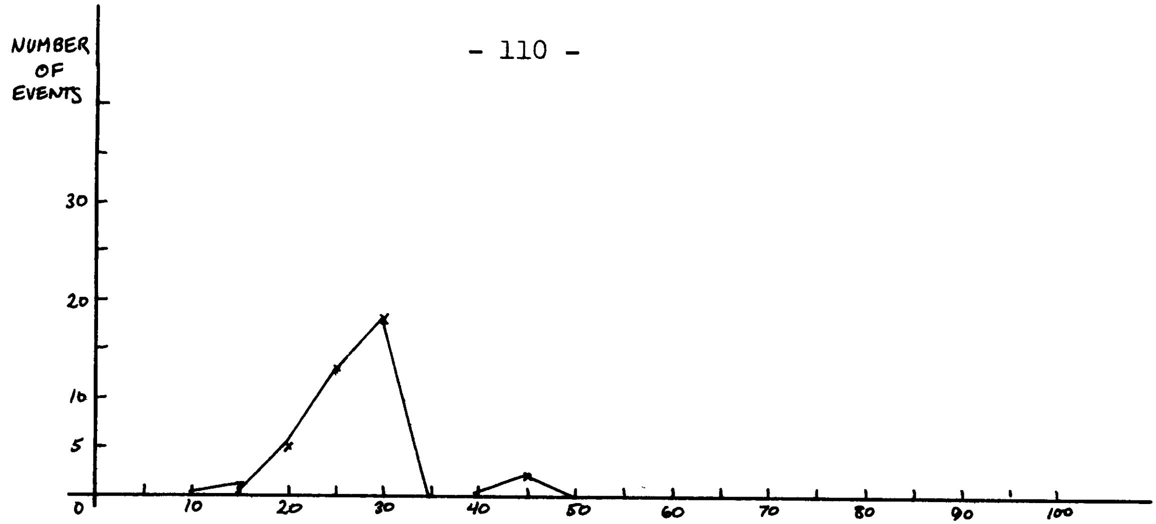
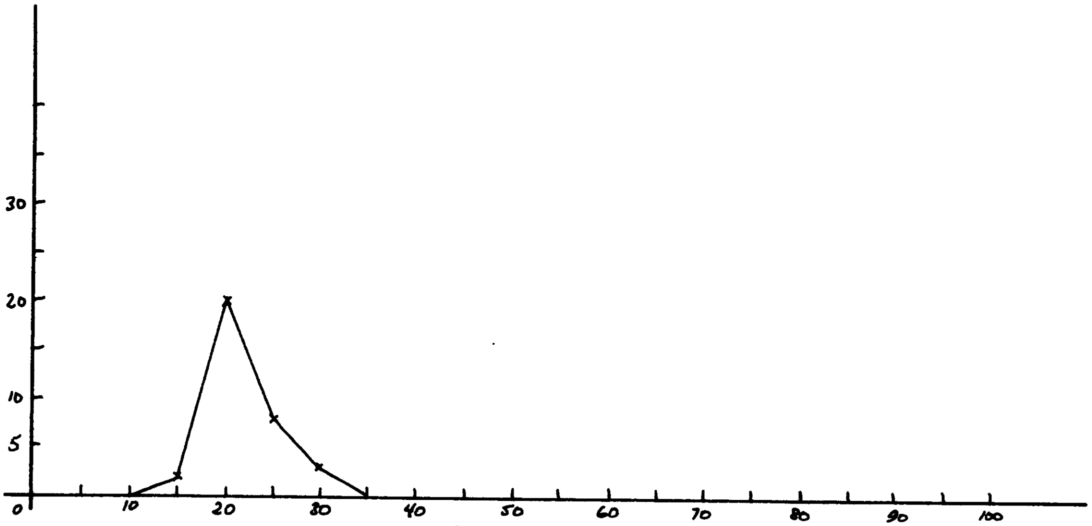


