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Development of Airport Surface Required Navigation Performance (RNP)

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ABSTRACT

The U.S. and international aviation communities have adopted the Required Navigation Performance (RNP) process for defining aircraft performance when operating in the en-route, approach and landing phases of flight. RNP consists primarily of the following key parameters - accuracy, integrity, continuity and availability. The processes and analytical techniques employed to define en-route, approach and landing RNP have been applied in the development of RNP for the airport surface.

The development of airport surface RNP began with the classification of the various phases of aircraft operations on airport surface areas. All aspects of an aircraft's movement on the airport surface were examined – exiting the runway, normal taxi, and apron taxi. Additional variables defined within these operational phases are aircraft taxi speeds, exposure times to the various phases of taxiing, and visibility conditions on the airport surface. A surface movement Target Level of Safety (TLS) was established, followed by an allocation of risks to each phase of surface movement. Other factors considered in the determination of the airport surface RNP include the reaction of the pilot to various navigation system failures and containment limits imposed on the aircraft when operating within the confines of the airport environment. The result is a set of proposed requirements for accuracy, integrity, continuity, and availability for each phase of surface movement.

To validate the proposed RNP requirements several methods were used. Operational and flight demonstration data were analyzed for conformance with proposed requirements, as were several aircraft flight simulation studies. The pilot failure risk component was analyzed through several hypothetical scenarios. Additional simulator studies are recommended to better quantify crew reactions to failures as well as additional simulator and field testing to validate achieved accuracy performance.

This research was performed in support of the NASA Low Visibility Landing and Surface Operations Program.

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1.0 INTRODUCTION

One of the anticipated applications of Global Navigation Satellite Systems (GNSS), including the Global Positioning System (GPS), is aircraft navigation on the airport surface. With the implementation of local area differential GNSS, technology will be available to enable aircraft to obtain accurate position information when taxiing on the airport. Currently, navigation performance standards do not exist for aircraft operations on the airport surface. Standards are under development by the International Civil Aviation Organization (ICAO) All Weather Operations Panel (AWOP) for Advanced Surface Movement Guidance and Control Systems (A-SMGCS) and by the RTCA Airport Surface Navigation and Surveillance subgroup of Special Committee 159. Under contract to NASA Langley Research Center as part of the Terminal Area Productivity Program, Rannoch is developing the Required Navigation Performance (RNP) requirements for surface movement navigation.

This report presents a summary of RNP development, including definition of the operation Target Level of Safety (TLS) and proposed requirements for the four RNP parameters–integrity, continuity, accuracy and availability. In addition to definition of system level requirements, the report presents proposed allocations for navigation sensor performance, which defines the performance needed by a GNSS-based system to satisfy system RNP requirements.

RNP is a relatively new concept that is being applied to develop navigation standards for all phases of aircraft operations, including en route, landing and surface operations. See references 1 and 2 for a description of RNP for approach and landing and references 3 and 4 as it pertains to the en route phase of flight. RNP is a probabilistic approach to evaluating an aircraft's deviation from its intended course. One of the benefits of the RNP approach is that it allows the design engineer to trade off elements of error budgets between subsystems. For example, a newer autopilot design may allow the use of a less accurate sensor or ground system. The RNP approach also goes beyond the accuracy of a system and provides quantitative requirements for a system's continuity and integrity. In this report the RNP process is applied to aircraft surface movements. The main components of RNP as developed for this application are:

- RNP Parameter Definition
- Operation Classification
- Target Level of Safety Risk Allocation
- Accident/Incident Ratio
- Risk Allocations
- Pilot Risk Factor
- Integrity and Continuity
- Containment Limit
- Accuracy
- Availability
- Validation

Each of these are discussed in the following sections.

2.0 REQUIREMENTS DEVELOPMENT

2.1 RNP Parameter Definitions

2.1.1 Required Navigation Performance (RNP)

RNP is a statement of the navigation performance accuracy necessary for operation within a defined airspace [3]. There are four primary parameters used to define RNP - accuracy, integrity, continuity and availability. The definitions given below are based on those used for other phases of flight [1,3]. However, they have been tailored for application to airport surface movement. As applied here the terms navigation and guidance have the same meaning.

2.1.2 Accuracy

Accuracy is defined in terms of the Total System Error (TSE) as the difference between the true position and the desired position. The accuracy requirement is for the TSE to remain within a normal performance region, under fault-free conditions, 95% of the time [5].

2.1.3 Integrity

Integrity relates to the trust which can be placed in the correctness of the navigation information supplied by the navigation system. Integrity includes the ability of the navigation system to provide timely and valid alerts to the user when the system must not be used for the intended operation. Integrity risk is the probability of an undetected failure that results in the TSE exceeding the Containment Limit (CL) [5].

2.1.4 Continuity

Navigation continuity is the capability of the navigation system (comprising all elements necessary to maintain aircraft position within the containment region) to perform the navigation function without unscheduled interruption during the intended operation. Continuity risk is the probability that the system will be interrupted and not provide navigation information over the period of the intended operation. More specifically, continuity is the probability that the system will be available for the duration of an operation, presuming that the system was available at the beginning of the operation [5].

2.1.5 Availability

Availability is an indication of the ability of the navigation function to provide usable service within the specified coverage area, and is defined as the portion of time during which the system is to be used for navigation, during which reliable navigation information is presented to the crew, autopilot, or other system managing the movement of the aircraft. Availability is specified in terms of the probability of the navigation function being available at the beginning of the intended operation [5].

2.2 Operation Classification

The surface operation is considered in phases, including rollout, high speed taxi exit, and normal taxi. The definition of phases is related to aircraft taxi speed and each phase of the operation is considered for different visibility conditions. Figure 1 shows a summary of the phases of operation selected for surface movement.

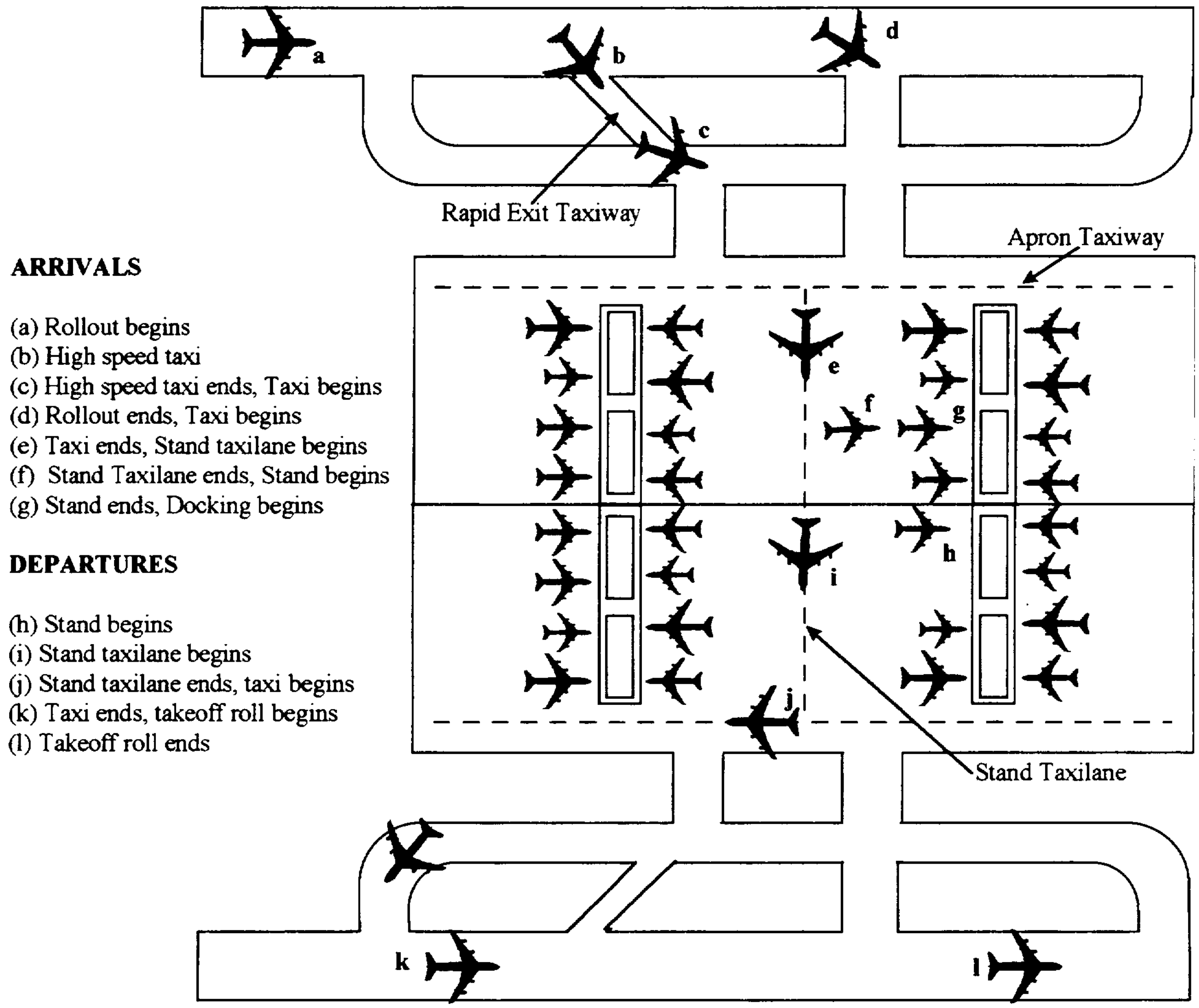

Figure 1. Phases of Surface Operation

Rollout is defined as touchdown to the point where the aircraft decelerates below 60 kts [1]. Operationally, rollout is considered to be a part of the aircraft landing, therefore the RNP for that phase of surface movement is defined by the Category III landing RNP. After completing rollout the aircraft will enter into the taxi phase, which is defined as either high speed, normal or apron taxi. For runways with a rapid exit taxiway (also referred to as a high speed exit), the aircraft will end rollout by taxiing at a high speed. After the aircraft has decelerated it enters the normal taxi phase. The aircraft then enters the apron area and initially will travel on an apron taxiway. When the aircraft enters the stand area it will be moving on a stand taxilane at its slowest taxi speed. In some operations there is also a docking maneuver.

For the departing aircraft, the order of the phases of operation is from the stand to normal/apron taxi to takeoff roll. The takeoff roll is covered in the RNP for aircraft departure and is therefore not included as part of the surface movement RNP. High speed taxi is normally at speeds between 30 and 70 kts, which occur with the use of rapid exits. This is based on measurements of operational speeds [6, Appendix A] and the need to limit lateral acceleration [7]. The study in reference 7 defined a requirement to limit the lateral acceleration to 0.15 g, which results in a maximum exit velocity of 70 kts. It should also be noted that the ICAO aerodrome design manual assumes a velocity of 50 kts for rapid exit taxiways [8]. However, operational data [6] shows instances of higher velocities, which should be accommodated in the analysis. Normal/apron taxiway speeds range from 10 - 50 kts. The 50 kts maximum for normal taxi is based upon a U.K. study that found maximum speeds on straight sections as high as 49 kts, with the average being slightly under 20 kts [6]. Speeds are reduced during turns, therefore the range is reduced to a maximum of 20 kts. When the aircraft enters the stand taxilane phase of surface movement it will have a ground speed between 0 and 10 kts. To determine the risk for each phase of operation, an associated exposure time must be assigned. Exposure times were determined by evaluating typical taxi distances for each phase for nine major U.S. airports [9, Appendix B]. Table 1 summarizes the velocities and exposure times for the different phases.

Table 1. Taxi Speeds and Exposure Times

Taxi Phase	Taxi Speed (knots)	Exposure Time (minutes)
Rapid Exit (High Speed)	30-70	0.5
Normal/Apron Taxiway - straight	10-50	6
Normal/Apron Taxiway - 90° turn	10-20	
Stand/ Stand Taxilane	0-10	3

As stated earlier, each phase of the surface operation must be considered for different visibility conditions. Currently, visibility conditions have four classifications according to ICAO [5] and are defined below. Conditions 3 and 4 are essentially equivalent to approach and landing Category III.

<u>Visibility Condition 1</u>: Visibility sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, and for personnel of control units to exercise control over all traffic on the basis of visual surveillance (RVR > 400 m/1300 ft).
<u>Visibility Condition 2</u>: Visibility sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, but insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance (RVR > 400 m/1300 ft).
<u>Visibility Condition 3</u>: Visibility sufficient for the pilot to taxi but insufficient for the pilot to avoid collision with other traffic on taxiways and at intersection by visual reference with other traffic, and insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance (75 m/250 ft < RVR < 400 m/1300 ft).
<u>Visibility Condition 4</u>: Visibility insufficient for the pilot to taxi by visual guidance only (RVR < 75 m/250 ft).

For the purposes of this report, Visibility Conditions 1 and 2 were treated as a single category (referred to as Visibility Condition 1,2) because these conditions are identical from the crew's perspective.

2.3 TLS Risk Allocation

The target level of safety established by ICAO for the entire operation or mission is one accident per 10^7 operations [5]. It is necessary to allocate a portion of this to the taxi phase. One method of determining an appropriate TLS for an operation is to base it upon the historical accident rate. Two sources of accident data are used here–worldwide data, and National Transportation Safety Board (NTSB) data for aircraft operations in the U.S. Worldwide accident data reveals the following:

- Overall fatal accident rate (1985-94) = 1.8×10^{-6} per operation [10,11]
- Taxi accidents (including load and unload) account for 5% of fatal accidents [12]
- Therefore, the fatal taxi accident rate = 9.0×10^{-8} per operation.

NTSB accident data for the U.S. is summarized as follows:

- Overall fatal accident rate (1985-94) = 0.56×10^{-6} per operation [13]
- Fatal taxi accidents account for 11% of all fatal accidents [13]
- Therefore, the fatal taxi accident rate = 6.2×10^{-8} per operation.

The ICAO and NTSB fatal taxi accident rates are similar (9.0 vs. 6.2×10^{-8} per operation). The final approach and landing phase was allocated 1.0×10^{-8} [1,2]. Similarly, the other phases of flight have allocations that use only a small portion of the overall TLS. Therefore, the taxi phase should be allocated a comparable portion. Based on the above, the surface movement TLS was established at 1.0×10^{-8} fatal taxi accidents per operation. This provides a margin of 6-9 over the historical accident rate and is in line with the allocations used for the approach and landing RNP. It should be noted that this TLS applies to all visibility conditions of surface operations. Figure 2 shows the allocation of risk from the TLS to integrity and continuity requirements for the guidance function. The TLS is initially divided between the four functions associated with surface movement (surveillance, guidance, control and routing). Risks were divided equally except for routing, which was assigned a lower risk because it is a less complex function. Following is an explanation of the allocation process for the guidance (or navigation) risk.

2.4 Accident/Incident Ratio

Since not all incidents translate to accidents, there is a ratio assigned. An incident is defined as any time the aircraft leaves the containment region (to be defined later). There are actually two ratios used - fatal accident/accident and accident/incident. These ratios were based primarily on NTSB data for accidents on the airport surface.

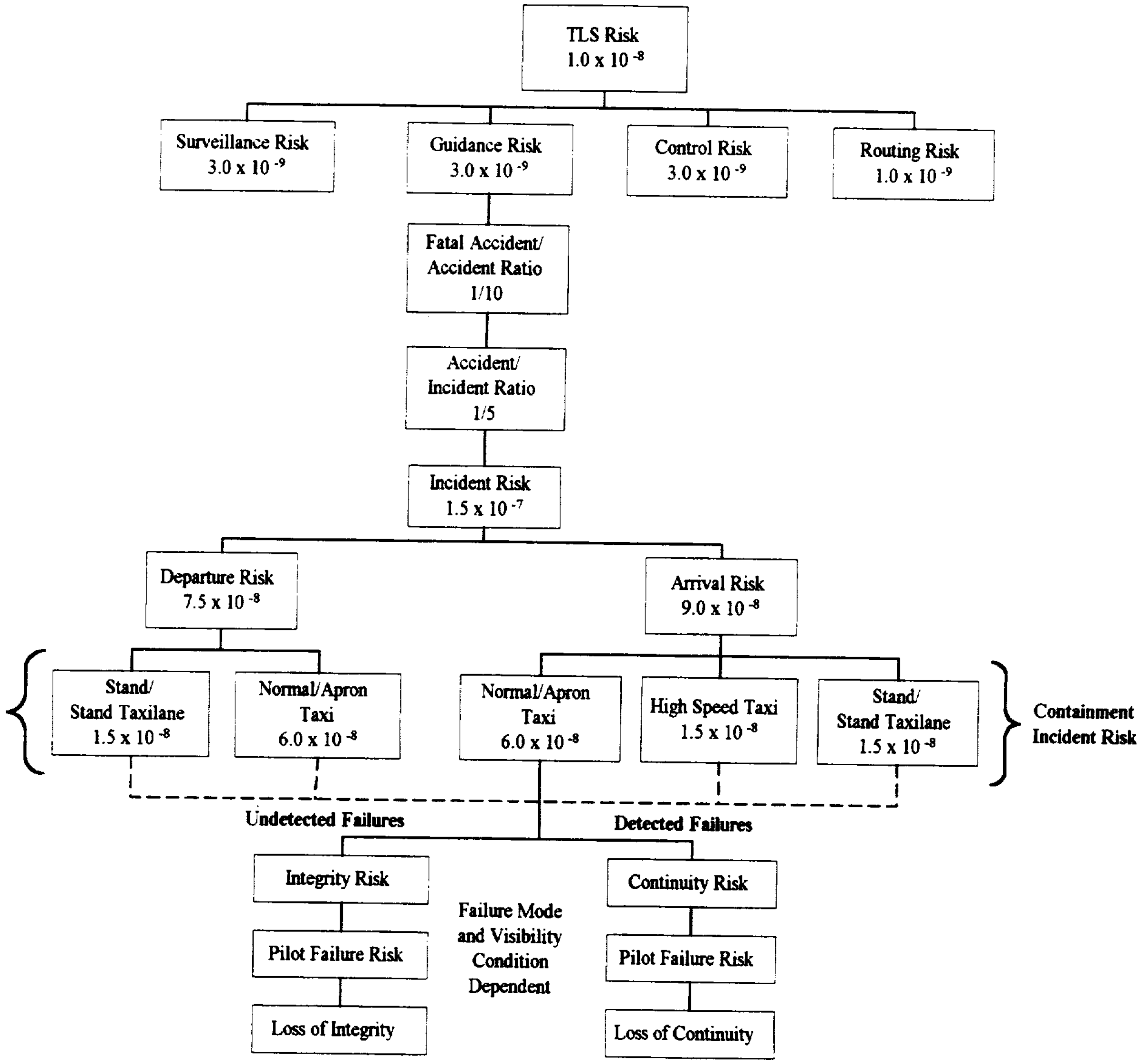

Figure 2. RNP Risk Allocation

2.5 Risk Allocations

The overall TLS is allocated to each phase of the surface operation. The TLS includes all phases of an operation, so for the surface, both departure and arrival must be included. Risk levels are assigned to each phase–high speed taxi, normal taxi, etc. Failures are identified as continuity or integrity. The reason for different allocations is different exposure times. The values shown in Figure 2 are on a per operation basis. The requirements have been allocated such that when normalized to a per hour basis they are roughly equal over all phases of the operation and are shown in Table 2.

