https://ntrs.nasa.gov/search.jsp?R=19790019014 2020-03-21T22:44:02+00:00Z

NASA CR-159,075

3 1176 00136 9967

NASA Contractor Report 159075

NASA-CR-159075
1979 0019014

Aircraft and Avionics Related Research Required to Develop an Effective High-Speed Runway Exit System

M. L. Schoen, J. E. Hosford, J. M. Graham, Jr.,
O. W. Preston, R. S. Frankel, J. B. Erickson

DOUGLAS AIRCRAFT COMPANY
LONG BEACH, CALIFORNIA

CONTRACT NAS1-15545
JUNE 1979

LIBRARY COPY

AUG 2 1979

LANGLEY RESEARCH CENTER
LIBRARY, NASA
HAMPTON, VIRGINIA

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665
AC 804 827-3966

NASA Contractor Report 159075

Aircraft and Avionics Related Research Required to Develop an Effective High-Speed Runway Exit System

M. L. Schoen, J. E. Hosford, J. M. Graham, Jr.,
O. W. Preston, R. S. Frankel, J. B. Erickson

DOUGLAS AIRCRAFT COMPANY
LONG BEACH, CALIFORNIA

CONTRACT NAS1-15545
JUNE 1979

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665
AC 804 827-3966

N79-27185 #

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ATL	Atlanta Hartsfield Airport
BOS	Boston Logan Airport
DABS	Discrete Address Beacon System
DCA	Washington National Airport
DEN	Denver Stapleton Airport
DFW	Dallas-Fort Worth Airport
DME	Distance Measuring Equipment
H	Heavy, (MTOGW over 136,000 Kilograms)
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
JFK	New York City Kennedy Airport
L	Large, (MTOGW between 5,670 and 136,000 Kilograms)
LAX	Los Angeles International Airport
LGA	New York City LaGuardia Airport
Lw	Length of Wheelbase
M & S	Metering and Spacing
MLS	Microwave Landing System
MTOGW	Maximum Takeoff Gross Weight
N.Mi.	Nautical Miles
ORD	Chicago O'Hara Airport
PC	Point of Curvature
PVC	Poor Visibility Conditions
S	Small, (MTOGW less than 5,670 Kilograms)
SFO	San Francisco International Airport
VAS	Vortex Alert System
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
WVAS	Wake Vortex Avoidance System

SUMMARY

Landing and takeoff delays are currently a very serious problem at major U.S. air carrier airports and almost all forecasters agree that they will get worse during the remainder of the century. These delays significantly increase airline operating costs, waste large quantities of fuel, degrade the level-of-service to travellers, and inhibit the airlines in planning the national air transportation system. The federal government is conducting or sponsoring several research programs to increase airport capacity by reducing the longitudinal separation between aircraft sequenced on final approach. The full benefit of these programs will not be realized unless runway occupancy times are reduced.

An effective high-speed runway exit system includes many components which must be analyzed with respect to other components. NASA Langley realized that a requirements analysis of high-speed runway exit systems was necessary before specific detailed research starts on these components. Therefore, the following is the statement of work for this Phase I research on Contract No. NAS1-15545, "Conduct Aircraft and Avionics Research Required to Develop an Effective High-Speed Runway Exit System."

> The Contractor shall perform the aircraft and avionics related research required to develop an effective high-speed runway exit system. This research involves a study of the multidisciplinary factors which influence the utility of high-speed exits for efficient runway operations and will specifically incorporate the following tasks:
>
> A. Review previous research on the use of high-speed exits and determine rationale for improving utilization of existing high-speed exits.
>
> B. Coordinate this review with the appropriate FAA, airline pilot, and airport operator organizations to assure complete identification of the pertinent issues involved in the effective use of high-speed exits.
>
> C. Perform a sensitivity analysis of factors which impact the design and usability of a high-speed exit system. The following are some of the present and future requirements to be examined:
>
> 1. Runway Occupancy Time
> 2. Touchdown Dispersion
> 3. Aircraft Performance
> 4. Pilot Information
> 5. Passenger Acceptance
> 6. Airport-Operations-Area Design
> 7. All-Weather Operation
> 8. Arrival/Departure Strategy
> 9. ATC Procedures
>
> D. Develop an analytical model to describe the optimum high-speed runway exit design and location(s) as a function of allowable runway occupancy time. Determine the importance and allowable range of each factor included in this analytical model.

E. Use of the analytical model developed in D. above to design candidate high-speed exit systems that could improve present runway utilization efficiency.

F. Review previous research leading to current state-of-the-art automatic landing systems and define MLS related landing flare/control law improvements that could potentially improve runway utilization efficiency. Identify the cockpit information required by the pilot to monitor adequately these automatic landing systems.

The following summarizes the highlights of this Phase I study.

1 Current runway occupancy times will not be acceptable for airports operating with reduced longitudinal separations.

2 Current field data on runway occupancy times is not representative of operations with reduced longitudinal separations because there is currently very little motivation for the pilot to minimize runway occupancy times.

3 The primary emphasis for a high-speed runway exit system is to minimize the frequency of runway occupancy times over approximately 50 seconds.

4 Multiple exits per runway are essential.

5 The variance in touchdown location can be significantly reduced; this would impact the percentage of the aircraft using an exit and the runway occupancy time.

6 The standard high-speed (angled) exit in the U.S. is at 30 degrees. It is anticipated that significant benefits can be obtained with a lower angle exit, or a spiral exit design, or a drift-off runway.

7 Improved pilot information is required. The most important additional data are runway and taxiway clearances plus runway traction conditions.

8 There is a wide diversity of opinion about the importance of passenger ride conditions. Passenger acceptance will probably become a major factor if lateral forces and jerk significantly increase over current levels.

9 It is possible that other airport capacity constraints will prevent increased operations even if the airport has advanced air traffic control systems and an effective high-speed runway exit system. There may also be a serious problem redesigning the runway exit system at the high demand airports.

10 Many of the candidate changes to the high-speed runway exit system impact the air traffic controllers. It is necessary to jointly analyze any changes to the runway exit systems, pilot information systems, and air traffic control systems.

INTRODUCTION

Airport delays currently increase airline direct operating costs by more than $500 million per year. Increased growth of air travel can significantly increase these costs because delays increase rapidly as the demand approaches capacity. Airport capacity is a scarce resource at most of the large U.S. metropolitan areas. It is unlikely that any new U.S. major air carrier airports will be opened during the 1980's, and it is quite possible that there will not be any major U.S. air carrier airports opened this century. There has also been a drastic reduction in major airport improvement programs. The U.S. air transportation system will have to learn to operate with today's airport system, and great emphasis is being placed on maximizing the capacity of existing airports.

The federal government is sponsoring research on many programs designed to increase the capacity of existing airports. These research programs basically increase airport capacity by reducing longitudinal separation between aircraft sequenced on approach. However, the full capacity improvement of these research programs cannot be realized unless there is a reduction in runway occupancy time.

This research is being performed to define the high-speed runway exit system requirements which are economically and operationally feasible and do not constrain the capacity of airports operating at reduced longitudinal separations on final approach.

Airport Delay Status and Forecasts

Delays at U.S. airports currently increase aircraft direct operating costs by over $500 million per year and waste approximately 4 percent of the fuel used by the air carriers. Airport delays have been increasing at a considerably higher rate than other elements of the air transportation system. Eastern Air Lines has been reporting detailed airport delay data to the FAA longer than other airlines. Figure 1 illustrates that Eastern's delay costs in 1977 were 8.45 times as large as in 1967; during the same time period Eastern's revenues increased by a factor of 3.01.

The FAA publication "Terminal Area Forecasts, Fiscal Year 1979-1990" (Reference 1) forecasts that 26 U.S. airports will become saturated before 1990, and another 34 airports will be over 90 percent of their saturation capacity. Saturation occurs when the forecast of total operations reaches twice Practical Annual Capacity (PANCAP). Of the 60 airports reaching at least 90 percent of saturation, 32 are air carrier airports and 28 are general aviation airports. Many of the saturated air carrier airports have a high percentage of general aviation operations and would not be saturated if a suitable general aviation reliever airport was available.

As air carrier airports become saturated, most general aviation flights are diverted to other airports due to increased minimum landing fees or other inducements to leave. Eventually, the air carrier demand grows to the point where it alone causes the airport to become congested. These are the airports which will receive the equipment to reduce longitudinal separation and are the airports of interest for this study. Table 1 presents preliminary data on the

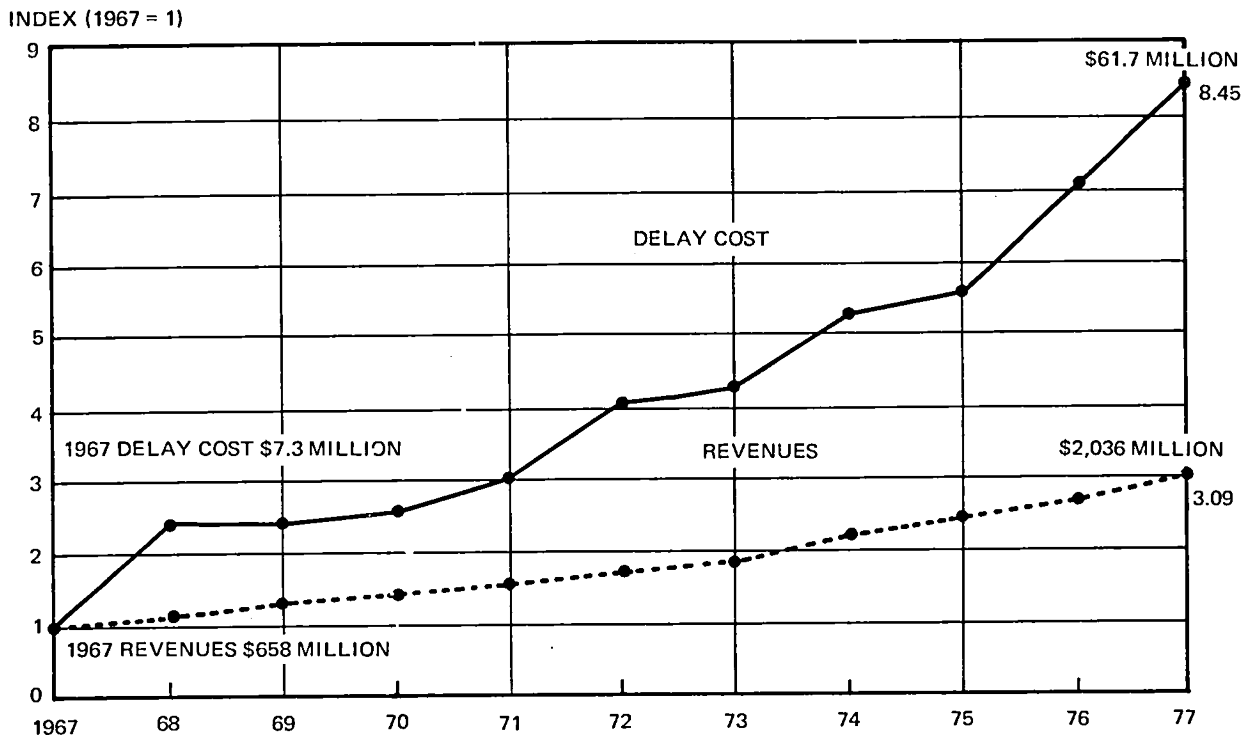


FIGURE 1. DELAY COST VERSUS REVENUES
EASTERN AIRLINES
(CURRENT DOLLARS)

TABLE 1
1977 DELAYS AT MAJOR AIR CARRIER AIRPORTS

AIRPORT		DAILY SCHEDULED ARRIVALS AUGUST 1977	AVERAGE DELAY PER OPERATION (MINUTES)		TOTAL ANNUAL AIRCRAFT DELAY* (HOURS IN THOUSANDS)
CITY	OAG CODE		ARRIVALS	DEPARTURES	
CHICAGO	ORD	967	11.31	7.29	102
ATLANTA	ATL	637	12.85	8.64	78
DALLAS – FT WORTH	DFW	628	4.42	4.50	32
LOS ANGELES	LAX	594	4.49	5.64	34
DENVER	DEN	436	8.34	5.67	35
NEW YORK CITY	LGA	416	8.68	7.72	39
BOSTON	BOS	410	9.10	5.88	35
NEW YORK CITY	JFK	410	11.16	8.81	46
SAN FRANCISCO	SFO	403	4.35	5.54	23
WASHINGTON, D.C.	DCA	346	7.93	5.70	27
PITTSBURGH	PIT	343	7.35	4.18	22
PHILADELPHIA	PHL	328	7.63	5.55	25
MIAMI	MIA	323	5.08	4.92	18
ST. LOUIS	STL	292	6.76	5.37	20
DETROIT	DTW	248	5.18	4.15	13
SEATTLE	SEA	226	4.13	3.13	9
NEWARK	EWR	226	9.50	5.20	19

*ANNUAL DELAY ASSUMES: ANNUAL ARRIVALS = 340 DAILY (AUGUST) ARRIVALS
SOURCE — PRELIMINARY FAA DATA

observed average delay at the largest 17 U.S. air carrier airports. "These 17 airports have 48 percent of the enplanements and 38 percent of the departures by U.S. scheduled interstate air carriers (Reference 2)." These 17 air carrier airports can best justify the advanced air traffic control systems to reduce longitudinal separation and therefore, they require reduced landing runway occupancy times. This study is concerned with only high delay airports, not the over 12,000 airports in the United States. Table 1 illustrates that the airport delays decrease rapidly as demand decreases.

There are eight airports which are being analyzed in detail to determine how to reduce delays. These delay analyses are being performed by specialists from the FAA (headquarters staff, regional office, and controllers), the airport authority, the airlines, and consultants. These eight airports are:

- Chicago O'Hare (ORD)
- Atlanta Hartsfield (ATL)
- Los Angeles (LAX)
- Denver Stapleton (DEN)
- New York City La Guardia (LGA)
- New York City Kennedy (JFK)
- San Francisco (SFO)
- Miami (MIA)

There are currently federally imposed restrictions on the allowable number of operations per hour the air carriers can schedule at:

- Chicago O'Hare (ORD)
- New York City Kennedy (JFK)
- New York City La Guardia (LGA)
- Washington National (DCA)

Airport Expansion Constraints

The Airport and Airways Development Act of 1970 included Airport and Airways Development Grants (usually called Airport Development Aid Program (ADAP)) for airport expansion. The ADAP was established because: "The Congress hereby finds and declares..... That the nation's airport and airway system is inadequate to meet the current and projected growth in aviation. That substantial expansion and improvement of the airport and airway system is required to meet the demands of interstate commerce, the postal service, and the national defense...." However, only a small percent of ADAP funds have gone for substantial expansion and improvement of the nation's inadequate airport and airways system. For the large hub airports, ADAP has helped finance the following projects:

- A new airport at Dallas - Ft. Worth (but it was well under construction prior to ADAP).

- Runway 9R-27L at Atlanta which significantly reduced congestion at this high delay airport.

- Runway 17L-35R at Denver which allowed more departures to the north (which is the least noise sensitive direction) and increased airport capacity as the number of wide-bodied aircraft operations increase.

- Runway 8R-26L at Honolulu which allowed departures to be farther from shore when they fly by the city.

- Runway 3R-21L at Detroit which significantly increased capacity at this airport which does not experience severe congestion.

The majority of the ADAP funds at large hub airports has been spent on noise abatement and renovating existing runways and taxiways. This renovation is necessary, but does not provide substantial expansion of the nation's inadequate airport and airways system.

Considerably more ADAP funds have gone to reduce noise impact than to reduce airport delays. Some new runways (e.g., the reef runway at Honolulu International) were designed primarily for noise relief rather than delay reduction. It is very difficult to get environmental approval to build a new runway or significantly expand an existing runway. Los Angeles International (LAX) recently obtained approval to strengthen the Sepulveda tunnel under the south runways. LAX originally tried to get this project approved in 1969.

There are financial constraints on airport expansion projects as well as environmental constraints. The cost of constructing a runway or taxiway was approximately $50 per square meter in 1976 (Reference 3). The annual inflation rate for the construction cost index has averaged approximately eight percent per year during this decade. ADAP funds can currently pay up to 75 percent of the construction cost for runways, high speed exits, and taxiways at the large airports. However, the airport's share of construction funds are so limited that airport operators are very disturbed that they have constructed several angled exits which are not used as extensively as predicted.

Research to Reduce Longitudinal Separation

The federal government is performing or sponsoring several research projects to increase airport capacity by reducing the longitudinal separation of aircraft on final approach. ATC hardware and software changes being studied to reduce longitudinal separations include:

- Metering and Spacing (M&S) to increase the accuracy of aircraft delivery for final approach spacing. The advanced terminal M&S systems include integration with DABS and data link.

- Cockpit display of traffic information to provide the pilot with the information required to assume more responsibility for maintaining adequate separation or to assure the pilot that the separations provided by the ground station are safe.

- Wake vortex reduction with Vortex Advisory System (VAS) and Wake Vortex Avoidance System (WVAS).

The wake vortex separation for approaching aircraft must be reduced before there is an urgent need to reduce runway occupancy times. Reduced runway occupancy time will be needed primarily at the high-delay airports which will have the ATC systems to reduce separations. These airports are the high-volume airports and many of them currently have a high percent of their operations by aircraft which require a wake vortex separation between them and the following aircraft. Several of these airports have reached the limit of allowable operations; these airports cannot serve more passengers unless they replace small airplanes with larger airplanes.

The ATC systems for reduced in-trail separations will probably not be operational until the late 1930's or early 1990's. By that date, the airports with these advanced ATC systems will have a high percent of their operations by heavy aircraft which must be followed at a greater distance due to their wake vortex. The longitudinal separation cannot be significantly reduced unless the wake vortex separation can be reduced. The current and undoubtedly the future U. S. longitudinal separation minimum standards are dependent upon the aircraft's maximum certified takeoff gross weight (MTOGW). The following three aircraft classes are used to insure an adequate separation is allowed for wake vortices:

H or Heavy: MTOGW over 136,000 kilograms (300,000 pounds)
L or Large: MTOGW between 5,670 kilograms (12,500 pounds) and 136,000 kilograms (300,000 pounds)
S or Small: MTOGW under 5,670 kilograms (12,500 pounds)

The current minimum longitudinal separations during instrument meteorological conditions (IMC) are:

CURRENT IMC SEPARATIONS (N MI)
(Reference 4)

		Trail		
		S	L	H
Lead	S	3	3	3
	L	4	3	3
	H	6	5	4

Several studies have forecasted future longitudinal separations once the advanced ATC systems are operational (References 4, 5, 6 and 7). The far term goal for IMC separation standards when the meteorological conditions will dissipate wake vortices are:

FUTURE IMC SEPARATION GOALS (N MI)
WAKE VORTICES DISSIPATE
(Reference 4)

		Trail		
		S	L	H
Lead	S	2.0	2.0	2.0
	L	2.5	2.0	2.0
	H	3.7	3.0	2.3

Similarly, the far term goal for IMC separations standards when the meteorological conditions do not dissipate wake vortices are:

FUTURE IMC SEPARATION GOALS (N MI)
WAKE VORTICES PERSIST
(Reference 4)

		Trail		
		S	L	H
Lead	S	3	3	3
	L	3.5	3	3
	H	5	4	3

The Vortex Advisory System (VAS) contains an algorithm to determine when vortices persist. This algorithm currently assumes the wake vortices will persist if the wind velocity and direction is within a 14-by-7 knot ellipse with the 14 knot axis parallel to the runway. Except for thunderstorms, the top U.S. airports generally have low winds during IMC when the visibility is less than 1.6 kilometers (1 mile). It will be necessary to use the increased longitudinal separations in poor visibility conditions.

The future separations during visual meteorological conditions (VMC) are based upon currently observed separations and the improvements believed possible with the advanced ATC systems (References 4, 5, 6 and 7). The current observed VMC separations are:

CURRENT OBSERVED VMC SEPARATIONS (N MI)
(Reference 4)

		Trail		
		S	L	H
Lead	S	1.9	1.9	1.9
	L	2.7	1.9	1.9
	H	4.5	3.6	2.7

FUTURE VMC SEPARATION GOALS (N MI)
WAKE VORTICES DISSIPATE
(Reference 4)

		Trail		
		S	L	H
Lead	S	1.9	1.9	1.9
	L	2.1	1.9	1.9
	H	3.4	2.7	2.1

FUTURE VMC SEPARATION GOALS (N MI)
WAKE VORTICES PERSIST
(Reference 4)

		Trail		
		S	L	H
Lead	S	1.9	1.9	1.9
	L	2.7	1.9	1.9
	H	4.5	3.6	2.7

The runway capacity increase from these advanced ATC systems depends upon the runway use configuration and the percent of heavy aircraft in the mix. An intersecting runway use configuration (e.g., ORD, LGA, DCA) must often space successive arrivals to allow a departure between arrivals. If the runways intersect far from the thresholds, it is impossible to significantly reduce the current longitudinal separation for the arrival stream (except behind heavy aircraft) and still allow time for a departure. Similarly the advanced ATC systems emphasize the reduction of the wake vortex separation distance behind heavy aircraft and obviously will benefit airports with a high percent of aircraft (i.e., LAX, JFK, SFO) more than airports with a very limited number of heavy aircraft (i.e., LGA, DCA). (Table 14 defines the current aircraft mix at the 20 largest U.S. airports).

The computerized runway capacity computation technique defined in Chapter 3 of reference 8 can compute capacity for future ATC systems as well as current systems. Figure 2 summarizes the runway capacity increase for advanced systems based upon this computerized runway capacity model.

HOURLY CAPACITY BASED ON FAA-RD-74-124, "TECHNIQUE FOR DETERMINING AIRPORT AIRSIDE CAPACITY AND DELAY," JUNE 1976

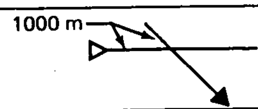
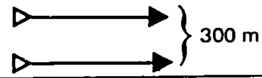
	RUNWAY USE CONFIGURATION							
AIR TRAFFIC CONTROL SYSTEM								
WEATHER	VMC		IMC		VMC		IMC	
AIRCRAFT MIX	LGA	JFK	LGA	JFK	LGA	JFK	LGA	JFK
PRESENT WITH ARTS III	72.0	63.8	60.2	55.3	108.7	78.6	60.2	55.3
F1 • METEOROLOGICAL ADVISORY SYSTEM	72.0	64.8	60.7	59.4	109.6	83.8	60.7	59.4
F2 • WAKE VORTEX PREDICTIVE SYSTEM • BASIC METERING AND SPACING	75.5	68.0	61.9	59.9	107.0	80.7	61.9	59.9
G3 • F_2 PLUS DABS AND MLS	75.8	70.9	64.4	64.2	109.7	101.6	68.0	73.3
H4 • WAKE VORTEX ADV M&S, DABS, MLS, HSE, REDUCED MISSED APPROACH	82.0	77.9	76.1	74.6	112.1	101.8	80.2	87.3

FIGURE 2. CAPACITY IMPROVEMENT FROM ADVANCED ATC SYSTEMS

CURRENT HIGH-SPEED EXIT USAGE

The current longitudinal separations do not levy a requirement on the pilots to minimize runway occupancy times. Therefore, it is currently impossible to obtain field data representative of operations with reduced longitudinal separations.

Importance of Runway Occupancy Time

The Air Traffic Control Handbook (Reference 9) states:

> "1120. SAME RUNWAY SEPARATION
>
> Separate an arriving aircraft from another aircraft using the same runway by ensuring that the arriving aircraft does not cross the landing threshold until one of the following conditions exists or unless authorized in 1102:
>
> a. The other aircraft has landed and taxied off the runway.
> b. The other aircraft has departed and crossed the runway end."

There are exceptions to the above rules for general aviation aircraft. This one-on-the-runway rule is the critical reason for reducing runway occupancy time. The reduced longitudinal separation directly relates to a reduced time between aircraft arriving over the threshold which correspondingly reduces available runway occupancy time.

The following is regulation 1122 from the Air Traffic Control Handbook (Reference 9):

> "1122. ANTICIPATING SEPARATION
>
> Landing clearance to a succeeding aircraft in a landing sequence need not be withheld if you observe the position of the aircraft and determine that prescribed runway separation will exist when the aircraft crosses the landing threshold. Issue traffic information to the succeeding aircraft."

ATC regulation 1122 allows the controller considerable flexibility in determining how rigidly to enforce the one-on-the-runway regulation. The flexibility of this regulation makes it impossible to state that a landing aircraft must clear the runway before the next aircraft is a specific distance from the threshold.

If the landing aircraft does not clear the runway as quickly as anticipated, one or more of the following will occur:

1 All, or a considerable part, of the controller implemented buffer time will be used and the controller may increase this buffer time for future arrivals.

2 The succeeding aircraft will be given a go-around in order to prevent a violation of the one-on-a-runway regulation.

3 The succeeding aircraft will land before the previous aircraft has taxied off the runway. A violation of regulation 1120 could cause an accident.

There is very limited data on the frequency of go-arounds due to excessive runway occupancy time or on the frequency of violation of the one-on-the-runway regulation. Los Angeles International Airport (LAX) averages approximately one go-around and 800 landings per day. Less than 40 percent of the go-arounds are traffic related. Hence, there is approximately one traffic related go-around for every 2000 landings, and excessive landing runway occupancy time is only one traffic related problem. There would be resistance to reduced longitudinal separations from pilots, controllers and airlines if the go-around frequency was significantly increased.

Observed Runway Occupancy Time

There are three known sources of runway occupancy time data:

1 Howard, Needles, Tammen and Bergendoff (HNTB) collected data in 1974 under contract to the FAA (References 10 and 11). These data were taken by setting up 15 to 20 infrared light beams across a runway with some of the light beams perpendicular to the runway, some at an angle, and some across an exit. Data were collected at:

  Atlanta William B. Hartsfield (ATL) runway 9R/27L
  Chicago O'Hare (ORD) runway 9R
  Denver Stapleton (DEN) runway 26L

  The primary objective of this data collection was to measure lateral landing dispersion. However, it is one of the best data sources for longitudinal touchdown dispersion, deceleration rates, and runway occupancy times.

2 Douglas Aircraft Company and Peat, Marwick, Mitchell & Co., (DAC/PMM) collected data at 18 airports during 1972 and 1973 to develop new techniques to estimate airport capacity (Reference 8). These data were analyzed by the DAC/PMM study team and by MITRE (Reference 12). These data were taken by an observer in the control tower who measured runway occupancy time with a stop watch.

3 The Dallas-Ft. Worth airport sponsored data collection on runway occupancy times and exit usage at their airport (Reference 13). This reference defines runway occupancy from touchdown to exiting the runway.

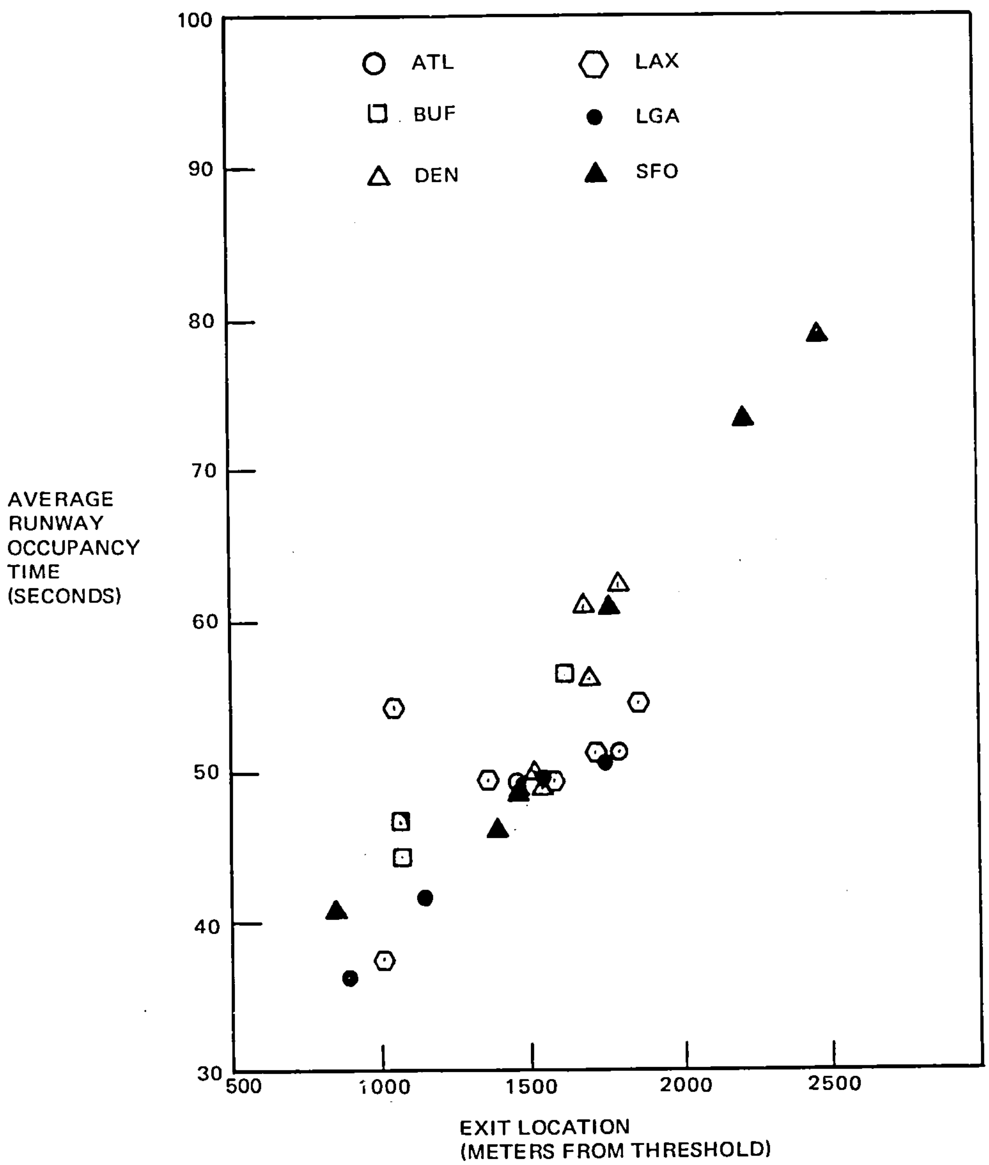
The observed runway occupancy times from these three data sets are expressed in terms of the average and standard distribution of observed runway occupancy times. The normal distribution may be a good fit to the entire data set, but it is probably not mathematically valid to use 50 to 300 data points to estimate the maximum allowable runway occupancy time that will not cause a go-around or violation of the one-on-the-runway regulation. Assuming a normal distribution, the runway occupancy time that will not be exceeded more than once in 2000 landings (the assumed allowable go-around frequency) is the average runway occupancy time plus 3.291 times the standard deviation of runway occupancy time. Hence, it is more important to reduce the standard deviation than the average runway occupancy time. There is also a problem estimating the true standard deviation of runway occupancy time if the data includes landings that remained on the runway a long time because they wanted to go to a building other than the main terminal.