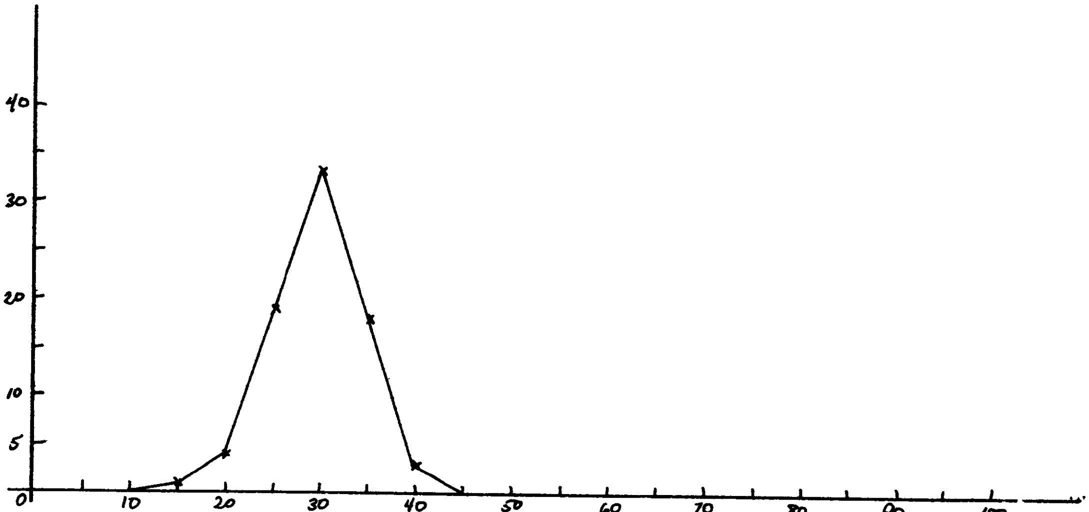
FIGURE 13 DC-9 TAKEOFF OCCUPANCY TIMES, ALL RUNWAYS



RUNWAY 22R

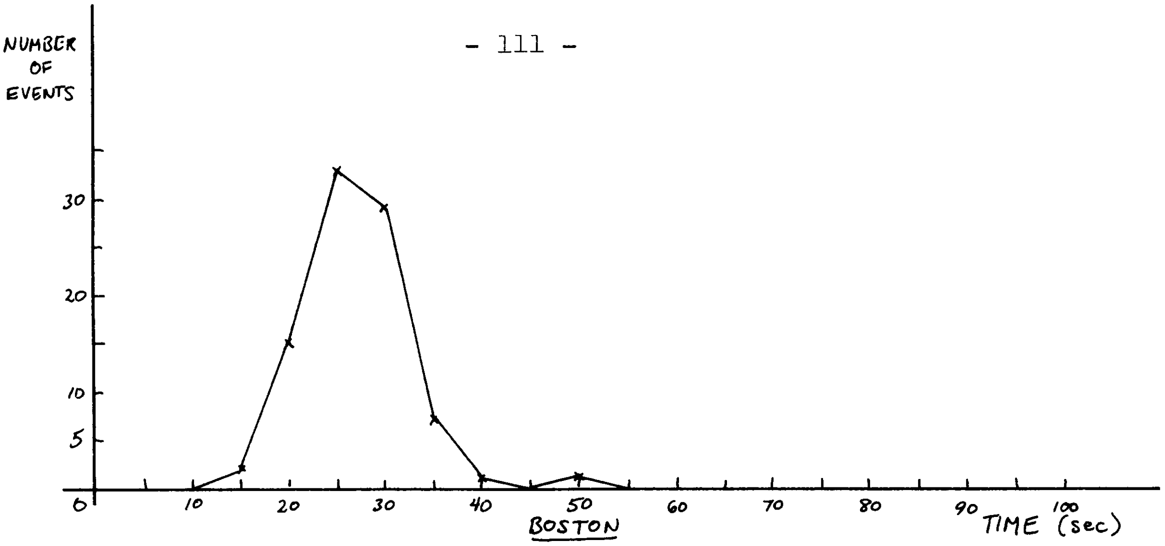


RUNWAY 33L

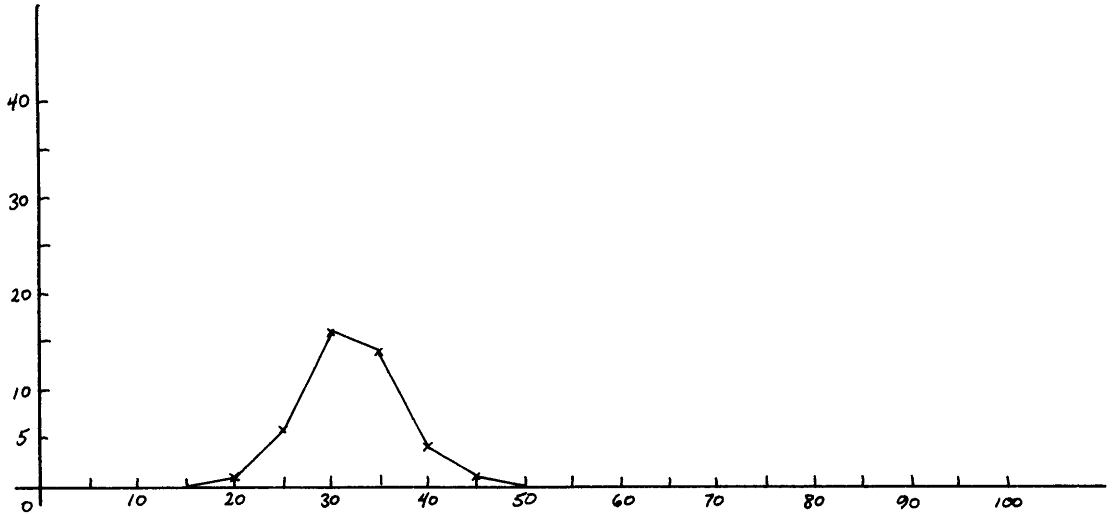


RUNWAY 27R

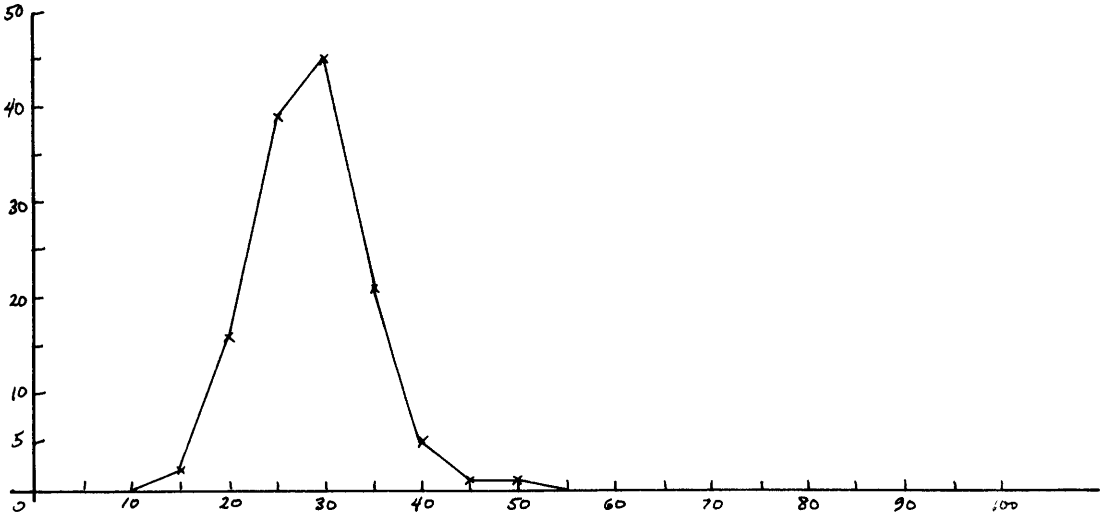
FIGURE 14 - DC-9 TAKEOFF OCCUPANCY TIMES, SELECTED RUNWAYS



BOSTON

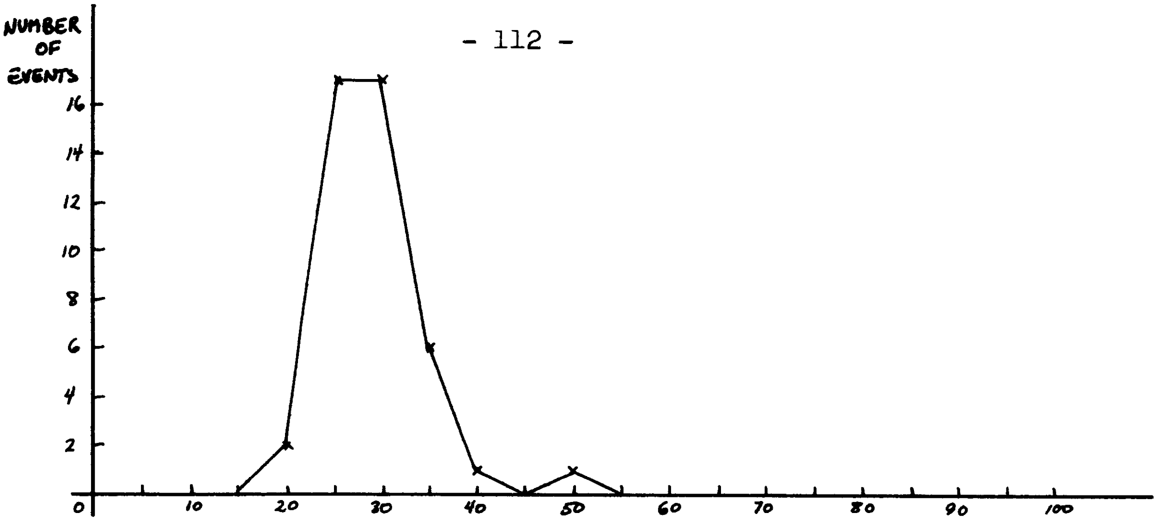


ATLANTA

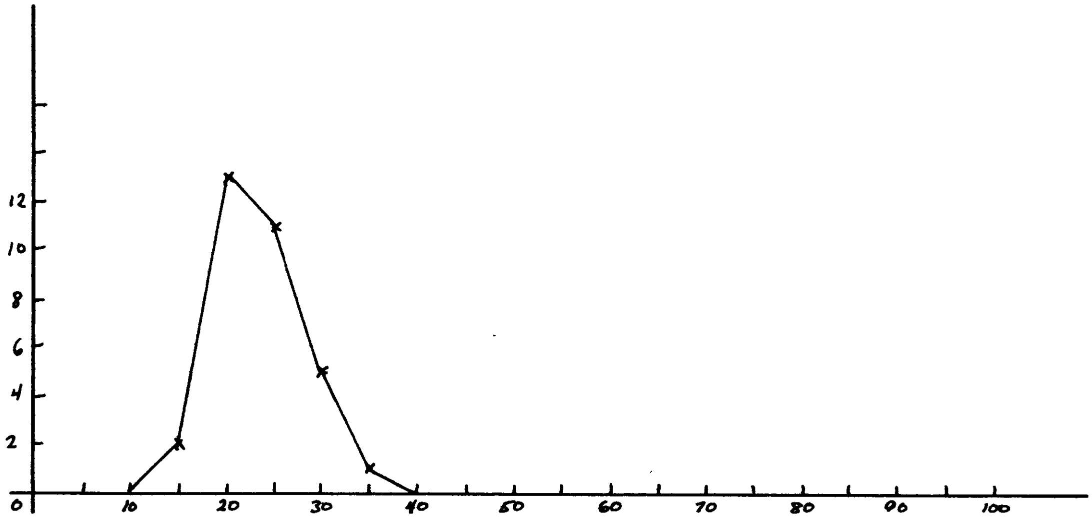


TOTAL

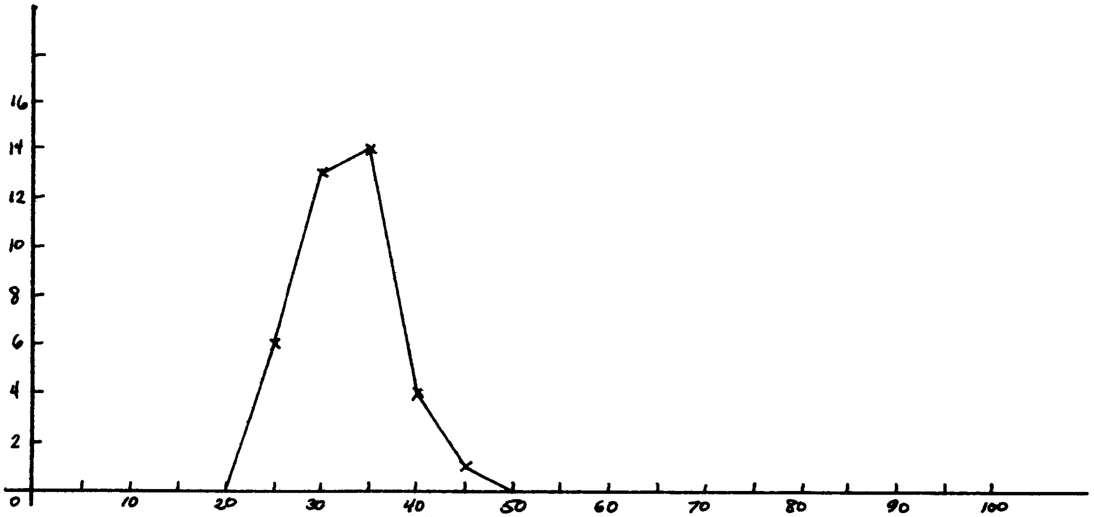
FIGURE 15 - 727 TAKEOFF OCCUPANCY TIMES, ALL RUNWAYS



RUNWAY 22R



RUNWAY 33L



RUNWAY 27R

FIGURE 16 - 727 TAKEOFF OCCUPANCY TIMES, SELECTED RUNWAYS

```
EXECUTION BEGINS...

DEPARTURES BY TYPE, ALL RUNWAYS
TYPE CL-RCLR  TCLR-CL RL-TCLR  TO*TIME TO*DIST    V*T/O  AV*ACCL
   1   31.66    -0.98   12.33    25.15 4517.50   193.20    12.76    MEAN
       13.01    18.87    7.27     3.04 1336.56    68.29     5.37    STD DEV
           9        9       9       12      12        9        9    NO OF EVENTS
   3   15.00    12.00    3.00    22.03 2536.00   116.24     8.24    MEAN
        0.0      0.0     0.0      3.23    0.0      0.0      0.0     STD DEV
           1        1       1        3       1        1        1    NO OF EVENTS
   4   29.26     9.30    5.25    27.90 3127.83   125.18     7.71    MEAN
       12.38    15.78    2.66     2.99  261.49    13.45     1.59    STD DEV
          10       10      10       12      12       12       12    NO OF EVENTS
   6   39.00     0.50   22.50    17.20 1931.00   116.52    11.18    MEAN