Table 2. Allocation of Integrity and Continuity Risk

Visibility Condition	Phase	Failure Mode	RNP Risk	Pilot Failure Risk	RNP Allocation	Exposure Time	Risk (per hour)

						(Minutes)	
1,2	Stand Taxilane	Continuity	7.50E-09	5.0E-06	1.5E-03	3.0	3.00E-02
	Stand Taxilane	Integrity	7.50E-09	5.0E-05	1.5E-04	3.0	3.00E-03
	Normal/Apron	Continuity	3.00E-08	1.0E-04	3.0E-04	6.0	*3.00E-03
	Normal/Apron	Integrity	3.00E-08	1.0E-04	3.0E-04	6.0	3.00E-03
	High Speed	Continuity	5.00E-09	1.0E-04	5.0E-05	0.5	6.00E-03
	High Speed	Integrity	5.00E-09	3.0E-03	1.7E-06	0.5	*2.00E-04
3	Stand Taxilane	Continuity	7.50E-09	5.0E-05	1.5E-04	3.0	3.00E-03
	Stand Taxilane	Integrity	7.50E-09	5.0E-03	1.5E-06	3.0	3.00E-05
	Normal/Apron	Continuity	3.00E-08	1.0E-04	1.5E-04	6.0	*3.00E-03
	Normal/Apron	Integrity	3.00E-08	1.0E-02	3.0E-06	6.0	*3.00E-05
	High Speed	Continuity	5.00E-09	1.0E-04	1.3E-05	0.5	6.00E-03
	High Speed	Integrity	5.00E-09	1.5E-02	3.3E-07	0.5	4.00E-05
4	Stand Taxilane	Continuity	7.50E-09	1.0E-04	1.5E-05	3.0	*1.50E-03
	Stand Taxilane	Integrity	7.50E-09	5.0E-02	1.5E-07	3.0	3.00E-06
	Normal/Apron	Continuity	3.00E-08	1.0E-04	3.0E-05	6.0	3.00E-03
	Normal/Apron	Integrity	3.00E-08	1.0E-01	3.0E-07	6.0	*3.00E-06
	High Speed	Continuity	5.00E-09	1.0E-04	2.5E-06	0.5	6.00E-03
	High Speed	Integrity	5.0E-09	1.0E-01	5.0E-08	0.5	6.00E-06

* Most stringent requirements for that visibility condition.

2.6 Pilot Risk Factor

Figure 3 shows the pilot failure risk factors assigned for various failure modes and visibility conditions at stand taxilane, normal/apron and high speed taxi aircraft movements. The risk factor is dependent on several variables, all of which affect the probability of an incident. The mode of failure determines whether the crew receives a warning that a failure has occurred. If a continuity failure occurs, the crew will receive a warning immediately following the failure. An integrity failure will yield no warning, therefore the crew will depend on visual cues to recognize that a failure has occurred. Consequently, longer response times can be expected for integrity failures. Since the crew relies on visual, out-the-window views, visibility will primarily drive pilot risk for the integrity failure mode. For example, low visibility can be expected to generate longer pilot response times and higher risk. Aircraft velocity affects the amount of time the crew has to respond to a failure. The greater the aircraft velocity, the longer the braking distance, and consequently the less time the crew has to respond to the failure. Crew response time will also be longer because of an increased crew workload when traveling at high speeds on the airport surface (i.e., high speed exit taxiing). See 3.4.1 for a complete discussion of the validation of the pilot risk factor values.

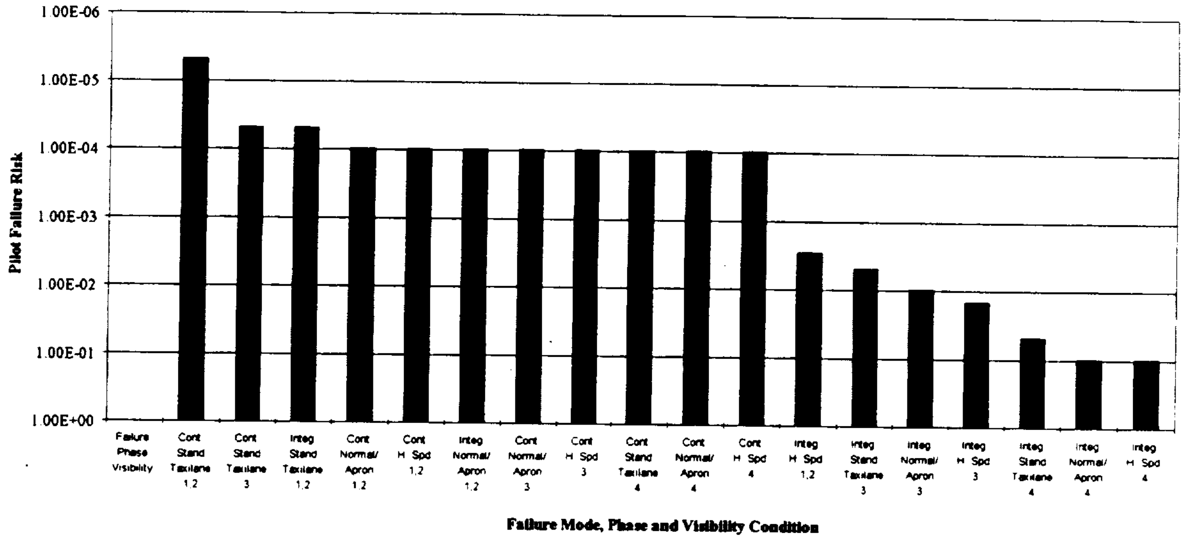

Figure 3. Pilot Risk Allocations

2.7 Integrity and Continuity Requirements

The RNP risk allocation is equally divided between integrity and continuity (Figure 2). Table 2 lists the allocations for all cases. Table 3 summarizes the most stringent integrity and continuity requirements for different visibility conditions. Each phase of surface operation is theoretically allocated a different risk, but in order to simplify the standards only the most stringent values are recommended as the requirement.

Table 3. Integrity and Continuity Risk (per hour)

	Visibility Condition		
	1,2	3	4
Integrity	2.0×10^{-4}	3.0×10^{-5}	3.0×10^{-6}
Continuity	3.0×10^{-3}	3.0×10^{-3}	1.5×10^{-3}

2.8 Containment Limit

Figures 4 and 5 illustrate key taxiway design standards [8,14, 15]. The two parameters of concern are the relationship of the main wheels to the edge of the taxiway and its shoulder, and the margin between the wing tips and the closest allowable objects. Figure 4 shows straight sections of taxiways and Figure 5 curved sections.

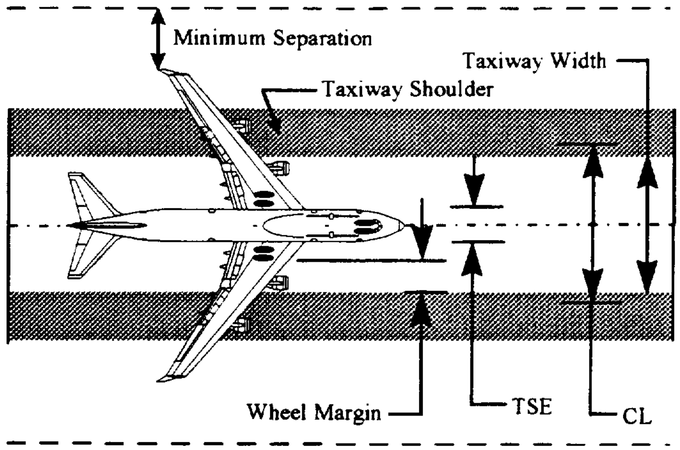

Figure 4. Taxiway Design Standards (straight segments)

The difference with curved sections is that normally there is additional pavement added to the inside of the curve in the form of a fillet. This compensates for the fuselage of the aircraft deviating to the inside when making a turn, assuming that the pilot steers by maintaining the cockpit (and nosewheel) over the centerline of the taxiway. The amount of extra fillet required is sufficient to maintain the same margins between the wheels and taxiway edge. At airports where there is no fillet the pilot is required to use "judgmental oversteering" to maneuver the aircraft, where the nosewheel is purposely steered outside the centerline, thus keeping the fuselage from deviating to the inside of the curve.

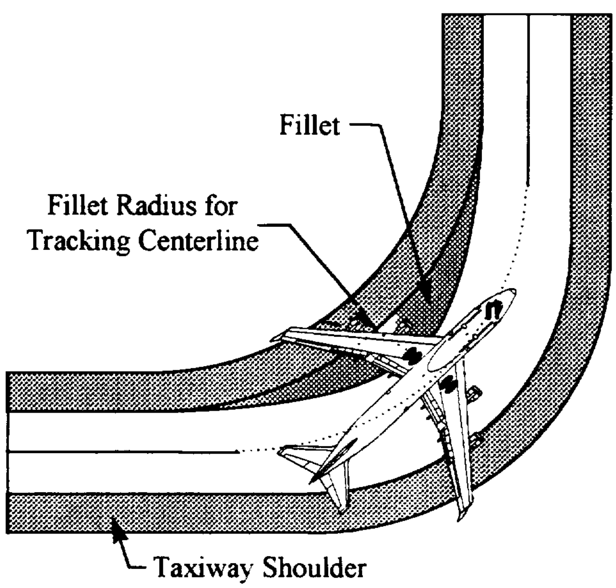

Figure 5. Taxiway Design Standards (curved segments)

The Containment Limit definition assumes operation at an aerodrome that meets taxiway widths and the minimum separation distances specified in ICAO Annex 14 [14]. Table 4 indicates the taxiway widths categorized according to aerodrome code. Codes D and E are designed to handle widebody commercial aircraft (B-747, DC-10), code C corresponds to midsize aircraft (B-737, DC-9), and codes A and B relate to general aviation aircraft. For code E, there is a 15.5 m margin between the wing tips and any objects, including wings of aircraft on parallel taxiways. The minimum margin between the main wheels and taxiway edge is 4.5 m. The standards also recommend a 10.5 m shoulder, thus yielding a 15 m margin between the wheels and outer edge of the shoulder. The result is that the aircraft can deviate by 15 m from the taxiway centerline before there is risk of an incident, and therefore the CL is defined to be this value. For the purposes of this report, it is assumed that all deviations are referenced to the nosewheel of the aircraft.

Table 4. Minimum Separation Distances for Different Taxiway Aerodrome Codes

Aerodrome reference code letter	Taxiway width (meters)	Maximum outer main gear wheel span (meters)	Margin between main gear and taxiway edge (meters)	Distance between centerline and object (meters)	Maximum wing span (meters)	Wing tip to object margin - taxiways (meters)	Wing tip to object margin - stand taxilane (meters)	Wing tip to object margin - stand (meters)
A	7.5	4.3	1.5	16.25	15	8.75	4.5	3.0
B	10.5	6.0	2.25	21.5	24	9.5	4.5	3.0
C	18	9.0	4.5	26.0	36	8.0	6.5	4.5
C	15	6.0	3.0	26.0	36	8.0	6.5	4.5
D	23	14.0	4.5	40.5	52	14.5	10.0	7.5
D	18	9.0	4.5	40.5	52	14.5	10.0	7.5
E	23	14.0	4.5	47.5	65	15.0	10.0	7.5

Note: Based on ICAO Aerodrome Design Manual, Part 2, Taxiways, Aprons and Holding Bays [8].

Table 5 lists the CL values based on minimum separation distances for aircraft for all taxiway design codes. The CL of 15 m is applicable only to codes D and E. Since the margin is less for codes A, B and C, the CL for those cases is defined accordingly as 8 m. In the stand taxilanes, the boundary is dependent on the minimum clearance between the aircraft's wing tips and other objects. In the stand area, the relationship of the main wheels to the edge of the taxilane is not of concern because there is a continuous pavement area; therefore, only the wing tip margins determine the CL. As would be expected, the safety margins and associated CLs decrease in the stand areas since it is assumed the aircraft is moving slower and is able to track the centerline more accurately. The probability of an aircraft deviating outside the boundary of the containment region is equal to the incident risk for the appropriate surface operation. These are indicated in Figure 2, and are either 1.5×10^{-8} (high speed taxi and stand/stand taxilane) or 6.0×10^{-8} (normal and apron taxi).

Table 5. Containment Limit Requirements

Aerodrome Code	Taxiways Containment Limit (meters)	Stand Taxilanes Containment Limit (meters)	Stand Containment Limit (meters)
A	8	4.5	3.0
B	8	4.5	3.0
C	8	6.5	4.5
D	15	10	7.5
E	15	10	7.5

Note: Aerodrome reference code is according to the code letter definition in Annex 14, paragraph 1.3 [14].

2.9 Accuracy

2.9.1 Derivation of Total System Error

The accuracy requirement establishes normal performance or 95% TSE, defined as the difference between actual aircraft position and the desired path (see Figure 6).

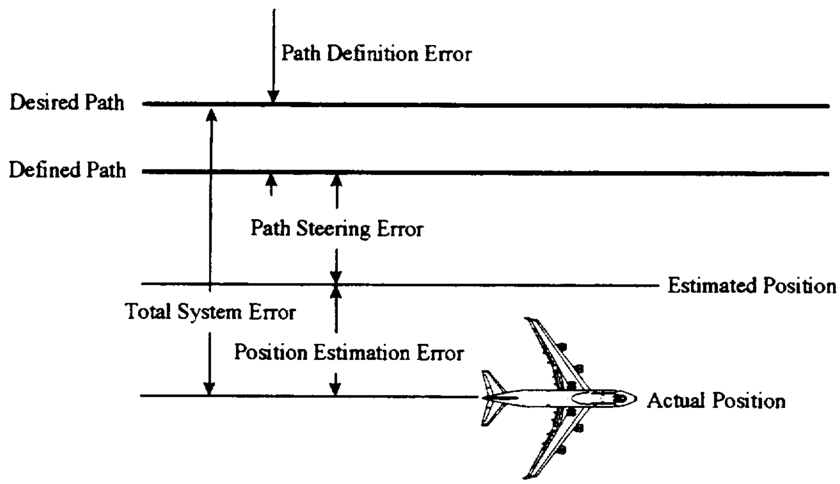

Figure 6. Components of Total System Error

The constraining limit used in establishing the accuracy requirement is the margin between the aircraft wheels and taxiway edge (4.5 m for codes D and E). The normal performance limit should be established to minimize the probability of the wheels leaving the taxiway. The probability allocated is the equivalent of 4σ or 6.3×10^{-5}, based on the assumption that the TSE distribution is gaussian. Defining the deviation to the taxiway edge as a 4σ value and the normal performance as 2σ (approximately 95%), the accuracy requirement is obtained by dividing the wheel margin by two. For aircraft with 4.5 m wheel margins the resulting accuracy requirement is ± 2.2 m. The resulting TSE requirements for all cases are given in Table 6.

Table 6. Normal Performance Requirements

Aerodrome Code	Taxiway Width (meters)	95% total system error (meters)		
		Taxiways	Stand taxilanes	Stand
A	7.5	0.7	0.7	0.5
B	10.5	1.1	0.7	0.5
C	15	1.5	1.0	0.7
C	18	2.2	1.0	0.7
D	18	2.2	1.2	1.0
D	23	2.2	1.2	1.0
E	23	2.2	1.2	1.0

The process for establishing the TSE limit is analogous to that used in establishing the relationship between the 95% TSE and the CL for other RNP applications. For en route and terminal area navigation the containment limit is set to two times the 95% value [3], while for approach and landing the relationship is a factor of three [1]. The difference is the direct relationship between normal performance and the boundary for wheel excursions, not the CL.

2.9.2 Stand Taxilanes

For the stand taxilanes, all separation distances are slightly reduced from those on taxiways because of lower taxi speeds. The margins associated with wing tips are indicated in the right-hand column of Table 4. Similarly, the assumed maximum deviations of the main gear are reduced [8], and are listed in Table 7. As for taxiways, the 95% performance requirement should be established with enough margin to these maximums so that the probability of exceeding the values shown in Table 7 is small. Extension of the philosophy with taxiways places the 95% limit at one half of the assumed maximums in Table 7, which are also shown in the table.

Table 7. Stand Taxilane Normal Performance Requirement Relationship to Gear Deviation

Aerodrome Code	Maximum Gear Deviation (meters)	95% Performance Requirement (meters)
A	1.5	0.7
B	1.5	0.7
C	2.0	1.0
D	2.5	1.2
E	2.5	1.2

2.9.3 Stand

For the stand, separation distances are reduced even further than those for stand taxilanes. Table 8 shows the margins [8], an assumed maximum-allowed gear deviation and required 95% performance. The maximum gear deviations and 95% performance requirements are maintained at the same ratios for each aerodrome code as allowed in the stand taxilane. It should be noted that this performance may not be sufficient for parking and docking. The requirements given here are related only to safety and are probably insufficient to accurately dock an aircraft at the gate.

Table 8. Stand Normal Performance Requirement Relationship to Wing and Gear Margins

Aerodrome code	Wing tip margin (meters)	Maximum gear deviation (meters)	95% performance requirement (meters)
A	3.0	1.0	0.5
B	3.0	1.0	0.5
C	4.5	1.5	0.7
D	7.5	2.0	1.0
E	7.5	2.0	1.0

2.9.4 Position Estimation Error Requirements

Referring again to Figure 6, the TSE is composed of Path Definition Error (PDE), Path Steering Error (PSE) and Position Estimation Error (PEE), represented mathematically as:

Instantaneous RNP accuracy = TSE = PDE + PSE + PEE (1)

PSE is defined as the difference between the defined path and the estimated aircraft position. PEE is the difference between the actual and estimated positions. PDE is any error in defining the desired path (survey and database errors etc.). The combination of PEE and PDE has traditionally been referred to as navigation sensor error (NSE). Since they are statistically independent, PEE, PSE and PDE are normally Root Sum Squared (RSS'd) together to compute TSE. It is also always assumed that the pilot or flight control system is attempting to fly the course provided by the guidance system (ILS, MLS, GNSS). However, this assumption is not applicable to surface movement. When visibility conditions are such that the pilot is able to track the actual centerline by visual reference the track defined by the guidance system may be different from the desired track without any effect on overall performance. In fact, in good visibility the role of electronic guidance is mainly for enhancing situational awareness. The result is that in those cases the PEE, PSE and PDE are not additive as in equation 1. It is only under the lowest visibility conditions (Visibility Condition 4) when the pilot is completely reliant on the guidance system (as for approach and landing) that the PEE, PSE and PDE would be additive. It is proposed that these factors be taken into account when allocating accuracy requirements.

Based on the background above, the proposed methodology for deriving PEE is as follows:

1. For Visibility Conditions 1 and 2 (>400 m RVR) the pilot primarily uses visual guidance. The electronic guidance is mainly for situational awareness. The accuracy required is only that necessary to allow the pilot to determine on which taxiway he is located. The proposed PEE is therefore based on the width of the taxiway, which varies according to aerodrome code. This applies to all taxiways except in the stand areas, since those have no defined width, and situational awareness should not be a problem in the stand in good visibility.
2. For Visibility Condition 3 (75 - 400 m RVR) the pilot still primarily uses visual guidance. The electronic guidance could be used for anticipating turns, particularly for implementations with a head up display. However, the PEE should not be allowed to be too large because the pilot may lose confidence in the system. The PSE and PEE are therefore recommended to be equal to the specified TSE. This also allows for visual conditions where the pilot may still use the electronic guidance, thus ensuring the errors do not exceed the allowed TSE.
3. For Visibility Condition 4 (<75 m RVR) the PSE and PEE are additive and are therefore RSS'd to compute TSE. The process used in determining the recommended allocations was based on maximizing the PSE allocation. The PEE was assigned a value equal to 50 percent of the TSE, and the PSE was assigned the remaining portion on an RSS basis.

Table 9 shows the allocations for rapid exits, normal and apron taxiways for the various airport categories by aerodrome code. The PEE values were derived using the methodology described above. All values are based on the largest aircraft type for each aerodrome code. For smaller aircraft operating on aerodromes designed to accommodate larger aircraft the margins go up accordingly, therefore allowing larger TSE, PSE and PEE. For example, a DC-9 is considered a code C aircraft and has an outer gear wheel span of 6.0 m. When operating on a code E aerodrome the wheel margin becomes 8.5 m instead of the minimum of 4.5. This would allow the TSE to be doubled from 2.2 m to 4.4 m. Assuming a constant for PSE, the PEE for Visibility Condition 4 (Table 9) could increase from 0.8 m to 4.0 m. The conclusion is that for the smaller aircraft operating at aerodromes designed to handle the largest aircraft, the increase in safety margins will allow significantly larger PEE values.