The analyses of the runway occupancy times have been performed by airport, runway, exit, and aircraft type. Table 2 summarizes the results of these data analyses from References 8, 10, 11, and 13. Figure 3 illustrates how runway occupancy times increase for exits which are farther from the runway threshold.

TABLE 2
OBSERVED RUNWAY OCCUPANCY TIMES

AIRPORT	DATA SOURCE	RUNWAY NUMBER	AIRCRAFT CLASS*	EXIT LOCATION (METERS)	R/W OCCUPANCY TIME (SECONDS)		NUMBER OBSERVATIONS
					AVERAGE	STANDARD DEVIATION	
ATL	HNTB	9R	DC-9-30	1400	31.5	1.9	29
			DC-9-30	1980	47.9	4.6	33
			B727-200	1980	42.3	4.4	29
		27L	B737	1580	39.1	3.8	19
			DC-9-10	1580	37.1	3.2	34
			DC-9-30	1580	37.6	3.6	139
			B727-100	1580	37.8	3.9	67
			B727-200	1580	33.0	2.9	30
			DC-9-30	2070	50.8	4.1	39
			3727-200	2070	47.4	5.0	30
			DC-8-60	2070	45.5	3.2	16
	FAA	27R	LG	ALL	51.4	7.5	97
			M-LG	ALL	49.5	—	—
BUF	FAA	5	LG	ALL	50.7	13.8	33
			M-LG	ALL	47.1	—	—
		23	LG	ALL	55.5	8.7	124
			M-LG	ALL	52.3	—	—
DEN	HNTB	26L	B737	1340	40.2	3.2	30
			B727-100	1340	37.8	3.4	38
			B727-200	1340	36.9	3.0	18
	FAA	26R	LG	ALL	51.5	8.4	314
			HV	ALL	55.1	9.4	100
			M-LG	ALL	48.4	—	—
			M-HV	ALL	55.1	—	—
DFW	DFW	17R	ALL	ALL	33	—	36
		17L	ALL	ALL	34	—	57
		35R	ALL	ALL	42	—	50
		35L	ALL	ALL	40	—	40
		ALL	ALL	HSE1	32	—	74
		ALL	ALL	HSE2	41	—	88
LAX	FAA	25L	LG	ALL	48.2	10.4	98
			M-LG	ALL	44.9	—	—
			HV	ALL	50.9	9.6	150
			M-HV	ALL	49.6	—	—
		25R	LG	ALL	52.6	14.1	138
			M-LG	ALL	50.5	—	—
			HV	ALL	60.2	16.8	50
			M-HV	ALL	49.6	—	—
LGA	FAA	31	LG	ALL	40.7	8.5	103
			M-LG	ALL	40.7	—	—
		22	LG	ALL	43.3	9.5	315
			M-LG	ALL	43.3	—	—
ORD	HNTB	9R	B727-100	1360	28.4	2.2	17
SFO	FAA	28R	LG	ALL	47.4	9.2	93
			M-LG	ALL	46.3	—	—
			HV	ALL	57.5	16.5	61
			M-HV	ALL	56	—	—
		28L	LG	ALL	49.3	8.1	138
			M-LG	ALL	49.1	—	—
			HV	ALL	55.0	13.4	130
			M-HV	ALL	53.4	—	—

*AIRCRAFT CLASS: LG IS JET AIRCRAFT WITH MAXIMUM WEIGHT UNDER 300,000 POUNDS.
HV IS JET AIRCRAFT WITH MAXIMUM WEIGHT OVER 300,000 POUNDS.
M DENOTES AIRLINES MOTIVATED TO REDUCE RUNWAY OCCUPANCY TIME.



SOURCE: FAA-EM-78-9 "ANALYSIS OF RUNWAY OCCUPANCY TIMES AT MAJOR AIRPORTS," MAY 1978

FIGURE IMPACT OF EXIT LOCATION UPON RUNWAY OCCUPANCY TIME

FIGURE 3

FACTORS IMPACTING RUNWAY OCCUPANCY TIMES

The observed runway occupancy time data are for conditions that existed in the early 1970's. These runway occupancy times will not be acceptable for the longitudinal separations that will exist in the 1990's. It will be necessary to improve one or more of the following elements of a runway exit system: runways, exits, and taxiways, pilot information, aircraft design and operations, plus air traffic control regulations and procedures.

It is necessary to thoroughly understand the present runway exit system before recommending changes to reduce runway occupancy times. The following discussion of the factors impacting runway occupancy times includes a description of their current status, importance, and feasibility for modification.

Touchdown Dispersion

The aircraft condition at touchdown obviously will have important effects upon the ability to utilize high-speed runway exits effectively. Important parameters are expected to be the longitudinal position and speed, which will affect the capability to slow down to the required exit speed, and the lateral deviation and lateral velocity, which will affect the capability to steer correctly and with stability to the exit position.

Unfortunately, these touchdown parameters are seldom measured for manual VMC landings which even today are far more common than automatic landings. Measurement of the desired parameters requires specialized equipment and personnel, and consequently is seldom done even for automatic landings. Many measurements of automatic landing performance are available both for in-test and service operations for parameters which are easily obtained by airborne instrumentation, such as airspeed and vertical velocity. Longitudinal and lateral position measurements, however, must be obtained from specialized sensors (commonly tracking photo-theodolites or tracking radars) which are seldom provided. For manual VFR landings, even the normal on-board instrument data are recorded only occasionally.

For this study, a survey of all available landing condition data was undertaken. The objective was to understand the typical behavior at touchdown for in-service manual VMC landings and automatic landings. Some data were obtained,which is summarized in the following paragraphs.

Manual VMC Landing Dispersion

The most extensive measurements of landing performance in the manual VMC mode were made and reported during 1961 and 1962 when turbojet transports were still in an early stage of airline usage and at a time when many operational characteristics were still poorly understood. Stickle of NASA-Langley reported in Reference 14 measurements obtained by tracking photo-theodolites at Los Angeles International Airport for two turbojets and one turboprop aircraft. The data are summarized in Table 3 which has been taken from Reference 14. Longitudinal position, airspeed, and airspeed/stall speed ratio are available for 395 landings. The mean touchdown position was about 375 meters (1230 feet) beyond the threshold and the standard deviation was about 164 meters (539 feet).

TABLE 3

NASA TECHNICAL NOTE D899 – MAY 1961

AN INVESTIGATION OF LANDING CONTACT CONDITIONS FOR TWO LARGE TURBOJET TRANSPORTS AND TURBOPROP TRANSPORT. DURING ROUTINE DAYLIGHT OPERATIONS: JOSEPH W. SHICKLE

STATISTICAL PARAMETER	TURBOJET A	TURBOJET B	TURBOPROP TRANSPORT
VERTICAL VELOCITY:			
MAXIMUM VERTICAL VELOCITY (FEET PER SECOND)	5.1	4.6	3.8
MINIMUM VERTICAL VELOCITY (FEET PER SECOND)	≈0.0	≈0.0	≈0.0
MEAN VERTICAL VELOCITY (FEET PER SECOND)	1.46	1.45	1.06
STANDARD DEVIATION (FEET PER SECOND)	0.923	0.944	0.713
COEFFICIENT OF SKEWNESS	0.905	1.01	1.05
AIRSPEED:			
MAXIMUM AIRSPEED (KNOTS)	152.9	136.1	121.8
MINIMUM AIRSPEED (KNOTS)	107.7	105.9	92.1
MEAN AIRSPEED (KNOTS)	126.9	118.5	108
STANDARD DEVIATION (KNOTS)	8.604	7.48	6.605
COEFFICIENT OF SKEWNESS	0.455	0.471	0.091
MAXIMUM AIRSPEED (PERCENT ABOVE STALL)	43.8	40.8	43.3
MINIMUM AIRSPEED (PERCENT ABOVE STALL)	13.6	10.5	6.0
MEAN AIRSPEED (PERCENT ABOVE STALL)	26.6	22.5	22.6
STANDARD DEVIATION (PERCENT ABOVE STALL)	6.42	6.15	6.88
COEFFICIENT OF SKEWNESS	0.019	0.069	0.163
ROLLING VELOCITY TOWARD FIRST WHEEL TO TOUCH:			
MAXIMUM ROLLING VELOCITY (DEGREES PER SECOND)	6.5	5.3	3.1
MINIMUM ROLLING VELOCITY (DEGREES PER SECOND)	≈0.0	≈0.0	≈0.0
MEAN ROLLING VELOCITY (DEGREES PER SECOND)	1.76	1.29	1.102
STANDARD DEVIATION (DEGREES PER SECOND)	1.20	1.163	0.747
COEFFICIENT OF SKEWNESS	0.803	1.645	–0.277
ROLLING VELOCITY AWAY FROM FIRST WHEEL TO TOUCH:			
MAXIMUM ROLLING VELOCITY (DEGREES PER SECOND)	4.9	3.6	2.2
MINIMUM ROLLING VELOCITY (DEGREES PER SECOND)	≈0.0	≈0.0	≈0.0
MEAN ROLLING VELOCITY (DEGREES PER SECOND)	1.47	1.361	0.876
STANDARD DEVIATION (DEGREES PER SECOND)	1.09	0.822	0.683
COEFFICIENT OF SKEWNESS	0.791	0.73	0.586
BANK ANGLE:			
MAXIMUM BANK ANGLE (DEGREES)	3.5	3.6	3.6
MINIMUM BANK ANGLE (DEGREES)	≈0.0	≈0.0	≈0.0
MEAN BANK ANGLE (DEGREES)	0.822	0.759	0.935
STANDARD DEVIATION (DEGREES)	0.645	0.586	0.703
COEFFICIENT OF SKEWNESS	1.51	1.793	1.32
TOUCHDOWN DISTANCE FROM RUNWAY THRESHOLD:			
MAXIMUM TOUCHDOWN DISTANCE (FEET)	3435	2614	2740
MINIMUM TOUCHDOWN DISTANCE (FEET)	290.0	100.0	204.0
MEAN TOUCHDOWN DISTANCE (FEET)	1300.8	1187.5	1203.5
STANDARD DEVIATION (FEET)	538.8	553.2	523.6
COEFFICIENT OF SKEWNESS	0.576	0.433	0.286

The distribution of touchdown position was very similar for the three aircraft. Touchdown distances for 1 in 100 landings ranged from 763 meters (2500 feet) for the turboprop to 854 meters (2800 feet) for the turbojets. The mean airspeeds at touchdown ranged from 22.5 to 26.6 percent above stalling speed with standard deviations ranging from 6.15 to 6.88 percent. Lateral position and lateral velocity (or crab angle) were not measured.

In 1962, the FAA Flight Standards Agency reported on landing condition measurements made by tracking phototheodolites at four airports for 183 daylight landings by six types of turbojet aircraft (Reference 15). Their results are summarized in Table 4 without change. The study included a statistical analysis for fitting to theoretical distributions. For most parameters, Pearson type III distributions, Reference 37, were found to have the best fit. Several approach, flare, and touchdown quantities were observed, including touchdown distance from threshold, and touchdown speed ratio. Lateral deviation and velocity (or crab angle) were not measured. The mean touchdown distance was 462 meters (1514 feet) beyond threshold with a standard deviation of 181 meters (593 feet). The mean touchdown speed ratio was 1.30 relative to stalling speed with a standard deviation of 0.072.

As jet transports came to be the most common aircraft type, and as more confidence developed in their landing qualities, attention was focused upon the initiation of the landing flare and relationships to the approach phase. The most common parameters observed were those relative to the approach decision height and to crossing over the runway threshold. We have been able to obtain data for approximately 1500 landings during the period from 1962 to 1974 as summarized in Table 5. The only parameter universally available has been the height of the aircraft wheels crossing over the runway threshold. This figure includes data on this parameter from the 1962 FAA study (Reference 15). A surprising variation of threshold crossing is revealed between aircraft types. The first generation narrow body jets typically cross at 6 meters (20 feet) to 9 meters (30 feet) quite consistently even after 10 to 15 years of service. Later shorter range twin-jets cross the threshold somewhat higher at 7 to 12 meters (25 to 40 feet), again quite consistently, and contrary to intuitive expectations. The current wide-body jets cross the threshold at 10 to 14 meters (35 to 45 feet) with good consistency and also contrary to intuitive expectations.

In an effort to understand the consistent and unexpected variation of threshold crossing height, we analyzed the data for 127 landings of DC-10 aircraft for which the threshold crossing height of the ILS glide slope beam was also available. The results are shown in Table 6. Contrary to intuitive expectation, the aircraft threshold crossing height tends to be constant for wide variations of ILS glide slope crossing height.

Qualitative information from many sources including pilot experience, direct observation, and runway tire markings indicates that the typical touchdown position is still from 300 to 460 meters (1000 to 1900 feet) beyond the threshold. Reference 11, which is discussed in the following paragraph, also confirms that the typical touchdown position is within that range. Our present conclusion is that the observed variation between aircraft types in the threshold crossing height is due to natural differences in handling and flying qualities which do not affect the landing touchdown position and which are not determined by ILS glide slope characteristics.

TABLE 4

FLIGHT STANDARDS SERVICE RELEASE NO. 470, 8 AUGUST 1962

STATISTICAL PRESENTATION OF OPERATIONAL LANDING PARAMETERS FOR TRANSPORT JET AIRCRAFT – APPENDIX A

HISTOGRAM FIGURE NO.	PROBABILITY FIGURE NO.	SYMBOL	PARAMETER	NO. OF LANDINGS	ARITHMETIC MEAN	STANDARD DEVIATION	SKEWNESS	KURTOSIS	MODE
1	2	0/3 DEG	APPROACH ANGLE RATIO	183	0.939	0.240	0.591	3.385	0.868
3	4	S_{50}	50-FOOT-HEIGHT DISTANCE TO THRESHOLD	183	755.0 FT	339.0 FT	0.282	3.202	707.0 FT
5	6	S_F	FLARE POINT DISTANCE TO THRESHOLD	183	330.0 FT	409.0 FT	0.610	3.108	205.0 FT
7	8	H_F	FLARE POINT HEIGHT	183	32.0 FT	15.1 FT	0.916	3.884	25.1 FT
9	10	$H_{th}/50$	THRESHOLD HEIGHT RATIO	183	0.399	0.200	0.773	3.869	0.322
11	12a, 12b	V_{th}/V_s	THRESHOLD SPEED RATIO	177	1.390	0.085	0.358	3.219	1.374
13	14	S_M	MAIN GEAR TOUCHDOWN DISTANCE FROM THRESHOLD	183	1514.0 FT	593.0 FT	0.632	4.902	1327.0 FT
15	16	V_{td}/V_s	TOUCHDOWN SPEED RATIO	177	1.300	0.072	–0.261	2.565	1.309
17	18	V_B	BLEEDOFF SPEED	183	8.63 KN	5.07 KN	0.831	3.815	6.53 KN
19	20	V_B/V_s	BLEEDOFF SPEED RATIO	177	0.089	0.052	0.831	3.737	0.067
21	22	t_{NW}	NOSE WHEEL DOWNTIME FROM TOUCHDOWN	111	3.59 SEC	1.59 SEC	0.779	3.031	2.83 SEC
23	24	t_{sp}	SPOILERS UP TIME FROM TOUCHDOWN	28	5.71 SEC	2.43 SEC	0.483	2.102	5.13 SEC
–	–	–	PROBABILITY ENVELOPES OF COMBINED VALUES OF:						
–	25	–	1. FLARE POINT HEIGHT	183	32.0 FT	15.1 FT	0.916	–	–
			FLARE POINT DISTANCE TO THRESHOLD	183	330.0 FT	409.0 FT	0.610	–	–
–	26	–	2. BLEEDOFF SPEED	183	8.63 KN	5.07 KN	0.831	–	–
			MAIN GEAR TOUCHDOWN DISTANCE FROM THRESHOLD	183	1514.0 FT	593.0 FT	0.632	–	–

TABLE 5
THRESHOLD WHEEL CROSSING HEIGHT MEASUREMENTS

AIRCRAFT	CROSSING HEIGHT/METERS	SAMPLE SIZE	LOCATION	APPROACH GUIDANCE	DATE	SOURCE
4-ENGINE JETS	6.09	183	VARIOUS	UNKNOWN	1962	FAA
DC-8/B707	6.40	100	LONDON	UNKNOWN	1961/62	ICAO
JETS	5.48	93	SPL/RWY 19, 23	UNKNOWN	1961	NLR
JETS	9.14	554	OSAKA	UNKNOWN	1969/70	ICAO
COMMON TURBINE AIRCRAFT	8.53	71 JET 120 TURBOPROP	2 AERODROMES	UNKNOWN	1965/66	QANTAS 1
COMMON TURBINE AIRCRAFT EXCEPT B747	8.53		2 AERODROMES	CEILING ⩾ 300 FEET	1971/72	QANTAS 2
DC-8	8.23	40	SPL/RWY 19	ILS	1966/67	NLR
DC-8	6.70	12	MIAMI 9L	UNKNOWN	1972	MDC
DC-8	9.47	12	SFO, ORD	UNKNOWN	1972	UAL
DC-9	11.88	17	SPL, RWY 19	FLIGHT DIRECTOR	1966/67	NLR
DC-9	12.50	28	SPL, RWY 19	A/P	1966/67	NLR
DC-9	10.36	10	MIAMI, 9L	UNKNOWN	1972	MDC
DC-9	7.32	8	SFO, ORD	UNKNOWN	1972	UAL
DC-10	13.72	11	MIAMI, 9L	UNKNOWN	1972	MDC
DC-10	10.06	4	SFO, ORD	UNKNOWN	1972	UAL
DC-10	10.67	161	VARIOUS	ILS	1973/74	KLM
DC-10		63	VARIOUS	DH > 100 FEET	1973/74	KLM
DC-10		57	VARIOUS	DH < 100 FEET	1973/74	KLM
B747	9.75	9	MIAMI, 9L	UNKNOWN	1972	MDC
B747	10.97	10	SFO, ORD	UNKNOWN	1972	UAL
B747	12.80		2 AERODROMES	UNKNOWN	1971/72	QANTAS 2

FAA: FLIGHT SERVICE RELEASE 470, FAA 8/62
ICAO 1: ICAO AIR C-WP/163
NLR 1: NLR REPORT V1900
ICAO 2: ICAO AIR C-WP/417
QANTAS 1: ICAO AIR C-WP/291
QANTAS 2: ICAO AIR C MEMO 173
NLR 2: NLR TR68018u
MDC: MCDONNELL DOUGLAS
UAL: UNITED AIRLINES
KLM: ICAO AIR C MEMO 173

TABLE 6
WHEEL HEIGHT VERSUS BEAM HEIGHT

AIRPORT/RUNWAY		ILS GS BEAM HEIGHT AT THRESHOLD IN METERS (FT)	DC-10 WHEEL HEIGHT AT THRESHOLD IN METERS (FT)	SAMPLE SIZE
JFK	31R	10.06 (33)	8.84 (29)	6
KHI	21R	10.06 (33)	14.93 (49)	7
ORD	27R	11.58 (38)	11.58 (38)	7
SPL	27	15.24 (50)	10.67 (35)	30
SPL	19R	15.54 (51)	10.97 (36)	36
SPL	06	17.07 (56)	10.97 (36)	20
ANC	06R	18.59 (61)	9.45 (31)	21

SOURCE: KLM-ICAO AIR C-B1P NO. 47
24 SEPTEMBER 1974

The only direct measurements of landing conditions made on a large scale since the early 1961-62 data are those reported by HoSang in Reference 11. The instrumentation methods were designed to measure aircraft positions and speeds at several particular locations along the runway, rather than at the point of touchdown. Even so, the data allow the distribution of landings within general nominal touchdown zones to be studied. The relevant results have been reproduced in Table 7 with additional analysis of distribution by groupings of aircraft types. More than 5,000 landings by eleven aircraft types were observed at nine airports. The large steps by which the touchdown zones are measured does not permit meaningful calculations of mean values, standard deviations and other usual statistical measures. However, the trend of the data is apparent. Only 19 percent of landings occur less than 305 meters (1000 feet) from the threshold. Most landings (79 percent) touchdown before reaching the 610 meter (2000 feet) distance. These results are consistent with the available data from the 1961-62 period. According to Reference 11, lateral deviations are characterized by a mean value not greater than 0.5 meter (1.6 feet) and a standard deviation of about 2.3 meters (7.5 feet). Lateral velocities or divergence was not measured.

A more direct comparison of the data of Reference 11 with the earlier data of Reference 15 have been constructed in Figure 4. Here, the touchdown distance from threshold has been plotted as a discrete cumulative distribution. The cumulative distribution of touchdown zones of Reference 11 has also been plotted for DC-8 and B707 aircraft only and for all eleven aircraft types. The plots suggest that a mean value of touchdown distance of about 460 meters (1500 feet) beyond threshold is representative of current transport aircraft operations.

Automatic Landing Dispersions

Aircraft automatic landing systems must meet the requirements of FAA Advisory Circular AC 20-57A (Reference 16). These requirements may be summarized as follows:

	(95 percent) Limits	Improbable (Prob. 10^{-6})
Longitudinal	Total Dispersion 1500 feet about nominal; not necessarily symmetrical	Outside zone between 200 feet beyond touchdown to point of which 4 touchdown zone lights are visible (usually about 2400 feet from threshold)
Lateral	27 feet	Closer than 5 feet to edges of 150 feet runway

The combination of the longitudinal limits constrain the mean touchdown position between about 370 to 427 meters (1200 to 1400 feet) beyond the threshold. For all practical purposes, the performance of automatic landing systems may be characterized by a mean touchdown position of 397 meters (1300 feet) with a standard deviation of about 61 to 69 meters (200 to 225 feet). The touchdown speed is not controlled by regulation, other than a general expection of sufficient margin above stall to maintain airworthiness. The characteristic natural or artificial stall warning (stick shakers) indicate that the minimum airspeed at touchdown will be at least 1.20 times the stalling speed. The maximum touchdown speed is not controlled, but is not likely to be greater than

TABLE 7

SUMMARY OF CUMULATIVE TOUCHDOWN DISTRIBUTIONS AT ALL AIRPORTS COMBINED

		CUMULATIVE PERCENTAGES AT NOMINAL DISTANCES FROM THRESHOLD		
AIRCRAFT TYPE	SAMPLE SIZE	1000 FEET	2000 FEET	3000 FEET
B747	61	20	67	88
DC-10-10	149 } 285	19 } 16%	73 } 64%	91 } 90%
L-1011	75	8	44	88
DC-8-60	210	13	72	91
DC-8-40, -50	262 } 911	14 } 14%	75 } 74%	96 } 93%
B707	439	14	75	93
B727-200	840 } 2139	16 } 17%	73 } 76%	90 } 95%
B727-100	1299	18	78	98
DC-9-30, -40	880	24	85	98
DC-9-10, -20	226 } 1681	22 } 25%	92 } 87%	98 } 98%
B737	376	25	87	96
BAC 1-11	199	30	94	100
C580	164 } 187	29 } 28%	85 } 85%	93 } 92%
YS-11	23	17	82	89
	5203	19%	79%	95%

FROM FIGURE 77 OF "FIELD SURVEY AND ANALYSIS OF AIRCRAFT DISTRIBUTION ON AIRPORT PAVEMENTS," FAA RD-74-36, FEBRUARY 1975

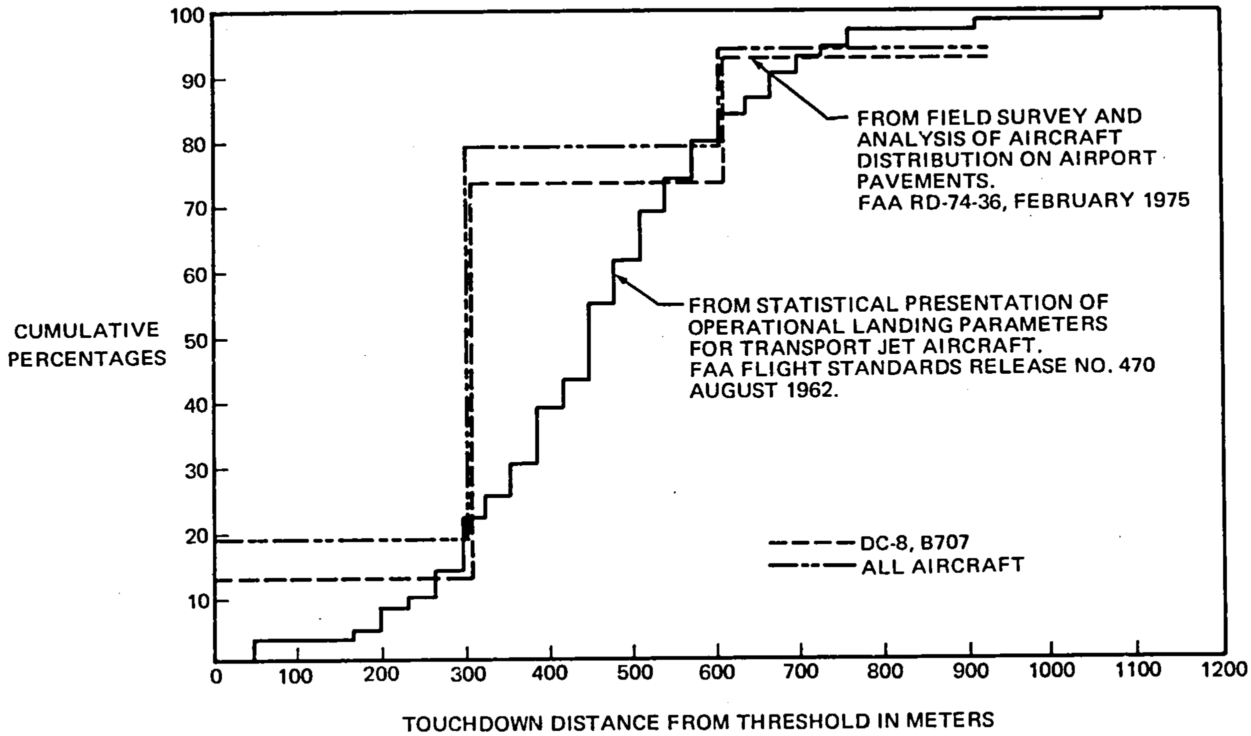


FIGURE 4. SUMMARY OF CUMULATIVE TOUCHDOWN DISTRIBUTIONS

the typical approach speed ratio of 1.35 since the flare maneuver is characterized by a speed bleed-off of 2.5 to 5 meters/second (5 to 10 knots). The lateral dispersions may be characterized by the FAA Certification limits. When aircraft landing gear dimensions are considered, standard deviations not greater than 3 meters (10 feet) may be expected. The mean deviation is usually small and may be neglected.

Summary of Landing Dispersions

For transport aircraft, manual VMC landings may be characterized by a mean touchdown position of 370 to 460 meters (1200 to 1500 feet) with a standard deviation of about 160 to 180 meters (540 to 590 feet). The distribution of touchdown position is not known except that it is not normal or symmetrical. Some early data suggest that the distribution may be characterized as Pearson type III with coefficients as given in Reference 15. There is a probability in the order of 5 percent that a given landing may occur after 915 meters (3000 feet) beyond the threshold. The airspeed at touchdown is less well characterized but may be expected to be between 1.2 and 1.4 times stalling speed. Automatic landings will touchdown between 370 to 460 meters (1200 to 1500 feet) beyond threshold on the average with a standard deviation of about 69 meters (225 feet). Touchdown positions closer than 61 meters (200 feet) and farther than 730 meters (2400 feet) beyond the threshold are improbable. The airspeed ratio at touchdown is not well characterized, but is not expected to be less than 1.2 or greater than 1.35. For both manual and automatic landings the lateral position at touchdown is near the centerline with a mean error less than 0.5 meter (1.6 feet) and with a standard deviation of 2 to 3 meters (6.5 to 10 feet). The lateral divergence from centerline after touchdown has not been measured and is not well known. This could potentially be a problem in the use of high speed exits if the ability to recover the centerline with stable steering were affected.