       22.63    27.58   19.09     2.23    0.0      0.0      0.0     STD DEV
           2        2       2        3       1        1        1    NO OF EVENTS
   7   35.20   -17.91   16.67    31.47 4953.60   203.67    12.62    MEAN
       11.99    56.10   12.31     7.46 1554.37    51.41     3.09    STD DEV
           5        7       7        9       5        5        5    NO OF EVENTS
   8   44.35    -1.34   12.81    31.29 4334.18   161.10     9.81    MEAN
       24.44    19.82   14.25     7.54  916.68    53.51     7.47    STD DEV
          10       14      15       16      11       10       10    NO OF EVENTS
   9   32.22     7.97    8.53    30.54 4697.19   169.96     9.54    MEAN
       17.12    21.23    8.78     6.50 1339.83    47.38     4.15    STD DEV
         144      150     149      177     138      132      132    NO OF EVENTS
  11   34.50    15.00    7.25    23.60 2695.33   127.89     9.56    MEAN
        2.12    29.70    0.35     4.85  105.15    19.64     3.01    STD DEV
           2        2       2        3       3        3        3    NO OF EVENTS
  13   20.00     4.50    4.40    22.30 2625.50   128.93     9.77    MEAN
        2.83     6.36    3.39     0.42  176.08    11.80     1.07    STD DEV
           2        2       2        2       2        2        2    NO OF EVENTS
  27   38.22     4.55    9.06    31.08 4701.99   165.06     8.88    MEAN
       26.07    15.03    7.16     5.70 1264.56    44.82     3.06    STD DEV
          87      105     109      130      98       89       89    NO OF EVENTS
```