Table 9. PEE Allocations For Rapid Exits, Normal, And Apron Taxiways

			Visibility 1,2	Visibility 3		Visibility 4	
Aerodrome Code	**Taxiway Width (m)**	**TSE (95%, m)**	**PEE (95%, m)**	**PSE (95%, m)**	**PEE (95%, m)**	**PSE (95%, m)**	**PEE (95%, m)**
A	7.5	0.7	7.5	0.7	0.7	0.6	0.4
B	10.5	1.1	10.5	1.1	1.1	1.0	0.6
C	15	1.5	15	1.5	1.5	1.3	0.8
C,D	18	2.2	18	2.2	2.2	1.9	1.1
D,E	23	2.2	23	2.2	2.2	1.9	1.1

Technically, we should also account for an allocation of the PDE. The PDE includes errors in the airport survey or navigation database, which have to be accounted for separately from GNSS or any guidance sensor. However, assuming these errors are limited to 1 ft (0.3 m) for most cases this still leaves almost all of the allocated value to the PEE. For example, for Visibility 4 and Codes D and E the PEE is 1.1 m. When subtracting out 0.3 m (on an RSS basis) for PDE this still leaves 1.06 m for PEE. Based on an assumption that the PDE is limited to 1 ft, all of the allocation is made to PEE. Figure 7 summarizes the PEE requirements for Visibility Conditions 3 and 4. Additional validation is required for the allocation process.

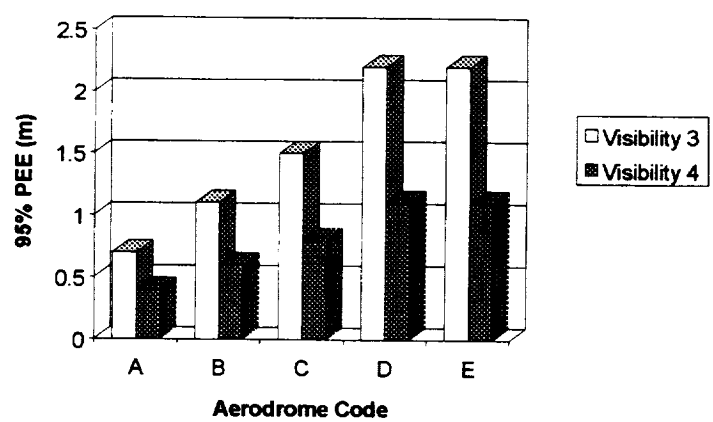

Figure 7. Recommended Lateral and Longitudinal PEE (Visibility Condition 3 and 4)

2.10 Availability

Availability is an indication of the ability of the guidance function to provide usable service within the specified coverage area. Availability is defined as the portion of time the system is to be used for navigation. During this time reliable navigation information is presented to the crew, autopilot, or other system managing the movement of the aircraft. Availability is specified in terms of the probability of the guidance function being available at the beginning of the intended operation. The availability required for surface movement should not limit the overall operations of the aerodrome. As an example, for low visibility operations the guidance function should have at least the same availability as the landing system guidance function, otherwise the total operation cannot be performed. For providing service in Visibility Conditions 3 and 4, the availability requirement should be equal to that of an associated Category III landing system and is 0.999. For Visibility Conditions 1 and 2, the availability is equal to that of an associated non-precision approach since the pilot can taxi visually, and is 0.95 [5].

3.0 VALIDATION

Several methods are being used to validate the proposed RNP. These include use of operational data, simulations, field demonstrations, and analysis.

3.1 Operations

Several sources of data were used to validate the accuracy allocations. One source was a statistical analysis of operational data from London Heathrow Airport consisting of over 77,000 aircraft taxiing movements on the airport surface [8]. Aircraft taxi centerline deviations recorded for various aircraft in the U.K. study are shown below in Table 10 and correlate well with RNP requirements. The majority of the 95% values are within the ± 2.2 m TSE requirement discussed in 2.8.1.

Table 10. Taxi Centerline Tracking Performance, Operational Data

Aircraft Type	Straight Sections 95% (m)	Curved Sections 95% (m)
A310	±1.4	±1.9
B72S	±1.4	±1.9
B73S	±1.6	±1.8
B747	±1.2	±2.5
B757	±1.4	±1.8
BAC1-11	±1.5	±1.9
DC9S	±1.5	±2.3
DC9	±1.4	±2.0
F27	±1.5	±1.9
F28	±4.6	±2.0
S360	±1.4	±1.9
L1011	±1.1	±2.3

Note: Data collected on normal and apron taxiways only.
Data Source: Heathrow Airport operational data [8]

3.2 Simulations

Data from several NASA simulator tests were analyzed, including a Runway Status Light System (RSLS) evaluation [16] and a moving map display study [17,18]. For the RSLS evaluation, data was collected in the Langley Research Center's Transport Systems Research Vehicle (TSRV) simulator during the summer of 1994. Twenty-one test subjects piloted a simulated Boeing 737 aircraft along ten different routes during various visibility conditions at Denver Stapleton Airport. This data was not originally collected to measure aircraft deviations from the centerline. However, since the data collected included aircraft position at discrete intervals, this data could be used to evaluate the aircraft's position throughout the taxiing phase. The data provided a unique look at how closely aircraft crews follow the centerline in an actual operating environment with their heads up.

For the moving map display study, NASA's TSRV simulator was again used to verify the performance of electronic maps in the cockpit. Fourteen pilots performed simulated taxiing runs along four different routes and two visibility conditions using two different types of map displays - a paper map and an electronic map. The deviation of the aircraft center-of-gravity (CG), which is located 37 feet behind the aircraft nose, was measured from the taxiway centerline. Centerline deviations collected from the RSLS simulation study (Table 11) are consistent with the Heathrow Airport data (see Table 10). However, the moving map study showed straight section 95% centerline deviations significantly greater than the others. The results indicate the limitation in the capability to taxi with only the map for guidance.

Table 11. Summary of Aircraft Taxi Centerline Tracking Performance, Simulation Data

Aircraft Type	Straight Sections 95% (m)	Curved Sections 95% (m)	Data Source
B737	±1.4	N/A	1. VFR/day
B737	±1.2	N/A	1. VFR/night
B737	±1.5	N/A	1. RVR 1200'
B737	±1.5	N/A	1. RVR 600'
B737	±3.9	±6.8	2. VFR
B737	±3.7	±6.2	2. RVR 150'
B737	±3.9	±5.2	2. VFR with map
B737	±3.7	±5.0	2. RVR 150' with map

Note: Data collected on normal and apron taxiways only.
Data Sources:
1. RSLS simulator data [16]
2. Moving map display simulator data [17,18]

3.3 Field Demonstrations

Field data was collected during the NASA LVLASO demonstration at Hartsfield Atlanta Airport in August 1997. These test were conducted with various configurations of the LVLASO cockpit displays, consisting of a Head Up Display (HUD) and moving map. The results (Table 12) are consistent with the other operational data, and are also well within the proposed RNP.

Table 12. Taxi Centerline Tracking Performance, NASA Demonstration Data

Aircraft	95% (m)	Test Conditions
B757	±1.3	HUD and Moving Map
B757	±1.3	HUD, No Moving Map
B757	±1.6	Moving Map, No HUD
B757	±1.6	No Moving Map, No HUD

The same field test was used to analyze the performance of local area differential GPS on the airport surface. The results indicated horizontal position errors of approximately 1.6 m (95%) [32]. This meets the position estimation error requirements for visibility 3 for most airports (2.2 m), and comes close to meeting the proposed requirement for visibility 4 (1.1 m).

3.4 Analysis

3.4.1 Pilot Failure Risk Analysis

3.4.1.1 Introduction

The purpose of the pilot failure risk analysis is to validate the pilot risk factor component of the RNP. This section will detail the analysis of the individual failure modes for several different scenarios that may occur on the airport surface. The pilot risk will then be associated with these scenarios according to the required response time to avoid an incident. As depicted in Figure 2, the total incident risk is comprised of both detected and undetected failures and therefore both failure modes must be examined.

3.4.1.2 Assumptions

To analyze the pilot failure risk, several assumptions were made including the failure mode experienced, the visibility condition, the cockpit display equipment, the number of crew members and their respective roles, and the aircraft velocity. Failure modes analyzed include continuity and integrity. A warning or signal will be given to the aircraft crew immediately upon a continuity failure. An integrity failure will yield no warning, therefore the crew will depend on visual cues to recognize that a failure has occurred. Consequently, longer response times can be expected for integrity failures. Since the crew relies on visual, out-the-window views, visibility will primarily drive pilot risk for the integrity failure mode. The three visibility conditions considered are described in 2.3.

As part of the NASA LVLASO (Low Visibility Landing And Surface Operations) program, additional cockpit display equipment will be available to assist the crew in low visibility conditions. This equipment includes a Head-Up Display (HUD) [20] which will display traffic cones outlining runways and taxiways, signs showing the pilot which way to turn, and other data pertinent to the operation of the aircraft (speed, heading, altitude, etc.). A Head-Down Display (HDD) will be available for either the pilot-in-command or co-pilot's use. This display will contain a map of the airport surface that shows location of own aircraft, other aircraft, airport runway/taxiway/gate area locations, and the preferred surface route for the aircraft to follow.

The availability of this cockpit display equipment led to assumptions regarding crew numbers and roles. For Visibility Condition 1,2, it was assumed that only one pilot would be present in the cockpit. Under this visibility condition the pilot should be able to monitor the HDD for situational awareness and guide the aircraft using external visual cues. However, under Visibility Conditions 3 and 4, it was assumed that both a pilot-in-command and a co-pilot would be required. The pilot-in-command would be responsible for monitoring the "out-the-window" view with the HUD available for additional guidance. The co-pilot would be responsible for monitoring the HDD and providing verbal feedback to the pilot-in-command on runway/taxiway location, other aircraft locations, and maintaining conformance to the designated route.

The aircraft velocity when a failure occurs will affect the amount of time the crew has to respond to the failure. The greater the aircraft velocity, the longer the braking distance, and consequently, the less time available for the crew to.respond. Crew response may also be longer because of an increased crew workload when traveling at high speeds on the airport surface (e.g., high speed exit taxiing). Aircraft speeds assumed for various scenarios are given in Table 1. Each scenario was analyzed for nominal and worst case aircraft velocity, shown in Table 13. Different speeds were chosen for the normal/apron taxi phase for the two failure modes, because of the nature of each scenario. Lower speeds were used for the continuity failure due to the 90° turn associated with this scenario. The scenarios will be discussed in more depth in the following section. Furthermore, worst case speeds were analyzed only under dry surface conditions and Visibility 1,2. It was determined that aircraft would probably not operate at these higher speeds under wet airport surface conditions and/or reduced visibility. Conversely, scenarios under Visibility Conditions 3 and 4 were analyzed at nominal speeds and wet airport surface conditions.

Table 13. Aircraft Speeds

	Nominal (kts.)	Worst Case (kts.)
High Speed	30	50
Normal/Apron Speed (Continuity)	10	20
Normal/Apron Speed (Integrity)	20	30
Stand Taxilane	5	10

3.4.1.3 Analytical Scenarios

To analyze the pilot risk factor, several scenarios were created to simulate a possible "real-world" situation that may occur while an aircraft is taxiing on the airport surface. These scenarios are based on observations made at airports with typical taxiing procedures. The navigation errors encountered were chosen to occur at the worst possible time in an attempt to build some conservatism into the results. Scenarios were created for both continuity and integrity failure modes. Furthermore, each failure mode was analyzed at three different phases of taxiing: high speed, normal, and stand taxilane.

3.4.1.3.1 Continuity Failure Scenarios

The continuity failure scenario is based on an aircraft making a turn from the runway to the taxiway. At the midpoint of the turn the navigation system fails and the crew is given a warning. The crew is instructed to bring the aircraft to an immediate stop. At the point of failure it is assumed the aircraft continues in a straight line as the crew responds to the failure and begins braking. This straight line assumption minimizes the distance between the failure location and the nearest possible object as defined by the ICAO Aerodrome Design Manual for Code E aircraft [8]. By minimizing this distance, the most critical scenario is chosen. A depiction of this scenario is shown in Figure 8 for normal taxi and in Figure 9 for high speed taxi.

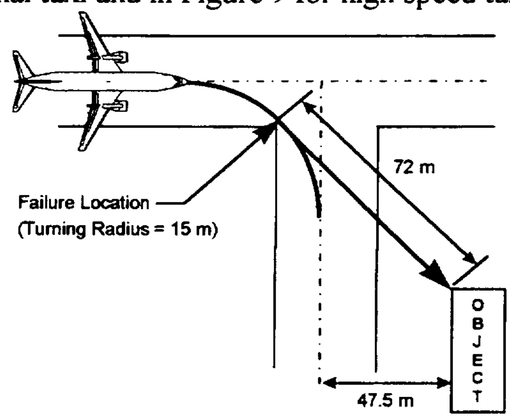

Figure 8. Continuity Failure During Normal Taxi

Note - Stand Taxilane scenario is similar, but distance from Centerline to Object is 42.5 m.

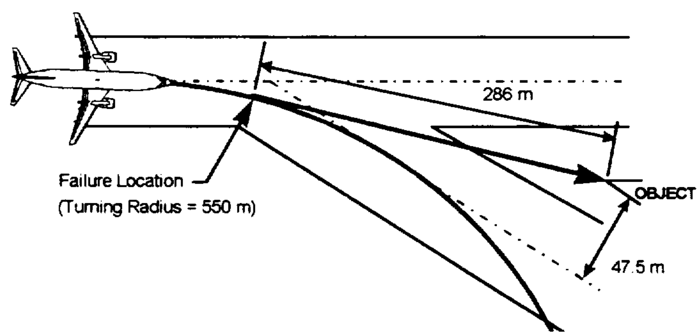

Figure 9. Continuity Failure During High Speed Taxi

3.4.1.3.2 Integrity Failure Scenarios

The integrity failure scenario is based on an aircraft taxiing along a straight section of runway when it encounters a 20 meter waypoint error in the navigation route. Since this error is undetected by the system, no warning or alert is provided to the crew. With no warning or alert, the crew must recognize that a failure has occurred and begin immediate braking of the aircraft to avoid running off the pavement. A 20 meter waypoint error was chosen to represent the largest error that may be possible without becoming obvious to the crew taxiing along a typical 46 meter wide runway. Waypoint errors of this size on a taxiway would presumably be more readily detectable to the crew due to the much smaller width of the taxiway (23 meters). A more reasonable waypoint error for the taxiways would be 10 meters and result in twice the distance before the aircraft left the pavement. Therefore, the runway was analyzed, because it presented a more demanding scenario with shorter distances to incident than taxiing along a taxiway. For the normal taxi phase, the distance chosen (300 m) for the error to occur is based on the average segment length of an aircraft's taxi route at Atlanta Hartsfield airport and Denver Stapleton airport. For the high speed taxi phase, the distance (344 m) is based on the spacing between high speed exits at Atlanta Hartsfield airport. Figures 10 and 11 below illustrate scenarios for normal and high speed taxi phases respectively. In both scenarios, the airplane was assumed to be off the pavement when the aircraft nose was 15 meters from the runway centerline.

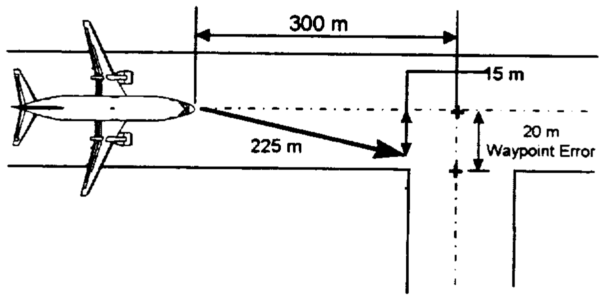

Figure 10. Integrity Failure During Normal Taxi

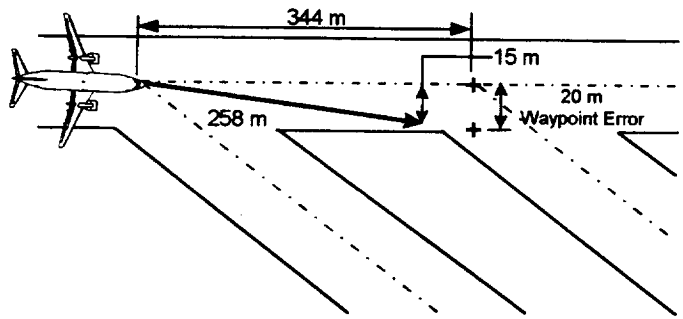

Figure 11. Integrity Failure During High Speed Taxi

The stand taxilane scenario is similar to the integrity failure during normal taxi phase (Figure 10) except the waypoint error is only 10 meters due to the tighter spacing within the gate area. The distance the aircraft is from the erroneous waypoint was set at 52 meters to represent typical gate spacing at Atlanta Hartsfield airport. Table 14 summarizes the Distance to Incident (d_i) for each of the scenarios described above.

Table 14. Distance to Incident

	Distance to Incident (m)	
	Failure Mode	
Taxi Phase	Continuity	Integrity
High Speed	286	258
Normal/Apron	72	225
Stand Taxilane	66	52

3.4.1.4 Response Times

3.4.1.4.1 Aircraft Crew Response Times

The average aircraft crew response times to the various modes of failure were determined by researching existing relevant human factors studies. Appendix C summarizes the studies used. Under a continuity failure, the crew is reacting to either a visual or audio warning from within the cockpit and relatively short response times can be expected. For integrity failures, the crew is reacting to a visual reference that is either an "out-the-window" view or the view obtained from the cockpit mounted HDD. Because the crew is relying predominately on the "out-the-window" view, longer response times can be expected with decreasing visibility. Figure 12 summarizes the crew response times assumed for this study.

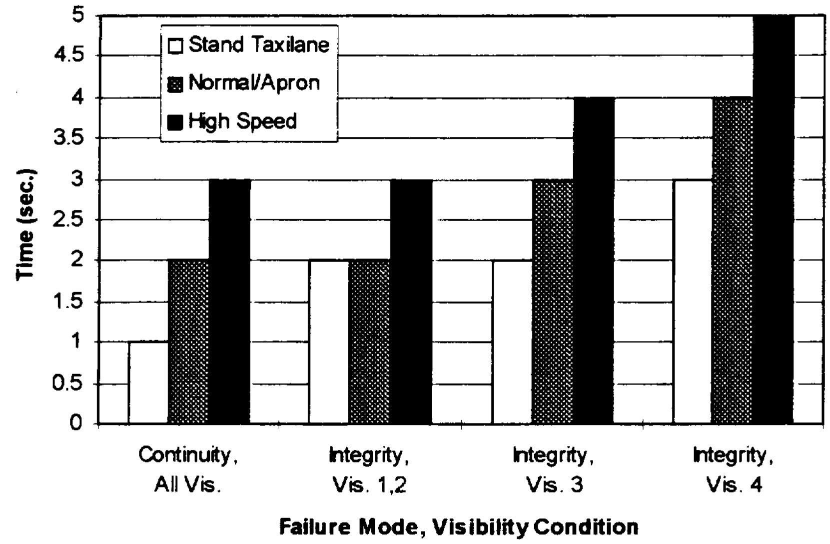

Figure 12. Aircraft Crew Mean Response Times

The times shown above represent the time required by the crew to initiate aircraft braking. Under all failure modes, the crew's response is to begin an immediate, hard/panic stop of the aircraft. Further validation of these response times should be performed through aircraft simulator testing using these emergency conditions. Appendix D describes the method used to correlate pilot response times with the risk of a pilot failing to respond in time to a failure (pilot risk). It was assumed that pilot response time could be modeled with a normal probability distribution. A value of one second was chosen for σ for continuity failures in all visibilities. This value is consistent with pilot reaction times to TCAS resolution advisories [21]. For integrity failures, it was assumed that visibility will affect reaction times. For degraded visibilities (Visibility Conditions 3 and 4), standard deviation was set equal to the mean response time (Figure 12). These values are consistent with studies conducted for pilot reaction times to more complex situations than an auditory alarm [22, 26].

3.4.1.4.2 Aircraft Response Times

The response time of the aircraft is that time required to bring the aircraft to a complete stop once the crew initiates braking. Maximum deceleration rates for the Boeing 747-400 were obtained from Boeing and used to calculate the braking distance. A firm, comfortable rate of 6 ft/sec^2 (.2g) was analyzed, as well as a hard, panic stop of 12 ft/sec^2 (.4g). Because of the shorter stopping distances, the .4g hard, panic stop was chosen for this analysis. The 747 was chosen to establish a worst case scenario. Most other aircraft will have shorter braking distances. Aircraft braking was analyzed under wet and dry airport surface conditions. Under wet runway conditions, aircraft stopping distances become longer because of the decreased coefficient of friction of the airport surface. Consequently, after a failure occurs under wet conditions, more time will be needed to brake the aircraft and less time will be available for the crew to respond. As stated under the assumptions in 3.4.1.2, wet conditions were assumed under Visibility Conditions 3 and 4 and only at nominal speeds.