Landing Dispersion Improvement

Current landing dispersions may be found to impose some limit on the use of high-speed runway exits and consequently upon runway occupancy time and capacity. It is of interest to evaluate the possibility that landing dispersions may be reduced and the degree of improvement that may be expected.

During Phase II of the FAA Microwave Landing System development program, McDonnell Douglas as a member of the ITT Gilfillan contractor team, conducted simulations to evaluate the effect of MLS upon automatic landing system performance (Reference 17). The results have been recapitulated in Table 8. The simulation was based upon an early developmental configuration of a DC-10 automatic landing system. The model was evaluated over a range of wind, turbulence, and ILS beam variations (not the same as subsequently used for FAA certification). ILS beam noise was represented, but radio altimeter noise was not (because of lack of data). A model of the MLS was substituted for the ILS beams, and computed height signals derived from MLS were substituted for radio altimeter signals. The MLS model was represented in two noise variations, the worst expected noise and an extreme noise case. Both the existing autopilot model and a version modified according to MLS noise characteristics were evaluated. The evaluation was somewhat biased to favor the ILS case because of the lack of noise in the radio altimeter signal.

TABLE 8

MLS AUTOMATIC LANDING PERFORMANCE

LIGHT TURBULENCE GUIDANCE	AUTOPILOT		RANGE FROM ELEVATION 1 (METERS)	VERTICAL SPEED (METERS/SEC)	PITCH ATTITUDE (DEGREES)	AIRSPEED (METERS/SEC)	LATERAL DEVIATION (METERS)	ROLL ATTITUDE (DEGREES)
ILS AND RADIO ALT – NO NOISE	STANDARD	MEAN	66.9	1.03	7.48	68.7	0.04	–0.013
		DEVIATION	49.3	0.15	0.46	0.70	0.44	0.292
ILS AND RADIO ALT – ILS NOISE ONLY	STANDARD	MEAN	65.5	1.08	7.38	67.8	0.12	0.024
		DEVIATION	65.2	0.17	0.54	0.70	1.84	0.633
MLS – WORST EXPECTED NOISE	STANDARD	MEAN	77.1	1.11	7.42	67.7	0.05	–0.078
		DEVIATION	67.2	0.22	0.36	0.58	0.57	0.325
MLS – WORST EXPECTED NOISE	MODIFIED	MEAN	27.1	0.88	7.14	69.1	0.02	0.010
		DEVIATION	59.0	0.27	0.15	0.52	0.65	0.422
MLS – EXTREME NOISE	STANDARD	MEAN	59.6	1.10	7.00	68.4	0.07	0.036
		DEVIATION	73.5	0.26	0.39	0.73	0.83	0.621
MLS – EXTREME NOISE	MODIFIED	MEAN	27.6	0.93	7.10	69.2	0.03	–0.061
		DEVIATION	69.2	0.25	0.24	0.73	0.69	0.518

The results depicted in Table 8 do not indicate any significant improvement in longitudinal dispersion characteristics. The ILS and MLS cases show roughly equivalent performance. Although disappointing, this is hardly surprising because the approach and flare control laws are the same. The unique qualities of the MLS (range data and flare elevation) are not effectively used in a direct substitution of ILS/radio altimeter signals. A significant reduction in lateral dispersion is apparent for the MLS case, however. The standard deviation is reduced to less than one-third that of the ILS case.

An additional analysis has been accomplished to evaluate the possible improvement if the autopilot laws were changed to better match the MLS characteristics. From a Monte Carlo simulation developed for DC-10 automatic landing certification, the contribution of particular factors of dispersion to overall dispersion was available. These have been summarized in Table 9 in forms of the percentage contribution to the total dispersion. The potential improvement in each factor has been estimated on a best possible or optimistic basis. Two strategies for improvement were identified. Some improvement will result directly from use of MLS rather than ILS because of more favorable noise characteristics and because of better average signal quality expected over the whole population of ground facilities. These improvements are identified as due to MLS Beam Quality. Another category of improvements is identified as Range Adaptive Control. This refers to potential autopilot modifications to use MLS range data to improve mode switching, gain programming, and adaptive flare control laws to account for variations of wind and speed.

In the table, the improvement ideally estimated for each factor and the strategy allowing the improvement are shown. From the results it can be predicted that the lateral dispersion may be reduced as much as 50 percent because of better beam quality, but will not be significantly improved by range adaptive control. (The approach accuracy was not evaluated in the factor analysis.) The longitudinal dispersion will be improved a little by MLS beam quality and somewhat more by range adaptive control. Both strategies must be used to realize an improvement to 56 percent over the original dispersion.

All potential improvements discussed so far have been for automatic landing systems. Most landings today and possibly well into the future are accomplished manually by visual reference of the runway. The question arises whether there are ways to improve the dispersions of manual VMC landings. If this is to be accomplished, it must, by definition, be by display or other means usable by pilots while maintaining visual contact with the runway. This immediately suggests the use of head-up displays.

There are some precedents for the use of head-up displays as visual landing aids. Some devices providing a simple aim line (without other instrument data) have been evaluated for commercial use. More importantly, head-up displays with complete display of attitude and path command data have been used operationally in France as aids in Category IIIa landings by see-to-land rules. The Super 80 DC-9 which is expected to be certified in 1980 to Category IIIa see-to-land rules, will also be certified with an instrumentally complete head-up display as an optional landing aid. The development of see-to-land automatic landing systems for Category IIIa weather minima conditions may represent a way to improve VMC landing dispersions intermediate in complexity and cost between fail-operational automatic landing systems and unaided simple manual visually-referenced landings.

TABLE 9
LANDING DISPERSION FACTOR ANALYSIS

	LONGITUDINAL (PERCENT) SHORT	LONGITUDINAL (PERCENT) LONG	LATERAL	HYPOTHETICAL BEST POSSIBLE LONGITUDINAL (PERCENT) SHORT	HYPOTHETICAL BEST POSSIBLE LONGITUDINAL (PERCENT) LONG	HYPOTHETICAL BEST POSSIBLE LATERAL	NOTE
WIND	–37	+24	+2	0	0	0	R
TURBULENCE	–39	+24	+7	–39	+24	+7	
ILS BEAM	–19	+28	±69	–10	+14	±35	M
ILS BEAM NOISE	–53	+45	±39	–27	+23	±20	M
ILS RECEIVER	–10	+0.3	±60	–5	+0.2	±30	M
AIRCRAFT WEIGHT	–24	+46	±1	0	0	0	R
AIRCRAFT CG VARIATION	–15	+15	±4	–15	+15	+4	
AIRCRAFT FLAP POSITION	–8	+0	±5	–0	+0	±0	R
AIRCRAFT PITCH TRIM	–16	0	–	–16	0	–	
AUTOPILOT TOLERANCES	–22	+19	±5	–17	+14	±4	R.
AUTOPILOT THROTTLE RETARD	–6	+13	–	0	0	0	R
AUTOPILOT SPEED ERROR	–47	+57	±4	0	0	0	R
ROOT SUM SQUARE	–100	+100	+100	–56	+41	±51	

RANGE ADAPTIVE + MLS BEAM QUALITY

–75% +62% ±100%

RANGE ADAPTIVE – CONTROL ONLY

–87% +89% ±52%

MLS BEAM QUALITY ONLY

NOTE: R MEANS RANGE ADAPTIVE CONTROL LAWS
M MEANS MLS BEAM QUALITY

At this time, very little data are available about the degree of landing dispersion improvement which could be attributed to the use of head-up displays. A development program was conducted by McDonnell Douglas in 1968 in a DC-9 aircraft (Reference 18). Figure 5 is a summary of the head-up display results. A full data head-up display with altitude, deviation, speed, and path command elements was used to evaluate manual landing performance. The system was evaluated by 21 airline and experimental test pilots. The results are shown in Figure 5 as a histogram for 19 landings. The dispersions can be seen to be roughly equivalent to typical automatic landing dispersions, although other characteristics were thought to require additional development. The result encourages consideration of a head-up display at least as a see-to-land aid in low-weather minima.

Aircraft Characteristics

Deceleration Rates

Deceleration data measured at Atlanta, O'Hare and Denver showed an average deceleration rate of 1.8 m/s^2 for those aircraft taking the first available exit and 1.5 m/s^2 for those taking the next available exit. Aircraft size had negligible effect on deceleration rates:

Aircraft Type	Average Decel Rate (Ref. 10)
DC-9/B737/B727	1.6 m/s^2
B707/DC-8	1.5 m/s^2
Wide bodies	1.7 m/s^2

Touchdown speed is a function of aircraft weight, flap angle, altitude, air temperature, and wind.

FAA regulations require that an aircraft cross the landing runway threshold (15m above the end of the runway) at 1.3 times stall speed. This results in a touchdown speed of 1.23 to 1.28 times stall speed which is the minimum speed at which aerodynamic lift will support the weight of the aircraft. Aerodynamic lift is proportional to velicity squared and to air density. Air density is a function of altitude and air temperature. As a result, the touchdown speed required is proportional to the square root of the airplane weight and is inversely proportional to the square root of air density. All this can be expressed as the following equation:

$$V_{TD} \approx 1.26 \frac{V_{STALL_o}}{\sqrt{\sigma}} \sqrt{\frac{W}{W_o}} - \text{Headwind}$$

V_{TD} = Touchdown velocity

V_{STALLo} = Stall speed at sea level, 15°C and at an arbitrary reference weight W_o

W = Aircraft Weight

Wo = An arbitrary reference weight

σ = Air density ratio = unity at sea level, 15°C

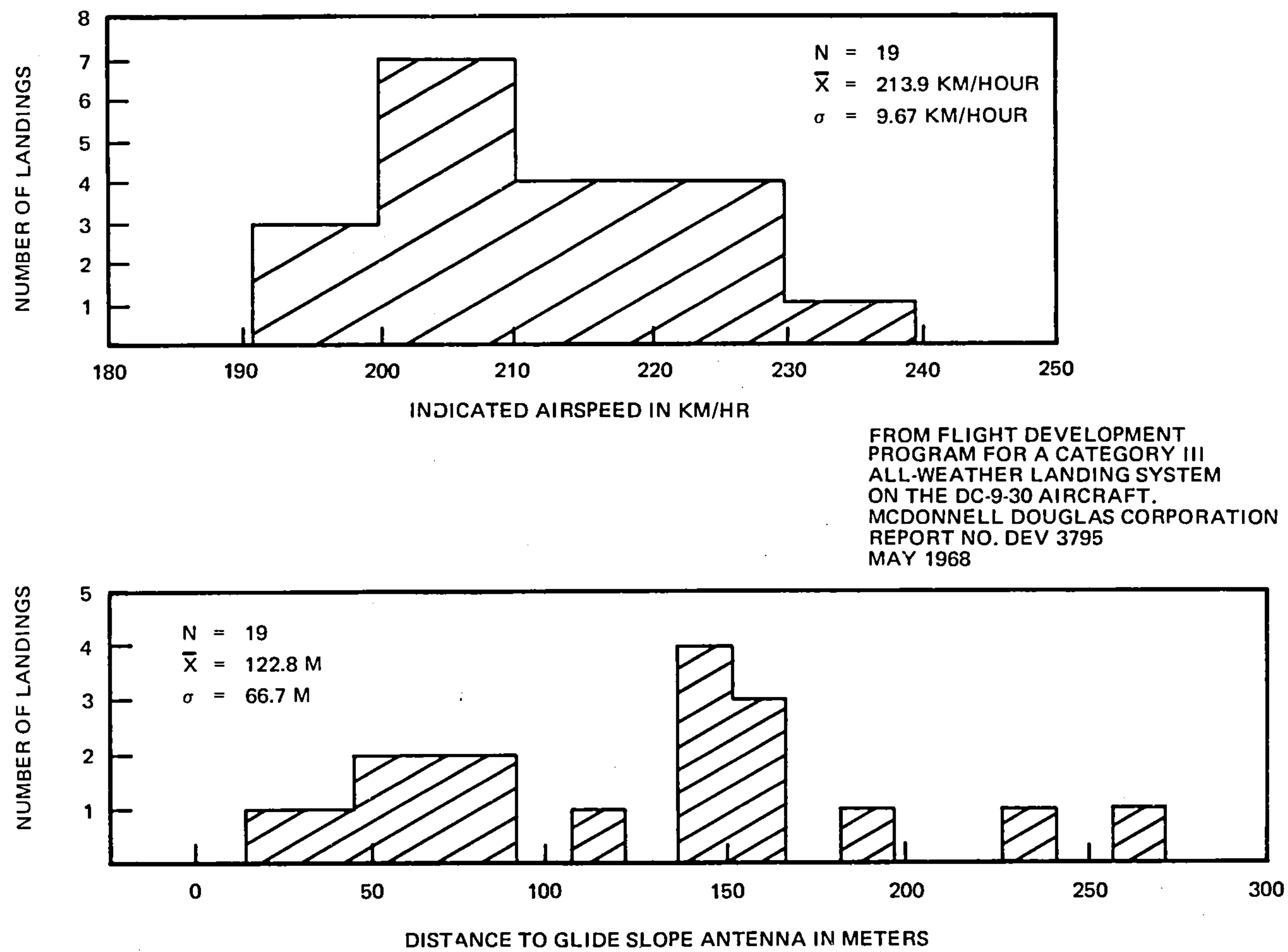


FIGURE 5. LANDING PERFORMANCE AT TOUCHDOWN – HUD

Since typical landing weights approximate 85 percent of maximum design landing weight, airplanes landing at maximum weight would be touching down 7 percent faster than typical aircraft. Touchdown speeds in Denver are 8 percent faster than at sea level because of the reduced air density. Whether pilots compensate for higher touchdown speeds by using harder brakes could not be conclusively separated from the effect of different exit locations, but the measured deceleration rates were higher in Denver than at the other two airports:

Airport(Altitude)	Average Deceleration (Ref. 10)
Atlanta 9R 313 m.	1.2 m/s^2
Atlanta 27L 313 m.	1.6 m/s^2
O'Hare 9R 203 m.	1.5 m/s^2
Denver 26 1626 m.	1.8 m/s^2

Since it is not entirely clear whether or not pilots brake harder to compensate for higher touchdown speeds, the conservative assumption relative to exit location is that they do not.

Data are not available on how surface condition affects braking levels used by pilots. The average deceleration 1.5 to 1.7 m/s^2 measured at Atlanta, O'Hare and Denver could easily be obtained on wet runways.

In summary, the average deceleration of airline jets after touchdown is 1.5 - 1.7 m/s^2 regardless of size. Data is insufficient to determine how touchdown speeds or surface condition affects braking levels.

Maintenance Problems as a Function of Deceleration Rate

During the landing rollout, the airplane is decelerated by the combined forces of aerodynamic drag, reverse thrust and braking. Figure 6 shows for a typical aircraft, the share of total stop energy absorbed by each as a function of deceleration rate. Average brake wear lift on the DC-10 is 1000 to 1200 landings. Hard braking reduces brake life thereby increasing brake maintenance costs which currently on the DC-10 run about $2.50 per brake per landing or $20 per aircraft per landing.

Brake life can be approximated by the following formula which was obtained a number of years ago from the brake design engineers at Goodyear Tire and Rubber Company:

$$N = No \left(\frac{BE_o}{BE}\right)^{2.25}$$

where N = Number of landings between overhaul

N_o = Number of landings between overhaul for baseline case

BE = Energy absorbed per landing

BE_o = Energy absorbed per landing for baseline case.

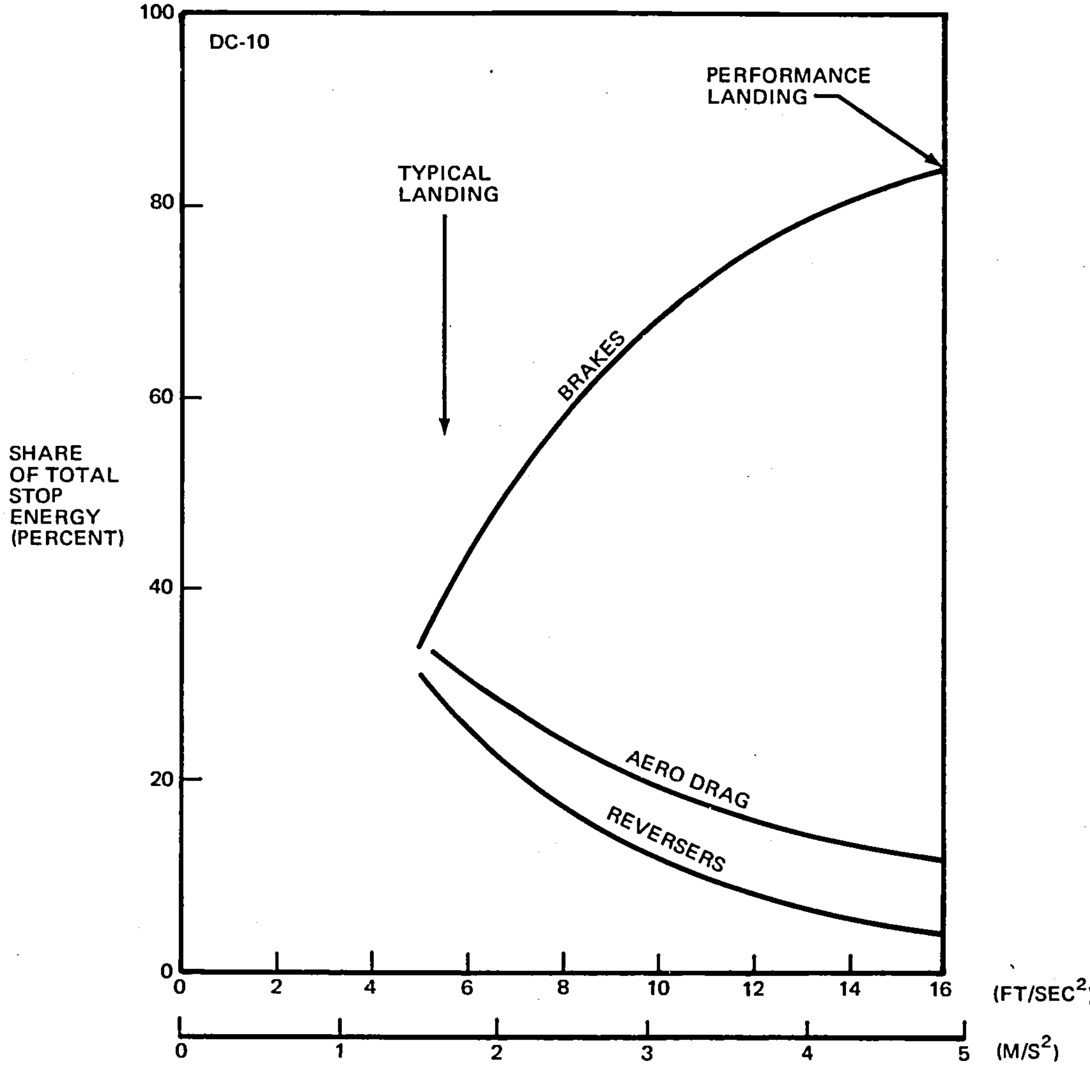


FIGURE 6. EFFECT OF DECELERATION RATES ON ENERGY ABSORPTION

Combining the brake energy of Figure 6 with the brake life formula and current average brake costs, we get the following relationship between deceleration rate and brake costs:

Deceleration	Brake Cost per aircraft per landing
1.68 m/s^2	\$ 20
1.82	26
2.13	38
2.44	48
2.74	59
3.04	70

Other maintenance costs such as tires and structural fatigue are relatively unaffected by reasonable variations in braking levels. The increased costs of using harder braking, therefore, are primarily brake costs. While \$20 per landing may be small compared to the 40 million dollar cost of the aircraft or compared to fuel costs, it can accumulate into a sizeable sum. Assuming four flights per day, annual brake costs for a fleet of 50 aircraft would be almost 1.5 million dollars. Increasing the deceleration from 1.68 m/s^2 to 2.13 m/s^2 would approximately double present brake costs. While the cost is minor relative to aircraft and fuel costs, annual fleet cost can be a sizeable figure that airlines would resist increasing unless an offsetting payoff can be demonstrated.

Aircraft Maneuverability

Aircraft are optimized for flying instead of maneuvering on the ground. The nose gear steering wheel is at the pilot's side instead of in front of him as on an automobile. Foot pedals provide rudder control in addition to wheel braking. Asymmetric braking control (left pedal brakes the left wheels, right pedal brakes the right wheels) requires that the pilot coordinate both pedals when braking to prevent the aircraft from pulling to one side. The pilot typically does not have a ground speed indicator and cannot accurately judge his taxi speed by visual cues. The main landing gear is mounted very nearly beneath the center of gravity to enable rotation of the aircraft for takeoff. The nose gear is typically left with only 3 to 10 percent of the ground load to provide directional control compared to around 50 percent on an automobile.

Nose Gear Directional Control

The ability of the nose gear to control the direction of the aircraft is a direct function of (1) its vertical load, (2) the side load it must develop to accomplish a particular maneuver, and (3) the ground coefficient of friction. For simplicity, the demand placed on the nose gear is expressed as the ratio where:

$$\mu = \frac{\text{Side Load on Nose Gear}}{\text{Vertical Load on Nose Gear}}$$

This allows direct comparison to the available ground coefficients of friction which are also expressed as μ :

Dry pavement:	$\mu=0.8$
Wet pavement:	$\mu=0.4$
Packed snow:	$\mu=0.2$
Ice:	$\mu=0.1$

The demand placed on the nose gear comes from three sources:

1. Centrifugal force:

$$\mu_c = V^2/(g\ R)$$

where

V = Velocity

g_c = Acceleration of gravity

R = Instantaneous turn radius

2. Rotation inertia resistance:

$$\mu_I = I\ \alpha/(g_c)\ (W)(L_w)(\%M/100)(1-(\%M/100))$$

Where I = rotational inertia of aircraft

α = rotational acceleration in radians/sec^2 $= -(V)\ (R')/R^2$

Where R' is the rate of change in turn radius

W = aircraft weight
Lw = aircraft wheelbase
%M = percent of gross weight supported by the main landing gears

3. Scrubbing resistance of the main gear:

Figure 7 shows μ scrub for five airplanes. The main landing gear's resistance to being turned is dependent upon the type of gears used and their location. Duals are very easy to turn, whereas the B747 configuration of two wing mounted gears and two body mounted gears 3.0 m aft is the most difficult of the commercial jets to turn. At steer angles above 20 degrees (applicable to turn radii below 91.4 m), the B747 body gears steer in addition to the nose gear.

Total maneuvering demand on the nose gear then is:

$$\mu = \mu_c + \mu_I + \mu_{scrub}$$

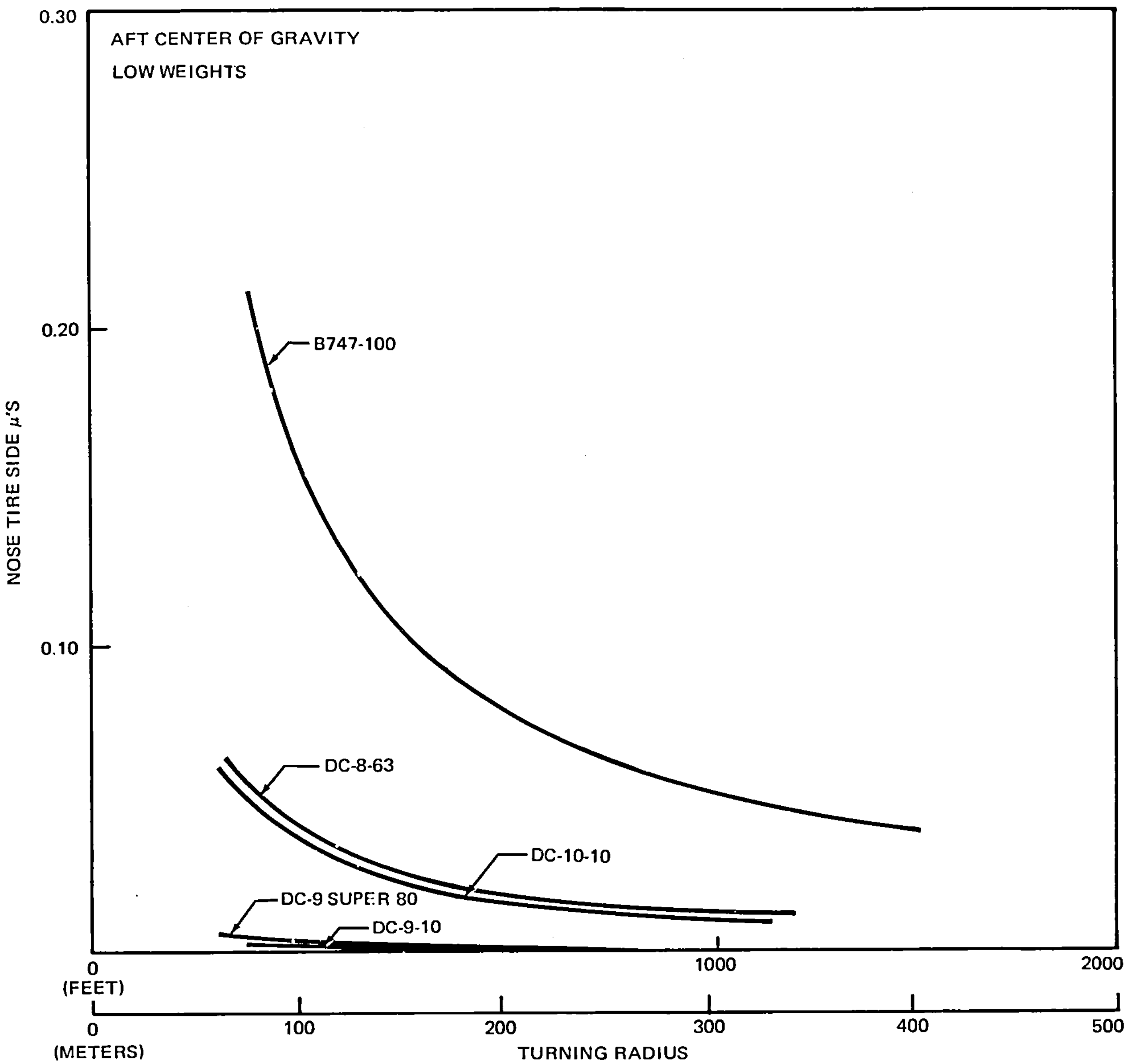


FIGURE 7. NOSE TIRE SIDE μ's VERSUS TURNING RADIUS DURING SLOW-SPEED TURNS

Turning Capability for Various Aircraft

Low weight, aft center of gravity conditions are the most critical. Aft center of gravity results in the least weight to the nose gear. Both rotational inertia and main gear turning resistance remain fairly high at low weights. Aircraft data used in the study are as follows:

Aircraft	Weight (Kg)	I (10^6 Kg m^2)	Lw (m)	%M (%)
DC-9-10	29,647	1.33	13.3	95.4
DC-9-80	46,448	5.23	22.1	96.8
DC-8-63	78,744	15.08	23.6	96.7
DC-10-10	131,905	22.18	22.1	94.2
747-100	204,661	56.94	25.6	96.4

Figure 8 and Table 10 show the relative turning capability of five aircraft when the aircraft is turned as fast as possible given a maximum available to the nose gear. The path traveled by the DC-9 Super 80 and DC-10-10 with a μ of 0.2 approximates that of the present high speed exit standard shown on Figure 9. It can be seen from the results that the primary difficulty in turning the aircraft is overcoming the rotational inertia without generating excessive side loads on the nose gear. Figure 10 shows for the B747 the relative importance of rotational inertia, centrifugal force and main gear turning resistance in accomplishing an exit at 27 m/s. It can be seen that rotational inertia is the source of more than half the turn resistance for the first 150m of the turn.

A μ of 0.2 is considered to be a practical limit for maneuvering at speeds of 18-27 m/s. This would leave the pilot with a margin of 4 against skidding on dry surfaces and a margin of 2 against skidding on wet surfaces. Pilots would probably refuse to consistently use margins less than 2.

Effect on Tire Wear and Structure

Scrubbing of the main landing gear tires during high speed exit type maneuvering is very small and would have very little effect on main gear tire life. The scrub angle of the nose gear tires with a side μ of 0.2 is between 1.3 degrees and 2.4 degrees as shown in Table 10. This would cause increased wear on the nose tires but would probably be minor.

The μ of 0.2, which is considered an upper limit for maneuvering at high exit speeds, is below that experienced at maximum steer angles during terminal parking of aircraft with dual tandem gears and is substantially less than the loads experienced during wheel spinup at touchdown and during heavy braking.