Table XXXIV.

```
37   26.10    7.36    5.51   30.75 4327.00  158.79    8.87   MEAN
     33.17   13.89    3.24    4.18  750.25   18.36    1.77   STD DEV
        13      12      12      13      13      13      13   NO OF EVENTS
47   43.00    3.33   10.67   34.90 5024.25  163.48    7.93   MEAN
      9.35    8.95    9.83    2.78  491.12    3.91    0.48   STD DEV
         4       3       4       4       4       4       4   NO OF EVENTS
58   24.10   19.50    9.13   24.10 3136.50  131.06    8.37   MEAN
     15.70   23.45    2.58    4.71   37.31   13.13    1.57   STD DEV
         2       3       3       3       2       2       2   NO OF EVENTS
73   35.68   12.10    7.30   28.20 4272.50  140.62    8.13   MEAN
     18.48   20.93    6.26    3.43  856.30     0.0     0.0   STD DEV
         6       4       4       5       2       1       1   NO OF EVENTS
81   40.11    3.52   14.93   33.55 4387.00  150.55    8.15   MEAN
      8.75   24.69   15.04    9.18 1014.45   24.45    2.68   STD DEV
         7       8       7       8       8       8       8   NO OF EVENTS
88   30.38   16.43    6.20   34.41 5153.43  165.75    8.06   MEAN
      9.52   20.50    4.03    5.72  802.01   31.97    2.48   STD DEV
         8       9       9      10       7       7       7   NO OF EVENTS
90   40.00    4.84    5.75   25.10 2663.60  112.21    8.06   MEAN
     12.73   15.39    3.74    3.69  647.04   32.49    3.13   STD DEV
         2       5       6       6       5       4       4   NO OF EVENTS
91   21.56   26.80    4.25   19.98 2746.33  111.88    7.03   MEAN
     12.78   14.30    2.63    8.85 1239.97   59.22    3.92   STD DEV
         5       4       4       5       9       2       2   NO OF EVENTS
92   33.25   29.75    4.88   27.75 2830.90  180.16   14.60   MEAN
     22.37   27.60    2.78    9.46 1255.20   37.65    4.30   STD DEV
         4       4       4       4      10       2       2   NO OF EVENTS
93   20.67    8.14    8.14   26.19 3484.67  141.89    9.03   MEAN
     21.25   19.16    9.97    5.65  584.75   12.02    2.22   STD DEV
         9       7       7       8       6       6       6   NO OF EVENTS
T=4.85/8.55 15:05:54
```

Table XXXIV continued.

```
EXECUTION BEGINS...
 TYPE1  TYPE2     T(1)    NO    T(2)    NO    T(CALC)     T(.025)
    9     27     30.54   177   31.08   130   -0.9709      1.98
    9     37     30.54   177   30.75    13   -0.1743      2.179
  * 9      1     30.54   177   25.15    12    7.1821      2.201
   27      7     31.08   130   31.47     9   -0.1465      2.306
    7      8     31.47     9   31.29    16    0.0826      2.306
    7     73     31.47     9   28.20     5    1.0897      2.776
    7     47     31.47     9   34.90     4   -2.7838      3.182
    8     88     31.29    16   34.41    10   -1.0331      2.262
   27      8     31.08   130   31.29    16   -0.0978      2.131
    8     81     31.29    16   33.55     8   -0.6092      2.365
    8     47     31.29    16   34.90     4   -1.4921      3.182
   22     58     21.70     4   24.10     3   -0.9445      4.303
   11     58     23.60     3   24.10     3   -0.1436      4.303
T=14.73/18.80 13:14:35
```

Table XXXV Departures comparing all aircraft types over all runways.

```
EXECUTION BEGINS...
 TYPE1    9
 TYPE2   27

 R/W     T̄(1)     NO    T̄(2)     NO    T(CALC)      T(.025)
  9      30.15    15   29.74     10    0.2929       2.262
 22R     30.60    39   31.91     44   -1.0566       2.02
 33L     24.39    33   26.16     32   -1.8783       2.04
 27R     32.79    79   34.62     38   -1.7316       2.02
 27L     33.10    11   30.40      4    0.9452       3.182



 TYPE1    9
 TYPE2   37

 R/W     T̄(1)     NO    T̄(2)     NO    T(CALC)      T(.025)
 27R     32.79    79   30.75     13    1.9880       2.179



 TYPE1    9
 TYPE2    1

 R/W     T̄(1)     NO    T̄(2)     NO    T(CALC)      T(.025)
  9      30.15    15   27.70      2    1.9702      12.406
*22R     30.60    39   24.53      3    6.1175       4.303
 33L     24.39    33   24.69      7   -0.2167       2.447



 TYPE1   27
 TYPE2    7

 R/W     T̄(1)     NO    T̄(2)     NO    T(CALC)      T(.025)
  9      29.74    10   29.80      2   -0.0328      12.706
 22R     31.91    44   36.55      4   -0.8829       3.182
 33L     26.16    32   25.80      3    0.2228       4.303
```

Table XXXVI Departures, comparing types, by runways.

```
EXECUTION BEGINS...
 TYPE1    7
 TYPE2    8

 R/W     T̄(1)    NO    T̄(2)    NO    T(CALC)      T(.025)
  9     29.80     2   35.55     2   -2.1698      12.706
 22R    36.55     4   31.50     6    1.0302       3.182
 33L    25.80     3   23.10     2    0.7804      12.706



 TYPE1    7
 TYPE2   73

 R/W     T̄(1)    NO    T̄(2)    NO    T(CALC)      T(.025)
  9     29.80     2   31.00     2  -12.0004      12.706
 33L    25.80     3   26.33     3   -0.2237       4.303



 TYPE1    7
 TYPE2   47

 R/W     T̄(1)    NO    T̄(2)    NO    T(CALC)      T(.025)



 TYPE1    8
 TYPE2   88

 R/W     T̄(1)    NO    T̄(2)    NO    T(CALC)      T(.025)
 22R    31.50     6   33.50     2   -0.4622      12.706
 27R    37.70     3   36.05     6    0.2700       4.303
```

Table XXXVII.

```
TYPE1  27
TYPE2   8

R/W     T̄(1)    NO   T̄(2)    NO   T(CALC)     T(.025)
 9      29.74   10   35.55    2   -7.1115     12.706
22R     31.91   44   31.50    6    0.1224      2.571
33L     26.16   32   23.10    2    1.8246     12.706
27R     34.62   38   37.70    3   -0.7659      4.303
27L     30.40    4   27.07    3    0.5100      4.303



TYPE1   8
TYPE2  81

R/W     T̄(1)    NO   T̄(2)    NO   T(CALC)     T(.025)
33L     23.10    2   25.90    2   -7.0002     12.706
27R     37.70    3   37.80    4   -0.0266      4.303
27L     27.07    3   32.70    2   -0.8689     12.706



TYPE1   8
TYPE2  47

R/W     T̄(1)    NO   T̄(2)    NO   T(CALC)     T(.025)
27R     37.70    3   34.90    4    0.4657      4.303



TYPE1  22
TYPE2  58

R/W     T̄(1)    NO   T̄(2)    NO   T(CALC)     T(.025)
33L     19.40    2   22.00    2   -1.6250     12.706
```

Table XXXVIII.

CHAPTER VIII

CONCLUSIONS

Sources of Error

A complete analysis of the data collected during our survey must include some discussion of the accuracy of that data. Certainly, part of the variations in the results is due to measurement error, and not to actual events. However, much of the data does seem to be internally consistent, and obvious errors were removed during the preliminary analysis.