Once braking distances were obtained, the maximum amount of time the crew had to respond to the failure was determined. This is simply the aircraft braking distance subtracted from the distance to the incident (d_i) divided by the aircraft velocity when the failure occurred. Subtracted out of this total was an additional .75 seconds that is required on the 747-400 to engage the brake pistons once braking action is applied. Refer to Appendix D for a detailed discussion of the mathematics.

3.4.1.4.3 Response Time Summary

The assumptions made in this analysis and the corresponding results are contained in Table 14. Based on runway conditions, aircraft braking distance, maximum time for crew to respond, and the "extra time" for the crew to respond were calculated. This calculated "extra time" to respond represents the excess time the crew has to respond to the failure, which in turn determines the pilot failure risk.

3.4.1.5 Pilot Failure Risk

Several factors must be taken into account when calculating pilot failure risk. The total pilot failure risk consists of essentially four components: the relative exposure for the failure condition, the reaction time distribution, the aircraft speed distribution, and the airport surface condition. These four factors are illustrated Figure 13.

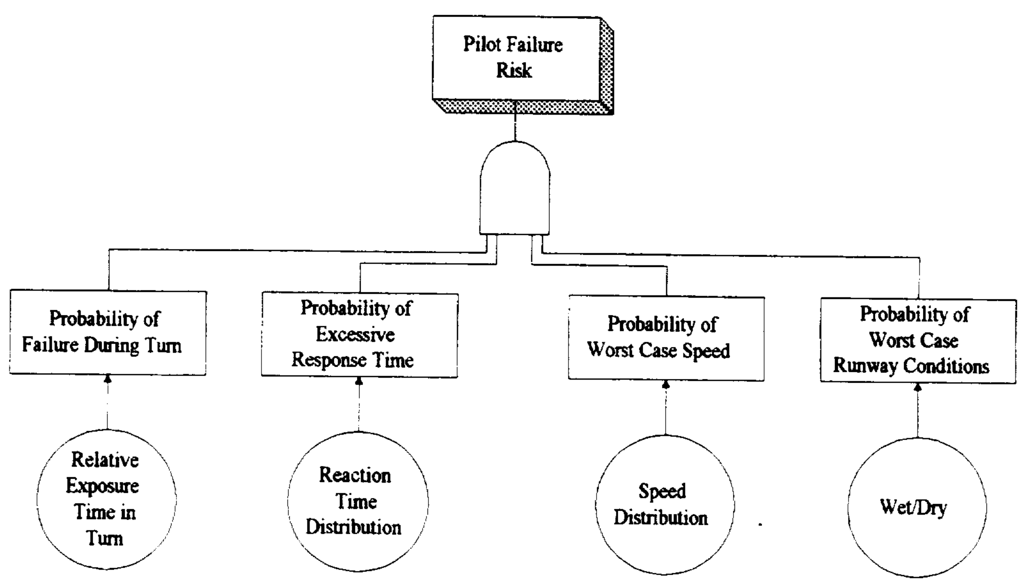

Figure 13. Pilot Risk Tree

The relative amount of exposure time the aircraft spends in a turn could be used to more accurately determine the probability of the failure occurring in the turn. To go one step further, the amount of exposure time the aircraft spends at the turn's apex (where continuity failure was assumed in this analysis) could be added into the total pilot risk calculation. This study did not factor in this probability, because of the lack of any substantial data collected to quantify this variable.

Reaction time distribution was the primary factor analyzed in this study to determine pilot failure risk. Based on the previously discussed scenarios and corresponding assumptions, the crew's excess time to respond to the failure was calculated. Once excess time was determined for each scenario, the probability of the crew response time exceeding this time could be modeled with a normal probability distribution. Appendix D contains a detailed discussion of this analysis.

The probability of the aircraft being at the worst case speed when the failure occurs can also be used to refine the calculations. In this analysis, this probability was factored into the calculation of the pilot failure risk for the continuity failure scenarios where the aircraft is in the stand taxilane and normal/apron phase of taxiing. It was assumed that aircraft speeds on the airport surface could be approximated by a normal probability distribution and the worst case speed represents two standard deviations of this distribution (2σ). This 2σ value equates to the aircraft traveling at worst case speeds or greater 5% of the time. Finally, the probability that worse case surface conditions will exist were indirectly taken into account in this study. As stated in the assumptions in 3.4.1.2, aircraft will probably operate under wet airport surface conditions under Visibilities 3 and 4, but only at nominal speeds. At Visibility Conditions 1,2, operations were assumed to take place on a dry surface, but at worst case speeds. Ice and snow covered surface conditions were not evaluated in this analysis.

Based on our analysis of the previously mentioned scenarios, the proposed pilot failure risks were conservative in their estimates for all but three scenarios. It was determined for these scenarios that the proposed pilot risks were too low and should be increased. These three scenarios are:

1. Visibility Condition 1,2, normal/apron taxi phase, continuity failure mode,
2. Visibility Condition 1,2, high speed taxi phase, integrity failure mode,
3. Visibility Condition 3, high speed taxi phase, integrity failure mode.

Of these three only the first two changed the previously proposed requirement. These changes resulted in a modification to the continuity and integrity specified risk for visibility condition 1,2. The allocated risk for continuity, Visibility Condition 1,2 decreased from 6.0×10^{-3} to 3.0×10^{-3}. The allocated risk for integrity, Visibility Condition 1,2 decreased from 3.0×10^{-3} to 2.0×10^{-4}, roughly an order of magnitude. The validated pilot risk allocations and the validation analysis results for each scenario are presented in Table 15. The pilot risk allocations are also listed in Table 2 and graphed in Figure 3.

3.4.2 Functional Hazard Assessment

The failure mode analysis demonstrated close correlation with the aircraft system design standards contained in Federal Aviation Regulation (FAR) 25-1309, FAA Advisory Circular 25.1309-1A [24] and Joint Aviation Requirement (JAR) 25 [25]. These standards relate the consequences and severity of effects of system failures and required probabilities. Table 16 shows these relationships and Table 17 shows how these compare to the most stringent surface movement risk requirements. Most cases fall within the minor category which requires a failure rate between 10^{-3} and 10^{-5} per hour. The only exception is Visibility Condition 4 integrity which is classified as Major, with a failure rate between 10^{-5} and 10^{-7}. Overall, the failure condition effects associated with the surface movement failure modes are consistent with the categories defined by the FAR and JAR requirements. It should be noted that this comparison can only validate that failure probabilities are within the right failure classification range, or roughly two orders of magnitude.

3.4.3 Further Validation

Due to limited data available to date, it is recommended that additional data be collected to further substantiate the proposed RNP requirements presented herein. Additional simulator testing should be conducted to verify the pilot reaction times to the various failures assumed in the pilot failure risk analysis. Further verification of the achieved accuracy performance should be conducted with additional simulator and field testing. These tests should be performed under the visibility conditions specified in this report in an attempt to recreate the scenarios analyzed. Naturally, varying visibilities will be easier to control under simulator conditions, but night conditions could be used during the field testing.

Table 15. Scenario Assumptions and Results

Visibility Condition	Phase	Failure Mode	Speed (kts.)	Surface Condition (Wet/Dry)	Mean Crew Response Time (s)	Standard Deviation (s)	Aircraft Braking Distance (m)	Max Time for Crew to Respond (s)	"Extra Time" for Crew to Respond (s)	Notes	Pilot Failure Risk	Validation Results
1,2	Stand Taxilane	Continuity	Worst Case (10)	Dry	1.0	1.0	4	11.3	10.3	2, 4, 5	5.0E-06	1.0E10-09
	Stand Taxilane	Integrity	Worst Case (10)	Dry	2.0	1.0	4	8.6	6.6	2, 5	5.0E-05	1.0E10-09
	Normal/Apron	Continuity	Worst Case (20)	Dry	2.0	1.0	14	4.9	2.9	2, 4, 5	1.0E-04	9.3E10-05
	Normal/Apron	Integrity	Worst Case (30)	Dry	2.0	1.0	33	11.7	9.7	2, 5	1.0E-04	1.0E10-09
	High Speed	Continuity	Worst Case (50)	Dry	3.0	1.0	91	6.8	3.8	2, 5	1.0E-04	7.2E10-05
	High Speed	Integrity	Worst Case (50)	Dry	3.0	1.0	91	5.8	2.8	2, 5	3.0E-03	2.6E10-03
3	Stand Taxilane	Continuity	Nominal (5)	Wet	1.0	1.0	1	24.3	23.3	2, 6	5.0E-05	1.0E10-09
	Stand Taxilane	Integrity	Nominal (5)	Wet	2.0	2.0	1	19.0	17.0	3, 6	5.0E-03	1.0E10-09
	Normal/Apron	Continuity	Nominal (10)	Wet	2.0	1.0	5	12.4	10.4	2, 6	1.0E-04	1.0E10-09
	Normal/Apron	Integrity	Nominal (20)	Wet	3.0	3.0	20	19.2	16.2	3, 6	1.0E-02	3.3E10-08
	High Speed	Continuity	Nominal (30)	Wet	3.0	1.0	50	14.5	11.5	2, 6	1.0E-04	1.0E10-09
	High Speed	Integrity	Nominal (30)	Wet	4.0	4.0	50	12.7	8.7	3, 6	1.5E-02	1.5E10-02
4	Stand Taxilane	Continuity	Nominal (5)	Wet	1.0	1.0	1	24.3	23.3	2, 6	1.0E-04	1.0E10-09
	Stand Taxilane	Integrity	Nominal (5)	Wet	3.0	3.0	1	19.0	16.0	3, 6	5.0E-02	4.8E10-08
	Normal/Apron	Continuity	Nominal (10)	Wet	2.0	1.0	5	12.4	10.4	2, 6	1.0E-04	1.0E10-09
	Normal/Apron	Integrity	Nominal (20)	Wet	4.0	4.0	20	19.2	15.2	3, 6	1.0E-01	7.2E10-05
	High Speed	Continuity	Nominal (30)	Wet	3.0	1.0	50	14.5	11.5	2, 6	1.0E-04	1.0E10-09
	High Speed	Integrity	Nominal (30)	Wet	5.0	5.0	50	12.7	7.7	3, 6	1.0E-01	6.1E10-02

Notes:

1. "Panic stop" braking assumed for all cases.
2. Crew response time standard deviation set to 1 for all Continuity Visibilities and Integrity Visibility 1,2.
3. Crew response time standard deviation set to the mean for Integrity Visibilities 3 and 4.
4. Assumed that for Continuity failure in stand and normal scenarios aircraft is only traveling at worst case speeds 5% of the time.
5. For all Visibilities 1,2 assumed pilot only crew member.
6. For all Visibilities 3 and 4 assumed two crew members.

Table 16. Relationship Between Probability and Severity of Effects

Probability (Quantitative)		1.0	10-3	10-5	10-7	10-9
Probability (Descriptive)	FAR	Probable		Improbable		Extremely Improbable
	JAR	Frequent	Reasonably Probable	Remote	Extremely Remote	Extremely Improbable
Failure condition severity classification	FAR	Minor		Major		Catastrophic
	JAR	Minor		Major	Hazardous	Catastrophic
Effect on aircraft and occupants	FAR	• Does not significantly reduce airplane safety (slight increase in safety margins). • Crew actions well within capabilities (slight increase in crew workload). • Some inconvenience to occupants.		• Reduce capability of airplane or crew to cope with adverse operating conditions. • Significant reduction in safety margins. • Significant increase in crew workload. <u>Severe Cases</u>: • Large reduction in safety margins. • Higher workload or physical distress on crew - can't be relied upon to perform tasks accurately. •Adverse effects on occupants.		• Conditions which prevent continued safe flight and landing
	JAR	• Nuisance	• Operating limitations. • Emergency procedures.	• Significant reduction in safety margins. • Difficult for crew to copy with adverse conditions. • Passenger injuries.	• Large reduction in safety margins. • Crew extended because of workload or environmental conditions. • Serious or fatal injury to small number of occupants.	• Multiple deaths, usually with loss of aircraft

Table 17. Comparison of the Analyzed Risk with the FAR/JAR Required Risk

Surface Movement Phase	Failure Condition	RNP Parameter	Failure Condition Effects	Comments	FAR 25.1309-1A Category/JAR Category	Required Proba-bility	Allocated Risk (per hour)
Normal/ Apron taxi (20 kts), Visibility Conditions 1 & 2	Detected failure: Loss of guidance	Continuity	1. Crew detects failure and must react to stop aircraft. 2. Crew actions well within capabilities (slight increase in crew workload). 3. Some inconvenience to occupants.	Crew should be able to maintain course and stop aircraft prior to exceeding boundaries of taxiway. Assumed crew response: 2 s	Minor/ Minor	10^{-3} - 10^{-5}	3.0×10^{-3}
High speed taxi (50 kts) Visibility Conditions 1 & 2	Undetected failure: Erroneous guidance	Integrity	1. Crew must detect failure by visual reference. 2. Crew actions well within capabilities (slight increase in crew workload). 3. Some inconvenience to occupants. 4. May require emergency procedures.	Crew should be able to intervene prior to exceeding taxiway, but less likely than for detected failures since failure is detected by visual reference only. Assumed crew response: 3 s	Minor/ Minor	10^{-3} - 10^{-5}	2.0×10^{-4}
Normal/ Apron taxi (10 kts), Visibility Condition 3	Detected failure: Loss of guidance	Continuity	1. Crew detects failure and must react to stop aircraft. 2. Crew actions well within capabilities (slight increase in crew workload). 3. Some inconvenience to occupants.	Crew should be able to maintain course and stop aircraft prior to exceeding boundaries of taxiway. Assumed crew response: 2 s	Minor/ Minor	10^{-3} - 10^{-5}	3.0×10^{-3}
Normal/ Apron taxi (20 kts), Visibility Condition 3	Undetected failure: Erroneous guidance	Integrity	1. Crew must detect failure by visual reference. 2. Crew actions well within capabilities (slight increase in crew workload). 3. Some inconvenience to occupants. 4. May require emergency procedures.	Crew should be able to intervene prior to exceeding taxiway, but less likely than for detected failures since failure is detected by visual reference only. Assumed crew response: 3 s	Minor/ Minor	10^{-3} - 10^{-5}	3.0×10^{-5}
Normal/ Apron taxi (10 kts), Visibility Condition 4	Detected failure: Loss of guidance	Continuity	1. Crew detects failure and must react to stop aircraft. 2. Crew actions well within capabilities (slight increase in crew workload). 3. Some inconvenience to occupants. 4. May require emergency procedures.	Crew should be able to maintain course and stop aircraft prior to exceeding boundaries of taxiway. Assumed crew response: 2 s	Minor/ Minor	10^{-3} - 10^{-5}	3.0×10^{-3}
Normal/ Apron taxi (20 kts), Visibility Condition 4	Undetected failure: Erroneous guidance	Integrity	1. Reduced capability of airplane/crew to cope with adverse operating conditions. 2. Significant reduction in safety margins. 3. Significant increase in crew workload. 4. Adverse effects on occupants.	Crew is less likely to be able to intervene prior to exceeding taxiway because of reduced visibility. Assumed crew response: 4 s	Major/ Major	10^{-5} - 10^{-7}	3.0×10^{-6}

4.0 CONCLUSIONS AND RECOMMENDATIONS

Use of RNP for all phases of flight is accepted by the aviation community, in the U.S. and internationally. The approach and landing RNP has pioneered the process and analytical techniques used to define aviation standards and requirements for accuracy, continuity, integrity, and availability. Application of the RNP described in this report to the runway surface has used the same process, but for a two-dimensional surface with unique navigation requirements. For the surface RNP, work to date has focused on the analytical aspects of the process, the classification of operations, the allocation of risks to each operational phase, and the calculation of containment limits, integrity and continuity requirements. Operational and simulator data have been used to validate the analyses; however, validation in some areas is limited, and further simulation and field trials are required. The process and data used to develop the surface RNP have been coordinated with aviation standards organizations including ICAO All Weather Operations Panel and RTCA. RTCA is in the process of developing requirements for airport surface navigation and surveillance. The RNP requirements presented in this paper can be a primary input to the navigation requirements. The following summarize the key RNP requirements.

- Target Level of Safety - 1.0×10^{-8} fatal taxi accidents per operation.

- Integrity and Continuity Risk (per hour):

	Visibility Condition		
	1,2	**3**	**4**
Integrity	2.0×10^{-4}	3.0×10^{-5}	3.0×10^{-6}
Continuity	3.0×10^{-3}	3.0×10^{-3}	1.5×10^{-3}

- Containment Limits (aerodrome codes D and E) - 15 m for taxiways, 10 m for stand taxilanes, 7.5 m for stand areas.

- Normal Performance Requirements (aerodrome codes D and E) - 2.2 m for taxiways, 1.2 m for stand taxilanes, 1.0 m for stand areas.

ICAO, FAA and RTCA are all currently developing requirements for local area differential GNSS to support Category I, II, and III approach and landing. It is intended that local area navigation systems be capable of supporting surface operations. The requirements described in this report should be considered in the development of local area differential GNSS standards to be sure that these systems will adequately support surface operations. It is recommended that further simulator studies and field studies be conducted to validate the proposed RNP. Specifically, simulator studies are recommended to characterize crew reaction to failures, while simulator and field tests are recommended to validate achieved accuracy performance. This should also include an evaluation of the magnitude of acceptable Position Estimation Errors for moving map and HUD applications under various visibility conditions.

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ACRONYMS

A-SMGCS - Advanced Surface Movement Guidance and Control Systems
ATIDS - Airport Surface Target Identification System
AWOP - All Weather Operations Panel
CG - Center-of-Gravity
CL - Containment Limit
DGPS - Differential Global Positioning System
FAR - Federal Aviation Regulation
GNSS - Global Navigation Satellite Systems
GPS - Global Positioning System
HDD - Head-Down Display
HUD - Head-Up Display
ICAO - International Civil Aviation Organization
ILS - Instrument Landing System
JAR - Joint Aviation Requirement
LVLASO - Low Visibility Landing And Surface Operations
MASPS - Minimum Aviation Systems Performance Standard
MLS - Microwave Landing System
NTSB - National Transportation Safety Board
PDE - Path Definition Error
PEE - Position Estimation Error
PSE - Path Steering Error
RNP - Required Navigation Performance
RSLS - Runway Status Light System
RSS - Root Sum Square
RVR - Runway Visual Range
SSR - Secondary Surveillance Radar
TCAS - Traffic Alert and Collision Avoidance System
TLS - Target Level of Safety
TSE - Total System Error
TSRV - Transport Systems Research Vehicle

APPENDIX A
TAXI SPEED ANALYSIS

A1 DEFINITION OF SURFACE MOVEMENT RNP TAXI SPEEDS

A1.1 Atlanta Hartsfield Data

Taxi data from Atlanta was gathered using the experimental Airport Surface Target Identification System (ATIDS). ATIDS is a multilateration system that receives Secondary Surveillance Radar (SSR) transmissions and triangulates, or multilaterates, from several receiver locations to determine the location of an SSR transponder. It is designed to work with aircraft equipped with Mode A/C and S transponders. All of the data used in the analysis presented here are from Mode S equipped aircraft.

The data available from Atlanta is used here primarily to evaluate velocities on high speed taxiways. The average velocity of the plane in that region, as well as its maximum and minimum velocities, were evaluated. For the high speed exits, as at Atlanta (Figure A1), the maximum velocity normally corresponds to the speed at which the plane exits the runway, and the minimum velocity usually corresponds to termination of the high speed exit phase. Examination of the data reveals that some aircraft will slow down and then accelerate to a faster speed, therefore it cannot be assumed that all aircraft constantly decelerate.