Pilot/Passenger Comfort

Passenger comfort is a major consideration to the pilot. In order to establish a minimum turn path that can be accomplished without discomfort to the passengers, it was necessary to first identify a passenger comfort limitation in terms of lateral acceleration (G's) and lateral jerk (J's). Using the comfort quality ratings shown in Table 13, the following limits were selected:

Maximum Lateral G's = 0.12
Maximum Lateral J's = 0.055

These levels should be comfortable for 90 percent of the passengers and acceptable for 95 percent of the passengers. Literature on passenger comfort, however, did not provide a means of evaluating the interactive effort of acceleration and jerk occurring simultaneously. Therefore, the following relationship was assumed

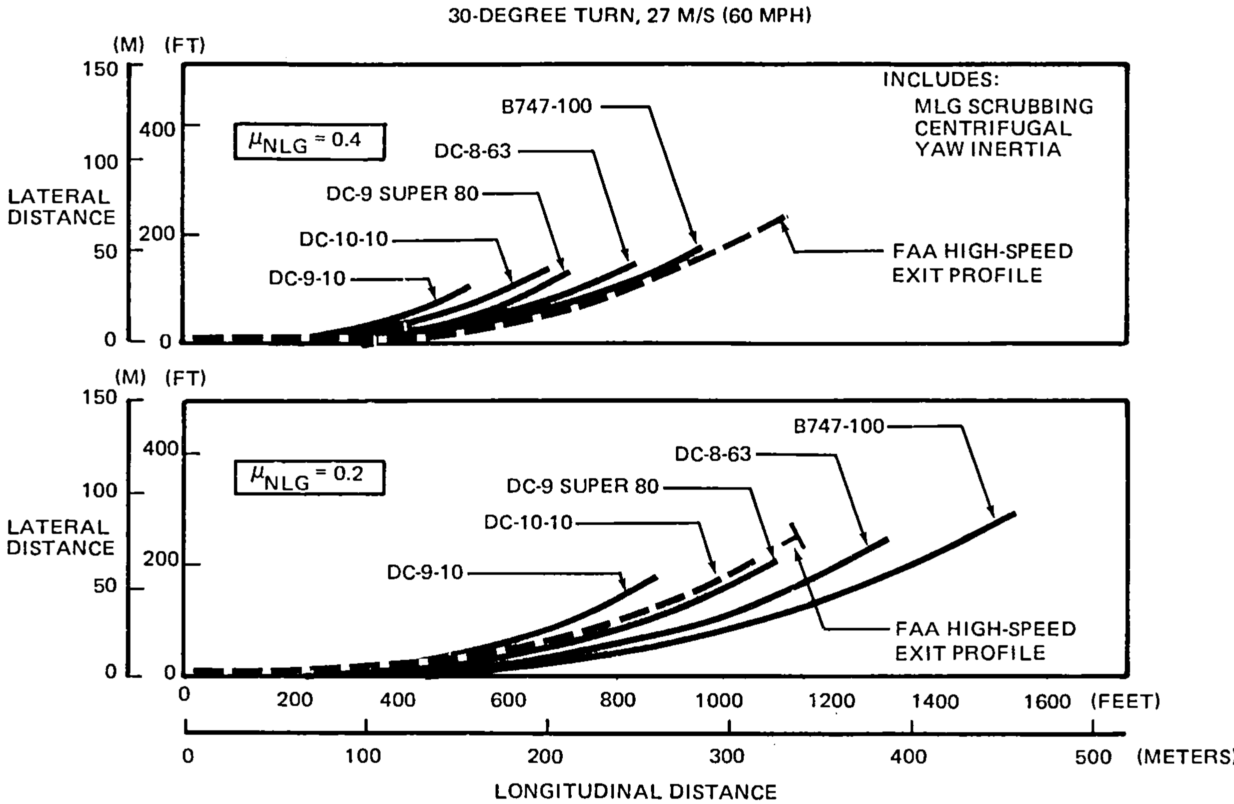


FIGURE 8. MINIMUM TURN – LIMITED BY NLG SIDE μ – VARIOUS AIRCRAFT

TABLE 10

COMPARATIVE TURNING CAPABILITY – VARIOUS AIRCRAFT

27 METERS/SECOND – 30-DEGREE TURN

AIRCRAFT	FINAL VALUE IN TURN				PEAK μ VALUES DURING TURN			NLG TIRE SCRUB ANGLE (DEG)
	TIME (SEC)	METERS						
		X	Y	R	μ_{SCRUB}	μ_{CENT}	μ_I	
DC-9-10	6.10	158	32	208	0.001	0.352	0.4	4.9
DC-9 SUPER 80	8.07	210	41	251	0.002	0.292		3.8
DC-8-63	9.77	254	49	296	0.019	0.248		2.6
DC-10-10	7.70	200	39	247	0.019	0.297		2.7
DC-10 STRETCH	10.93	284	55	331	0.059	0.220		2.2
B747-100	11.13	289	56	341	0.068	0.215		3.4
DC-9-10	9.97	258	56	381	0.001	0.192	0.2	2.4
DC-9 SUPER 80	12.52	325	66	423	0.001	0.173		1.9
DC-8-63	14.99	389	77	491	0.016	0.149		1.3
DC-10-10	12.21	316	66	433	0.015	0.169		1.4
DC-10 STRETCH	17.00	441	89	570	0.044	0.129		1.1
B747-100	17.43	452	91	588	0.050	0.125		1.7

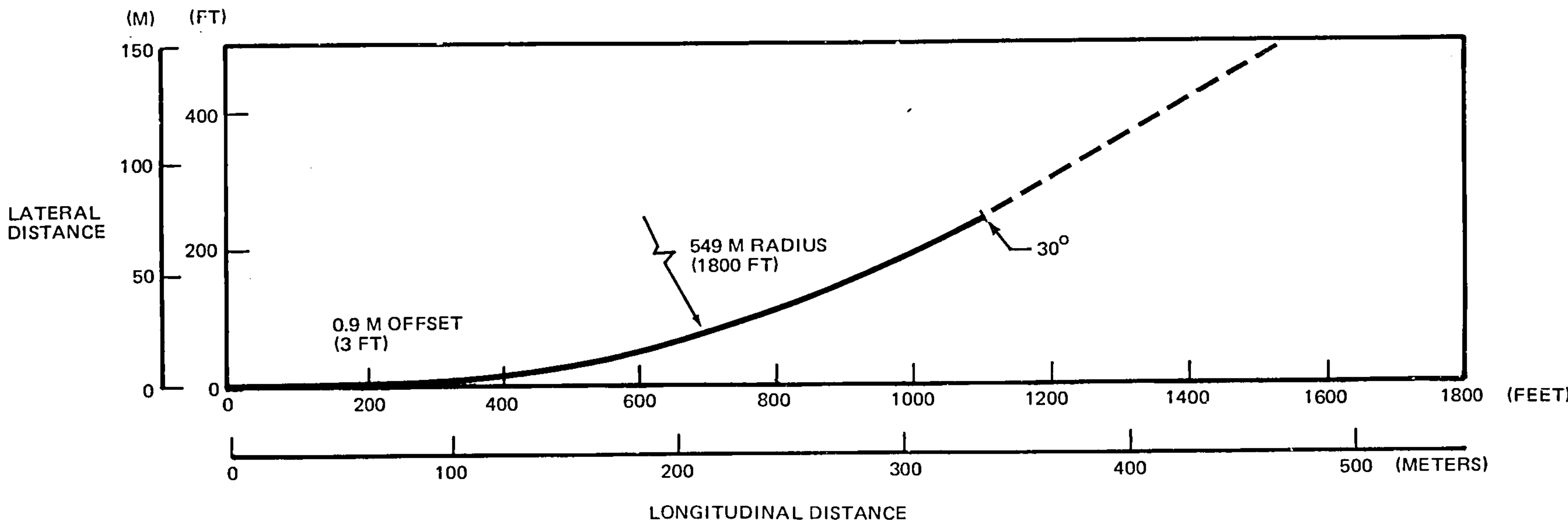


FIGURE 9. FAA HIGH-SPEED EXIT DESIGN TURN RATE

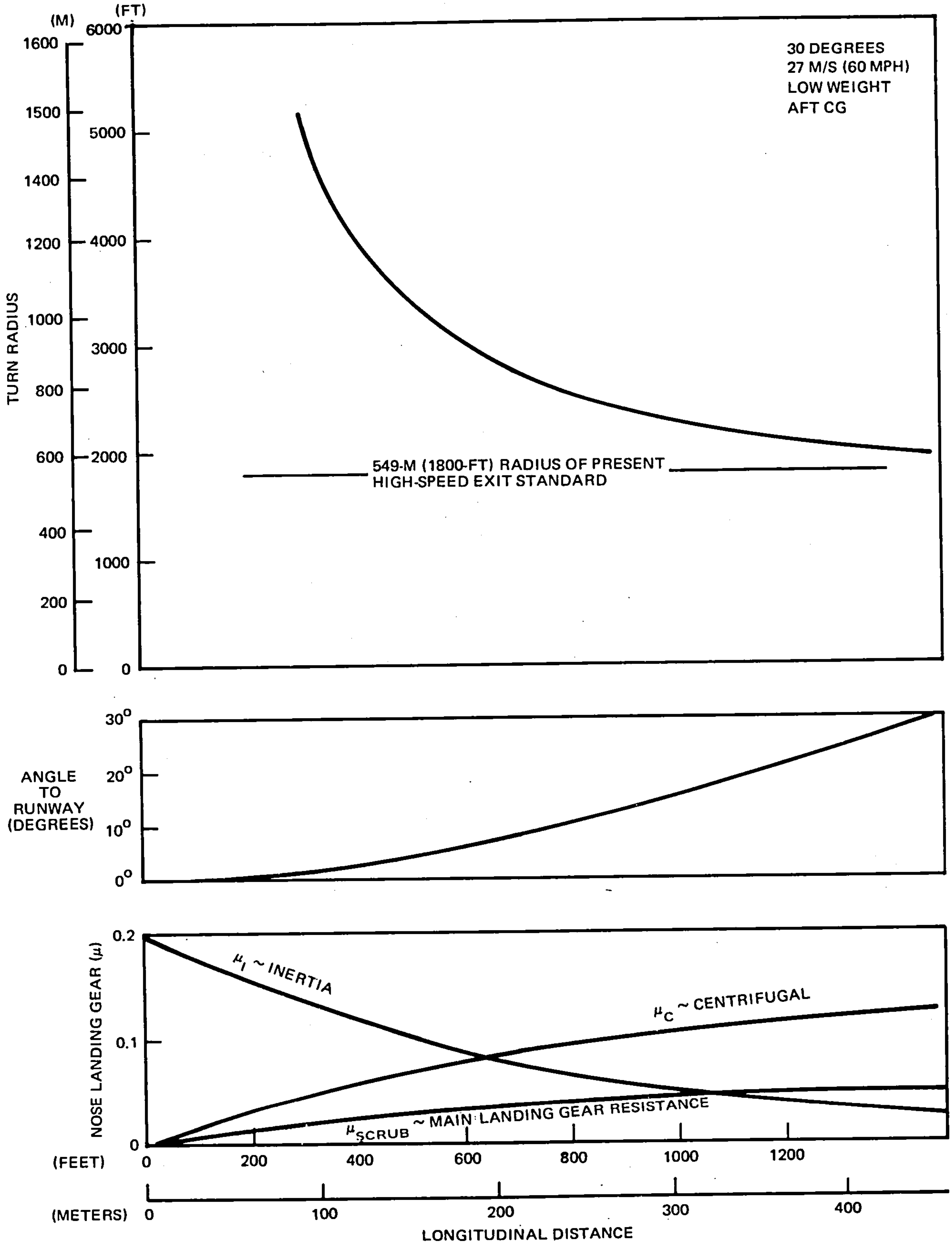


FIGURE 10. EXAMPLE B747 TURN LIMITED BY A SIDE μ ON NOSE LANDING GEAR OF 0.2

occurring simultaneously. Therefore, the following relationship was assumed because of its simplicity:

$$\frac{G}{G_{MAX}} + \frac{J}{J_{MAX}} \leq 1$$

Where $G_{MAX} = 0.12$
$J_{MAX} = 0.055$

Seat design and the passenger environment must have a significant effect on passenger tolerance to lateral acceleration and jerk. The limits noted above from Table 13 were based upon train systems which could be substantially different for airline passengers.

Figure 11 shows the minimum turn paths that can be accomplished with the above limitations on lateral acceleration and jerk. These paths were obtained by solving the equations shown on Figure 11A.

<u>Exit Shaping for Both Airplane Maneuverability and Passenger Comfort</u>

The limitation of passenger comfort apply equally to all aircraft. The B747, as shown on Figure 8 is the critical aircraft in terms of the side μ developed on the nose gear during a high speed maneuver.

Figure 12 shows the maximum turn rate that can be accomplished by a B747 given the following criteria:

Comfort: Acceptable to 90 percent of passengers
Maximum Lateral acceleration = 0.12 g

Maximum lateral jerk = 0.055 g/sec
Combined acceleration and jerk limited by the following equation:

$$(G/G_{MAX}) + (J/J_{MAX}) \leq 1$$

Airplane: Side μ on nose tires equal or less than 0.2

This provides a margin of 4 on dry pavement and a margin of 2 on wet pavement.

As shown on Figure 12, the B747 could use the current high speed exit at slightly over 18 m/s. Literature indicates, however, that the actual exit speeds for the widebody aircraft are 11-13 m/S. The difference may be largely accountable to the lack of an accurate indication of ground speed. In any event, the curves shown in Figure 12 are the ideal shape for the B747 and deflect the sharpest turning that can reasonably be expected from the B747.

Basic Crew Functions

<u>Decision Process</u>

The basic sequence of events during a typical approach and landing includes three primary decisions which must be made by the flight crew:

1. During final approach, the crew must decide to continue the landing or execute a missed approach.

MAX G'S = 0.12G
MAX JERK = 0.055G/SECOND } COMFORTABLE FOR 90 PERCENT OF PASSENGERS
ACCEPTABLE FOR 95 PERCENT OF PASSENGERS

LIMITATION FOR COMBINED G'S AND JERK BASED ON: $\frac{G}{G_{MAX}} + \frac{J}{J_{MAX}} \leqslant 1$

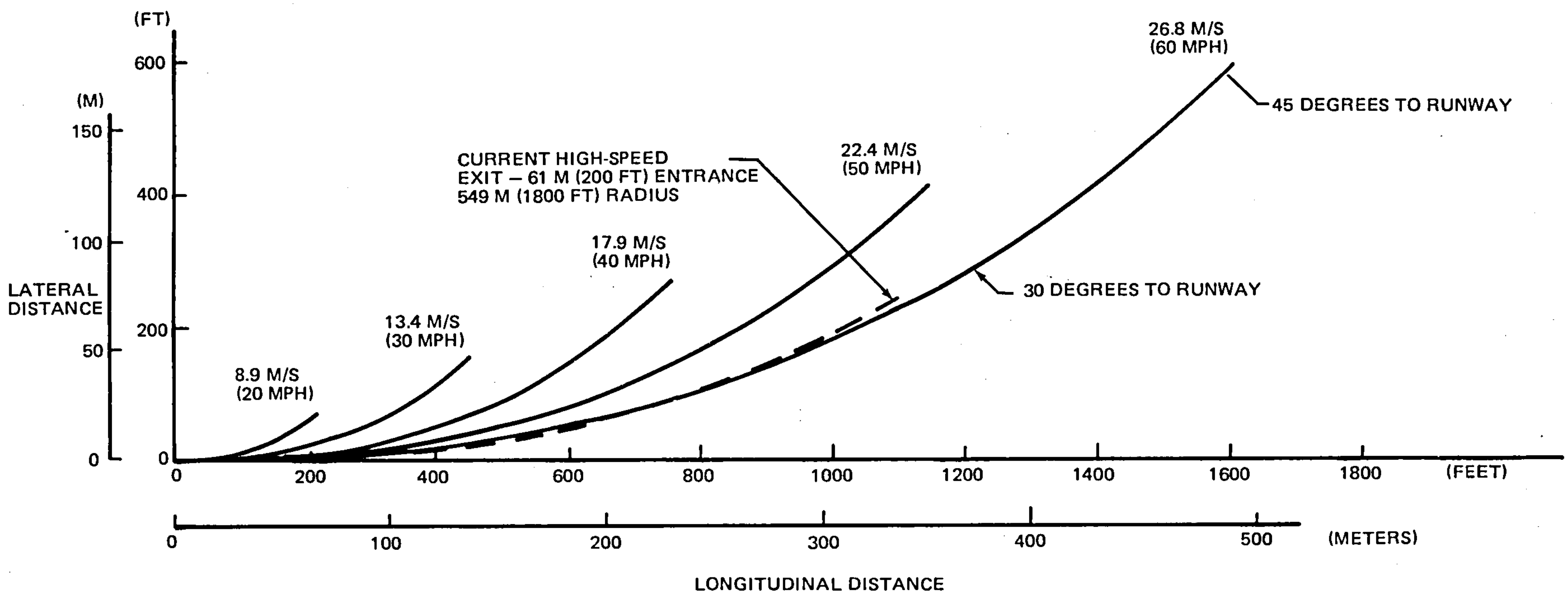


FIGURE 11. MINIMUM TURN – LIMITED BY PASSENGER COMFORT

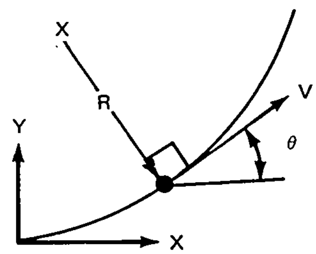
$G_{MAX} = 0.12$
$J_{MAX} = 0.055$
$G = 0$
$\theta = 0$
$T = 0$
$\Delta T = 0.001$
$X = 0$
$Y = 0$
V = VELOCITY

$R = V^2/gcG)$

$$J = J_{MAX}\left[1 - \frac{G}{G_{MAX}}\right]$$

$\theta = V/R$

$T = T + \Delta T$
$X = X + V \times \Delta T \times \cos\theta$
$Y = Y + V \times \Delta T \times \sin\theta$
$\theta = \theta + \theta\ \Delta T$
$G = G + J\ \Delta T$



WHERE: T = TIME
ΔT = INTEGRATION STEP TIME
R = TURN RADIUS
g_c = GRAVITATIONAL CONSTANT

FIGURE 11A. SOLUTION OF COMFORT-LIMITED TURN PATH

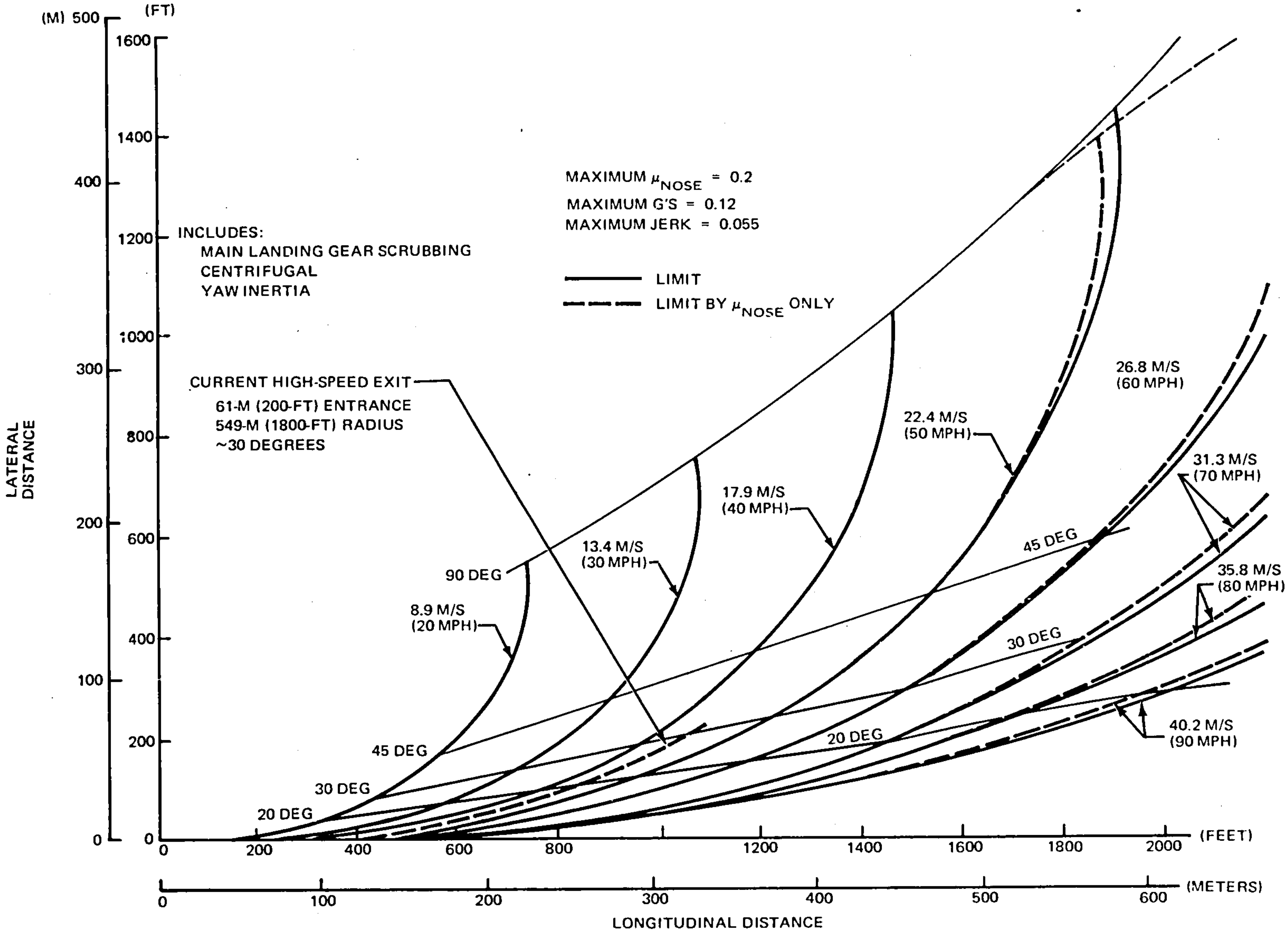


FIGURE 12. B747-100 MAXIMUM TURN RATE LIMITED BY BOTH NOSE LANDING GEAR SIDE μ AND PASSENGER COMFORT

2. Assuming that the landing is completed, the crew must then determine whether to take the designated high-speed exit or continue decelerating.

3. As the turnoff maneuver is completed, the crew must decide to enter the taxiway or wait for traffic to clear.

Because of the minimal separation between aircraft, timely information regarding the position of other aircraft and potential traffic conflicts will constitute an essential information requirement for the landing aircraft. For example, if the lead aircraft fails to take the designated exit, the trail aircraft may be required to execute a missed approach. If an aircraft fails to clear an exit or taxiway within the time allowed, it may be necessary for the following aircraft to use alternate exits and/or taxi routes. The diagram in Figure 13 illustrates the relationships between landing aircraft performance and information requirements for trail aircraft. This information could be provided to the flight crew in several ways:

1. Direct visual reference (assuming adequate visibility)
2. Air traffic control or ground control advisories
3. Cockpit display of ground and local traffic information
   a. Current
   b. Predicted

Control Process

In order to control the aircraft safely through the landing roll and turnoff, the pilot and automatic control system must be provided with continuous information regarding speed, alignment and distance to exit. In addition, the crew must be aware of certain characteristics specific to the aircraft and operating environment which may have an impact on directional control.

Factors influencing performance of the high-speed turnoff maneuver may be divided into four basic categories:

1. Aircraft Characteristics
2. Runway/Exit Characteristics
3. Environmental Conditions
4. Flight Crew Experience/Training

Examples of each type of factor are presented in Table 11. Items listed under categories 1, 2 and 3 may be viewed as potential information requirements for contol of the aircraft. Factors identified under category 4 will influence the efficiency and accuracy with which the crew can process this information and perform the required control actions.

Pilot Survey

An opinion survey was conducted in order to obtain the judgments of experienced pilots regarding needs for improved information and methods for presenting information to the crew. A total of 12 pilots were asked to rate the utility of various types of pilot information in performing high-speed turnoff maneuvers. The survey participants were Douglas Aircraft Company employes (instructor or engineering test pilots) with commercial air carrier experience. All but one of the pilots had previous experience with existing high-speed runway exits. For purposes of completing the questionnaire (Appendix A), pilots were asked to make the following assumptions:

BASIC PILOT INFORMATION REQUIREMENTS

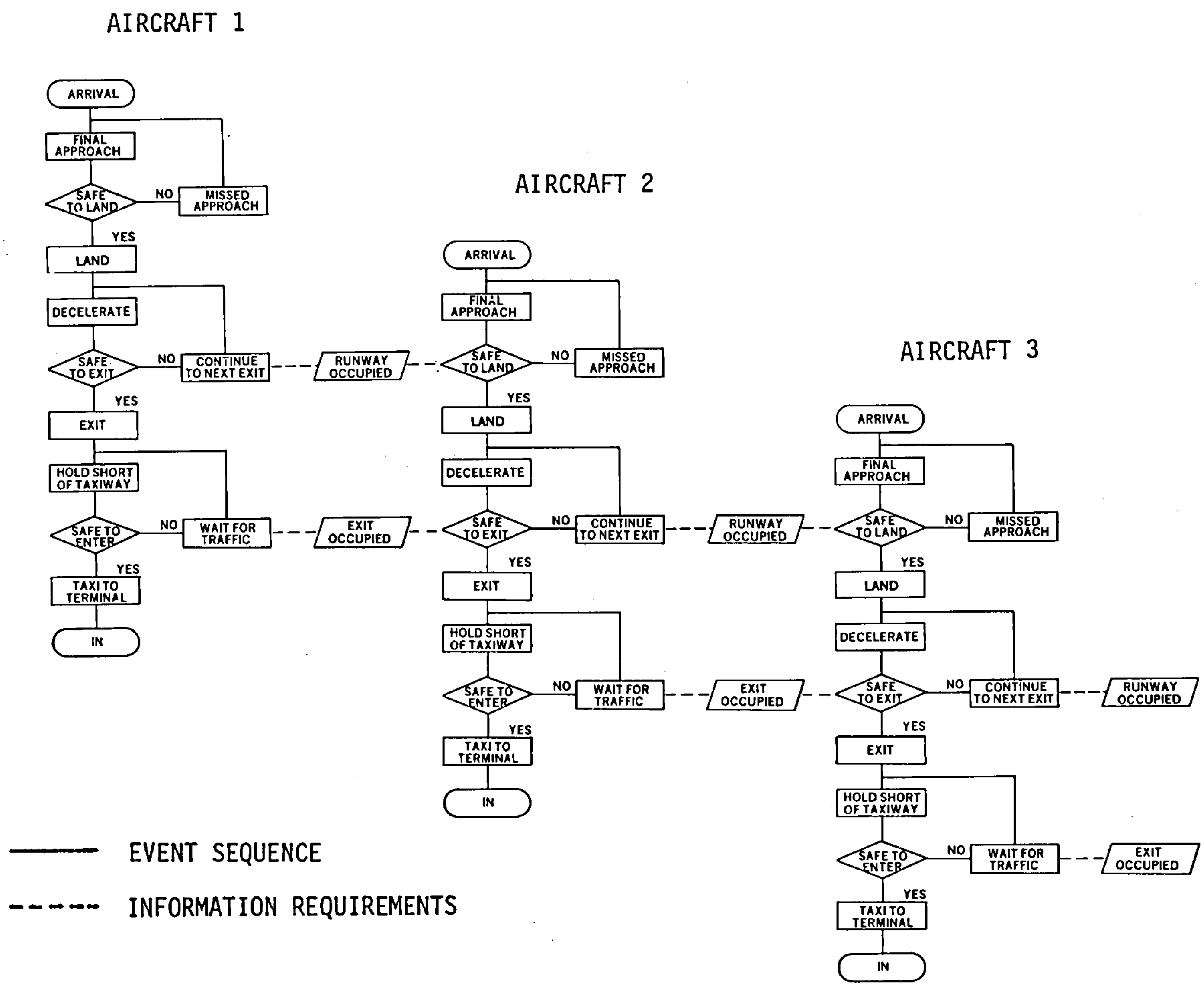


FIGURE 13.

TABLE 11

FACTORS INFLUENCING PERFORMANCE OF HIGH-SPEED TURNOFFS

1. <u>AIRCRAFT CHARACTERISTICS</u> • AIRCRAFT TYPE • GROSS WEIGHT • CENTER OF GRAVITY • CONTROL TYPES – GAINS – RUDDER – BRAKES – NOSEWHEEL STEERING	2. <u>RUNWAY/EXIT CHARACTERISTICS</u> • ROUGH-SMOOTH • CROWNED-FLAT • WET-DRY • GROOVED-NOT GROOVED • LIGHTING • MARKING • SIGNING
3. <u>ENVIRONMENTAL CONDITIONS</u> • VISIBILITY – DAY – NIGHT – WEATHER • WIND – DIRECTION – INTENSITY – SHEAR – TURBULENCE	4. <u>FLIGHT CREW EXPERIENCE/TRAINING</u> • AIRCRAFT HANDLING QUALITIES • HIGH-SPEED EXITS (GENERAL) • SPECIFIC AIRPORT – RUNWAY – EXIT – TAXIWAY SYSTEM

1. Exit angle = 30 degrees
2. Exit speed = 30 to 50 knots
3. Aircraft approach intervals of 2 to 3 miles
4. Worst-case visual conditions for high-speed exit operations would be CAT IIB.
5. The high-speed exit system would have to accommodate night operations.
6. Aircraft would be required to stop prior to crossing taxiway or active runway. Available stopping distance will vary substantially across airports.