The observational technique used for this survey was not perfect. Much can be done to minimize the errors it produced in the data. Some of the problems, however, are inherent to the technique, and cannot be easily changed.

One serious defect is in the large number of observers required. Coordinating the actions of so many is difficult. So is ensuring consistent results from two people working at two different times, especially when so many events are matters of judgment (e.g. when is the aircraft finally clear of the runway? when does it actually start to roll on takeoff?). This despite attempts to set up objective criteria for such items.

Judgment is so important primarily because the obervers are located so far from the events they are trying to measure. The control tower at Logan is as far as a mile and a half from some of the runway thresholds. Visual angles were poor in some other cases, such as for the threshold of runway 22R and 22L in Boston. In such situations, the only solution is to move the observation point, but this may not be practical or desirable, in terms of the tradeoffs required for adequate observation of other runways.

On the other hand, certain minor improvements in the procedures are possible. More care can be taken with theodolite readings, which could be recorded to a finer precision than a tenth of a degree. Better timing techniques, using high speed electic counters rather than stopwatches, could be used. And it is always possible to limit the number of variables to be recorded, so that either fewer observers are needed, or the observers are less hurried and can be more precise in their work. But unfortunately, the human element - judgment, reaction time, and fatigue - will always be present.

Conclusions and Recommendations

Despite these drawbacks, it is felt that some useful results have been obtained. The information on taxiing speeds, intersection delays, and pre-takeoff delays for instance, is believed to have been unavailable before. More data was accumulated on runway occupancy times and exit-use patterns.

It was found that some factors do not have the expected effects on taxiing speeds or on occupancy times. Ground speed on a certain stretch of taxiway does not seem to depend on the length of the stretch, the type of aircraft, or the direction of travel. Time to liftoff does not seem to depend on aircraft type, either. And although the overall runway occupancy time on landing does vary as expected with aircraft size, the time to a particular exit does not seem to be affected - which may be a useful simplification in modelling runway operations.

Much more work, however, remains to be done. Many of the variables recorded during the survey have not yet been introduced into the analysis, although some could present interesting new relations.

For example, further research can be done on the effect of congestion at the airport, based on either time of day or the number of aircraft in the takeoff queue, both of which have been recorded. Or the delays prior to takeoff could be classified according to whether the aircraft came to a complete stop before entering the runway, or rolled straight on to the runway from the taxiway. This is also possible with the data which has been obtained.

There is also some additional data which should be taken if this survey is ever run again. This would include, for taxiway movements, the time of day and some measure of queuing on the taxiways. Perhaps these could be combined, using continuous timing techniques to measure the real time of each event, rather than measuring only the interval time with stopwatches.

For taxiway intersections, it would be of interest to compare, once again, aircraft which stopped short of the intersection with those which slowed but did not stop. This would have to be recorded in any future survey.

Above all, many more events must be observed, before all the fine distinctions can be recognized in the data. For example, a breakdown of all arrivals by airline as well as aircraft type, runway and exit used would produce few samples of useful size. As it is, the average number of a particular aircraft type which used an exit, computed just over the observed data, was only 3.9.

As to the method to be used to collect this additional data, it is strongly recommended that the feasibility of a permanently instrumented system be fully investigated. Except for minor changes, little can be done to improve the accuracy of the labor-intensive method used herein, that of employing several observers with stopwatches. The main drawbacks have already been discussed: coordination problems, individual variations in judgment, and optical sighting problems.

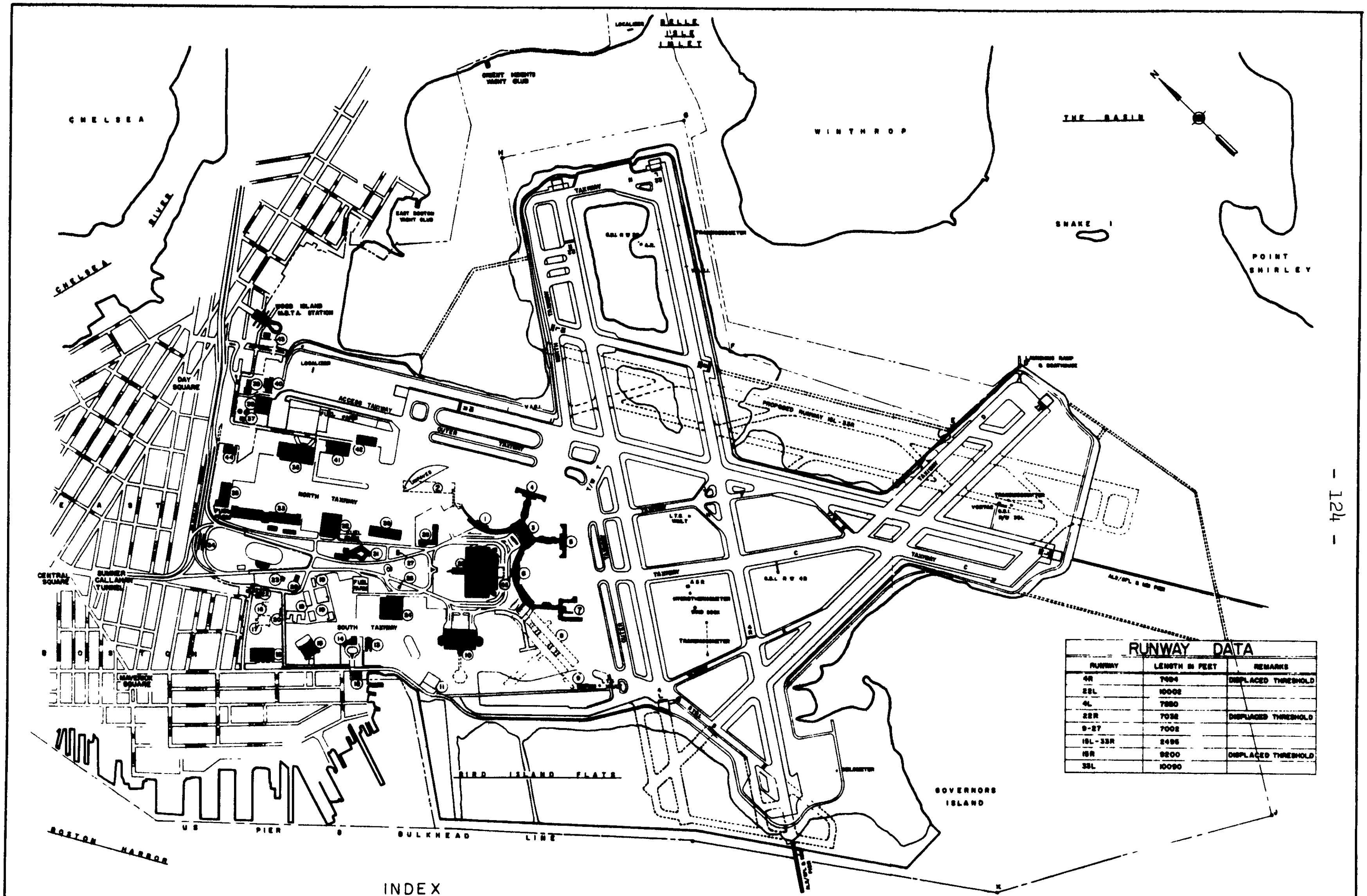
It is not known which of several possible sensors would be best suited for this work. The Port of New York Authority favored buried induction loop detectors in its proposal for a surface traffic control system (STRACS) at Kennedy Airport.[11,12] Radar, ultrasonic or laser devices, compressed air tubes or other pressure devices are all possibilities.