For Atlanta Airport, the maximum, minimum and average velocities were calculated for each aircraft exiting at one of the high speed exits, exit B11 (Figure A2). Tables A1 and A2 summarize the calculations and are grouped according to aircraft type. Since the B11 exit was used most often, estimates there are more statistically significant than for the B7 exit. For the B11 exit, the maximum velocity for any aircraft was 60 knots, with only three having maximums greater than 50 knots. The minimum velocity was 13.2 knots and the overall average velocity was 31.7 knots. For the B2 exit, the maximum velocity was 48.1 knots, the minimum velocity was 15.1 knots, and the average velocity was 29.4 knots. Figures A3 and A4 illustrate typical velocities measured for aircraft using both the normal and high speed runway exits and subsequent taxi to the apron areas. There is not sufficient data available for a statistical analysis of taxi speeds on normal taxiways. The main reason is due to current procedures, where transponders are switched off immediately after landing and prior to arrivals in the gate area.

A1.2 London Heathrow Data

The second set of data came from London Heathrow Airport [6]. Figures A5 and A6 summarize results as bar charts. For the outer curve the average velocity was 16.4 knots and the 95% values are all less than 24 knots. The maximum velocity for any aircraft was 33 knots, with all others being less than 30 knots. However, this data was collected on a more shallow curve (approximately 60°) than the taxiway turn for which the taxi speed range was established in Table 1 (90°), so a direct comparison cannot be made. For the straight section, the average velocity was 16.9 knots and the 95% values are all less than 27 knots. The maximum velocity for any aircraft was 49 knots, with the maximum for most being slightly over 30 knots.

A1.3 Conclusion

Based on this analysis, the range of taxi speeds for the various phases are as shown in Table 1 of the report.

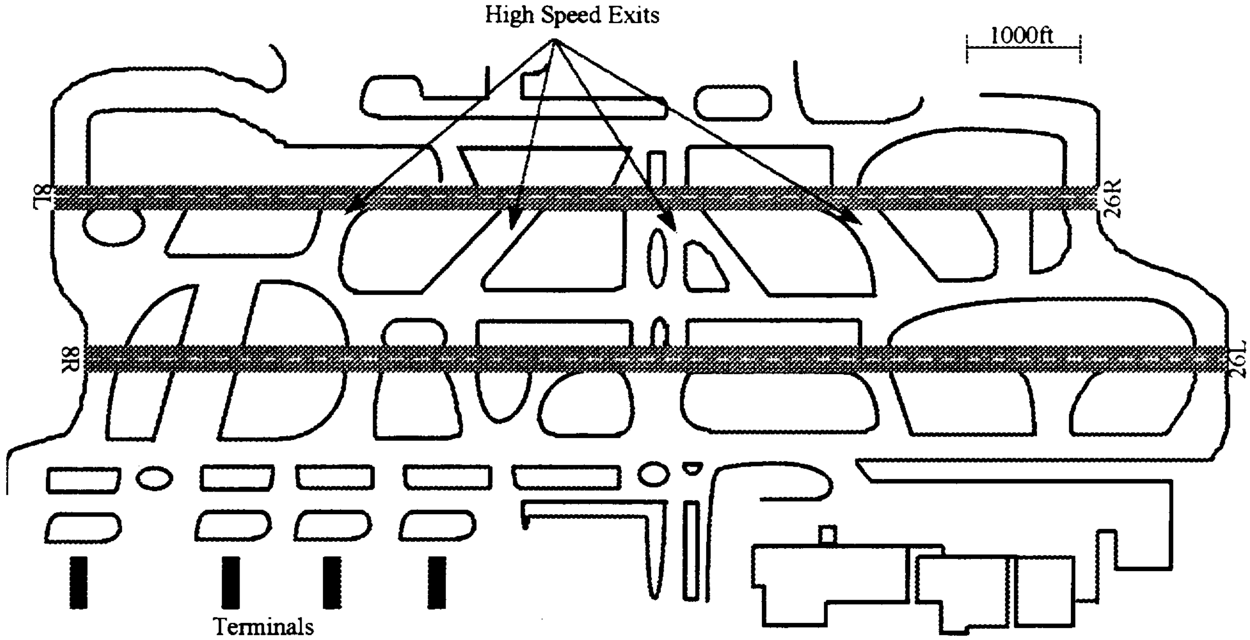

Figure A1. Atlanta Hartsfield Airport Layout (North End)

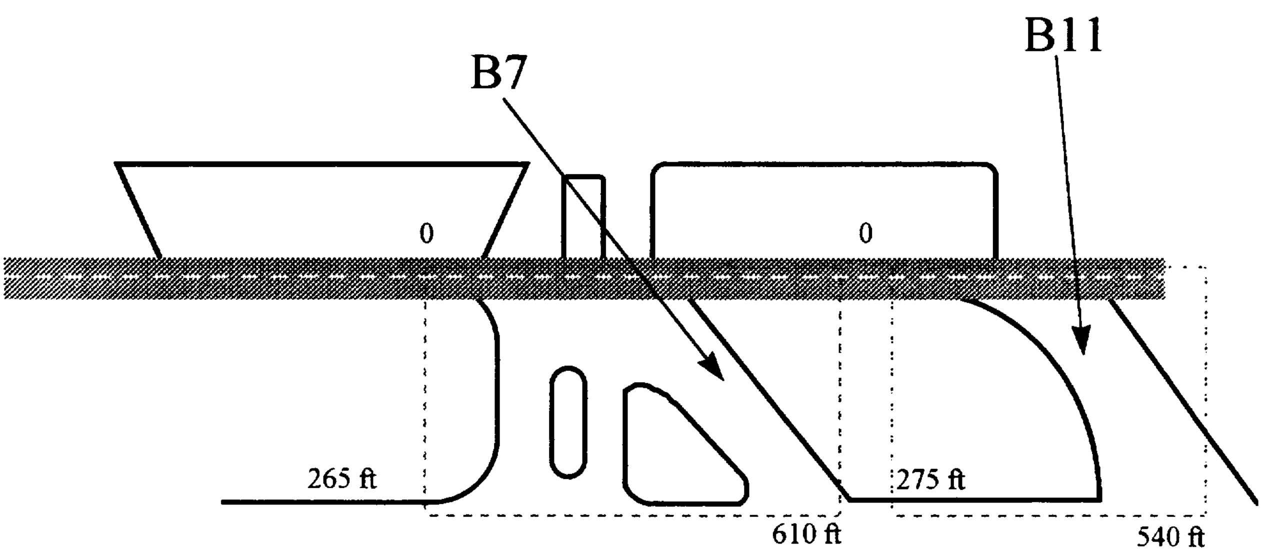

Figure A2. Atlanta Runway 8L High Speed Exits - Regions Defined for Velocity Evaluation

Aircraft Type	Taxiway	Ave. Vel (kts)	Max Vel (kts)	Min Vel (kts)
727	B11	31.7	42.5	25.3
727	B11	33.5	44.9	30.5
727	B11	29.2	35.3	24.8
727 total average		31.5		
737	B11	27.3	37	21.6
737	B11	22.7	31.4	13.7
737	B11	26.8	24.3	26
737	B11	32.5	37.7	29.2
737 total average		27.3		
757	B11	28.2	31.7	13.2
757	B11	35.6	41.4	23.5
757 total average		31.9		
767	B11	31	34.4	27.9
767	B11	26.9	32.2	21.2
767	B11	29.6	35	26.3
757 total average		29.2		
DC9	B11	27	32.7	17.2
L-1011	B11	28	38.6	13.9
MD-88	B11	31.4	34.3	29.7
MD-88	B11	44.6	57.1	38.6
MD-88	B11	31.4	38.2	30.2
MD-88	B11	38.3	40.6	35.6
MD-88	B11	41.7	60	37.6
MD-88	B11	27.3	39.7	23.7
MD-88	B11	36.6	33.9	36.4
MD-88	B11	34.1	36.5	32.3
MD-88	B11	40	46.5	31.1
MD-88 total average		36.2		
unknown	B11	23	26.6	18.6
unknown	B11	30.2	42.6	18.1
unknown	B11	35.9	50.5	unknown
Overall Average		31.7	60	13.2

Table A1. Atlanta High Speed Exit B11 Velocity Data

Aircraft Type	Taxiway	Ave. Vel (kts)	Max Vel (kts)	Min Vel (kts)
727	B2	35.4	38.1	32.9
727	B2	20.3	27.9	19.4
727 total average		27.85		
737	B2	34.8	36.9	29.7
737	B2	21	38.4	16.3
737 total average		27.9		
757	B2	38.7	40.4	34.9
767	B2	24.4	28.5	18.9
DC-9	B2	29.2	40.1	15.1
DC-9	B2	20.1	25.1	18.1
DC-9 total average		24.65		
MD-88	B2	36.5	48.1	31.9
	B2	33.2	40.1	29.9
Overall Average		29.4	48.1	15.1

Table A2. Atlanta High Speed Exit B2 Velocity Data

Atlanta, B-737, October 19, 1995

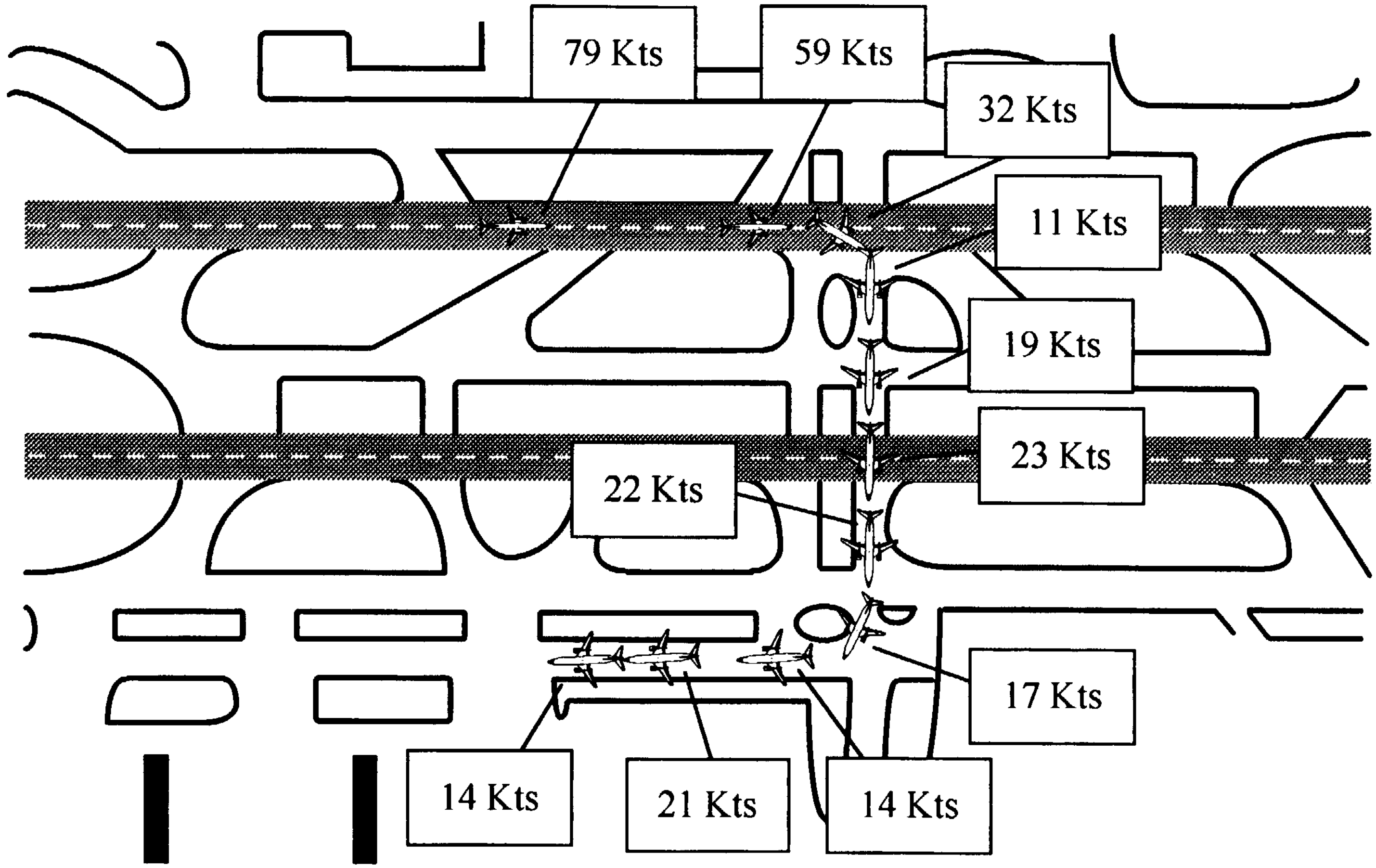

Figure A3. Typical Taxi Velocities (normal runway exit)

Atlanta, B-737, October 19, 1995

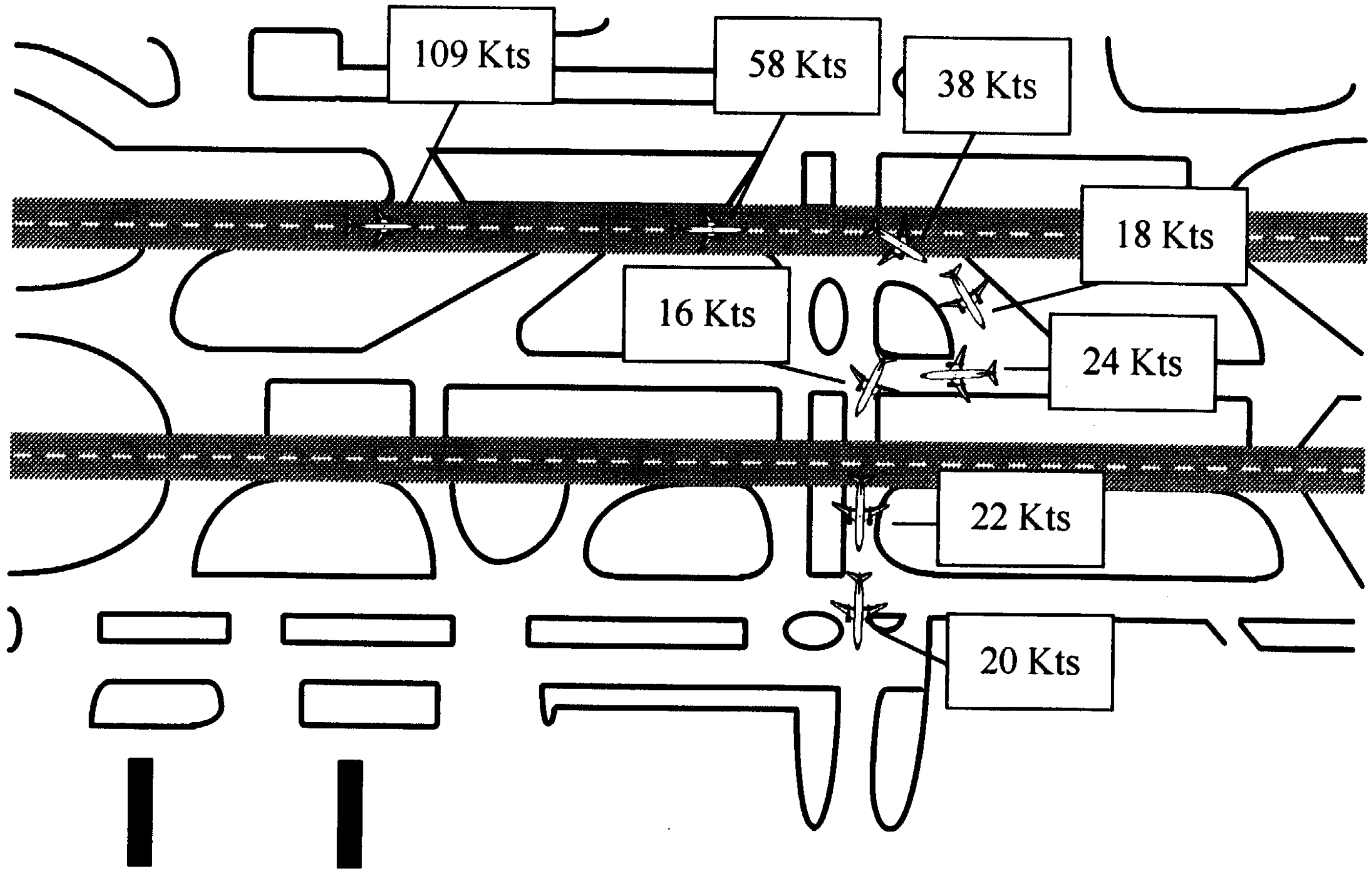

Figure A4. Typical Taxi Velocities (high speed runway exit)