Comments and suggestions for improved cockpit displays and external visual aids were obtained from several pilots during informal follow-up interviews. A complete breakdown of responses of objective questionnaire items is shown in Table 12. Some highlights of the survey results are summarized below:

- In general, pilots were more concerned with improving the accuracy of information on present status rather than predicted status (e.g., speed, distance, alignment, etc.).

- Improved information on runway conditions (runway traction) was considered very important for performance of all decision and control functions.

- Improvements in the availability and accuracy of information on current speed and position was generally considered more useful than deviation from optimum parameters (e.g., nominal deceleration profile).

- Improved traffic information (runway, exit, and taxiway clearance) was considered very important by most pilots. This is probably due in part to the requirement for reduced visibility and night operations.

- Improved information on taxi routes was considered helpful by most pilots both as a criterion for exit selection and as information for performing the exit activity.

- Feedback on available braking capacity was considered to be a desirable feature by most questionnaire respondents.

Exit Identification

Many of the current standards for design of runway exits are based on a research report prepared in 1958 by the University of California at Berkeley (Reference 20). This report recommended additional research engineering and development to assess requirements for improved lighting, marking and signing. Although research programs to define these requirements were never undertaken, there is a general consensus within the industry and FAA that further effort is needed in identification of exit locations from the pilot's point of view (Reference 22). A review of existing standards reveals a number of specific areas requiring further study, e.g., for exit lighting (Reference 24) and for exit marking and signing (Reference 20).

Exit Lighting

FAA advisory circular 150/5340-19 (Reference 24) provides a standard for high-speed angled exits with in-pavement centerline lighting systems. The recommended configuration consists of a series of green lights spaced at 50

TABLE 12
SUMMARY OF PILOT SURVEY RESPONSES (n = 12)*

1. DECISION ACTIVITY – LANDING VERSUS GO-AROUND

ADDITIONAL OR IMPROVED INFORMATION	USE-LESS	LIMITED USE	HELP-FUL	VERY HELP-FUL	ESSEN-TIAL
VISIBILITY (DISTANCE)			3	5	4
PREDICTED TOUCHDOWN POINT	6	2	2	1	1
PREDICTED TOUCHDOWN SPEED	7	3	1		1
PREDICTED GROUND SPEED AT EXIT THRESHOLD	7	3	2		
RUNWAY TRACTION (COEFFICIENT OF FRICTION)		1	2	4	6
RUNWAY CLEAR	1	1		2	8
EXIT CLEAR	2	2	3		5

2. LANDING ACTIVITY

ADDITIONAL OR IMPROVED INFORMATION	USE-LESS	LIMITED USE	HELP-FUL	VERY HELP-FUL	ESSEN-TIAL
TOUCHDOWN POINT	8	2		1	1
TOUCHDOWN SPEED	8	1	1	1	1
DISTANCE TO EXIT	1	1	2	5	3
RUNWAY TRACTION (COEFFICIENT OF FRICTION)		1	2	5	4
PREDICTED SPEED AT EXIT THRESHOLD	6		4	2	
RUNWAY CLEAR	1			2	9
EXIT CLEAR	1	1	3		7

3. DECISION ACTIVITY – EXIT/CONTINUE DECELERATION

ADDITIONAL OR IMPROVED INFORMATION	USE-LESS	LIMITED USE	HELP-FUL	VERY HELP-FUL	ESSEN-TIAL
PREDICTED SPEED AT EXIT THRESHOLD	6	1	3	2	
PREDICTED ALIGNMENT AT EXIT THRESHOLD	7	1	1	3	
RUNWAY TRACTION (COEFFICIENT OF FRICTION)	1		1	5	6
DEVIATION FROM NOMINAL DECELERATION PROFILE	5		2	4	1
COMPUTER GENERATED SOLUTION (GO-NO GO) BASED ON CURRENT ENVIRONMENTAL AND AIRCRAFT INFORMATION	4	1	3	2	
EXIT CLEAR	1			1	10
TAXI ROUTE TO GATE	3	1	2		6

4. RUNWAY EXIT ACTIVITY

ADDITIONAL OR IMPROVED INFORMATION	USE-LESS	LIMITED USE	HELP-FUL	VERY HELP-FUL	ESSEN-TIAL
ALIGNMENT	3		5	1	2
GROUND SPEED	3	1	4	3	1
DEVIATION FROM OPTIMUM PATH	7	1	3	1	
DEVIATION FROM NOMINAL DECELERATION PROFILE	7	2	2	1	
RESERVE BRAKING CAPACITY	3		3	5	
RUNWAY TRACTION (COEFFICIENT OF FRICTION)			3	3	6
LATERAL G-FORCES (OBSERVED)	7	3		1	
LATERAL G-FORCES (ALLOWABLE LIMITS)	7	2		2	
TAXI ROUTE TO GATE	3		1	4	4
GROUND TRAFFIC INFORMATION	3		1	4	4

*NOTE: IN SOME CASES FREQUENCIES DO NOT TOTAL TO 12 BECAUSE OF ITEMS OMITTED OR AMBIGUOUS RESPONSES foot intervals and extending onto the runway parallel to the runway centerline lights (Figure 14). This arrangement is considered generally adequate for providing guidance to the taxiway.

When multiple exits are in use, however, the pilot may require additional information identifying the particular exit to be taken. One concept under consideration would employ flashing lights, activated manually by the controller to designate the appropriate exit. Researchers at the University of Toronto (Reference 22) have recommended an experimental evaluation of the feasibility of this concept.

Alternative concepts for exit lighting include the following:

1. Use of sequential flashing centerline lights to identify the exit and provide directional guidance through the exit rollout.

2. Color coding applications

   a. Provide safe/unsafe indication (green-red) at the exit threshold based on
      - Landing aircraft speed and alignment
      - Presence of conflicting traffic

   b. Identification of primary and secondary exit options

Exit Marking and Signing

The Berkeley report (Reference 20) recommended that minimum width of centerline markings for high-speed turnoffs should be 12 inches. Present standards for centerline markings specify 6 inches as the minimum allowable width for centerline markings. There are currently no centerline marking requirements for high-speed turnoffs with in-pavement lighting systems. Some researchers (ARD-410) have expressed concern that the light fixtures themselves do not provide adequate visual reference when the lights are turned off. Similar ambiguities exist with respect to design standards for taxiway guidance signs. Current FAA advisories do not require any unique signs for identification of high-speed turnoffs.

As part of the phase II simulation program, alternatives for improved lighting devices and markings should be evaluated. Concepts should be developed for exit identification and minimum requirements for exit and taxiway visual references should be established.

Braking Performance

The timing and manner in which brake pressure is applied varies significantly with individual pilot technique. According to Attri and Amberg (Reference 19) acceptable braking performance can also vary substantially with runway conditions. On dry runways with good traction, the pedals can be pressed firmly for efficient use of available braking capacity. On wet or icy runways, brake pressure should be applied sparingly with partial braking early to avoid wheel lockups.

Braking performance during high-speed turnoffs will be particularly critical due to the following fundamental requirements:

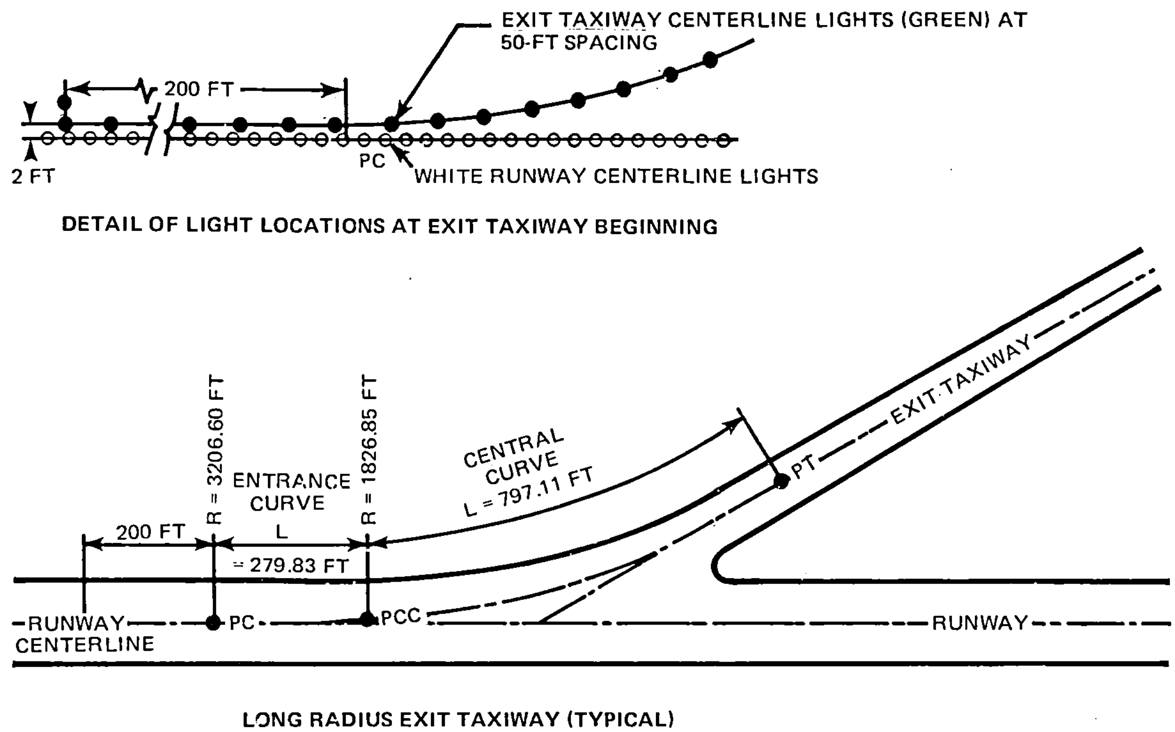


FIGURE 14. RECOMMENDED IN PAVEMENT CENTERLINE LIGHTING OF ANGLED EXIT

1. The crew must be able to bring the aircraft to a complete stop prior to entering a taxiway.

2. High-speed turnoffs must be performed under a variety of weather conditions.

3. Excessive tire and brake wear must be avoided.

4. Smooth deceleration profiles should be maintained for passenger comfort.

Results of 1971 simulator evaluations of pilot performance during rejected takeoffs indicate that pilots often fail to apply full available braking pressure when required to make emergency stops (Reference 23).

Results of these tests also demonstrate the value of a high fidelity motion base simulator as a training device for aircraft ground handling characteristics.

In view of these findings it is recommended that the Phase II simulation program should include an evaluation of the following:

1. Improved cockpit display to provide the pilot with feedback on braking efficiency and/or reserve braking capacity.

   a. Visual display
   b. Auditory display

2. Pilot training on correct braking technique for high-speed turnoffs.

   a. Good runway conditions
   b. Adverse runway conditions

Speed and Distance Information

In performing a high-speed turnoff, the basic speed parameter of interest is true ground speed in relation to the criterion ground speed for the designated exit. In conventional aircraft, accurate information on ground speed and distance to exit cannot be obtained readily. Sources of speed information are generally restricted to the following:

1. External visual cues
2. Cockpit airspeed indicator
3. (a) Analog scale readout
   (b) Digital readout
3. Digital readout of ground speed on a pedestal-mounted Control Display Unit for some aircraft equipped with inertial navigation systems.

The ability of pilots to make accurate estimates of ground speed based on external visual cues can vary as a function of training and experience with the particular aircraft type. Also, some recent studies of pilot behavior during simulated rejected takeoffs suggests that there may be a systematic tendency for pilots to underestimate ground speed. For example some FAA, airline and Douglas pilots may have felt that speeds were much lower than actual when speed decreased below 80 knots in a DC-10 engineering development simulator (Reference 21).

The cockpit airspeed instrument is of limited use during rollout for three reasons:

1. Airspeed may not correspond closely to ground speed due to the presence of wind components.

2. Airspeed data is only reliable during the high-speed segment of the landing roll (prior to thrust reverser deployment).

3. In order to read the instruments, the pilot must direct his visual scan inside the cockpit while attempting to maintain directional control through outside visual reference.

In view of the critical nature of ground speed information and the limitations discussed above, it is evident that improvements in speed and distance-to-exit information should receive high priority for follow-on study efforts.

Lateral Guidance

In conventional aircraft, runway alignment is maintained by direct reference to external visual cues and manual control using rudder pedals and active nose-wheel steering. The basic alignment reference for daytime and clear weather operations is the painted runway centerline markings. For night operations in good visibility, lateral guidance information is provided by runway centerline and edge-lighting systems. The primary function of alignment information during runway rollout is to guide the aircraft to the optimum point for initiating the turning maneuver. It is assumed that this point (PC) would correspond to the intersection of the runway centerline and the line defining the optimum exit path. Significant deviations from proper runway alignment could necessitate excessive or abrupt control movements to achieve the optimum exit ground track.

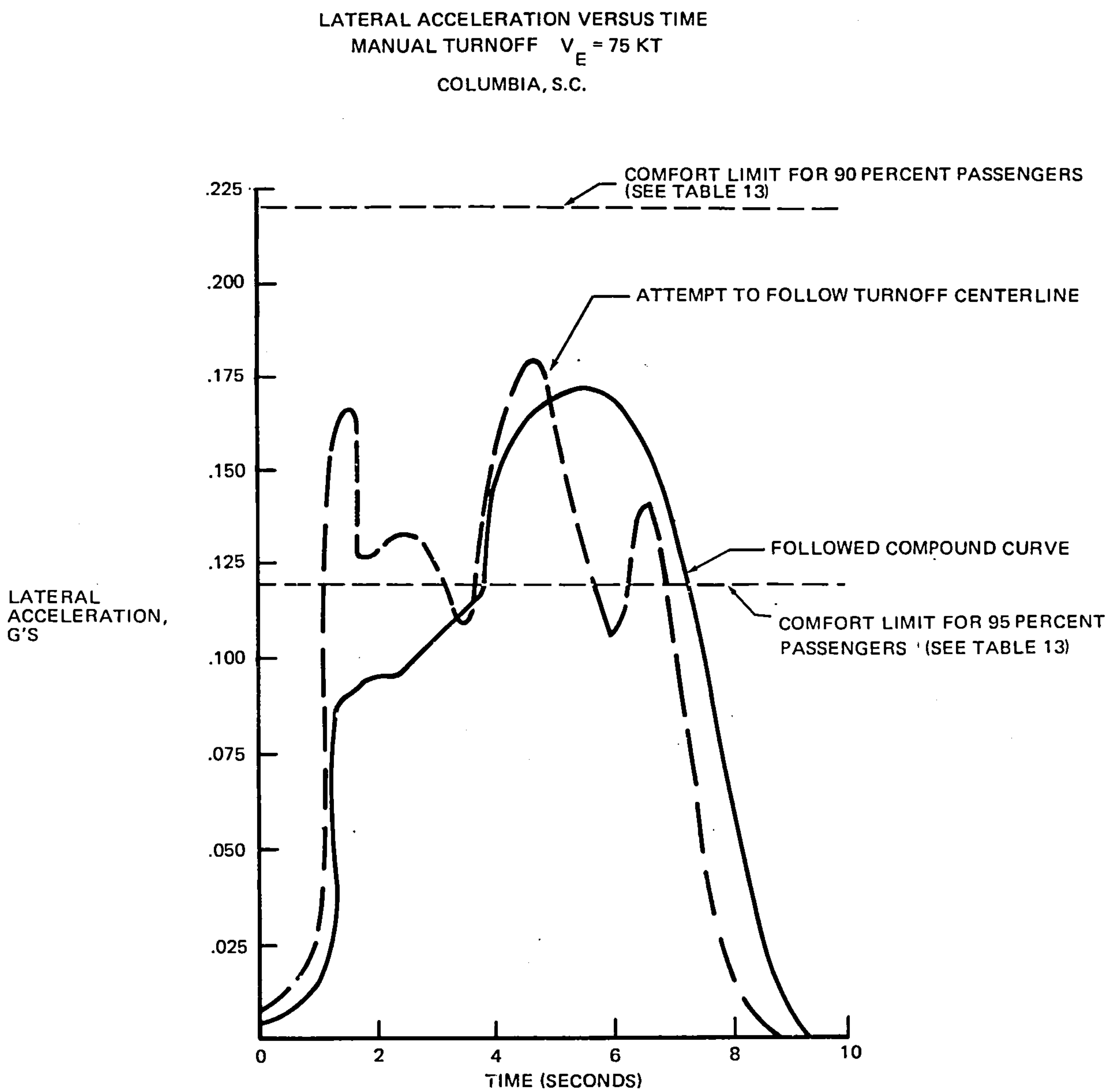
Lateral guidance information during performance of the turnoff maneuver must satisfy two basic requirements:

1. Assist the pilot in maintaining a safe position, well within the exit boundaries.

2. Define a nominal ground track that will minimize side loads on the aircraft and passengers.

The effect of visual alignment information on pilot performance is shown graphically in Figure 15. These data were obtained during actual high-speed turnoff maneuvers on a standard 30 degrees angled exit at Columbia, S.C. using the NASA Terminal Configured Vehicle (TCV) research aircraft. Lateral acceleration time histories are plotted for turnoffs using two guidance strategies: (a) following the exit centerline and (b) following the alternate compound curve exit path.

Based on inspection of these data, it is evident that the attempt to follow the compound curve resulted in a relatively smooth acceleration profile while exit centerline guidance resulted in more frequent variations in magnitude and rate of change of lateral forces (jerk). Also, peak values for both types of lateral acceleration profiles fall within the 90 to 95 percent passenger comfort limits (Reference 28). (The maximum lateral acceleration for the turnoff centerline trial corresponds roughly to a side load of 0.18g).



LATERAL ACCELRATION PROFILES FOR MANUAL HIGH-SPEED TURNOFFS USING TWO TYPES OF DIRECT VISUAL REFERENCE FOR LATERAL GUIDANCE
(ADAPTED FROM UNPUBLISHED DATA FROM NASA LANGLEY RESEARCH CENTER)

FIGURE 15. LATERAL ACCELERATION PROFILES

It should be noted that these data are based on single trials do not account for practice effects or variations in individual pilot strategy. The data do suggest, however, that simulation tests should be conducted to evaluate alternatives for improving external visual reference information for lateral guidance.

Reduced Visibility Operations

Under conditions of limited visibility (e.g., Category IIIa) operations, the light guidance systems may still provide adequate information for maintaining runway alignment. With runway visual ranges of 700 feet or less, visual information on exit location and distance will be minimal, and the pilot's ability to estimate ground speed from external visual cues may be substantially degraded. In the future, there may be a requirement for runway and exit operations without external visual reference (Category IIIb). Landing and turnoff maneuvers may be controlled manually or automatically using speed, alignment and distance data derived from nonvisual sensing devices.

In the absence of external visual cues, the crew must rely on cockpit information displays for rollout guidance and/or assessment of autoland system performance. The crew must have access to all essential information in order to complete the rollout and exit manually if an automatic control system failure occurs. Three basic types of information are required:

1. Nominal performance parameters (ground speed profile, ground track, etc.)

2. Current aircraft status relative to nominal values (direction and magnitude of corrective action required).

3. Feedback on accuracy of control actions (amount of overshoot, undershoot, etc.)

The display of relevant and accurate information in the cockpit will be an essential requirement for reduced visibility operations. Some alternatives under consideration for simulation tests include the following:

1. Visual display of speed, alignment, and distance information on an electronic head-down display (similar to the current TCV concept).

2. Head-up display of rollout and exit guidance information.

Pilot Performance

The controller is to order an approaching aircraft to execute a go-around if it is going to cross the threshold before the preceeding aircraft has exited the runway. This one-on-the-runway rule makes it essential to control the frequency of long runway occupancy times. Most of the variation in runway occupancy times is due to pilot performance. The following discusses the factors which cause the large variation in pilot performance which currently occurs.

Pilot Motivation

The following quote is from Reference 12:

"The single most significant contributing factor to higher runway occupancy time was made by carriers utilizing exits which were convenient to terminal gate locations. This fact was made clear by the existing patterns of most carriers at almost all airports."

An extreme example of pilot motivation exists at Los Angeles International (LAX) in comparing runway occupancy times on the south runways (25 L and 25 R) for United Airlines and Trans World Airlines. United uses the terminal nearest to the threshold of 25 L and 25 R; TWA uses a terminal on the other side of the field and all arrivals must use taxiway 47 which is approximately 3000 meters from the runway thresholds. The observed average runway occupancy times (Reference 12) were:

Average LAX Runway Occupancy Times

Heavy Aircraft			Large Aircraft		
Runway	UAL	TWA	Runway	UAL	TWA
25L	50.9 sec.	53.3 sec.	25L	44.8 sec.	51.9 sec.
25R	56.8 sec.	64.0 sec.	25R	52.6 sec.	61.5 sec.

These differences in observed runway occupancy times are because:

- UAL is more motivated than TWA to use an early exit.
- Runway 25R is very near the outbound taxiway and an aircraft must be able to stop very soon after exiting from this runway.

A pilot is motivated to perform the landing and runway exit to minimize time from threshold to gate and provides a ride that minimizes passenger discomfort and aircraft maintenance. The pilot generally tries for a precise touchdown, but the emphasis is on a smooth landing. Pilots will avoid runway exits that result in taxiway routes that are long, have sharp turns, and have traffic interference.

Some airlines have pilot evaluation programs which measure time and cost from touchdown to the gate. Airlines vary in their operating procedures regarding use of brakes, spoilers, and reverse thrust.

The controller cannot order a pilot to use a specific runway exit. However, he can request that the pilot expedite turning off the runway and suggest a specific exit be used. A test was performed at Denver Stapleton where the controller requested the pilot exit from the runway as soon as possible; the average runway occupancy time was reduced approximately 20 seconds. Controllers report that 90 to 95 percent of the pilots honor their request to expedite runway clearance by using a particular exit. The controller cannot order the pilot to land long (or short) in order to reduce runway occupancy time. It is unlikely that pilots would honor a request to land long because that reduces the available runway to stop the airplane in case something went wrong. The controllers report there is a difference between airlines in their compliance with controller requests to reduce runway occupancy times.

Airport Familiarity

To keep the wave off frequency less than one in two thousand, it is more important to reduce the standard deviation of runway occupancy time then to reduce the average runway occupancy time. (There is one chance in two thousand of exceeding the mean plus 3.29 standard deviations if the variable is normally distributed.) Many of the exceptionally long runway occupancy times are due to the pilot being unfamiliar with the airport.

Again, Los Angeles International is a good example of the extremes in pilot familiarity. A pilot for PSA, an intrastate carrier, can easily have three landings at LAX during a days work. A pilot for a foreign airline might not have three landings a year at LAX. The PSA pilot is so familiar with the airport that he can anticipate controller instructions. The foreign airline pilot isn't sure where the exits are, doesn't know which exit he wants, and isn't sure which taxiway the controller requests he use. The foreign pilot may not have experienced many flights into high density airports where he must minimize runway occupancy time because there is another airplane 2 miles behind him. The foreign pilot may never have experienced landing at LAX at night and/or in reduced visibility; these conditions will further complicate his orientation problems.

Pilot Training

There is basically no current pilot training in the use of high speed runway exits because they are not real important with today's longitudinal separation standards. Special pilot training will be required when separations are reduced and it becomes necessary to minimize runway occupancy times. This pilot training should include both simulator and actual flight operations. Unfortunately, the pilots of large domestic airlines are the most likely to receive special training in high-speed exit usage; while in practice these pilots are not responsible for the extreme runway occupancy times.

Impact of the Variation in Pilot Performance

One of the current research activities to increase airport capacity is the Wake Vortex Avoidance System (WVAS). The WVAS computes the minimum safe (from wake vortices) separation between two aircraft based upon the aircraft characteristics and the meteorological conditions. There is currently such a large difference in pilot performance in runway occupancy times that it would be necessary to consider the airline of the lead aircraft in determining the in trail separation which will keep the wave-off probability to an acceptable level. This variation in pilot performance will be reduced significantly when the pilots realize that they will cause a wave-off if they do not keep their runway occupancy time below a specified limit. The variation in pilot performance can be further reduced by:

- High-speed exits which also minimize time and effort to the gate
- Providing taxiway identification information to the pilot who is not familiar with the airport
- Pilot training.

Passenger Acceptance

A number of studies have demonstrated that perceived ride quality is a significant factor in determining passenger satisfaction and acceptance of various modes of public transportation (References 29 and 31). It is anticipated that introduction of high-speed exits at major hub airports may have a negative effect on passenger comfort due to excessive or unfamiliar motion forces associated with performance of the exit maneuver. A primary consideration for follow-on research is to assess the impact of these motion cues on ride quality and to establish limits for passenger acceptance. These criteria will be used in evaluation of alternatives for design and placement of candidate high-speed exits.

Passenger comfort during landing, rollout and taxi is a function of two primary motion cues: acceleration and "jerk" or rate of change in acceleration. The basic changes in acceleration forces associated with introduction of high-speed angled exits will consist of:

1. Increased lateral g forces as a result of following a curved path at high speed

2. Increased longitudinal g forces resulting from more rapid deceleration profiles.

The direction and magnitude of acceleration forces are dependent upon the velocity of the aircraft, the radius of the curve, degree of cant of the exit surface, the suspension system of the vehicle, the pathway guidance strategy and the smoothness with which the pilot performs the maneuver.

Passenger Comfort Criteria

The effects of motion forces on subjective judgments of comfort have been evaluated in numerous experimental and field research studies. Rinalducci (Reference 30) noted a close correspondence between ride quality data acquired in ground based simulators and field test data recorded in an actual aircraft. These findings suggest that valid criteria for passenger comfort might be established through simulation of aircraft motion characteristics. The results of previous studies constitute a data base for estimating passenger acceptance limits for high-speed exit ride quality characteristics. It should be noted, however, that direct application of previous research findings to the present problem is limited to some extent by several basic considerations:

1. The majority of studies dealing with motion characteristics and ride quality have dealt with vibration rather than sustained g forces. According to McKenzie and Brumaghim (Reference 29) vibration inputs representing vehicle motion are often of a single frequency, single axis nature.

2. Relatively little information is currently available on the combined effects of multiaxis motion forces on subjective response within the comfort acceptability range.

3. Quantitative data on the interactions between acceleration forces and other environmental factors is generally lacking.

4. The particular environmental context and individual expectations may have a significant effect on perceived ride quality and acceptability. As a consequence, acceptable ride criteria for one transportation mode may not generalize directly to another form of transportation.

Based on an extensive review of the literature on ride quality, Jacobson (Reference 28) concludes that "the wide variation in the data of both researchers requires a conservative approach to criteria at this date." Jacobson also emphasizes the importance of environmental factors, duration of exposure, and type of passenger restraint and their possible effects on specific criterion values.

Given these limitations, it is apparent that comfort criteria may be subject to revision based on the outcome of passenger simulation trials. The ride quality criteria cited in this report should be viewed as guidelines for further testing and will be valuable in establishing priorities for simulation effort.

Acceleration Forces

Lateral g forces

Jacobson (Reference 28) points out the need for better definition of criteria for passenger acceptance of steady state lateral (side to side) g forces that might be experienced in flight or ground maneuvers. The best available information at present may be derived from data on passenger comfort in ground transportation systems during high-speed turns. Proposed criteria for comfort and acceptability of lateral g forces and rate of change of g forces (jerk) are presented in Table 13. These criteria are based on passenger ratings of motion cues in train systems.

Longitudinal g forces

Relatively little data is currently available on subjective judgments of comfort in response to motion in the longitudinal (back and forth) direction. Available information indicates that criteria for acceptability lie approximately in the same range as those proposed for lateral motion. Jacobson (Reference 28) suggests the following allowable values for longitudinal accelerations which apparently correspond to the 95% passenger comfort limits for lateral acceleration (Table 13).

Acceleration or deceleration	0.13 g
Rate of change (jerk)	0.03 g/sec.