But some kind of mechanical, semi-automated installation is necessary if all potential data is to be obtained. It should then be possible to record operations at night, in fog or heavy rain, or coverage of operations on both parallel runways, simultaneously. This type of data we were unable to record, due to the limitations of our technique.

Postscript

Although some questions have been answered, many more have been raised. There is much more work which can still be done in this field, for the factors affecting airport traffic are many; it is quite possible that some significant factors have been overlooked in this report.

The interest shown to date in the results of this analysis and in the whole area of airport simulation by computer has been most encouraging. Hopefully this support will continue, and more research will be undertaken for a better understanding and more efficient use of the airport facilities.



RUNWAY DATA

RUNWAY	LENGTH IN FEET	REMARKS
4R	7494	DISPLACED THRESHOLD
22L	10002	
4L	7860	
22R	7032	DISPLACED THRESHOLD
9-27	7002	
15L-33R	2496	
15R	9200	DISPLACED THRESHOLD
33L	10090	

INDEX

1 INTERNATIONAL TERMINAL
2 INTERNATIONAL TERMINAL (UNDER DESIGN)
3 NORTH TERMINAL
4 PIER-B
5 PIER-C
6 CONTROL TOWER - TOWER RESTAURANT
7 INTERIM SOUTH TERMINAL (TO BE DEMOLISHED)
8 SOUTH TERMINAL (UNDER DESIGN)
9 FIRE & CRASH STATION
10 SOUTHWEST TERMINAL (EASTERN AIRLINES)
11 MOHAWK HANGAR (TO BE DEMOLISHED)
12 EMERY AIRFREIGHT
13 VAN DUSEN HANGAR
14 GENERAL AVIATION ADM BLDG
15 BUTLER AVIATION HANGAR
16 U.S. POST OFFICE
17 SKY CHEFS (UNDER DESIGN)
18 HERTZ SERVICE CENTER (UNDER DESIGN)
19 AIR NATIONAL GUARD (TO BE DEMOLISHED)
20 HERTZ INTERIM SERVICE CENTER
21 NATIONAL SERVICE CENTER
22 PORTER ST POWER SUBSTATION
23 AVIS SERVICE CENTER
24 EASTERN AIRLINES HANGAR
25 TAXICAB STORAGE AREA
26
27 ESSO SERVICE STATION
28 MULTI-LEVEL PARKING GARAGE
29 M.P.A HEATING PLANT
30 A.A.L AIRFREIGHT & SKY CHEFS
31 HOTEL SONESTA
32 AMERICAN AIRLINES HANGAR
33 WILLIAMS AIRFREIGHT
34 AIRPORT M B T A STATION
35 PAN AMERICAN AIRFREIGHT
36 NORTHEAST AIRLINES HANGAR
37 M.P.A. PUMPING STATION
38 ALLEGHENY HANGAR
39 DAVES AIRFREIGHT
40 M P A FIELD MAINTENANCE CENTER
41 T W A HANGAR
42 T.W.A AIRFREIGHT
43 WOOD ISLAND SUBSTATION
44 N E A RESERVATIONS
45 NEW CONTROL TOWER (UNDER CONST)