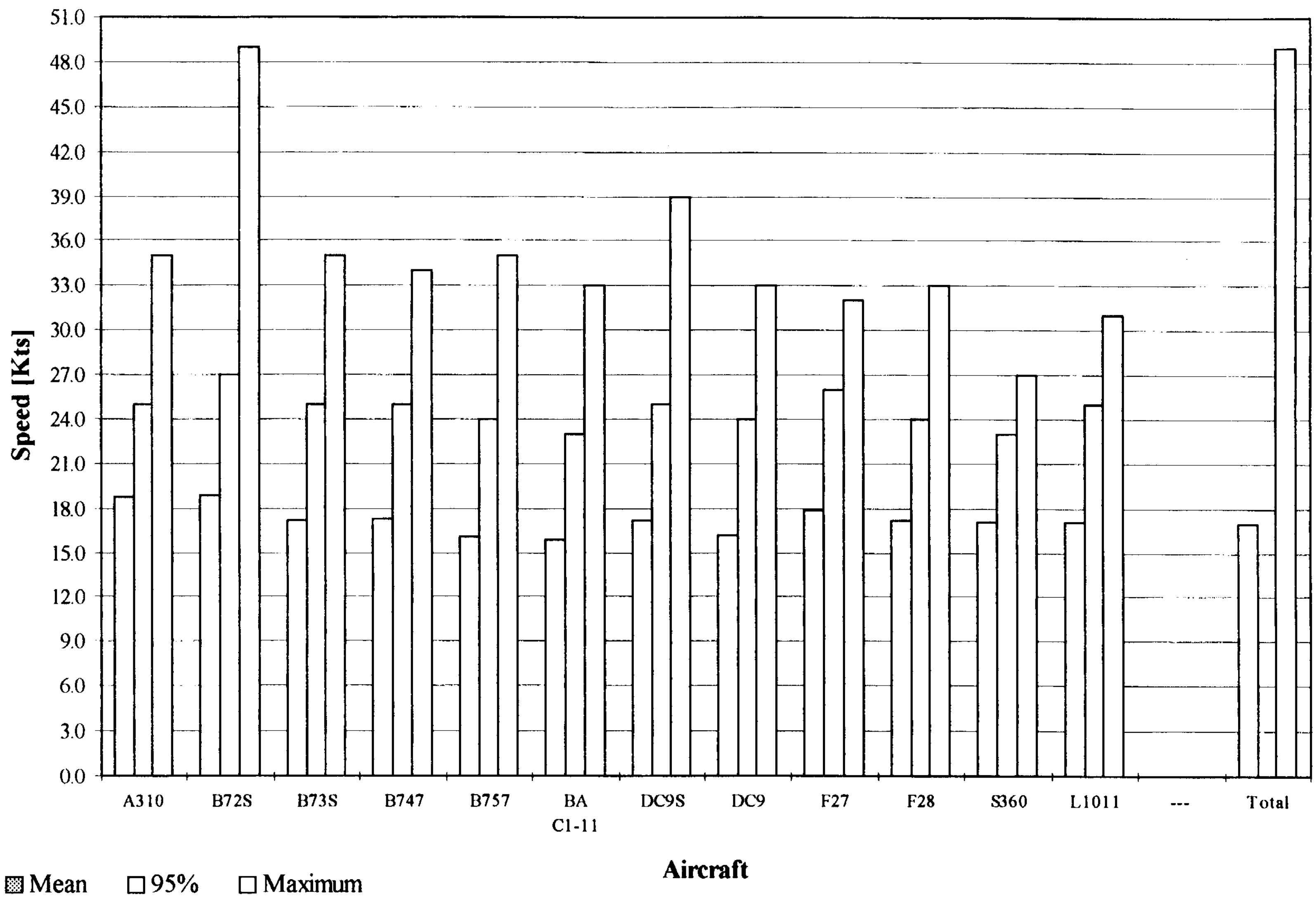

Figure A5. Heathrow Measured Taxi Speed - Straight Section

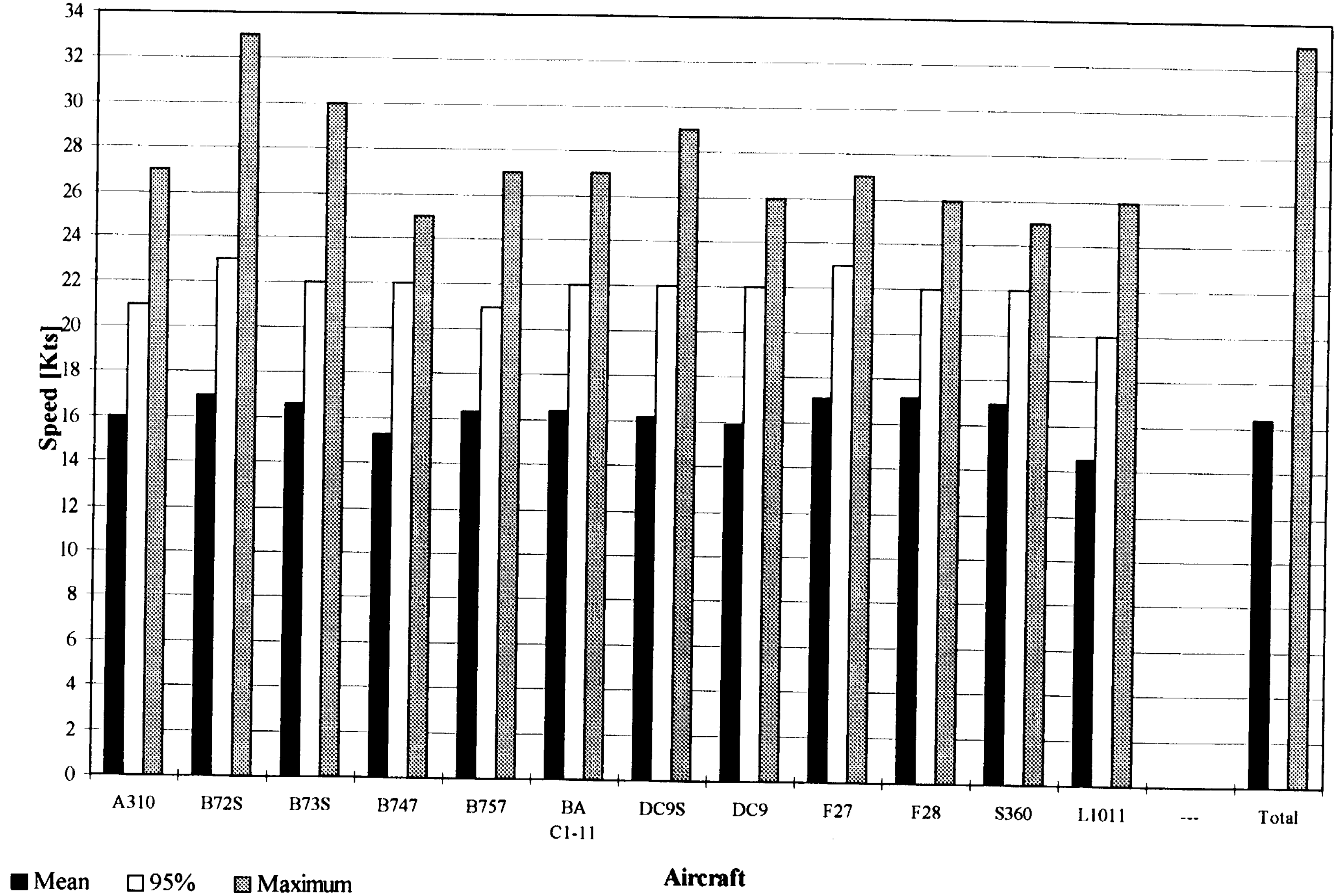

Figure A6. Heathrow Measured Taxi Speed - Curved Section

APPENDIX B
EXPOSURE TIME ANALYSIS

B1 DEFINITION OF SURFACE MOVEMENT RNP EXPOSURE TIMES

For each phase of aircraft surface movement (high speed taxi, normal taxi, apron) a risk of failure associated with each RNP function (integrity and continuity) is calculated given various visibility conditions. A risk rate (risk/time) can be determined by estimating the exposure time for each phase of surface movement.

B1.1 Normal Taxi and Apron Exposure Time Calculation

This section estimates exposure times during the three phases of taxiing at various international U.S. airports. To calculate exposure times for normal taxi and apron maneuvers, taxi phase velocities were assumed to be 20 knots and 5 knots for normal taxi and apron, respectively. Three cases were examined: worst case, and two average taxiing run cases. Taxiing distances were measured from airport schematics with proper scaling. The worst case scenarios were assumed to have the longest normal taxi and (possibly) apron distances. The nominal cases were assumed to have average distances from two major runways to a centrally located terminal. Results are shown in Table B1, and the taxiing routes for each airport are shown in Figures B1 through B9.

B1.2 High Speed Taxi Exposure Time Calculation

Taxi data from Atlanta was gathered using the experimental ATIDS. Data on aircraft landing on runway 8L at Atlanta Airport and exiting onto high speed taxiway B11 were analyzed. Landing and taxiing data were segregated to include only high speed taxi data. The segregation followed two criteria. First, the data used must have fallen within specific boundaries imposed on the taxiway. Second, once the aircraft entered this boundary, the first data point where velocity reduced below the assumed high speed taxi maximum (60 kts) became the first segregation point. Searching the data from the exit termination backwards, the first data point that was larger than the high speed taxi minimum was declared the second segregation point. All data between these two points were used for exposure time calculation (even though some data were outside the velocity bounds). In addition, boundary dimensions were chosen to include data that might be slightly outside the high speed taxi exit but still be within the velocity bounds (30 knots $< V <$ 60 knots).

High speed taxi velocities were calculated using three different methods (see Figure B10). The first (I) involved numerically integrating the curve-fitted line length over velocity functions from data gathered at Atlanta Airport. The average exposure time was found by taking the mean of all individual exposure times calculated. The second method (II) again used fitted functions of the position and velocity. Mean values of second-degree interpolation coefficients were used for an average line-length over velocity integration yielding an average exposure time. The final method (III) used the mean log time of all runs from the Atlanta data as the average exposure time. Figure B11 shows a histogram of the number of aircraft within time ranges of 10-20 seconds, 20-30 seconds and greater than 30 seconds, and Table B2 lists the average exposure times calculated by the three methods.

B1.3 Conclusions

The results of the study indicate that for high speed taxi, the maximum exposure time (worst case scenario) is around 20 seconds. It is reasonable to assume that this does not vary significantly for different runways. Therefore, it is recommended that the exposure time be specified at 30 seconds, placing an upper bound on the value. For normal taxi, the maximums were found to be approximately 6 minutes, with the average taxi routes being approximately 3 minutes. The majority of scenarios will be significantly less than 6 minutes, but is difficult to quantify due to the large variation in taxi routes possible. The recommendation is to define the exposure time to be 6 minutes, on the assumption that this value encompasses 95% of all cases. For the apron phase, the maximums were found to be approximately 3 minutes, with the average at 2.5 minutes. Using reasoning as stated for normal taxi, it is recommended that the exposure time be defined at 3 minutes.

Facility	Taxi Phase	Worst Case Time (min)	Distance (ft)	Nominal 1 Time (min)	Distance (ft)	Nominal 2 Time (min)	Distance (ft)
ATL	Normal (20 kts)	5.4	10943	2.66	5377	2.38	4811
	Apron (5 kts)	4.29	2170	2.79	1415	2.79	1415
BOS	Normal (20 kts)	6.4	12900	1.5	3000	2.1	4200
	Apron (5 kts)	0.9	460	1.6	796	2.4	1200
DEN	Normal (20 kts)	9.4	19000	6.3	1300	5.8	11700
	Apron (5 kts)	1.1	559	1.5	745	1.5	745
DFW	Normal (20 kts)	3.8	7700	1.7	3400	2.6	5400
	Apron (5 kts)	4.2	2100	1.7	860	1.7	860
IAD	Normal (20 kts)	6.5	13100	5.3	10700	3.0	6000
	Apron (5 kts)	8.3	4200	4.9	2500	4.5	2300
JFK	Normal (20 kts)	8.1	16500	3.4	6800	1.0	2000
	Apron (5 kts)	3.7	1900	4.9	2500	1.9	980
LAX	Normal (20 kts)	5.0	10100	2.2	4500	3.0	6200
	Apron (5 kts)	1.6	800	2.1	1000	1.9	960
ORD	Normal (20 kts)	6.9	1400	2.9	5800	2.8	5700
	Apron (5 kts)	2.3	1100	2.0	1000	2.0	1000
SEA	Normal (20 kts)	3.8	7700	2.6	5200	0.3	600
	Apron (5 kts)	3.2	1600	1.0	480	3.9	2000
Averages	Normal (20 kts)	6.1	11038.1		Nominal 1&2	2.9	5165.0
	Apron (5 kts)	3.3	1654.3		Averages	2.5	1245.0

Table B1. Taxi Phase Exposure Time and Route Distances for Various U.S. Airports

Method	Exposure Time (sec)
I	20.7
II	13.0
III	14.0

Table B2. High-Speed Taxi Exposure Times

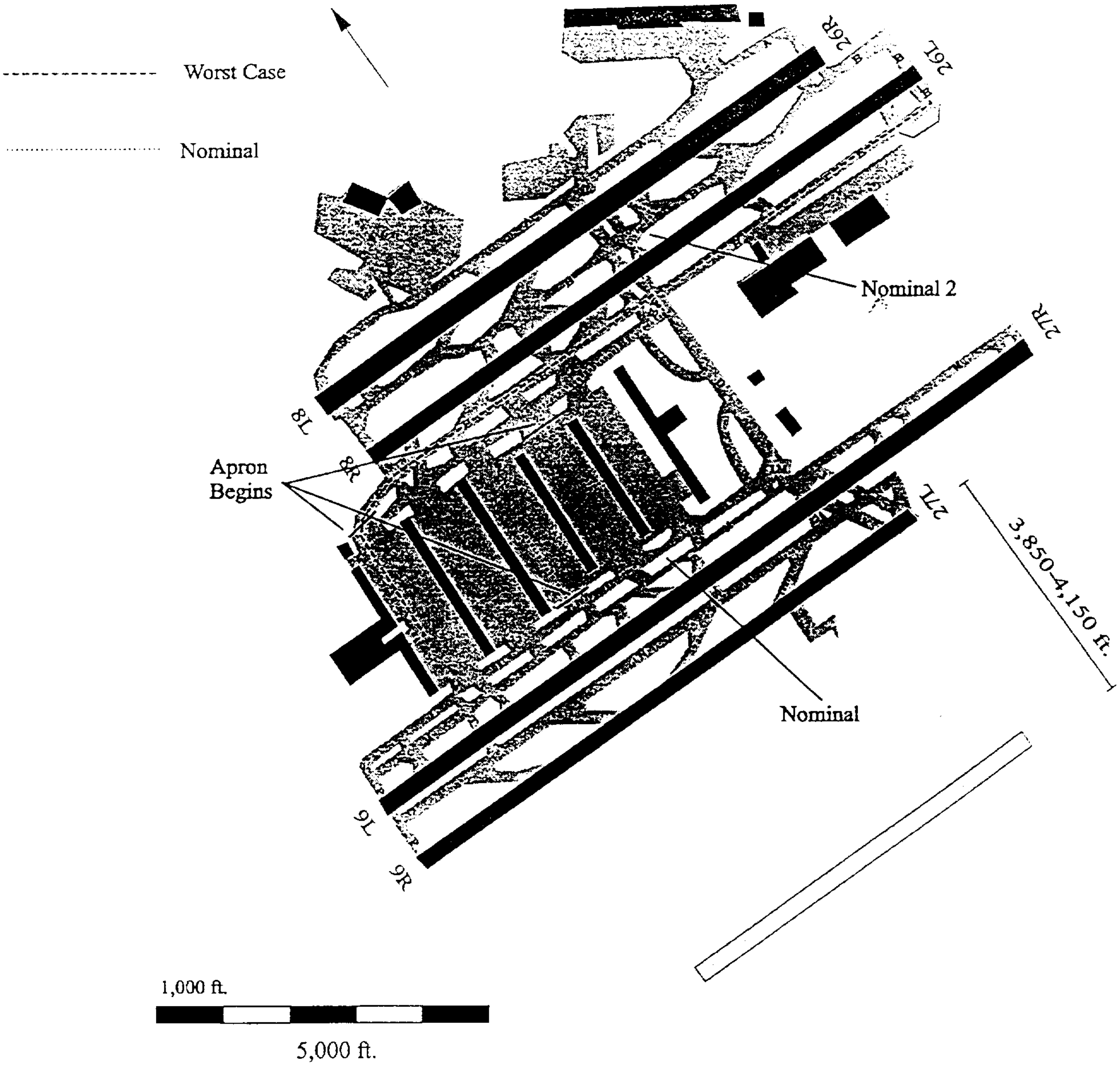

Figure B1. Schematic of Atlanta International Airport (ATL) Showing Worst Case and Nominal Taxi Routes

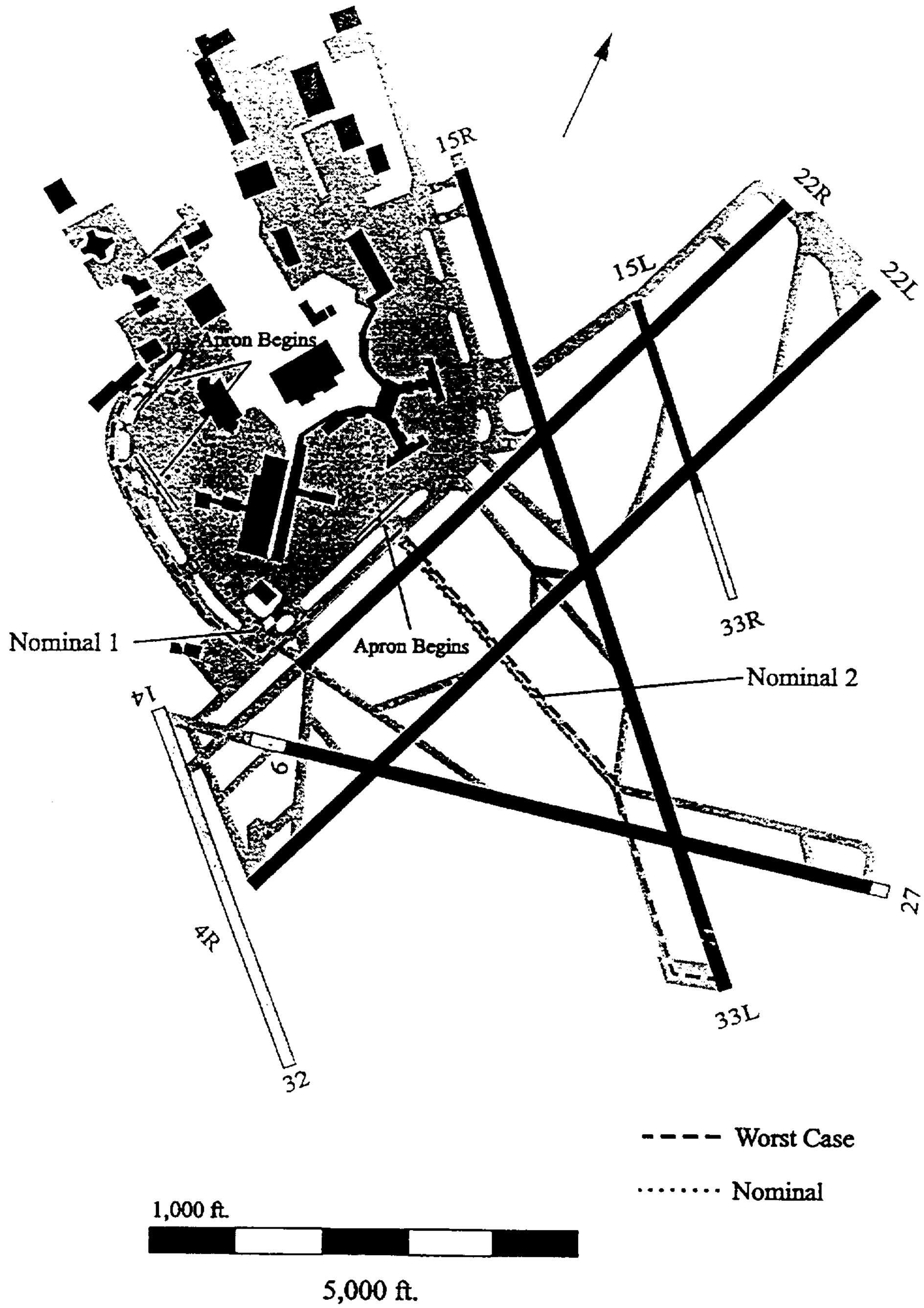

Figure B2. Schematic of Boston-Logan International Airport (BOS) Showing Worst Case and Nominal Taxi Routes

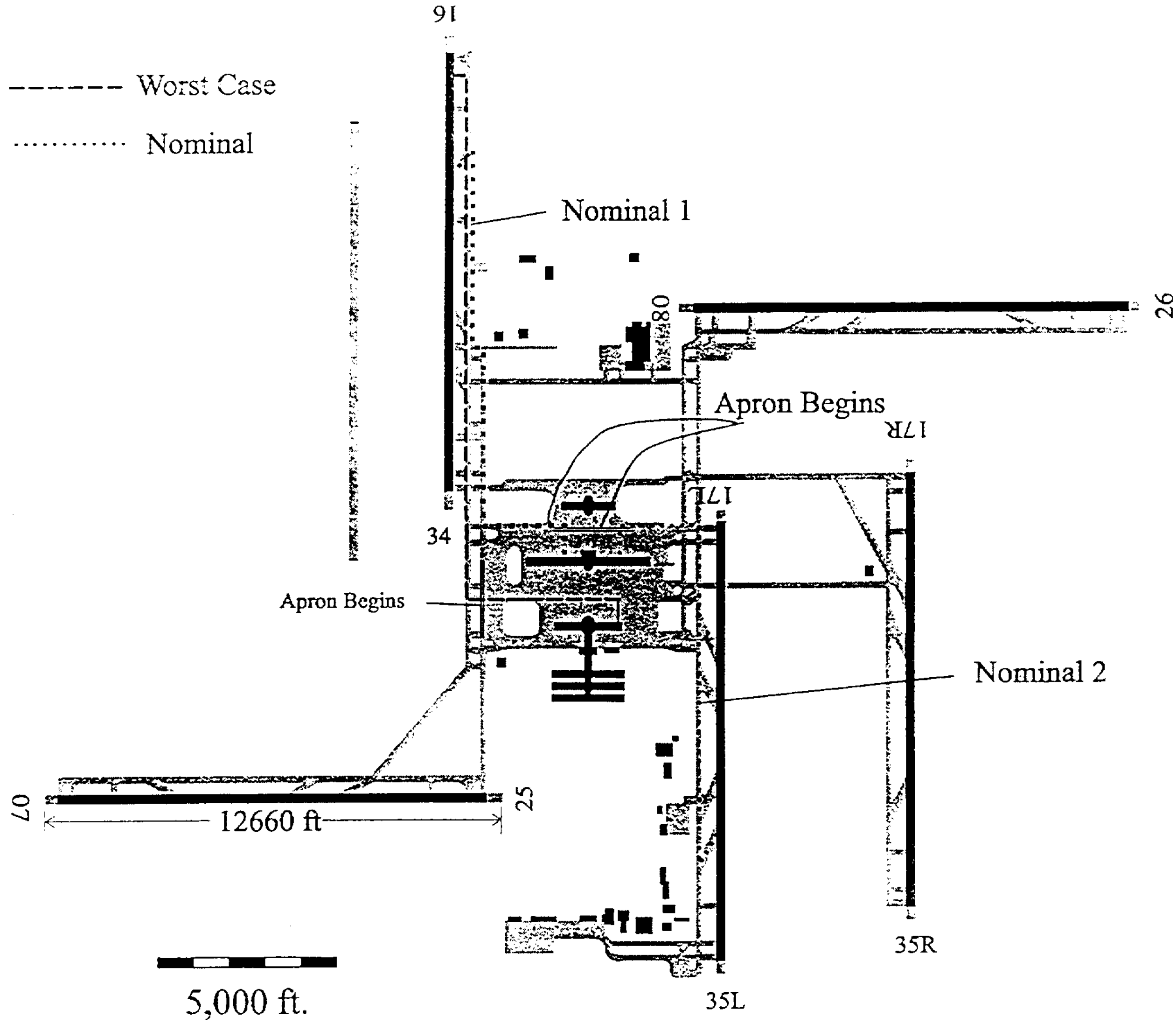

Figure B3. Schematic of Denver International Airport (DEN) Showing Worst Case and Nominal Taxi Routes