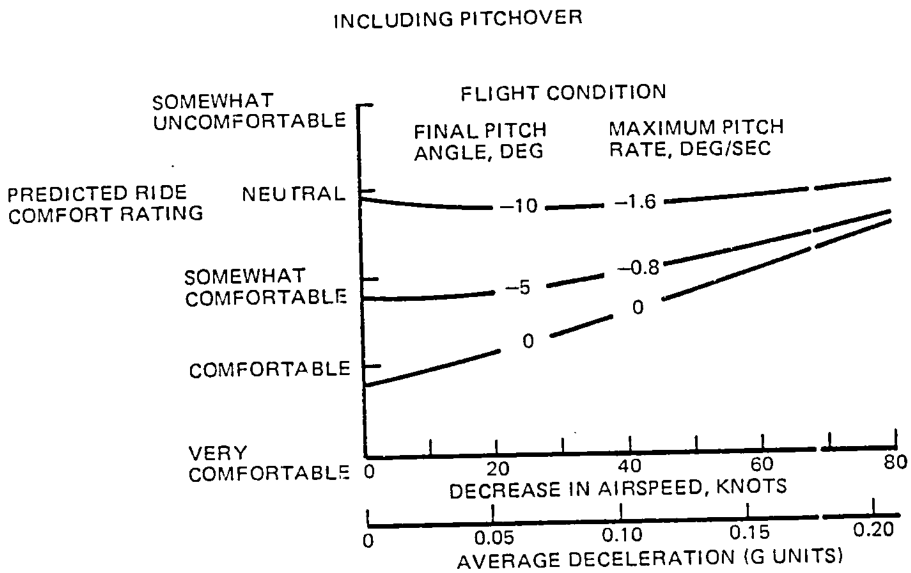
Results of recent studies of passenger response to motion in flight maneuvers indicate that these criteria may be somewhat conservative. Schoonover (Reference 31) recorded subjective responses of passengers to motion during a variety of terminal area flight maneuvers. Figure 16 shows ride comfort rating trends for a 20 second deceleration from 200 to 120 knots followed by a 10 second pitchover maneuver. Ride comfort was only mildly affected by longitudinal deceleration. Longitudinal forces as high as 0.20g failed to elicit uncomfortable ride quality ratings even when combined with angular accelerations of the pitchover maneuver. The higher upper limit obtained by Schoonover could be due to a 90 percent rather than a 95 percent passenger comfort limit, a different in subject populations or other considerations such as prior experience. A follow-on investigation should be performed to more clearly define the longitudinal comfort limit parameters.

TABLE 13

LATERAL ACCELERATIONS

QUALITY RATING	PERCENT PASSENGERS	CHARACTERISTICS OF LATERAL ACCELERATION ACCELERATION (G)	JERK (G/SEC)	DURATION (SEC)
COMFORTABLE	90	<0.22	0.07	NO LIMIT
	95	<0.12	0.05-0.06	NO LIMIT
ACCEPTABILITY	90	<0.12	0.05	NO LIMIT
(EQUALS LUXURY)	95	≤0.07-0.08	0.03-0.04	10-20 (FOR MAXIMUM VALUES)

*NOTE: ADAPTED FROM JACOBSON (1974)



PREDICTED COMFORT OF LONGITUDINAL DECELERATIONS
FOR VARIOUS FINAL PITCH ANGLES (SCHOONOVER, 1975)

FIGURE 16. PREDICTED COMFORT OF LONGITUDINAL DECELERATIONS

Other Environmental Factors

Definitive information on the combined effects of variables on ride quality is generally lacking in the literature. As a consequence, few conclusions may be drawn regarding interactions between acceleration forces and other environmental factors (e.g., visual and auditory cues). Researchers generally agree that certain combinations of motion variables are judged more stressful than any component variable alone (References 28 and 29).

Although the effects of visual cues have not been fully investigated, some data suggests that the presence of an external visual reference may have a significant influence on ride quality ratings. Conner (Reference 25) found that the effect of external visual cues was highly dependent upon the nature of the maneuver being performed. For random motion ride environments, presence of a window adjacent to the passenger's seat appears to have a slightly favorable effect on comfort. An unfavorable effect was noted during tight turning maneuvers at low altitude. The discomfort sensation was attributed in part to the changes in forces on vestibular organs resulting from the interaction of head movements and aircraft accelerations.

Although ambient noise characteristics are significant factors influencing passenger comfort, it is unlikely that auditory stimuli will play a major role in determining acceptability of high-speed exit configurations. No significant changes in the quality or intensity of auditory cues are anticipated as a result of angled exit use. The primary importance of auditory stimuli in the passenger acceptance tests involves maintaining the fidelity of the simulation environment.

Individual Differences

Review of existing ride quality data indicates that there may be substantial differences between individual passengers in subjective evaluation of vehicle ride quality. According to McKenzie and Brumaghim (Reference 29), the passenger's age, background, ride experience, motivation, physical and psychological condition have a direct affect on the subjective ratings of acceptability and comfort.

Hanes (Reference 27) points out that most investigations of human response to motion have used small samples of test subjects selected primarily because of their availability, not because they are representative of the population of interest. Most data on passenger comfort obtained from simulator tests are based on experiments using a small number of subjects with professional or semiprofessional backgrounds. Criteria derived from empirical studies of this type often do not agree in interpretation of acceptable comfort limits.

Wolf, Rezek and Gee (Reference 32) suggest that volunteer groups of the type that are typically used in aircraft ride quality research are strongly biased toward liking to fly. Results reported by Duncan and Conley (Reference 26) demonstrated that subjects having a positive attitude toward flying tend to be more tolerant of motion forces. Significant differences in mean comfort ratings were also noted as a function of sex and measures of state anxiety. The researchers concluded that demographic, attitudinal and personality variables should be considered in selection of subjects for ride quality studies.

Implications for the Simulation Program

Based on results of previous studies, a number of conclusions can be drawn with respect to the proposed passenger acceptance tests.

1. A complete assessment of passenger acceptance will require a relatively high-fidelity simulation with accurate representation of motion profiles and visual cues.

2. Presentation of realistic auditory cues would be desirable since it would enhance the fidelity of the simulation and would be easy to implement.

3. The subject sample should be stratified on the basis of demographic attributes and should be representative of the typical airline passenger population.

AIRPORT DESIGN AND OPERATIONS

This study is primarily concerned with airports which will operate with reduced in-trail separations because they have advanced air traffic control systems (i.e., metering and spacing, wake vortex avoidance systems, discrete address beacon system, microwave landing systems, etc.). It is doubtful if more than twenty airports will be so equipped by the end of the century. There are only about ten airports where these systems could be justified today.

There is no standard airport design. The primary factors in designing the landside components of an airport (terminal buildings, parking, and support facilities) are:

- ground access
- number of enplaned passengers and transfer percentage
- domestic and international percentages
- enplaned cargo tonage
- design of airside components
- support facility requirements (e.g., maintenance)
- available real estate
- number of operations and aircraft mix (by airline)
- funds available and year constructed

The primary factors in designing the airside components of an airport (runways, taxiways, and apron gate area) are:

- available real estate
- restrictions (obstacles, airspace, environmental)
- number of aircraft operations
- aircraft mix and stage length
- meteorological conditions and altitude
- funds available and year constructed

No two airport designers would design identical airports for the same set of conditions.

Table 14 summarizes some of the key airport characteristics of the major airports in large U.S. hub cities. Aircraft 4W, 3W, and half of 4N (4 engine widebody, 3 engine widebody, and 4 engine narrowbody) are classified as heavy aircraft.

Angled Exit Inventory

The following is from the FAA Advisory Circular on airport design (Reference 34):

> "A decision to design and construct an acute-angled exit taxiway is based upon an analysis of the existing and contemplated traffic. The main purpose of the angled exit, commonly referred to as the "high-speed exit," is to enhance the capacity of the airport.
>
> Configuration. The establishment of a single standard for angled exits has many advantages. Pilots become familiar with the configuration and can expect the same results when landing at any airport with these facilities.

TABLE 14

TOP 25 U.S. AIRPORTS: SIZE, LOCATION, DEMAND, AND FLEET MIX RANKED BY TOTAL SCHEDULED ARRIVALS

AIRPORT		FIRST COMM SERVICE	RUNWAYS OVER 1500 m	AREA (km^2)	km FROM CBD	AUGUST 1978 SCHEDULED AIRCRAFT ARRIVALS						
							PERCENT PER AIRCRAFT TYPE (1)					
CITY	CODE					TOTAL	4W	3W	4N	3N	2N	PROP
CHICAGO	ORD	1959	6	28.3	30	1031	3	11	11	39	19	17
ATLANTA	ATL	1930	4	15.2	13	690	0	9	6	39	39	7
LOS ANGELES	LAX	1928	4	14.2	27	658	5	15	13	35	15	17
DALLAS	DFW	1973	3	72.8	27	548	1	4	5	55	15	20
DENVER	DEN	1929	4	18.8	11	493	0	4	12	32	23	29
SAN FRANCISCO	SFO	1926	4	21.1	24	423	6	9	16	39	23	7
BOSTON	BOS	1933	4	9.3	5	421	1	5	8	27	19	40
NEW YORK	LGA	1939	2	2.6	13	420	0	3	0	48	24	25
NEW YORK (2)	JFK	1948	4	20.0	24	407	17	11	27	18	10	15
MIAMI (3)	MIA	1929	3	13.1	8	375	1	11	10	41	23	13
PITTSBURGH	PIT	1952	3	40.5	27	371	0	0	5	20	44	31
WASHINGTON	DCA	1941	2	3.4	5	348	0	0	0	49	26	25
PHILADELPHIA	PHL	1940	3	10.1	11	346	1	7	7	21	21	43
ST. LOUIS	STL	1942	4	8.1	16	312	0	4	9	35	35	17
HOUSTON	IAH	1969	2	32.4	27	284	2	8	3	43	24	20
DETROIT	DTW	1955	3	15.0	24	272	4	7	9	31	29	20
SEATTLE	SEA	1942	2	8.9	24	242	3	13	8	39	13	24
NEW YORK	EWR	1928	3	9.3	23	239	1	10	10	30	22	27
HONOLULU	HNL	1927	4	19.5	16	229	15	7	5	0	38	34
MINNEAPOLIS	MSP	1920	3	12.1	16	225	3	7	1	44	25	20
KANSAS CITY	MCI	1972	2	20.2	24	218	0	1	4	55	12	28
CLEVELAND	CLE	1925	5	6.5	19	211	0	3	6	36	43	12
TAMPA	TPA	1927	3	13.4	10	202	0	4	5	52	29	10
LAS VEGAS	LAS	1948	3	6.9	11	171	0	7	7	25	43	18
NEW ORLEANS	MSY	1946	2	6.9	19	162	0	9	2	49	28	12

(1) AIRCRAFT TYPE IDENTIFIES: NO. OF ENGINES, WIDE OR NARROW BODY

(2) JFK ALSO HAS 1 PERCENT 2W AND 1 PERCENT SST

(3) MIA ALSO HAS 1 PERCENT 2W

(1) To achieve the desired entrance speed (or runway turn-off speed) capability of up to 60 m.p.h., a minimum radius of curve of 1,800 ft. is required as noted in Figure 12,* page 17, and Figure 13,* page 18. These figures illustrate angled exit taxiways with a 30 degree angle of intersection. This angle can vary but the curve radii should be maintained as standard.

* From Reference 34 report.

(2) The entrance point at which turnoff speed of 60 m.p.h. may be realized is located on the runway centerline at the beginning of the curve (point of curvature, P.C.) as shown on the figures.

(3) The taxiway centerline marking starts 200 ft. back of the P.C., and is offset three feet from the runway centerline. (See AC 150/5340-1B.)

Location. The locations of exit taxiways depend upon the performance of the airplanes and the configurations of the exits.

(1) To accommodate the average mix of today's air carrier airplanes, locate the P.C of the angled type taxiway exits at intervals beginning approximately 3,000 ft. from the threshold to approximately 2,000 ft. of the stop end of the runway."

Table 15 summarizes an inventory of angled exits at the top ten U.S. airports. There is considerable disagreement on the effectiveness of these existing angled runway exits.

Table 15 only defines the characteristics of runway exits which have an angle less than 40 degrees. Most of these runways also have exits greater than 40 degrees which are not listed on the table. Multiple exits are essential because:

- A single exit could become congested if it intersects an active runway or taxiway. The time between consecutive landings will be less than one minute and the taxiway system must have an adequate capacity or it will prevent the ruwnway from operating at its full potential.
- There is a difference between aircraft types in approach speeds and deceleration rates. The optimal exit design and location for one aircraft type could be far from optimal for other aircraft types.

Table 15 illustrates the very large variation in the location of high-speed exits. All seven high speed exits at La Guardia (LGA) are within 1500 meters of the threshold. Eight of the ten high-speed exits at Denver (DEN) are more than 1500 meters from the threshold. The primary reasons for the difference in exit location at LGA and DEN are:

- DEN is at an elevation of 1625 meters and this increases the average landing field length requirement by 200 to 400 meters.
- DEN has more large aircraft than LGA.
- Exits near the threshold at LGA have better terminal access. Distance from the threshold to the gate is not reduced by an early exit from 35L, R and most cases from 26L, R at DEN.

TABLE 15
ANGLED EXIT INVENTORY

RUNWAY				ANGLED EXITS					
AIR-PORT	RWY NO.	LENGTH (METERS)	WIDTH (METERS)	IDENT	DISTANCE TO THRESHOLD (METERS)	ANGLE (DEG)	TERMINAL ACCESS	STOPPING DISTANCE (METERS)	FILLET RATING
ATL	8	3048	46	E	1370	25	GOOD	210	FAIR
	9R	2743	46	X	1400	30	GOOD	370	FAIR
				Y	1980	30	GOOD	370	FAIR
	27L	2743	46	W	1580	30	FAIR	370	FAIR
				U	2070	30	GOOD	370	FAIR
	27R	2439	46	Q	1310	30	GOOD	210	FAIR
BOS	15R	3073	46	G	1680	30	FAIR	240	POOR
	27R	2133	46	E	1350	20	GOOD	300	POOR
	33L	3073	46	F	1280	20	GOOD	180	POOR
DCA	18	2094	61	RWY 21	1460	30	FAIR	610	GOOD
	36	2094	61	RWY 33	1460	32	FAIR	730	POOR
DEN	8R	3050	46	C-6	1310	29	GOOD	120	FAIR
	17L	3658	61	Z-4	2740	29	EXC	690	FAIR
	17R	3505	46	N	1750	29	EXC	180	FAIR
				O	2290	27	EXC	180	FAIR
	26L	3049	46	U	1340	29	GOOD	180	GOOD
				T	1900	27	GOOD	180	GOOD
	35L	3658	46	P	1900	29	GOOD	180	FAIR
				Q	2740	29	GOOD	180	FAIR
	35R	3658	61	Z5	1750	28	GOOD	200	FAIR
				Z6	2290	28	GOOD	200	FAIR
DFW	17L	3471	61	1S	1490	30	GOOD	370	GOOD
				2S	1890	30	GOOD	370	GOOD
				3S	2350	30	GOOD	370	GOOD
	17R	3471	61	1S	1463	30	GOOD	370	GOOD
				2S	1830	30	GOOD	370	GOOD
				3S	2380	30	GOOD	370	GOOD
	35L	3471	61	1N	1280	30	GOOD	370	GOOD
				2N	2070	30	GOOD	370	GOOD
				3N	2500	30	GOOD	370	GOOD
	35R	3471	61	1N	1460	30	GOOD	370	GOOD
				1N	2190	30	GOOD	370	GOOD
				3N	2590	30	GOOD	370	GOOD
JFK	4R	2560	46	F	1190	30	GOOD	1100	GOOD
				FA	1920	30	GOOD	1100	GOOD
	13R	4442	46	M	1430	30	EXC	150	FAIR
	22L	2560	46	H	1190	37	EXC	1100	GOOD
				J	1920	29	FAIR	460	GOOD

TABLE 15
ANGLED EXIT INVENTORY (CONTINUED)

AIR-PORT	RUNWAY: RWY NO.	LENGTH (METERS)	WIDTH (METERS)	IDENT	ANGLED EXITS: DISTANCE TO THRESHOLD (METERS)	ANGLE (DEG)	TERMINAL ACCESS	STOPPING DISTANCE (METERS)	FILLET RATING
LAX	6L	2720	46	52	1100	35	GOOD	300	GOOD
	6R	3135	46	52	1740	30	GOOD	240	GOOD
	24L	2720	46	65	1370	30	GOOD	460	GOOD
				75	2100	30	FAIR	370	FAIR
	24R	3135	46	65	1830	30	FAIR	180	FAIR
	25L	3658	61	32	1190	30	EXC-POOR	370	FAIR
				42	1740	25	EXC	370	GOOD
	25R	3685	46	28	1280	30	EXC-POOR	150	FAIR
				L47	2100	30	EXEC.	120	FAIR
LGA	22	2134	46	C	1460	25	GOOD	183	FAIR
	4	2134	46	F	940	35	EXC	210	GOOD
				Q	1100	25	GOOD	210	GOOD
	13	2134	46	L	1160	32	FAIR	180	POOR
				N	1460	32	FAIR	180	FAIR
	31	2134	46	J	1070	32	GOOD	180	POOR
				T	1250	27	GOOD	180	FAIR
ORD	4R	2460	46	4C	980	30	GOOD	460	GOOD
	9R	3091	46	2A	1360	30	EXC	180	GOOD
					1980	30	GOOD	180	GOOD
	14L	3049	46	6A	1360	30	GOOD	300	FAIR
				6B	1930	42	GOOD	300	POOR
	22L	2286	46	RWY 7	1400	30	GOOD	300	GOOD
				4A	1870	30	GOOD	300	GOOD
	27L	3091	46	2B	1200	32	EXC	240	GOOD
	27R	2260	46		1280	30	EXC	300	GOOD
	32R	3049	46	6B	2100	32	EXC	210	GOOD
SFO	19L	2896	61	H	1650	24	EXC	410	EXC
	28R	3618	61	T	1650	25	EXC	490	EXC
	28L	3231	61	J	1460	20	EXC	470	EXC

- The runways at LGA were designed during the days of propeller aircraft. There have been significant runway improvement projects at DEN during the 70's.

The stopping distance is a very important, and often ignored, parameter in determining the speed at which a high-speed exit can be used. The stopping distance is also a measure of how many aircraft can occupy the exit; this is very important if the exit intersects an active taxiway (or runway) which aircraft cross in batches. Exits from runway 25R at LAX have the least stopping distance of any angled exit surveyed. Runway 25R is only 107 meters (350 ft.) centerline to centerline from taxiway J; this is the main taxiway for departures on runways 25L or 25R. The average landing runway occupancy time on runway 25R is nearly 6 seconds longer than on runway 25L because aircraft must be able to stop immediately after exiting runway 25R. The angled exits from runway 4R at JFK have over a kilometer of stopping distance. This large stopping distance encourages pilots to exit at a high speed because they must travel a sizable distance before stopping and their time to the gate will be increased if they exit slowly.

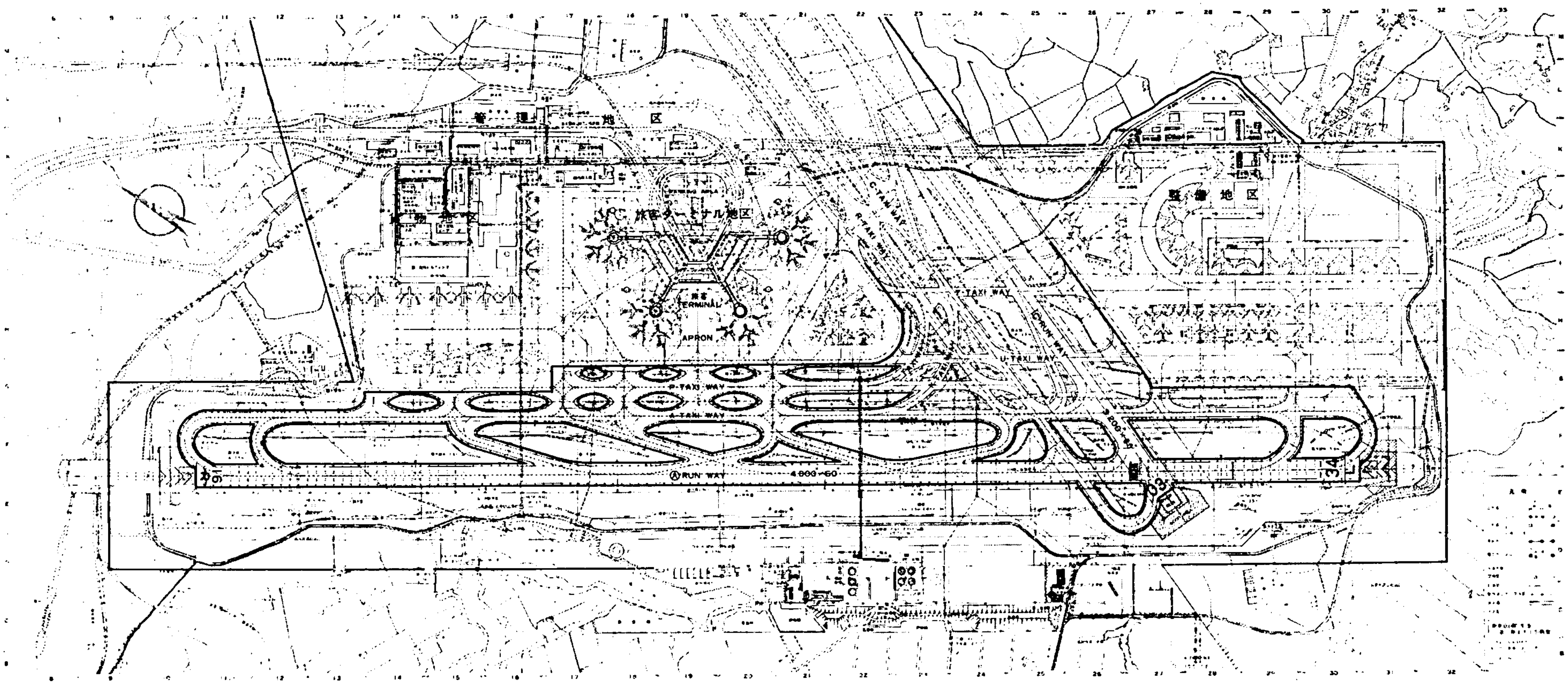
Table 15 only lists exits where the angle is less than 40 degrees. Most of the angled exits have an angle of approximately 30 degrees, and most used a fixed rather than a variable turn angle. (The angles were measured with a protractor and can easily be off a couple degrees.) The FAA's recommended design for an angled exit (Reference 34) has a 30 degree angle and a 550 meter (1800 ft.) radius turn. Most of the angled exits are similar to the FAA's recommended angle exit design (Reference 34) which is based on research performed by Professor Horonjeff during the 1960's (Reference 20). Horonjeff recommended a variable turn radius; the FAA approximated Horonjeff's design with a constant turn radius angled exit which is very similar to Horonjeff's variable radius exit.

The air traffic control handbook (Reference 9) states that an arriving aircraft cannot cross the threshold until "the other aircraft has landed and taxied off the runway." Taxied off the runway is generally understood to mean that no part of the aircraft is over the runway. A runway exit with a small angle will permit the aircraft to exit at a higher speed; however, an aircraft must travel farther to be off the runway when using a small angle exit.

Taxiway construction costs approximately $65.00 (in 1979 dollars) per square meter when it is part of a major project. The cost of adding a fillet to an existing exit would be considerably higher. The airport authority is concerned about the cost of constructing high-speed runway exits. They want to be sure the exit is properly designed originally due to the added construction cost and the administrative cost and delay with obtaining approval to modify an existing facility.

Tokyo's new international airport, Narita, has one of the best high-speed exit systems of any airport in the world. (Figure 17). Runway 34L has three exits at a 16 degree angle. These exits are approximately 1500 meters, 2050 meters, and 2600 meters from the threshold. Each exit is 30 meters wide, has approximately 400 meters stopping distance before the turn angle increases, and each exit has a very generous fillet at the taxiway system and very good terminal access.

第 1 期 計 画 平 面 図 (縮尺) 1／4000



FIRST STAGE CONSTRUCTION DRAWING NEW TOKYO INTERNATIONAL AIRPORT (NARITA)

FIGURE 17

Airport Operations

The runway use strategy, like the airfield design, is very site specific. A major airport delay study at Chicago O'Hare International Airport (ORD) was completed in 1976 (Reference 4). This study identified 18 different runway use configurations; the summary report identified 14 different common runway use configurations for visual meteorological conditions and 6 for instrument meteorological conditions. O'Hare has six air carrier runways, and two pairs of intersecting runways are in use most of the time. Other major airports which make extensive use of intersecting runways include: San Francisco International (SFO), Washington National (DCA), New York City LaGuardia (LGA), and occasionally Boston Logan International (BOS). Unfortunately, airports which use intersecting runways will not receive significant benefit from reduced longitudinal spacing for arrivals because it is often necessary to leave enough time to interleave a departure between consecutive landings. This reduces the minimum practical longitudinal separation on final approach and the need for high-speed runway exits at these airports.

Similarly, there are several airports that have both landings and takeoffs on the same runway in visual meteorological conditions. Minimum runway occupancy time is important for mixed operations because the landing aircraft should be off the runway before the departing aircraft starts the takeoff roll. Takeoff clearance need not be withheld until prescribed separation exists if there is a reasonable assurance it will exist when the aircraft starts takeoff roll. The departing aircraft can taxi into takeoff position as soon as the landing aircraft passes the threshold. Takeoff roll can start as soon as the landing aircraft is off the runway. The departing aircraft must cross the runway end before the next approaching aircraft crosses the landing threshold. The current 3 N MI longitudinal separation on approach is not adequate to allow a departure between consecutive landings; a 2 N MI separation would not be adequate even with a zero landing runway occupancy time.

The need for reduced landing runway occupancy time is greatest at those airports which will have:

- advanced air traffic control systems allowing reduced longitudinal separations on approach

- a runway use strategy which includes an arrivals only runway that operates independent of other runways

- a high arrival demand that exceeds capacity with current longitudinal separations on approach.

In general, the airports which will have the advanced air traffic control systems are the airports where demand will exceed current capacity. Table 16 gives the current hourly scheduled arrivals and departures at the top ten U.S. airports. Atlanta (ATL) has wide surges in hourly demand because both Delta and Eastern Airlines (which each have about 40 percent of the operations) use ATL as a transfer hub. They have about seven surges a day with an arrival from fifteen to twenty cities in a short time period, the aircraft are on the ground for 30 to 60 minutes while the passengers transfer, and then all the aircraft depart. Washington National (DCA) has a constant demand because there are quotas on the allowable number of scheduled operations per hour. Kennedy (JFK) has an afternoon arrival peak and an evening departure peak because there are many flights to and from Europe and these are the best hours for the time zone difference and European curfews. La Guardia (LGA), like DCA, has a quota

TABLE 16
DAILY SCHEDULED AIRCRAFT OPERATIONS PROFILE
AUGUST 1978

HOURLY SCHEDULED ARRIVALS (A) AND DEPARTURES (D)

HOUR ENDING	ATL		BOS		DCA		DEN		DFW		JFK		LAX		LGA		ORD		SFO	
	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D
0100	3	49	3	2	0	0	6	3	8	6	8	4	15	19	0	0	8	2	10	9
0200	1	0	3	0	0	1	3	2	6	9	5	3	13	10	0	0	14	4	9	6
0300	1	0	0	2	0	0	0	1	1	4	7	3	4	3	0	0	7	8	4	2
0400	0	2	1	0	0	0	2	1	2	0	4	6	3	0	0	0	5	6	2	1
0500	1	0	0	0	0	0	0	3	5	0	1	3	4	2	0	0	7	8	1	2
0600	24	4	1	0	0	0	1	2	10	2	5	1	1	4	0	0	24	13	3	4
0700	1	45	2	6	3	4	1	10	11	6	11	2	12	11	1	1	10	29	6	9
0800	4	3	13	22	14	19	12	22	30	32	12	13	27	38	15	32	50	49	18	29
0900	36	9	31	25	22	22	39	18	15	43	14	26	32	55	26	28	47	69	15	37
1000	69	30	21	35	22	23	38	44	21	19	11	27	24	42	21	31	59	49	22	27
1100	19	76	20	20	25	21	37	36	44	25	11	25	46	39	29	25	70	72	26	20
1200	53	27	28	25	20	22	41	46	33	44	12	15	53	40	30	25	46	69	36	22
1300	25	55	27	29	21	21	22	36	40	30	7	19	32	49	29	26	65	52	24	39
1400	34	24	24	27	24	21	32	31	31	48	18	10	30	40	25	30	80	65	19	23
1500	36	49	26	27	22	25	26	20	37	32	21	15	36	26	24	32	71	86	26	26
1600	49	25	37	25	23	25	35	33	25	32	37	15	31	38	29	24	60	67	13	18
1700	43	49	25	35	23	23	23	25	39	24	52	23	34	30	30	29	73	51	28	15
1800	63	42	30	34	24	25	46	25	43	43	38	37	41	26	32	31	68	67	26	22
1900	23	67	44	30	23	22	31	52	25	41	27	36	37	39	28	31	58	69	29	21
2000	77	9	24	30	22	22	36	33	31	23	38	38	58	31	27	30	68	57	35	24
2100	9	76	21	16	26	17	22	24	41	20	32	29	35	20	33	22	73	64	29	15
2200	42	7	19	14	20	24	18	13	23	38	14	38	36	33	23	17	28	50	13	19
2300	9	39	12	11	13	8	16	9	14	24	14	12	31	30	9	3	22	17	13	17
2400	69	4	10	2	0	0	7	4	15	3	8	9	24	28	9	3	19	9	16	10
TOTAL ARRIVALS	690		421		348		493		549		407		657		419		1031		422	

throughout the day. Chicago O'Hare (ORD) has a quota from 3 to 8 pm and the peaks just before and after these hours are the best available hours to schedule additional arrivals.