▨ SOUTH TERMINAL TEMPORARY FACILITIES

SCALE IN FEET
500 0 500 1,000 1,500 2,000

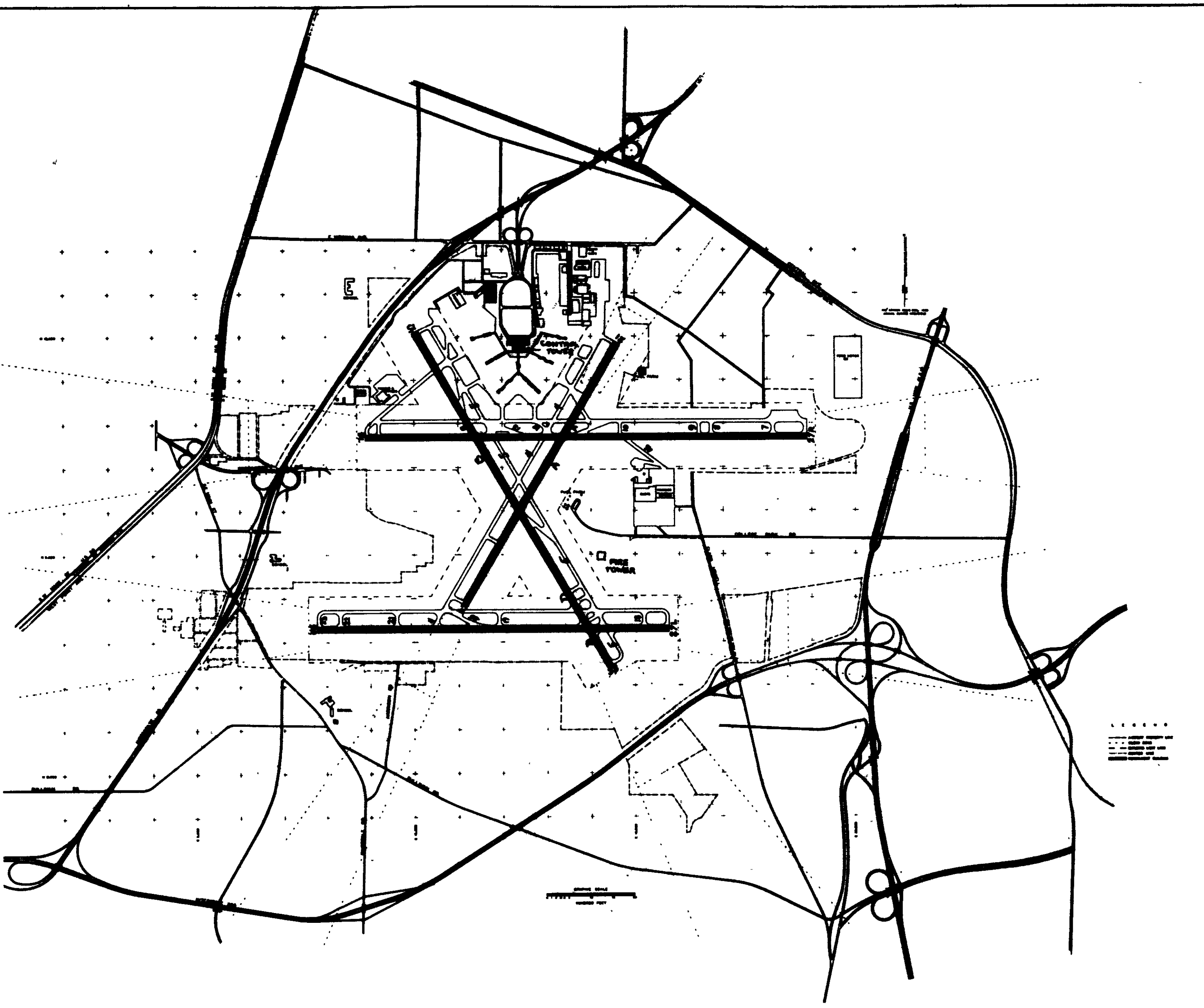
REVISED DECEMBER 1970

MASSACHUSETTS PORT AUTHORITY
BOSTON-LOGAN INTERNATIONAL AIRPORT

GENERAL LOCATION PLAN

SCALE	APPROVED BY		REVISED
GRAPHIC			NOV 1969
DATE	DRAWN BY	CHECKED BY	DWG NO
NOV 1969	SWM	JRD	071219

Final



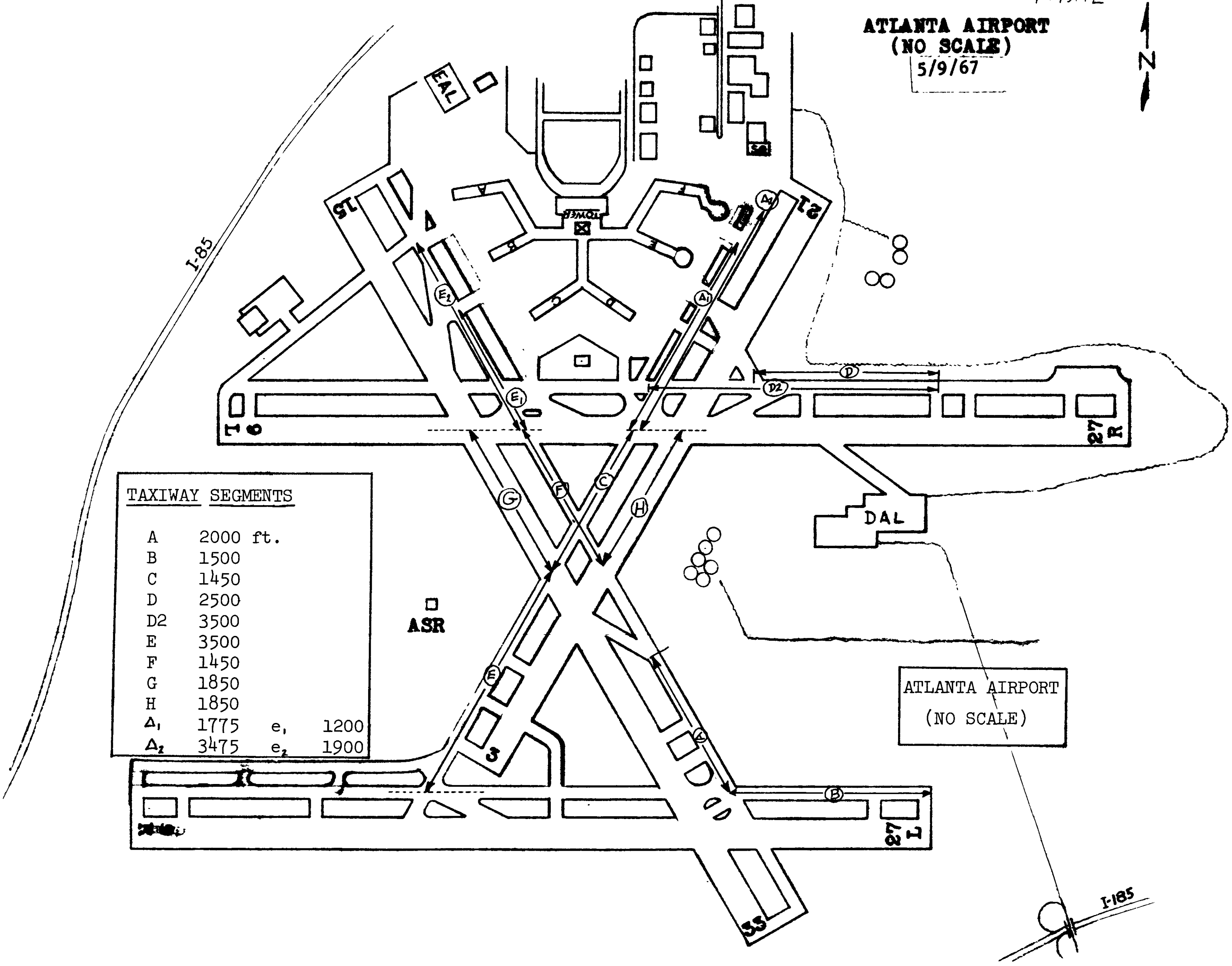
EXISTING AIRPORT LAYOUT PLAN

ATLANTA

FINAL

1.

ATLANTA AIRPORT
(NO SCALE)
5/9/67



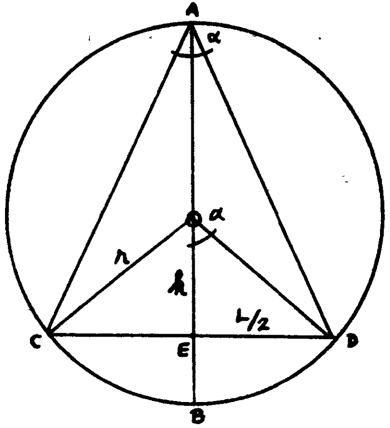
TAXIWAY SEGMENTS

A	2000 ft.		
B	1500		
C	1450		
D	2500		
D2	3500		
E	3500		
F	1450		
G	1850		
H	1850		
Δ_1	1775	e_1	1200
Δ_2	3475	e_2	1900

Appendix B - Conversion from Bearing to Distance

Since we had the bearings of opposite ends of each runway from the control tower, we knew the visual angle subtended by that runway from our position. The locus of points at which a given straight line subtends a given angle is an arc of a circle with the straight line as a chord. The approach, then, was to compute this circle for different runways and find their points of intersection, one of which would be the location of the tower on the field.