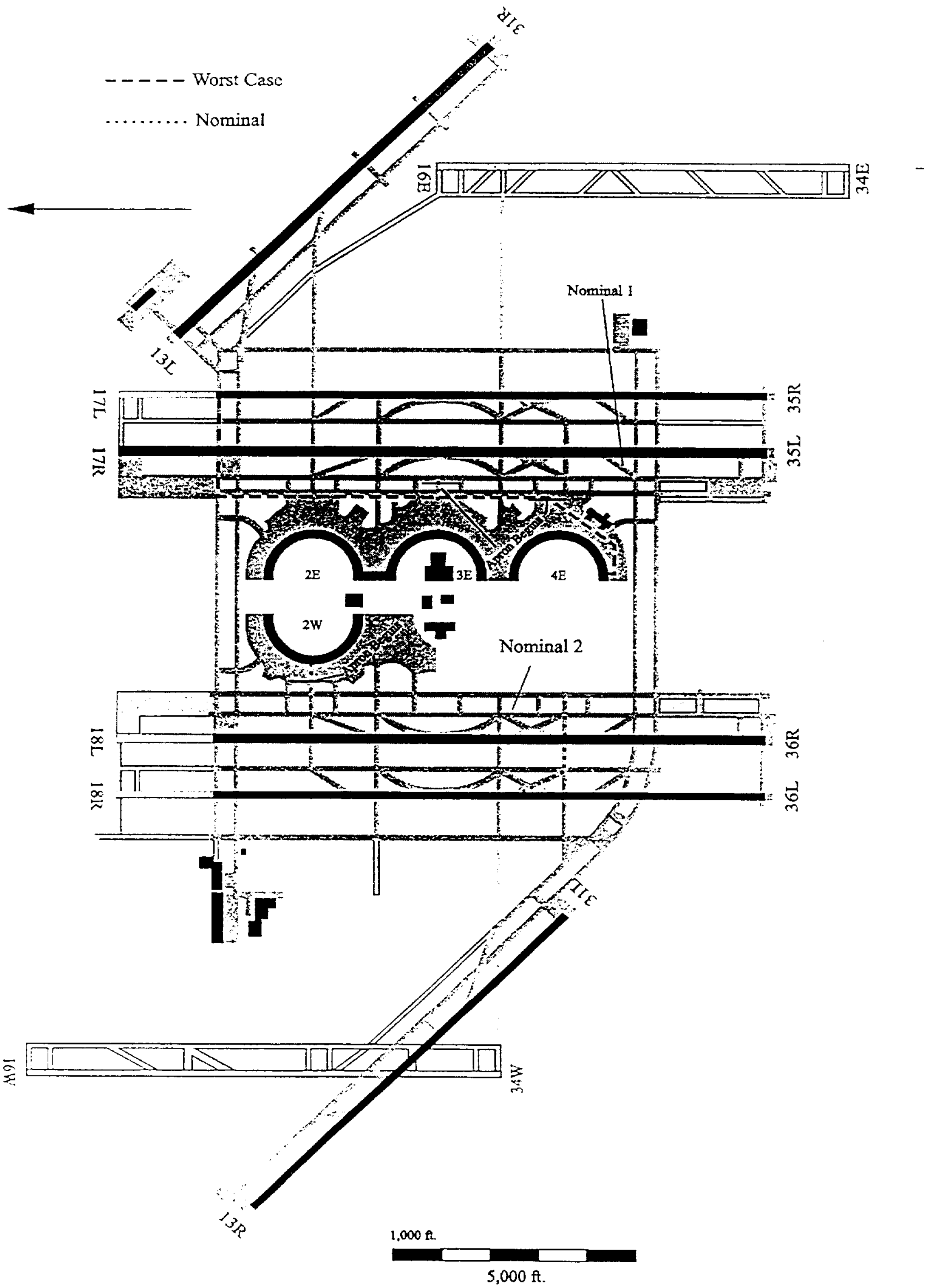

Figure B4. Schematic of Dallas-Fort Worth International Airport (DFW) Showing Worst Case and Nominal Taxi Routes

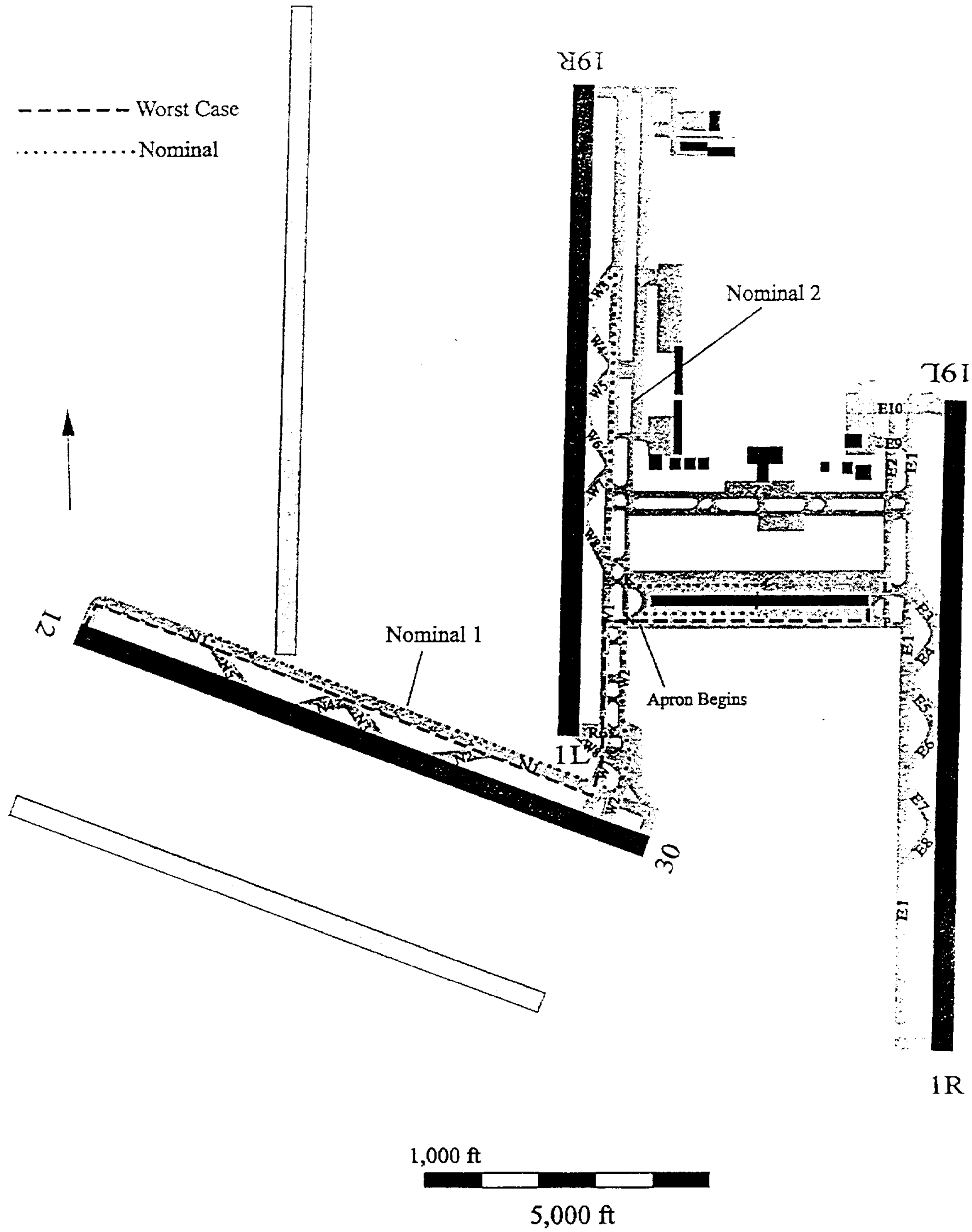

Figure B5. Schematic of Dulles International Airport (IAD) Showing Worst Case and Nominal Taxi Routes

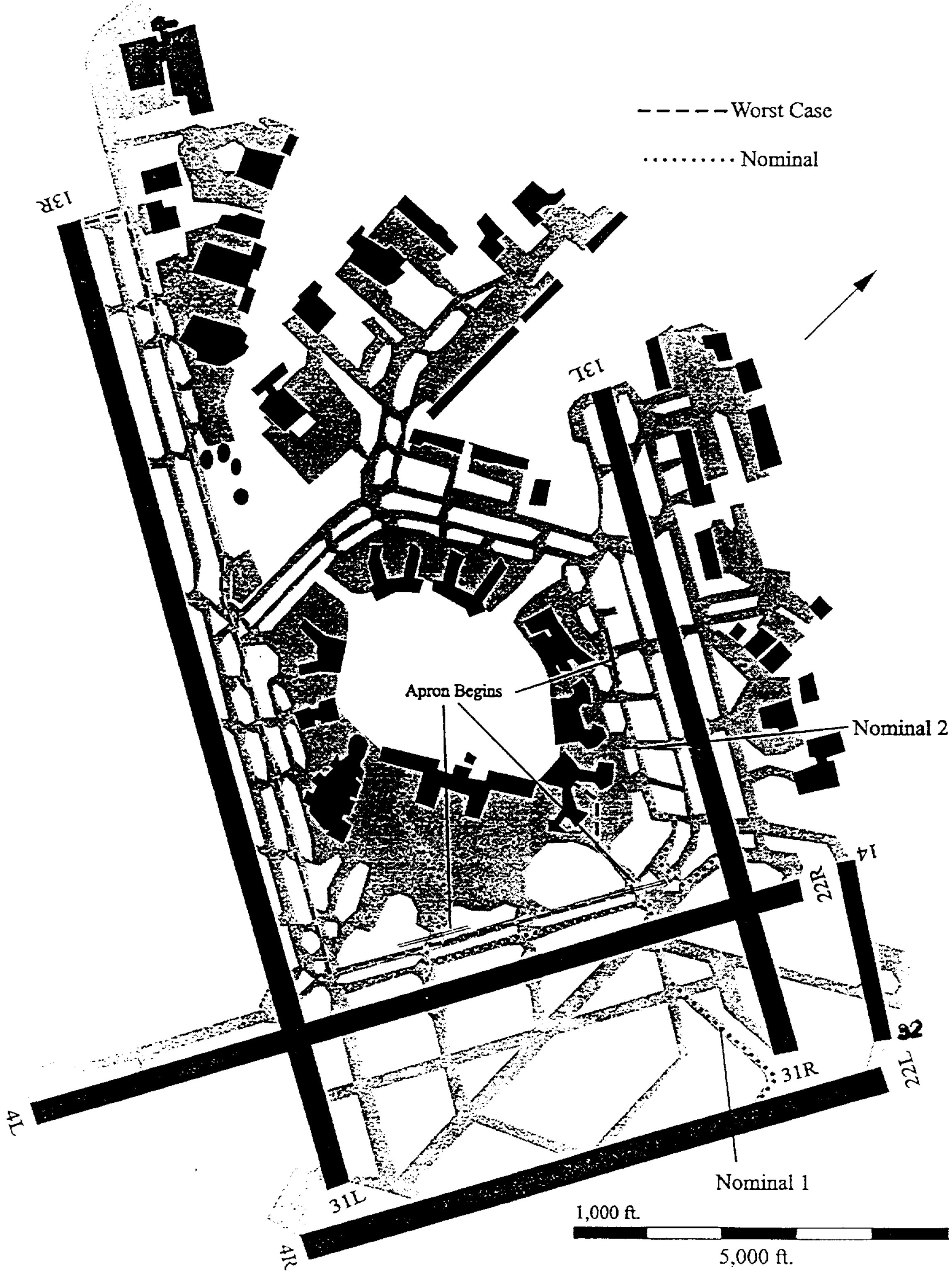

Figure B6. Schematic of John F. Kennedy International Airport (JFK) Showing Worst Case and Nominal Taxi Routes

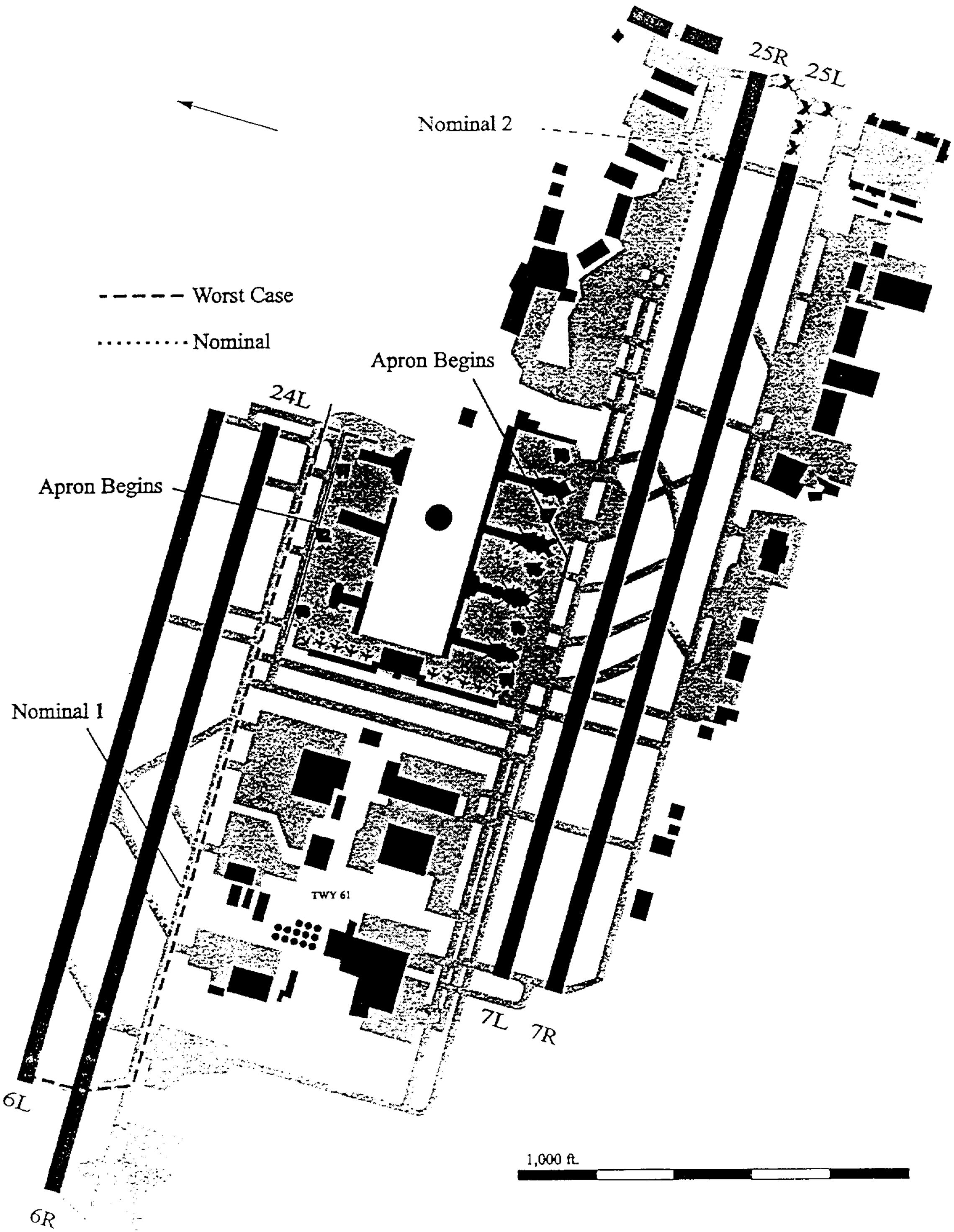

Figure B7. Schematic of Los Angeles International Airport (LAX) Showing Worst Case and Nominal Taxi Routes

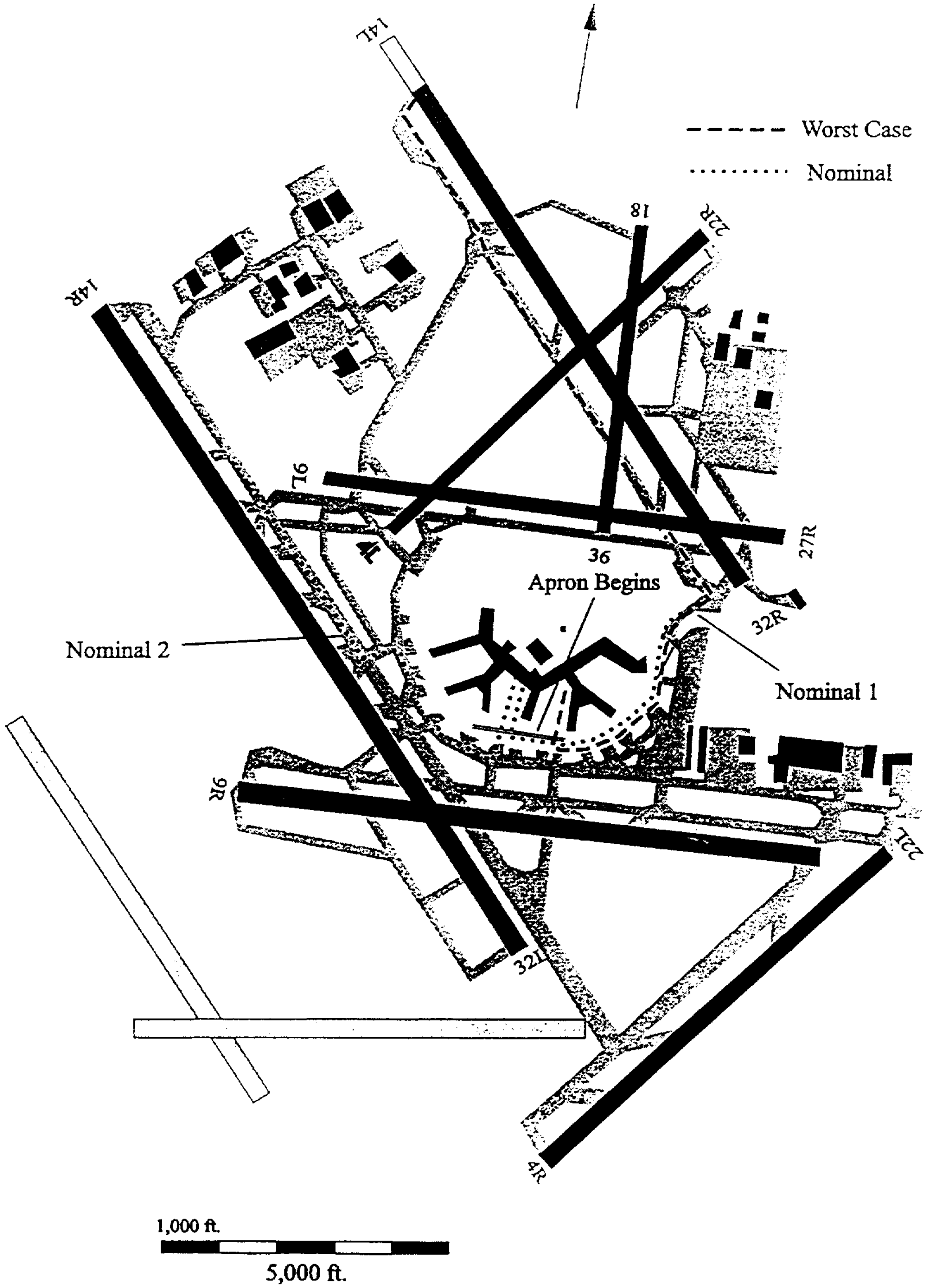

Figure B8. Schematic of Chicago O'Hare International Airport (ORD) Showing Worst Case and Nominal Taxi Routes