In general, the hours from 6 pm until 6 am can be considered nighttime. From Table 16 the importance of reduced runway occupancy times at night can be determined by comparing the nighttime hourly arrival demand with the day- time demand. The following defines the five hours with the largest arrival demands which occur between 6 pm and 6 am at the airports in Table 16.

		Hourly Arrival Demand			
Airport	Busiest	2nd	3rd	4th	5th
ATL	Night	Night	Day	Day	Day
BOS	Night	Day	Day	Day	Day
DCA	Night	Day	Day	Day	Day
DEN	Day	Day	Day	Day	Day
DFW	Day	Day	Night	Day	Day
JFK	Day	Day	Night	Day	Day
LAX	Night	Day	Day	Day	Night
LGA	Night	Day	Day	Day	Day
ORD	Day	Day	Night	Day	Day
SFO	Day	Night	Night	Night	Day

The above illustrates that it is necessary to reduce runway occupancy time during nighttime as well as daytime hours.

There is a growing trend to restrict aircraft operations during the sleeping hours (i.e., generally from 10 or 11 pm until 6 or 7 am). These nighttime restrictions include curfews (e.g., San Diego), quotas on operations (e.g., Minneapolis), airline agreements not to schedule operations (e.g., La Guardia and Washington National), and restrictions on operating procedures (e.g., reduced use of reverse thrust at Boston). However, the nighttime hours with high arrival demands are usually from 6 to 10 pm and these late night restrictions do not diminish the need for reduced runway occupancy times at night.

Most aviation planners forecast a 6 to 8 percent annual growth in passenger enplanements. However, the congested airports will not have a high increase in aircraft operations due to the following reasons:

1. The average number of passengers per aircraft will continue to increase because:

    - larger aircraft are replacing smaller aircraft

    - airlines are increasing the seating density of existing aircraft

    - load factors are increasing.

2. There are quotas today on the number of flights which the airlines can schedule per hour at four congested airports (DCA, JFK, LGA, and ORD). Quotas will be imposed at other airports if their delays increase significantly.

3. Several congested airports are the central hub in a transfer operation. (For example, the transfer rate at ATL is 75% and 50% at ORD). Airlines are setting up alternative transfer hubs or offering direct service to avoid the high delay airports.

4. Some congested airports will have to limit increases in passenger growth due to other constraints such as:

   - ground access capacity

   - parking, terminal, or apron/gate capacity

   - environmental constraints which limit growth in aircraft operations.

Air Traffic Control Operations

Two distinct controller tasks performed in the air traffic control tower are local control and ground control. They are performed by different individuals in all the airports of interest. The ground controller guides departing aircraft from the gate until the takeoff queue, and guides arriving aircraft from the time they leave the runway until they reach the gate. The local controller is in charge of all runway operations. The local controller receives departures from ground control and hands them off to departure control after takeoff. Arrivals are transferred from approach control to local control and are transferred to ground control as they exit the runway. (Aircraft which must cross an active runway controlled by the same controller are not transferred to ground control until they have crossed the active runway. For example, aircraft landings on 25L at LAX do not transfer to ground control until they cross 25R). The transfer from local control to ground control is an important factor in reducing runway occupancy time.

The local controller and ground controller basically operate independently. The ground controller will coordinate with the local controller if he has an aircraft that wants to cross an active runway. There is generally no verbal communication between the ground and local controller when they transfer control. However, some airports have a "shrimp boat" identification strip that the ground controller places in the local controller's departure queue rack. There is generally no verbal or written communication when control of an arrival is transferred from the local controller to the ground controller. The local controller informs the pilot of the transfer with a message similar to "American 321, contact ground control on 121.9" as the aircraft is taxiing off the runway. The ground controller does not know the aircraft is coming and may be busy guiding aircraft at another area. The ground controller is often the busiest individual in the control tower, and may not be immediately available to give taxiing instructions to the aircraft that has just landed. Therefore, the length of a high-speed exit from the point it leaves the runway to the point it intersects an active taxiway or runway is very important because the pilot may have to stop and wait for clearance to cross the taxiway or runway.

It would be necessary to significantly change the controller procedure in order to give the pilot taxiing clearance before he exits the runway and contacts the ground controller. However, such clearance may be necessary in order to give the pilot the assurance required to exit at a high-speed where there is a short distance to an intersection with an active runway or taxiway.

HIGH-SPEED EXIT REQUIREMENTS

The high-speed exit system must permit operations with reduced longitudinal separation of aircraft in trail for landing. The high-speed exit system must ensure that the wave-off frequency does not exceed an acceptable limit or the controllers will increase the longitudinal separations and defeat the objective of this, and other, research to increase airport capacity. Hence, the emphasis is to keep the frequency of excessively long runway occupancy times below a prescribed limit; it is not to keep the average runway occupancy time below a prescribed limit.

Allowable Runway Occupany Time

The objective of this research is to help ensure that runway occupancy time does not make it impossible to realize the full capacity increase potential of advanced air traffic control systems currently being developed by the federal government. These systems include basic and advanced metering and spacing, vortex advisory, wake vortex avoidance, vortex alleviation, discrete address beacon, cockpit display of traffic information, microwave landing systems, etc. These advanced air traffic control systems will reduce the longitudinal separation of aircraft in trail on approach for a landing. The future in-trail separations are dependent upon aircraft type and meteorological conditions. The aircraft type are:

H or Heavy:	Max. Takeoff Gross Wt. (MTOGW) over 136,000 kilograms
L or Large:	MTOGW between 5,670 and 136,000 kilograms
S or Small:	MTOGW under 5,670 kilograms

The meteorological conditions include visibility conditions and whether or not wake vortices will dissipate. The visibility conditions are:

- VMC or visual meteorological conditions (with a ceiling over 1,000 feet (300 meters) and runway visual range over 3 statute miles (4.8 km)). It is possible to operate with visual flight rules (VFR) in VMC.

- IMC or instrument meteorological conditions. There are many different categories of visibility possible in IMC; however, the longitudinal separations do not change.

The wake vortex conditions are basically a yes or no factor even though the wake vortex avoidance system should be able to consider the rate at which the vortices will dissipate.

The following are the FAA forecasted longitudinal separations between consecutive aircraft in trail for approach at airports which will have the advanced air traffic control systems (References 4 and 7):

VMC LONGITUDINAL SEPARATIONS

(Kilometers)

Wake Vortices Dissipate

		Trail		
		S	L	H
Lead	S	3.52	3.52	3.52
	L	3.89	3.52	3.52
	H	6.30	5.00	3.88

Wake Vortices Persist

		Trail		
		S	L	H
Lead	S	3.52	3.52	3.52
	L	5.00	3.52	3.52
	H	8.33	6.67	5.00

IMC LONGITUDINAL SEPARATIONS

(Kilometers)

Wake Vortices Dissipate

		Trail		
		S	L	H
Lead	S	3.70	3.70	3.70
	L	4.63	3.70	3.70
	H	6.85	5.56	4.26

Wake Vortices Persist

		Trail		
		S	L	H
Lead	S	5.56	5.56	5.56
	L	6.48	5.56	5.56
	H	9.26	7.41	5.56

Wake vortices dissipate when the wind is strong enough to blow away and/or help break up the vortices. These winds do not exist at the airports of interest during poor visibility conditions (PVC) when the ceiling is under 150 meters, or the visibility is under 1 N. Mi. Therefore, the minimum allowable longitudinal separations behind each aircraft type are:

S: 3.52 kilometers, 5.56 km. in PVC
L: 3.52 kilometers, 5.56 km. in PVC
H: 3.88 kilometers, 5.56 km. in PVC

All of the above minimum allowable longitudinal separations occur when the trail aircraft is heavy. The approach speed for any aircraft primarily depends upon its landing weight and the wind velocity. The approach airspeed for a heavily loaded DC-10-30 is approximately 142 knots (73 meters per second)for the last 3 N. Mi. This is not the worst case, but is probably about 5 to 10 percent over the average approach speed for heavy aircraft.

The controller is to prevent the trail aircraft from crossing the threshold before the lead aircraft is off the runway. The controller does not need to withhold landing clearance if it can be determined that the prescribed separation will exist when the aircraft crosses the landing threshold. Therefore, the following are the maximum runway occupancy times that can be allowed:

S: 48.2 seconds; 76.2 seconds in PVC
M: 48.2 seconds, 76.2 seconds in PVC
H: 50.7 seconds; 76.2 seconds in PVC

Model of Exit Usage

The use of a high speed exit is dependent upon many factors:

- The touchdown location and speed
- The time required to start deceleration
- The deceleration rate and duration of deceleration
- The ability to use the exit

Of course, each of the above factors depends upon several items. The design of a high-speed runway exit system is based on the above factors and the allowable runway occupancy time. The above factors influence the probability that an arriving aircraft will be able to use a high-speed exit and the resulting runway occupancy time.

A model to compute the probability that an arriving aircraft will be able to use a high-speed runway exit (and the resulting runway occupancy time) is essential to parametrically evaluate possible changes to:

- Systems to improve touchdown precision
- Changes in aircraft operating procedures
- Increased deceleration rate due to improved brakes and/or runway improvements
- Exit design, location and identification

A simulation model was developed to estimate the probability that an arriving aircraft would be able to use an exit. This simulation model was not computer programmed because its use with existing data would be analogous to performing the analysis with a seven place log table when the input data had two significant figure accuracy. However, the simulation model uses an interesting concept and its computer implementation would be recommended if adequate input data existed.

A simple probabilistic model was recently developed to estimate the probability that an arriving aircraft would be able to use an exit. This probabilistic model makes several simplifying assumptions and does not have the precision of the computerized simulation model; similarly, it does not have the input requirements of the computerized simulation.

The computerized simulation and the probabilistic models are defined below. As stated the computerized simulation model was not used because existing data does not justify using a sophisticated analysis technique. The following discussion of the computerized simulation technique is presented to guide mathematical model developers who someday will have better input data; it is recommended that other readers skip this section and proceed to the discussion of the probabilistic model.

Computerized Simulation Model

This computerized simulation model was not used because it is not cost effective to set up and run the model with existing data. The only existing field data on touchdown dispersion, deceleration rates, and exit speeds are from Howard, Needles, Tammen, and Bergendorf (Reference 10 and 11). These data were not originally collected for high-speed runway exit analysis and were taken during 1974 under conditions significantly different than expected when aircraft operate at reduced longitudinal separations. It is possible that future motion base simulator test landings will provide data adequate for the model, and use of a more sophisticated model to evaluate runway exit usage (such as this computerized simulation) will be justified.

The computerized simulation model utilized is a direct probabilistic simulation technique (Reference 33) rather than the standard Monte Carlo technique used in most simulations. This direct simulation technique determines the probability of each event with one run while a Monte Carlo simulation makes many replicates of the same set of conditions and then determines the percent of the time an event did, or did not, occur. (In the Monte Carlo simulation each replicate will have different random numbers and therefore different results.) The advantage of the one run is very important for the high-speed runway exit usage analysis because it is important to estimate the frequency of an event that has a very low occurrence probability.

This simulation technique is based upon a vector which defines the "state" of the aircraft at any specific time. The state vector is a series of probabilities which sum to 1.0 that define whether the aircraft is flying, on the runway, or exited from the runway. An example of a 50 state vector would be:

- state 1: still airborne
- states 2 through 10: just landed, and the ground speed is

  74 m/sec for state 2

  72 m/sec for state 3

  etc. to

  58 m/sec for state 10
- states 11 through 45: landed and decelerating with a ground speed

  74 m/sec for state 11

  72 m/sec for state 12

  etc.

  6 m/sec for state 45

- states 46 through 50: exited from the runway at

    exit number 1 for state 46

    exit number 2 for state 47

    etc.

    exit number 5 for state 50

When the aircraft comes over the threshold, it is in state 1 with probability one. Then the state vector is updated every 100 meters by multiplying it by a transition matrix which defines the probability of going from one state to another. For the example, the transition matrix would have 50 rows and 50 columns where the entry in the ith row and jth column denotes the probability of going from state i to state j. The transition matrix has the following properties: (1) every row sums to 1.0; (2) the probability of going from state i to a state less than i is zero; and (3) it is impossible to leave states 46 through 50. The process of multiplying the state vector by the transition matrix is repeated every 100 yards down the runway until the last runway exit. Every transition matrix can be different to reflect the distribution of touchdown locations, the time on the runway, the distance to an exit, the probability of exiting as a function of speed, etc.

This simulation technique needs the computational and storage capabilities of a computer. The transition matrices should be calculated by the computer based upon a set of equations and the conditions for the particular location. This computerized simulation model requires considerable time to set up. The computer time for a run should not be long because it is unlikely that any row of the transition matrix will contain more than five entries where the probability of going from one state to another is not zero. This computerized simulation requires extensive data on touchdown location, deceleration rates, and exit speeds in order to justify the required set up effort. These data do not currently exist.

<u>Probablistic Runway Exit Model</u>

The model to estimate the probability that an aircraft will be able to use a runway exit (Figure 18) is a heuristic model which makes extensive use of the "normal" statistical distribution. The model assumes:

- touchdown speed and location are normally distributed even though existing data indicates the log-normal distribution is a better fit of touchdown location.

- the time from touchdown until start of deceleration is normally distributed and the speed is constant from crossing the threshold until start of deceleration.

- the deceleration rate is normally distributed.

- the probability that an exit will be used is defined by a cumulative normal distribution with speed as the independent variable.

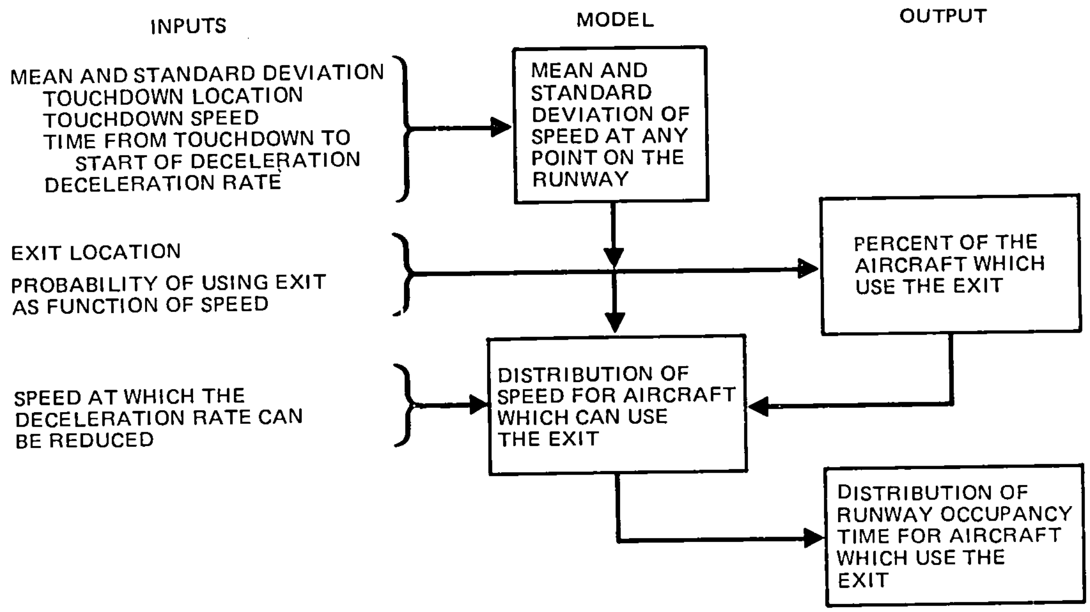


FIGURE 18. PROBABILISTIC RUNWAY EXIT MODEL

The model also approximates the speed at any point on the runway with a normal distribution.

The inputs to the model are:

Parameter	Units	Notation Ave.	Notation Std. Dev.
Touchdown location (distance from the threshold)	meters	UA	US
Touchdown speed	m/sec	VA	VS
Time from touchdown until start of deceleration	sec	WA	WS
Deceleration rate	m/sec2	XA	XS
Probability of using exit (Cumulative distribution)	m/sec	YA	YS

The basic equations determine the mean and standard deviation of speed at any point on the runway. There are three locations of particular interest.

Location A: the location (distance from the threshold) where deceleration starts.

Location B: the location where the speed equals the speed where reverse thrust stops. This speed will be defined as ZA.

Location C: the location of the exit being studied. Location C is usually after location B, but it can be between locations A and B.

The average speed at any location from the threshold to location A is VA. The average speed at location B is defined to be ZA. The average speed at location C is:

$$\text{Ave. speed at C} = ASC = ((VA)^2 - 2(XA)(C-A))^{1/2}$$

The standard deviation (SD) of speed at locations A, B, and C is approximated by the following:

$$SDA = ((VS)^2 + ((US)(XA)/(VA))^2 + ((WS)(XA))^2)^{1/2}$$
$$SDB = ((SDA)^2 + (2(XS)(B-A)/((VA) + (ZA)))^2)^{1/2}$$
$$SDC = ((SDA)^2 + (2(XS)(C-A)/((VA) + (ASC)))^2)^{1/2}$$

The average speed at the exit is ASC and the standard deviation of speed is SDC. It is possible to compute the percent of the aircraft in any speed interval (e.g., the percent between 30 and 32 meters/second) based upon ASC and SDC. Similarly, the percent of the aircraft travelling between 30 and 32 meters/second that will use the exit is computed based upon YA and YS. The total percent of the aircraft that will use an exit is then computed by multiplying the percent of the aircraft in each speed interval by the exit usage percentage for that interval and summing over all intervals.

It is assumed that the aircraft which have decelerated the most are the aircraft that will be able to use the exit. For example: if half of the aircraft can use the exit, they will be the aircraft going ASC or slower; similarly, if 75 percent of the aircraft can use the exit, they will be the aircraft going slower than ASC + 0.676 (SDC).

The calculation of runway occupancy time includes both the average runway occupancy time and the standard deviation of runway occupancy time. The percent of the aircraft where the runway occupancy time exceeds a prescribed time is calculated with the mean and standard deviation of runway occupancy time. The average runway occupancy time is based upon the runway occupancy times for those aircraft which are going slow enough to use the exit.

The calculation of the percent of the aircraft that will use an exit assumed that aircraft continued to decelerate at a constant rate until they reach the exit. Hence, it is possible that ASC could be negative. A very low, or negative, speed at the exit would yield a very unrealistic runway occupancy time. In actual operations, the pilot would reduce the deceleration rate if he was far from the exit. The computation of runway occupancy time assumes that the aircraft does not slow down below YA - 1.5 (YS), and the deceleration rate slows at location B so the aircraft is travelling at this minimum speed at location C.

Runway occupancy time is calculated for an aircraft going at the average speed and an aircraft going one standard deviation below the average speed. For an aircraft going at the average speed, the equations for the locations are:

$$\text{Location A} = UA + (VA)(WA)$$
$$\text{Location B} = A + ((VA)^2 - (ZA)^2)/2(XA)$$

The average speeds at locations A, B, and C are:

$$SA = ASA = VA$$
$$SB = ASB = ZA$$
$$SC = \text{Max}\ (YA - 1.5(YS),\ ASC)$$

If location C is beyond location B, the average runway occupancy times at locations A, B, and C are:

$$TA = ((UA)/(VA)) + (WA)$$
$$TB = (TA) + 2\ (B-A)/(SA + SB)$$
$$TC = (TB) + 2\ (C-B)/(SB + SC)$$

If location C is between locations A and B, the average runway occupancy times at locations A and C are:

$$TA = ((UA)/(VA)) + (WA)$$
$$TC = (TA) + 2\ (C-A)/(SA + SC)$$

For aircraft travelling one standard deviation below the average speed, the symbols for locations A, B and C will be replaced with A′, B′ and C′, respectively. Location A′ is the same as location A; location B′ is where the speed is ZA; and location C′ is the same as location C. It is assumed that there is a linear deceleration from the threshold to location A′, from location A′ to location B′, and from location B′ to location C′. The equations for the locations are:

Location A′ = Location A
Location B′ = A + (B-A)((ASA-SDA)-ZA)/((ASA-SDA(-(ZA-SDB))
Location C′ = Location C

The speeds at the threshold is VA-VS, and the speeds at location A′, B′ and C′ are approximated by:

SA′ = ASA-SDA
SB′ = ZA
SC′ = Max (YA-1.5(YS), ADC-SDC)

If location B′ is before location C′, the runway occupancy times at locations A′, B′ and C′ are approximated by:

TA′ = 2A/((VA-VS)+SA′)
TB′ = TA′ + 2(B′-A′)/(SA′ + SB′)
TC′ = TB′ + 2(C′-A′)/(SB′+SC′)

If location B′ is beyond location C′, the runway occupancy times at location A′ and C′ are approximately by:

TA′ = 2A/((VA - VS)+SA′)
TC′ = TA+ 2(C′-A′)/(SA′+SC′)

The above calculations yield the runway occupancy time for an aircraft at the average speed (TC) and an aircraft one standard deviation below average speed (TC′). Again the normal distribution is assumed to calculate the percent of the aircraft which have a runway occupancy time in excess of the maximum allowable time. The average runway occupancy time for all aircraft using the exit is calculated based upon the assumption that slower aircraft are the ones that are able to use the exit. For example, if 30 percent of the aircraft can use the exit the average runway occupancy time is the average for all aircraft with a runway occupancy time more than TC + (0.526)(TC′ - TC); similarly, if 70 percent of the aircraft can use the exit the average runway occupancy time is the average for all aircraft with a runway occupancy time more than TC - (0.526)(TC′ - TC).

If there are multiple exits on the runway, the following must be calculated for each exit:

1) The percent of the aircraft which can use the exit.

2) The percent of the aircraft which have a runway occupancy time over the maximum allowable time.

3) The average runway occupancy time for aircraft that use the exit.

The actual percent of the aircraft which use each exit is the percent which can use the exit minus the percent which could use the previous exit (if any). The overall percent of the aircraft which have a runway occupancy time over the maximum allowable time is the percent for each exit times the actual usage percentage, and summed over all exits. The overall average runway occupancy is the weighted average for all the exits, and the weighting is based on the actual percent of the aircraft which use each exit.

Example Use of Probablistic Model

The following example illustrates the probabilistic model. The baseline data are primarily based upon the HNTB data (References 10 and 11) for two engine narrow body jet aircraft. The basic input data are:

Parameter	Units	Ave.	Std. Dev.
Touchdown location (distance from threshold)	meters	440	180
Touchdown speed	m/sec	67	2
Time from touchdown to start of deceleration	sec	6	1
Deceleration rate	m/sec^2	1.75	0.2
Cum. probability of using 30° exit	m/sec	29	4

Assume that the exit being evaluated is 1900 meters from the threshold and that location B is defined as the location where the average speed is 32 m/sec.

The following values are calculated using the above inputs:

Location A: (start of reverse thrust) is 842 meters from the threshold.

Location B: (where average speed is 32 meters/second) is 1832 meters from threshold.

ASA = 67 meters/sec
ASB = 32 meters/sec
ASC = 28.0 meters/sec
SDA = 5.40 meters/sec
SDB = 6.72 meters/sec
SDC = 6.74 meters/sec

The percent of the aircraft which could use the exit at location C (1900 meters from the threshold) is 55.06 percent.

The following values are the calculations to compute the runway occupancy time for the 55.06 percent of the aircraft which can use the exit.

Location A = 842 meters
Location B = 1832 meters
Location C = 1900 meters
SA = 67 meters/sec
SB = 32 meters/sec.
SC = 28 meters/sec.
TA = 12.57 sec.
TB = 32.57 sec.
TC = 34.83 sec.
Location A′ = 842 meters
Location B′ = 1648.8 meters
Location C′ = 1900 meters
SA′ = 61.6 meters/sec.
SB′ = 32 meters/sec.
SC′ = 23 meters/sec.
TA′ = 13.30 sec.
TB′ = 30.54 sec.
TC′ = 39.68 sec.

Therefore, it is calculated that the runway occupancy time is normally distributed with a mean of 34.83 seconds and a standard deviation of 4.85 seconds. Since 55.06 percent of the aircraft can use the exit, the average runway occupancy time for aircraft using the exit only considers aircraft with a runway occupancy time over 35.15 seconds. The average runway occupancy time for aircraft using the exit is 38.33 seconds. Approximately 0.29 percent of the aircraft have a runway occupancy time over 48.2 seconds (the maximum allowable time for large aircraft).

A second example was calculated using the same input data with the exception of the mean and standard deviation of touchdown location. The mean used was 340 meters (instead of 440 meters) and the standard deviation was 18 meters (instead of 180 meters). This resulted in an exit turn off rate of 88.65 percent versus 55.06 percent in the first example, and an average runway occupancy time of 38.07 seconds, (38.33 seconds runway occupancy time was calculated in the first example).

CANDIDATE EXIT DESIGNS

An effective high-speed runway exit system includes more than concrete, and the concrete it does contain includes more than that required to exit the runway. An effective high-speed runway exit system must include the information systems, operating procedures, and motivation which will insure that the maximum allowable runway occupancy time is not exceeded too frequently.

This research is being performed to help ensure that runway occupancy times will not restrict the full potential capacity increase possible with advanced air traffic control systems. These advanced air traffic control systems will only be operational at a limited number of airports and this study is concerned with these few airports, not the over six hundred U.S. airports which will continue to serve air carrier flights with existing longitudinal separation standards.

Unfortunately, there are not any airports currently operating with the reduced longitudinal separations, and it is impossible to obtain field data representative of how these few airports will operate. The only currently feasible ways to estimate these data are to have special test flights to an airport such as NASA's Wallops Island or the Miami Everglades airport, or to conduct special simulated landings using a cockpit simulator. The following defines the features of candidate high-speed runway exit designs that should be evaluated for a high-speed runway exit system.

Number of Exits

The high-speed runway exit system must allow operations at reduced longitudinal separations without significantly increasing the probability of having to do a go-around. Hence, the lead aircraft must be off the runway before the trail aircraft crosses the threshold. If the controllers must frequently request a go-around to prevent a violation of this one on the runway rule, it is likely that the controllers and/or pilots will increase longitudinal separation. For this reason, a high-speed runway exit system which has an average runway occupancy time of 35 seconds and a standard deviation of 5 seconds is preferable to one with an average of 30 seconds and a standard deviation of 10 seconds.

It is essential that the high-speed runway exit system have multiple exits because the emphasis is on minimizing the frequency of excessively long runway occupancy times. Multiple exits are generally located approximately 500 meters apart and this often allows a pilot to keep the runway occupancy time within limits even if he is unable to use the first high speed exit. Multiple exits increase the probability that a high-speed exit is conveniently located for easy access to the ground destination. Multiple exits also help solve the runway exit location problems associated with different aircraft types. A high-speed exit that is ideally designed and located for wide body aircraft could be so far down the runway that a small commuter aircraft would have an excessive runway occupancy time before it reached the exit. The most important benefit of multiple exits can be to prevent taxiway congestion from making the high-speed exit unusable. The future separations for arriving aircraft result in approximately one landing per minute; a single speed runway exit would become congested if it crosses another active runway or taxiway. This study is primarily concerned with those airports which have a high enough demand to justify the cost of advanced air traffic control systems; most of these airports currently have taxiway congestion as well as runway congestion.

Exit Design Concepts

There are five distinct design concepts for high-speed runway exits that should be evaluated. These five design concepts are:

1. FAA's current 30 degrees angled exit design. (Figure 19). This design is the basis for most of the current angled (high-speed) runway exits (Reference 34). This design will serve as the baseline and all other designs will be judged relative to this design.

2. Low angle high-speed exit design (Figure 17). A high-speed runway exit with an angle less than, or equal to, 20 degrees should be the prime candidate to reduce runway occupancy times. The new Narita airport near Tokyo has excellent exits of this design.

3. Variable angle, or spiral, design (Figure 20). Many pilots object to the initial high turn radius with the FAA's 30 degrees angled exit design. It is likely that exit usage would increase if the exit was designed for a constant lateral force as the aircraft decelerates throughout the turn.

4. Drift-off high-speed runway exit design (Figure 21). The ultimate high-speed runway exit design could be a very wide runway (starting approximately 1500 meters from the threshold) where the arriving aircraft could drift-off the runway and decelerate on the parallel and joined runway extension. There are many air traffic control procedural questions which could arise with the drift-off concept.

5. High angle exit design (Figure 22). The runway exit system should contain more than one exit to provide the pilot a second chance to exit the runway without exceeding the maximum allowable runway occupancy time. The aircraft will not be going at a high speed when it arrives at the last exit. This exit could have an angle between 40 degrees and 45 degrees. However, the turning radius should be larger than the one for small airplanes in AC 150/5335 - 1A.