i. Characteristics of the Circle



line CD subtends angle α at A $(\alpha < 90^\circ)$

length CD = L

AO = OD = r

$\measuredangle OAD = \measuredangle ADO = \alpha/2$

$\measuredangle AOD = 180^\circ - \alpha$

$\measuredangle DOE = \alpha$

$$\sin\alpha = \frac{ED}{OD} = \frac{L/2}{r}$$

$$r = \frac{L/2}{\sin\alpha} = \frac{L}{2\sin\alpha} \tag{B.1}$$

$$\cos\alpha = OE/OD$$

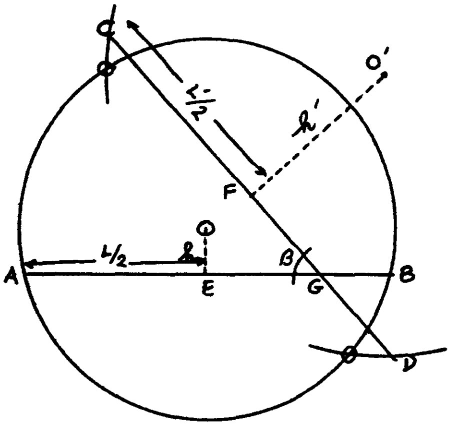
$$OE = OD\cos\alpha = r\cos\alpha$$

$$h = \frac{L}{2}\,\frac{\cos\alpha}{\sin\alpha} \tag{B.2}$$

For $\alpha > 90^\circ$, the results are the same, only now the chord and the point are on the same side of the circle; i.e., the angle is subtended at point B.

ii. Location of the Tower

Now, having been able to calculate the radius and centers of the two intersecting circles, we can derive their equations and compute their intersections.



coordinate system is chosen so that

O is (0,0), line AB is horizontal

E is (0,-h)

A is (-L/2,-h)

B is (L/2,-h)

and the equation of the first circle is

$$x^2 + y^2 = r_1^2 \qquad \text{(B.3)}$$

The coordinates of G are measured to be (g,-h). Angle CGA is β, also known, as are lengths CG and GD.

$$F = (g - FG\cos\beta, -h + FG\sin\beta) = (f_x, f_y)$$

where FG = CG - L'/2

$O' = (f_x + h'\sin\beta, f_y + h'\cos\beta) = (x_2, y_2)$, and the circle is

$$(x - x_2)^2 + (y - y_2)^2 = r_2^2 \qquad \text{(B.4)}$$

We thus have equations for the two circles which can be solved simultaneously to find their points of intersection. The result is

$$y' = \frac{AB \pm \sqrt{Cr_1^2 - A^2}}{C} \qquad \text{(B.5)}$$

$$x' = \sqrt{r_1^2 - y'} \qquad \text{(B.6)}$$

where r_1 is the radius of the first circle with center at (0,0)

$$A = \frac{r_1^2 + x_2^2 + y_2^2 - r_2^2}{2x_2}$$

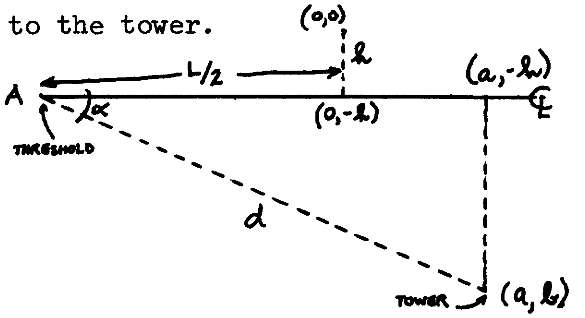
$B = y_2/x_2$

$C = 1 + B^2$

Two solutions are obtained by this method, the correct one being chosen by comparison with an airport map.

iii. Threshold Angle and Distance

Once the coordinates of the tower had been obtained, it was quite simple to compute the distances from the tower to the runway thresholds, and the angles formed by the runway centerlines and the lines of sight to the tower.



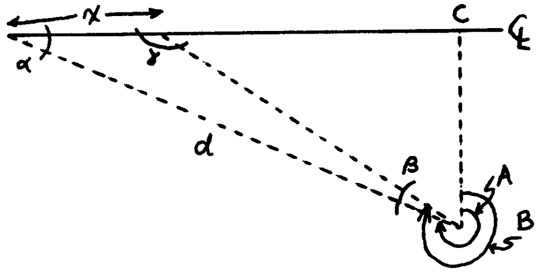
$$d = \sqrt{(b - h)^2 + (L/2 + a)^2} \qquad (B.7)$$

$$\alpha = \sin^{-1}\left(\frac{b - h}{L/2 + a}\right) \qquad (B.8)$$

Now all the parameters which are necessary to convert bearings into distances along the runway have been found.

iv. Conversion formulae

a. Runways 15R, 15L, 22R, 22L, 27, 33R, 27R



A = threshold bearing

B = observed bearing

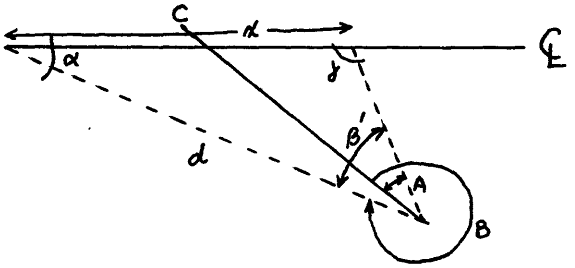
C is arbitrary zero point

$\beta = B - A$

by the law of sines $\dfrac{x}{\sin\beta} = \dfrac{d}{\sin\gamma}$

$$x = \frac{d \sin \beta}{\sin[180^\circ - (\beta + \alpha)]} = \frac{d \sin \beta}{\sin(\beta + \alpha)} \qquad (B.9)$$

b. Runways 4R, 4L, 9, 33L, 27L



$$\beta' = (360^\circ - B) + A$$

$$\frac{x}{\sin \beta'} = \frac{d}{\sin \gamma}$$

$$x = \frac{d \sin[360^\circ - (B - A)]}{\sin(\beta' + \alpha)} = \frac{d\,[\sin(B - A)]}{\sin(\beta' + \alpha)}$$

$$x = \frac{d \sin \beta}{\sin(\beta' + \alpha)} = \frac{d \sin \beta}{\sin(\beta - \alpha)} \qquad (B.10)$$

Appendix C - Intermediate Points Used for Speed Measurements

RUNWAY		INTERMEDIATE POINT			
		1	2	3	4
4R	intersecting	9	F	33R	N
22R		cross-taxiway	15L	15R	F
27		C	E	S	
33L		27	D	F	north
27R		7	9	16	A
27L		18	5	D	19

APPENDIX D

Sample Data Sheets

MIT RUNWAY AND TAXIWAY TRAFFIC SURVEY

Date: ______________ Time: ____________ Page _____ of _____

	airline	type	flight	runway	bearing	weather
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						

A2

MIT RUNWAY AND TAXIWAY TRAFFIC SURVEY

Date: ______________ Time: __________ Page _____ of _____

	airline	type	threshold	touchdown	exit	name
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						

MIT RUNWAY AND TAXIWAY TRAFFIC SURVEY

Date: ______________ Time: ____________ Page _____ of _____

[illegible]	airline	type	flight	runway	queue	bearing	weather
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							

MIT RUNWAY AND TAXIWAY TRAFFIC SURVEY

Date: ______________ Time: __________ Page ____ of ____

	airline	type	stop line roll	stop line wait	r/w clr	cntrline	t/o clr	start roll
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								

T2

MIT RUNWAY AND TAXIWAY TRAFFIC SURVEY

Date: ____________ Time: __________ Page ____ of ____

	airline	type	intersection	stop	pass	clrance	start	clear
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								

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