Information Systems

The high-speed runway exit system must include information systems which will help the pilot keep runway occupancy times below the maximum allowable time. As previously stated, the most important information are:

- runway clearance
- taxiway clearance
- runway traction data

The secondary information requirements include:

- speed
- distance to exit
- alignment

There are many options to provide these data including:

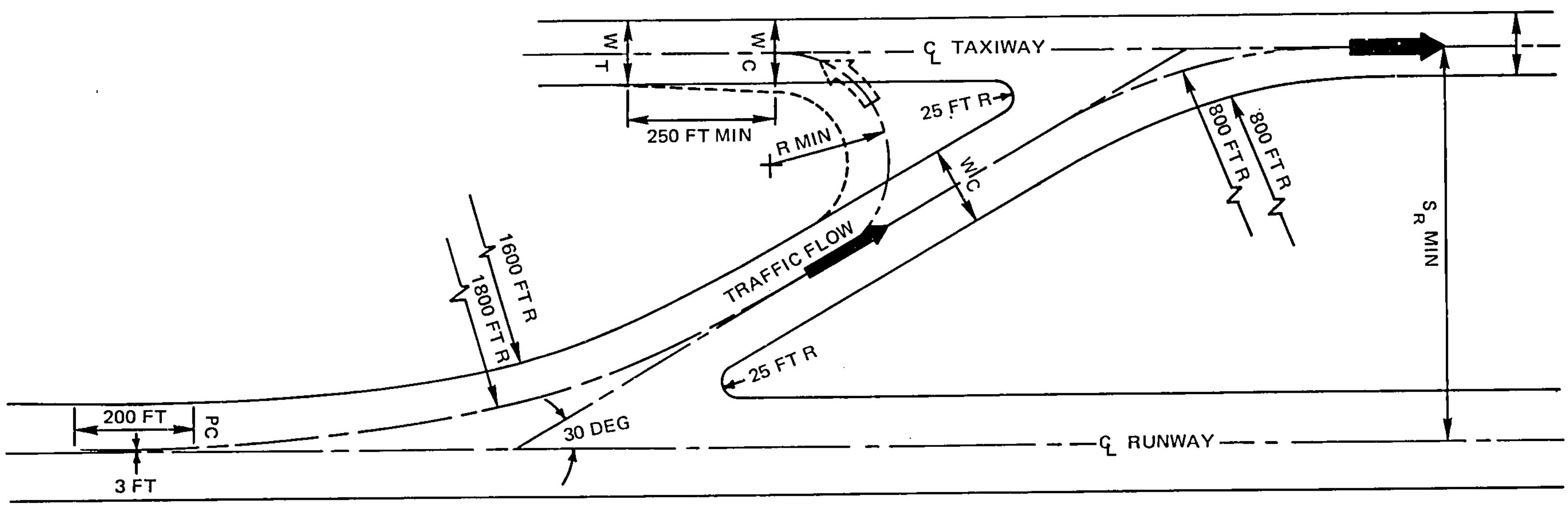


FIGURE 19. FAA'S 30-DEGREE ANGLED EXIT DESIGN

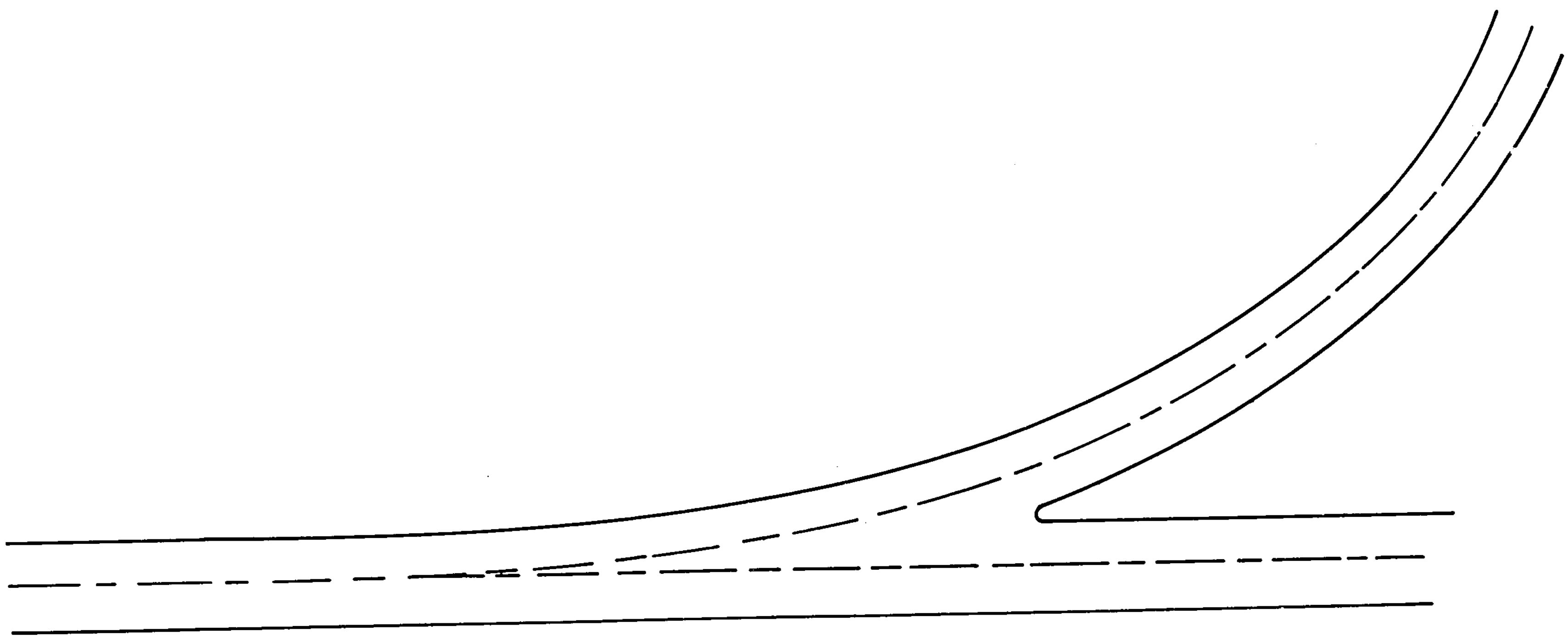


FIGURE 20. VARIABLE ANGLE EXIT DESIGN

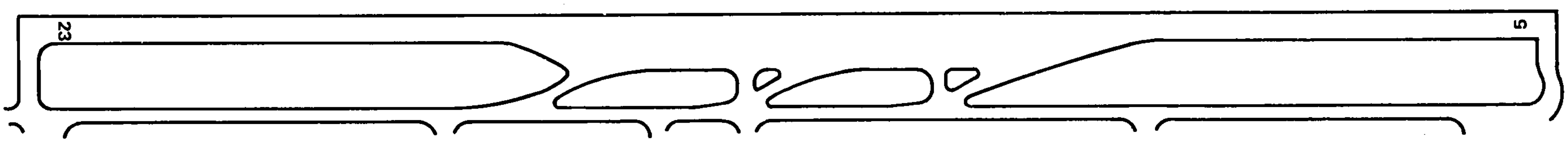


FIGURE 21. DRIFT-OFF EXIT DESIGN

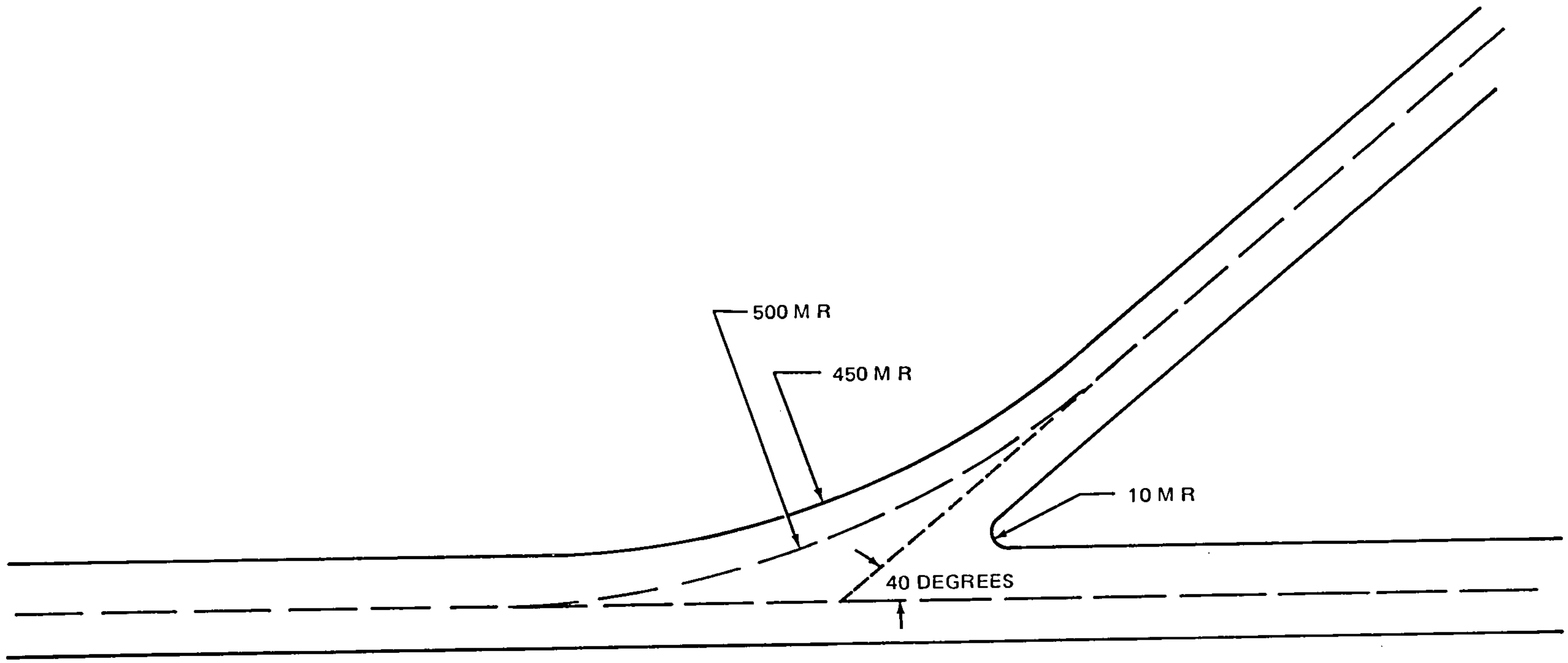


FIGURE 22. FORTY-DEGREE EXIT DESIGN

- cockpit displays
- verbal instructions from controllers
- ground based systems

Testing of high-speed runway exit designs must also include the information systems because the information system could impact the high-speed exit usage as much as exit design concept.

Exit Location

The location of the high-speed runway exits should minimize the probability of exceeding the maximum allowable runway occupancy time. The location of the exit depends upon the following:

- maximum allowable runway occupancy times
- number of exits in the exit system
- pilot information systems
- available distance from start of the turn until a location the aircraft could be required to stop
- aircraft mix
- runway width
- exit design
- terminal access and taxiing usage patterns
- existing facilities

A first cut approximation to exit location can be made locating the last exit to be the minimum of the following two conditions:

1. approximately 1999 of 2000 landings can use the exit.
2. approximately 99 of 100 aircraft using the exit have a runway occupancy time below the maximum allowable time.

The other exits are spaced at approximately 500 meter intervals if there is a homogeneous aircraft mix. The interval should be increased if there is a large variety of aircraft types using the runway.

Of course, the above first cut approximation to exit location is only applicable to new airports where the taxiway system and terminal design can be modified to fit the high-speed runway exit system. All of the airports that will operate at reduced longitudinal separations are currently operational. Any changes to their runway exit system will require detailed airport specific analysis and more information on high-speed runway exit usage than is currently available.

REQUIRED RESEARCH

This report defines the results of the first phase of "Aircraft and Avionics Related Research Required to develop an Effective High-Speed Runway-Exit System." This phase is a requirements analysis which included reviewing previous research, defining the requirements for high-speed runway-exits, and recommending the research programs required to develop an effective high-speed runway-exit system.

There is inadequate data to currently define an effective high-speed runway-exit system. Existing data are of limited value because the current longitudinal separations of approaching aircraft do not require that pilots expedite turning off the runway. An effective high-speed runway-exit system requires more than concrete, and it will be necessary to have data on all elements of a high-speed runway-exit system before a recommended system can be defined.

The following research is recommended to develop an effective high-speed runway-exit system.

Pilot Performance Tests

There are many factors which impact the runway occupancy time of a high-speed runway-exit system, and most of these factors are dependent upon each other. It is necessary to evaluate the impact of the individual factors and combinations of the factors in order to define an effective high-speed runway-exit system. This evaluation cannot be performed with field data of actual operations because there are many factors (e.g., reduced longitudinal separations, new exit design concepts, improved pilot information, etc.)that do not exist today. Therefore, these factors must be evaluated in a controlled environment such as a specially modified airport (e.g., Wallops Island or the Miami Everglades airport) or a cockpit simulator (e.g., at NASA Langley or Douglas Aircraft Company). The cost of modifying the airport and aircraft for all the conditions currently being considered would be too expensive. It is recommended that the NASA Langley flight simulator facility be used to evaluate candidate high-speed runway-exit systems. It is possible that the simulator research will indicate that one or two high-speed runway-exit systems should be evaluated in the field.

There are many combinations of factors that should be evaluated. The factors include:

exit design concept
pilot information systems
exit locations
aircraft type and weight
meteorological conditions
runway conditions
pilot experience and motivation

The parameters to be measured include:

touchdown location, speed, sink rate
deceleration rates

exit usage percentage
runway occupancy time
pilot workload
passenger ride comfort

Landing Improvement Tests

The biggest single factor in determining the variance in runway speed is the variance in touchdown location. The emphasis of the high-speed runway-exit system is to minimize the probability of exceeding the maximum allowable runway occupancy time. This makes it important to reduce the impact of all factors which contribute to the variation between landings.

The landing improvement program includes the following:

- define touchdown performance requirements
- determine improvement with flare angle versus range, and DME and flare angle
- evaluate nonexponential flare control laws
- evaluate existing autoland systems and refinements
- determine MLS requirements

Runway and Exit Guidance Concept Evaluation

This requirements study verified the need for improved pilot information systems from the start of final approach until arrival at the gate. These information systems are particularly needed by the pilot who does not frequently operate at the airport. The five basic means of providing the information are:

- verbal instructions from the controller
- advanced cockpit instrumentation
- ground visual displays
- systems built into the airport and airplane
- combinations of the above

The runway and exit guidance concept evaluation will be a review of proposed systems with recommendations on which systems have the best near term and long-term potential of aiding airport operations. The output of this task will help define pilot information systems to be considered in the pilot performance simulation tests and may define required changes to air traffic control regulations and procedures. The guidance systems will include the following functions:

- transfer from landing to ground control
- automatic landing systems
- automatic runway exiting systems
- taxiing systems

Passenger Acceptance Tests

Airlines and pilots will resist using a high-speed runway-exit system which does not provide a smooth ride for the passengers. It is possible that the pilot acceptance tests will provide data illustrating that the lateral and longitudinal g-load and jerk could be unacceptable.

The passenger acceptance tests would determine if the high-speed exit ride qualities are unacceptable. The passenger acceptance tests can be performed by modifying a motion base simulator for passenger ride quality or by operating a specially modified vehicle over a defined course on an unoccupied pavement.

Other Airport Constraints

The advanced air traffic control and reduced runway occupancy time systems are being developed to improve service at saturated airports. This improved service will decrease delays and/or allow an increase in air carrier operations. The need for reduced delay is readily understood and techniques are available to estimate this benefit. The need, feasibility, and benefits of increased air carrier operations are much harder to quantify.

It is possible that an increase in runway operations is not possible because the airport capacity is restricted by the capacity of taxiways, gates, terminals, parking or ground access. Most of the high density airports which will receive the advanced air traffic control systems are currently near capacity for several elements. The analysis of the capacity of all elements of the airport is a very site specific problem and can best be performed by specialists such as those currently on the airport capacity task forces at ATL, DEN, JFK, LAX, LGA, MIA, ORD, and SFO and those being formed for several other airports. This analysis requires the use of an airport delay simulation model such as that being used by the task forces.

These airport task forces also include the specialists required to determine where additional high-speed runway exits can and should be located at these airports. There should be close coordination between the high-speed runway exit study team and the airport capacity task forces. This coordination is particularly needed after the pilot performance tests have been completed.

Modified Air Traffic Control Procedures

There are many elements of the candidate high-speed runway exit systems that will require changes to the air traffic control procedures. For example:

1. The maximum allowable runway occupancy times do not include any buffer time from when the aircraft exits the runway until the next aircraft crosses the landing threshold. It is doubtful if controllers would operate without a buffer time because they have a high probability of violating paragraph 1120 of the Air Traffic Control Handbook (Reference 9).

2. The drift-off high-speed exit-design concept would undoubtedly require some modification to the one-on-the-runway regulation. It is likely that a special separation regulation would be required because it would probably be possible to have another aircraft cross the threshold while there is an aircraft on the drift-off; however, it is unlikely that it would be permissible for an aircraft on the runway to pass an aircraft on the drift-off section.

3. Some of the pilot information systems would have to involve controllers. For example, an unoccupied high-speed runway exit could be identified with blinking lights. A controller would have to initiate the lights. Similarly, taxiway clearance data is a very high priority pilot information need; this data would probably require significant changes in controller procedures.

The analysis of air traffic control procedure changes should be included in the analysis of candidate high-speed runway exit systems which are still being considered after the pilot performance tests.

REFERENCES

1. FAA - AVP - 78-6 "Terminal Area Forecasts; Fiscal Years 1979-1990", by P. G. Kruzic, T. E. Henry, C. R. Wine, June 1978.

2. Airport Activity Statistics of Certificated Route Air Carriers, 12 Months Ending December 31, 1976", CAB - Financial and Traffic Data Section, FAA - Information Operations Branch.

3. "Establishment of New Major Public Airports in the United States", Report of the Secretary of Transportation to the United States Congress pursuant to Section 26 of the Airport and Airway Development Act Amendments of 1976 (P.L. 94-353), August 1977.

4. FAA - AGL - 76-1, II, "O'Hare Delay Task Force Study; Volume 2 Technical Report", July 1976.

5. MTR - 7183 Capacity Impact of Revising Aircraft Categories and Final Approach Separation Standards", V. P. Gupta, MITRE, March 1976.

6. MTR - 7333 "An Analysis of a 2.5 n.mi. Final Approach Separation Standard", Dr. A. L. Haines, MITRE, June 1977.

7. FAA - EM - 78-8A, "Parameters of Future ATC System Relating to Airport Capacity/Delay", FAA, June 1978.

8. FAA - RD - 74-124, "Techniques for Determining Airport Airside Capacity and Delay", June 1976.

9. "Air Traffic Control Handbook", FAA 7110-65 A Chg. 4, October 2, 1978.

10. "An Analysis of High-speed Exit Utilization on Selected Runways", prepared for the FAA by Howard, Needles, Tammen & Bergendoff, May 1975.

11. FAA-RD-74-36, "Field Survey and Analysis of Aircraft Distribution on Airport Pavements", V. A. HoSang; Howard, Needles, Tammen & Bergendoff, February 1975.

12. FAA-EM-78-9, "Analysis of Runway Occupancy Times at Major Airports", May 1978.

13. "Survey of Runway Exit Use , Dallas Ft. Worth Airport, March 1978.

14. Stickle, J. W.: "An Investigation of Landing Contact Conditions for Two Large Turbojet Transports and a Turboprop Transport During Routine Daylight Operations", NASA TN D-899, May, 1961.

15. Geoffrian, D. R. and Kibardin, V. M.: "Statistical Presentation of Operational Landing Parameters for Transport Jet Airplanes", FAA Flight Standards Service Release No. 470; August 8, 1962.

16. "Automatic Landing Systems", FAA Advisory Circular AC No. 20-57A, 12 January 1971.

17. "Microwave Landing System Development Plan as Proposed by ITT/Gilfillan During the Technique Analysis and Contract Definition Phase of the National MLS Development Program", FAA RD-74-118; 1974.

18. "Flight Development Program for a Category III All Weather Landing System on the Model DC-9 Series 30", McDonnell-Douglas Report No. DEV-3795; May 1968.

19. Attri, N. S. and Anberg, R. L., "Improvements in Airplane Stopping Performance on Adverse Runways", AIAA Paper No. 74-965, August 12-14, 1974.

20. Horonjeff, R.; Finch, D. M.; Belmont, D. M. and Ahlborn, G.; "Exit Taxiway Location and Design". Institute of Transportation and Traffic Engineering, University of California for the Airways Modernization Board under Contract AMB-4; August, 1958.

21. Jansen, G. R., "Flight Crew News Letter". Volume II. Issue No. 6; Long Beach, California; August, 1978.

22. Schaefer, E., "Preliminary Investigations in Connection with the High Speed Exit Program". Department of Transportation FAA Letter Report RD-76-8-LR; ARD-410; August, 1976.

23. Stephans, W. A. and O'Massey, R. C., "Rejected Takeoff Simulation: Accident Prevention Research". Paper presented at the 31st Annual International Air Safety Seminar; Flight Safety Foundation; Caracas, Venezuela; November 6-9, 1971.

24. "Taxiway Centerline Lighting System". FAA Advisory Circular AC 150/5340-19; Department of Transportation, November 14, 1968.

25. Conner, W. D., "Nonmotion Factors Which can Affect Ride Quality", in 1975 Ride Quality Symposium, National Aeronautics and Space Administration, NASA-TM-X-3295, 1975.

26. Duncan, N. C. and Conley, H. W., "Demographic and Psychological Variables Affecting Test Subject Evaluations of Ride Quality", in 1975 Ride Quality Symposium, National Aeronautics and Space Administration, NASA-TM-X-3295, 1975.

27. Hanes, R. M., "Human Sensitivity to Whole Body Vibration in Urban Transportation Systems: A Literature Review," APL/JHV-TPR 004, John Hopkins University, May 1970.

28. Jacobson, I. D., "Environmental Criteria for Human Comfort - A Study of University of Virginia, Charlottesville, Va. Report No. BE-4088-101-74; February 1974.

29. McKenzie, J. R. and Brumaghim, S. H., "Review of Ride Quality Technology Needs of Industry and User Groups", in 1975 Ride Quality Symposium, National Aeronautics and Space Administration, NASA-TM-X-3295, 1975.

30. Rinalducci, E. J., "Passenger Comfort Response Times as a Function of

Aircraft Motion", NASA Technical Report 403906 Short-Haul Air Transportation Program; University of Virginia, Charlottesville, Va., Report No. ESS-4039-104-75; October, 1975.

31. Schoonover, W. E., "Ride Quality of Terminal Area Flight Maneuvers", in 1975 Ride Quality Symposium, National Aeronautics and Space Administration, NASA-TM-X-3295, 1975.

32. Wolf, T. D.; Rezek, T. W.; and Gee, S. W., "Passenger Ride Quality Response to an Airborne Simulator Environment", in 1975 Ride Quality Symposium, National Aeronautics and Space Administration, NASA-TM-X-3295, 1975.

33. Hosford, J. E., "Simulation by Incremental Stochastic Transition Matrices (SISTM)," presented at the 36th National Meeting of the Operations Research Society of America, 1969.

34. Advsory Circular 150 (5335-1A Change 2, "Airport Design Standards - Airports Served by Air Carriers - Taxiways," December 29, 1976.

35. Coggins, Max H. "The Airport Capacity Increasing Potential of Angled Runway Exit Designs" presented at the Society of Automotive Engineers, Air Transportation Meeting, Boston, May 1 - 4, 1978.

36. Ahlers, R. B., "Status Report on Recommended R, E & D Actions to Reduce Runway Occupancy Time Via Improved High-Speed Taxiway Utilization." Report to FAA SRDS Airport Division, August 1975.

37. Mood, Alexander McFarland, "Introduction to the Theory of Statistics," Pg. 118, McGraw-Hill Book Co., 1950.

APPENDIX

HIGH-SPEED RUNWAY EXIT
QUESTIONNAIRE

Name_______________________________ Telephone____________________

Flying experience in commercial aircraft (hours) ____________

Air carrier experience (hours) ____________

Previous experience with existing high-speed turnoffs? Yes___ No____

Return to: J. B. Erickson
C1-253, Code 35-36
Telephone: (59) 38827

HIGH-SPEED RUNWAY EXIT
QUESTIONNAIRE

A study is currently in progress to determine the feasibility of high-speed runway exits to increase airport capacity at major hub airports. One part of the study is to determine additional information that would be needed by the aircraft crew in order to perform the exit maneuver safely and accurately.

The purpose of this questionnaire is to identify requirements for additional information or improvements in the accuracy and completeness of existing information (speed, visibility, traffic, etc.). The results of this preliminary survey will be used to develop concepts for evaluation in a simulation study.

Many of the specific characteristics of the high-speed exits will not be determined until the study is completed. However, for purposes of completing this questionnaire, the following assumptions should be made:

1. Exit angle = 30° (see attached illustration)

2. Exit speed = 30-50 kts

3. Aircraft approach intervals of 2-3 miles

4. Worst case visual conditions for high-speed exit operations would be Cat IIB.

5. The high-speed exit system would have to accommodate night operations.

6. Aircraft would be required to stop prior to crossing taxiway or active runway. Available stopping distance will vary substantially across airports.

For each of the following pilot/aircraft activities, indicate which types of information would be useful and rate the degree of importance by checking the appropriate column. If you have any specific suggestions, please list them in the comments section. (Consider improved exit signs, lighting, markings, etc., as well as cockpit information displays.)

1. <u>Decision Activity--Landing vs. Go-around.</u>

Additional or Improved Information	Useless	Limited Use	Helpful	Very Helpful	Essential
Visibility (distance)					
Predicted TD point					
Predicted TD speed					
Predicted ground speed at exit threshold					
Runway traction (coefficient of friction)					
Runway clear					
Exit clear					
Other: ____________________					
____________________					
____________________					

Comments:

2. <u>Landing Activity</u>

Additional <u>or</u> Improved Information	Useless	Limited Use	Helpful	Very Helpful	Essential
TD point					
TD speed					
Distance to exit					
Runway traction (coefficient of friction)					
Predicted speed at exit threshold					
Runway clear					
Exit clear					
Other: ____________________					
____________________					
____________________					

Comments:

3. Decision Activity--Exit/Continue Deceleration

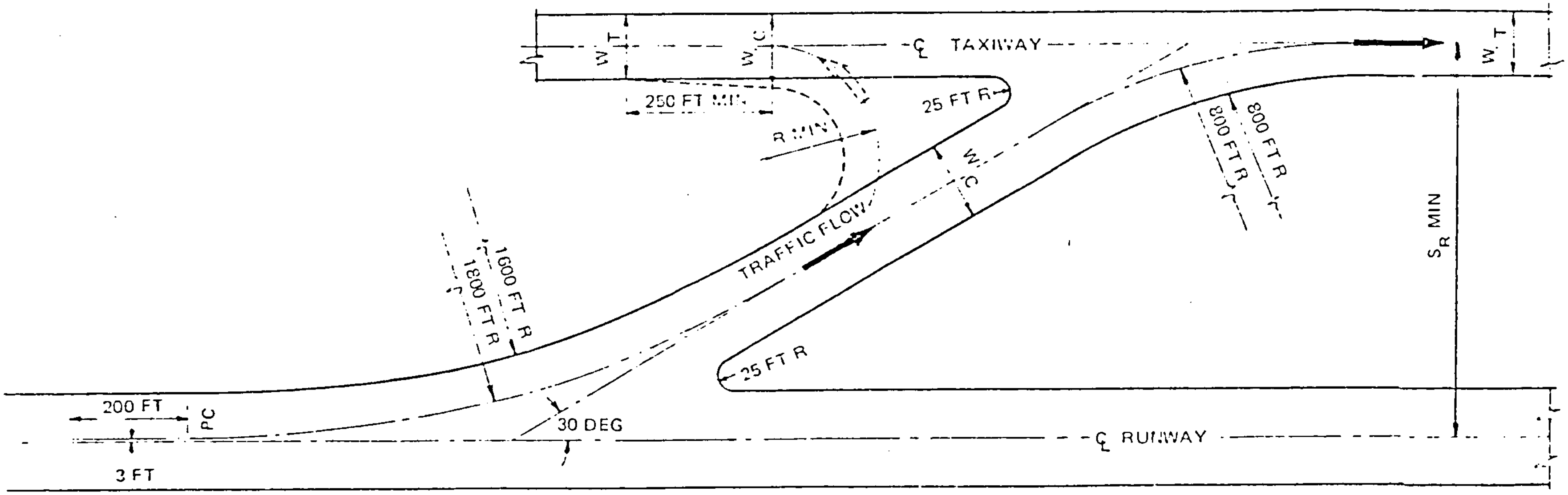
Additional or Improved Information	Useless	Limited Use	Helpful	Very Helpful	Essential
Predicted speed at exit threshold					
Predicted alignment at exit threshold					
Runway traction (coefficent of friction)					
Deviation from nominal deceleration profile					
Computer generated solution (go-nogo) based on current environmental and aircraft information					
Exit clear					
Taxi route to gate					
Other: ______________________					
______________________					
______________________					

Comments:

4. Runway Exit Activity

Additional or Improved Information	Useless	Limited Use	Helpful	Very Helpful	Essential
Alignment					
Ground speed					
Deviation from optimum path					
Deviation from nominal deceleration profile					
Reserve braking capacity					
Runway traction (coefficient of friction)					
Lateral G-forces (observed)					
Lateral G-forces (allowable limits)					
Taxi route to gate					
Ground traffic information					
Other: ______________________					
______________________					
______________________					

Comments:



ANGLED EXIT TAXIWAY DESIGN

DOUGLAS AIRCRAFT COMPANY