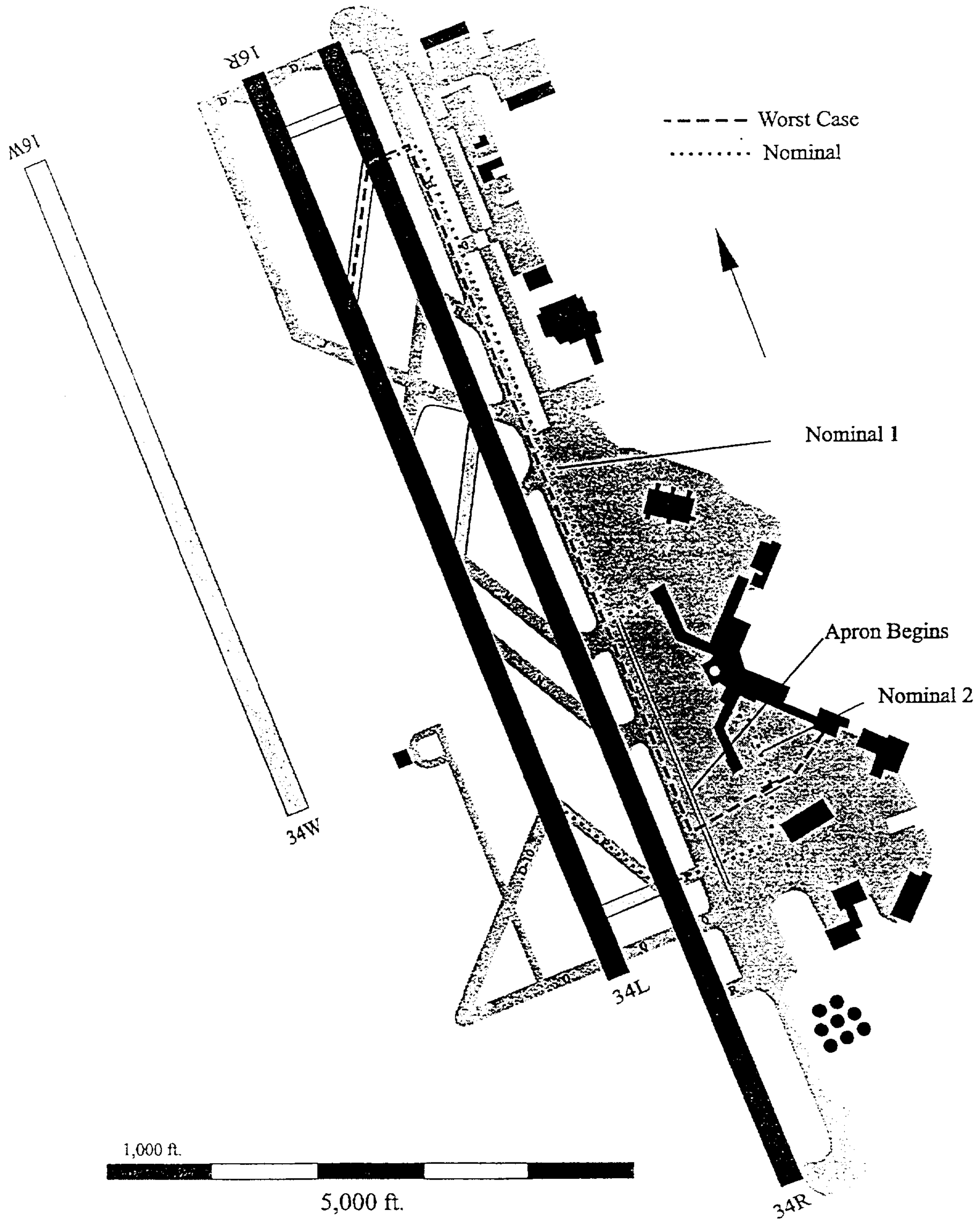

Figure B9. Schematic of Seattle-Tacoma International Airport (SEA) Showing Worst Case and Nominal Taxi Routes

$$\bar{t} = \frac{\sum_{i=1}^{n} \int_{x_o}^{x_f} \frac{\sqrt{(b_i^p + 2a_i^p x)^2 + 1}}{a_i^v + b_i^v x + c_i^v x^2} dx}{n}$$

... Method I

$$\bar{t} = \int_{\bar{x}_o}^{\bar{x}_f} \frac{\sqrt{(\bar{b}^p + 2\bar{a}^p x)^2 + 1}}{\bar{a}^v + \bar{b}^v x + \bar{c}^v x^2} dx$$

... Method II

$$\bar{t} = \frac{\sum_{i=1}^{n} T_i^{\log}}{n}$$

... Method III

Figure B10. Average Exposure Time Equations

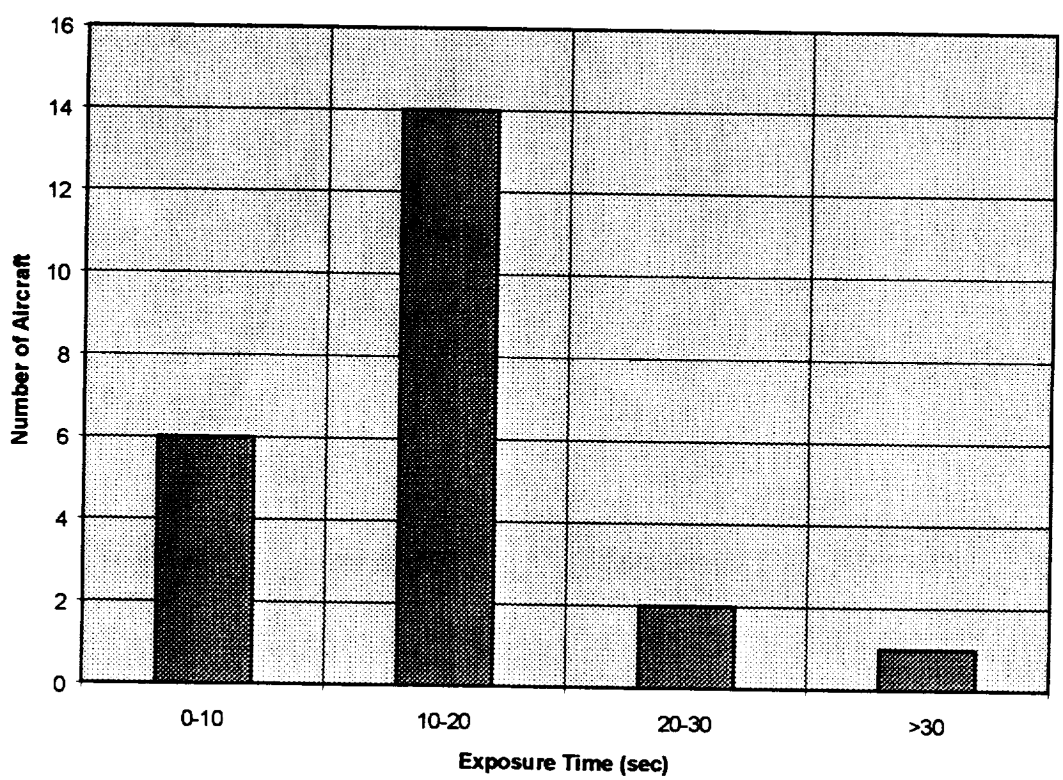

Figure B11. Measured High Speed Exposure Times (ATL)

APPENDIX C
SUMMARY OF REACTION TIME STUDIES

Pilot Reaction Times Studies Summary

Scenario	Audio/ Visual Warning	Avg (s)	Median (s)	Std Dev (s)	Range (s)	n	Comments	Data Source	Ref.
Autopilot Commanded Roll During Level flight @ 7,000 ft.	N	5.9 (90 % = 9)	5.9	N/A	1.7 - 11.8	18	Def. Commanded Roll, autopilot overshoots target bank angle @ 6°/s. Pilot response is to disconnect autopilot.	GA Stationary Piper Malibu Simulator with 150° field of view	# 22, p. 8, 9, 10.
Autopilot Roll Sensor Failure During Descent From Cruise Altitude.	N	11.7	11.5	N/A	4.5 - 21.2	16	Roll Sensor Failure is characterized as a "soft" failure. Pilot response is to disconnect autopilot.		
Autopilot Pitch Sensor Failure During Climb to Cruise Altitude.	N	17.7	17.4	N/A	6.5 -31.5	12	Pitch Sensor Failure is characterized as a "soft" failure. Pilot response is to disconnect autopilot.		
Autopilot Runaway Pitch-Trim Failure during Cruising Climb from 6K-7K.	Y	9.1	6.2	N/A	0.2 - 39.2*	13	Auditory & visual warning provided. *Range for all pitch-trim failures (25 runs).	GA Stationary Piper Malibu Simulator with 150° field of view	# 22, p. 9, 16.
Autopilot Runaway Pitch-Trim Failure during ILS Approach.	Y	11.8	10.4	N/A	0.2 - 39.2*	12	Auditory & visual warning provided. *Range for all pitch-trim failures (25 runs)		
Pilot Transmission Response Time to Controller Collision Avoidance Directives.	Y	3.31	N/A	4.80	1-31	80	49 calls in high workload environment; 31 in lower workload environment, however no statistical significance was noticed. $t(78) = .23,\ p > .05$	46 hrs of En Route audio tapes from 3 ARTCCs (16 hrs from LA, 15 hrs from NY, 15 hrs from Salt Lake)	# 26, p. 2-1, 3-2, 3-3.
Rejected Takeoffs	Y	2.32	1.6	1.45	1-5.5	9	Individual values = 1.6, 1.9, 1.3, 5.5, 1, 3, 4, 1.5, 1.1 s, Times are approximate. Statistics calculated by Ramsey	Data from 9 aircraft accidents	# 23, p. 30, 32, 33, 34.
Pilot Response Time to ATC command to turn on approach (measured at 200 feet DH)	Y	4.9	N/A	2.8	max of 13	36	Time measured is time between beginning of the breakout instruction and the beginning of the a/c turn. * Histograms available with response times rounded to whole second.	FAA B-727 Simulator FedEx DC-10 Simulator	# 27, p. 340, 341.
Reaction Time to Normal TCAS Resolution Advisories (Study 1)	Y	1.9		1.43		57	Pilot given 15 - 20 s warning before resolution advisory was issued.	B-727 Full Motion Simulator (full mission workload)	# 21, p. 56.

Scenario	Audio/ Visual Warning	Avg (s)	Median (s)	Std Dev (s)	Range (s)	n	Comments	Data Source	Ref.
Reaction Time to Amended TCAS Resolution Advisories (Study 2)	Y	1st - .49 2nd - .75 3rd - 1.94		.56 .69 1.37	.32-8.7 .32-7.23 .32-8.4	40 0 29 8 69	Pilots response to the 1st, 2nd, or 3rd amended advisory given in close sequence.	B-727 Full Motion Simulator (not a full mission workload)	# 21, p. 62.
Reaction Time to Avoid Midair Collision	Y	12.5					Total Time calculated as follows: See object = 0.1; Recognize a/c = 1.0; Become aware collision course = 5.0; Decision to turn left or right = 4.0; Muscular reaction = 0.4; Aircraft lag time = 2.0	U.S. Naval Aviation Safety Bulletin (Bulletin could not be found)	# 28, p. 7.

Note - See main report for references.

Other Related Reaction Times Studies Summary

Scenario	Audio/ Visual Warning	Avg (s)	Median (s)	Std Dev (s)	Range (s)	n	Comments	Data Source	Ref.
ATC Controller reaction time study: Simulated radar failure followed by performing a simple information processing task.	Y	2.91	*	*	*	*	High-intensity group (white noise alarm of 104 dB). * Cumulative Probability distribution graph provided.	Monitoring a simulated ATC radar control.	# 29, p. 7.
	Y	2.84	*	*	*	*	Low-intensity group (white noise alarm of 67 dB).		
Automobile driver reactions to simulated emergencies.	Y	1.64					Response time after prolonged driving		# 29, p. 1.
	Y	.73					Braking time for unexpected situations.		
	Y	.54					Anticipated situations.		

Note - See main report for references.

APPENDIX D
CALCULATION OF PILOT FAILURE RISK

To validate the pilot failure risk, the probability that an aircraft crew would exceed an allotted time to respond to an integrity or continuity failure was investigated. The following variables and equations were used to solve for this probability.

Variables defined:

t_{total} — time elapsed from when the failure occurs to when the aircraft leaves the pavement or impacts an object

d_i — total distance from where the failure occurs to an object or the runway edge (Section 3.4.1.3)

$t_{respond}$ — $= t_{recognize} + t_{react}$ where $t_{recognize}$ is the time it takes for the pilot to identify a failure and t_{react} is the time required for the pilot to physically react to the failure. Pilot reaction time (t_{react}) is a measure of the pilots muscular reaction time and was assumed to be 0.5 seconds for each case. This is consistent with human response studies conducted with aircraft midair collision avoidance and automobile collision avoidance reaction times [28, 29]. Time to recognize ($t_{recognize}$) will vary with visibility and speed (workload). Table D1 lists the assumed values for $t_{respond}$ for the various scenarios and visibility levels.

t_{brake} — time elapsed from initiation of braking until the aircraft comes to a stop

d_{brake} — total distance traveled from initiation of braking until the aircraft comes to a stop

t_{extra} — the amount of safety margin the pilot has before the aircraft leaves the pavement or impacts an object if the pilot were to respond in the assumed amount of time in table D1

t_{RMax} — maximum time for the crew to respond ($t_{respond} + t_{extra}$)

a — deceleration rate of aircraft (-12 ft/sec^2)

Taxi Phase	Average Crew Response Times (sec.)			
	Continuity	Integrity		
	All Visibilities	Vis 1,2	Vis 3	Vis 4
High Speed	3	3	4	5
Normal	2	2	3	4
Stand	1	2	2	3

Table D1. Average Crew Response Times ($t_{respond}$)

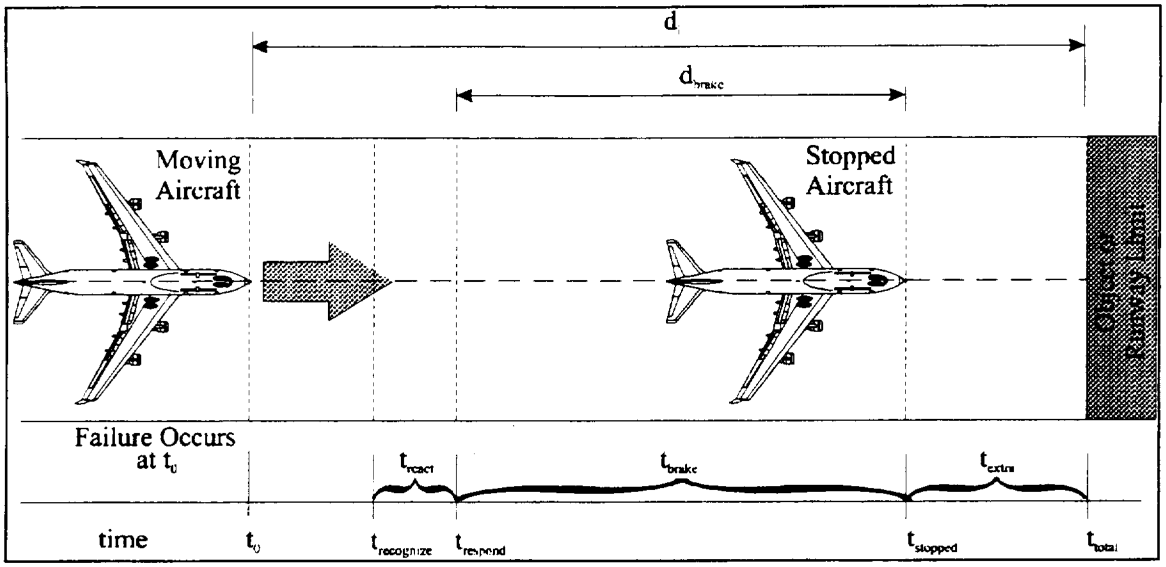

Figure D1. Relationship Between Variables

The maximum hard, panic stopping deceleration rate of -12 ft/sec^2 for the Boeing 747-400 was used. The time to stop the aircraft (t_{brake}) can then be solved with the following equations:

$$V_{final} = V_{initial} + a^*t_{brake} = 0 \tag{D-1}$$

solving for t_{brake}:

$$t_{brake} = -\frac{V_{initial}}{a} \tag{D-2}$$

Braking distance can now be solved for:

$$d_{brake} = (V_{initial}{}^*t_{brake} + ½^*a^*t_{brake}{}^2)^*\mu_{factor} \tag{D-3}$$

where the μ_{factor} is the ratio of friction coefficients of dry pavement to wet (if applicable).

Now, the maximum time the crew has to respond, t_{RMax} ($t_{extra} + t_{respond}$), can be solved for:

$$t_{RMax} = \frac{d_i - d_{brake}}{V_{initial}} - 0.75 \tag{D-4}$$

where 0.75 is the time for the brake piston stacks to engage.

Next, the following relationship can be written between the various times:

$$t_{total} = t_{respond} + t_{brake} + t_{extra} \tag{D-5}$$

$t_{total} = t_{brake} + t_{RMax}$ (D-6)

substituting t_{total} (equation D-6) into equation D-5 and solving for t_{extra} yields:

$t_{extra} = t_{RMax} - t_{respond}$ (D-7)

Now the relationship between t_{extra} and pilot risk is established. The probability of the pilot exceeding t_{extra} was solved for by assuming pilot response times may be modeled with a normal probability distribution. The probability that t_{extra} will be exceeded is equal to the area under the normal probability curve from t_{extra} to ∞ (Figure D2).

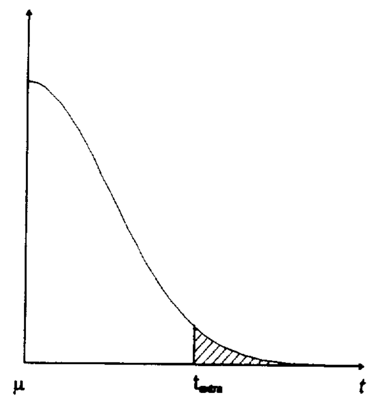

Figure D2. Probability of Exceeding t_{extra}

The normal probability function [30] is given by:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2}\left[(x-\mu)/\sigma\right]^2} \quad \text{(D-8)}$$

where σ is the standard deviation and μ is the mean of the distribution.

The area under the curve can be solved for by integrating f(x) from t_{extra} to ∞. More simply, this same area can be solved for by integrating f(x) from μ to t_{extra} and subtracting from the total area under the curve. The total area under half of a normal distribution is equal to ½. In equation form, the probability is given by:

$$P(t_{extra}, \mu, \sigma) = \frac{1}{2} - \int_{\mu}^{t_{extra}} \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2}[(t_{extra}-\mu)/\sigma]^2} \quad \text{(D-9)}$$

The integral is not explicitly solvable, but can be approximated to a high degree of accuracy with numerical methods. In this case, the Romberg numerical integration technique [31] was used.

The input values for σ and μ were selected as follows. In all cases the probability curves are centered at t = 0, therefore the mean value, μ, is always equal to zero. This is because the probability being investigated is the probability of a pilot exceeding the average response time

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13. ABSTRACT *(Maximum 200 words)*
The U.S. and international aviation communities have adopted the Required Naviagation Performance (RNP) process for defining aircraft performance when operating the en-route, approach and landing phases of flight. RNP consists primarily of the following key parameters - accuracy, integrity, continuity, and availablity. The processes and analytical techniques employed to define en-route, approach and landing RNP have been applied in the development of RNP for the airport surface. To validate the proposed RNP requirements several methods were used. Operational and flight demonstration data were analyzed for conformance with proposed requirements, as were several aircraft flight simulation studies. The pilot failure risk component was analyed through several hypothetical scenarios. Additional simulator studies are recommended to better quantify crew reactions to failures as well as additional simulator and field testing to validate achieved accuracy performance. This research was performed in support of the NASA Low Visibility Landing and Surface Operations Programs.

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($t_{respond}$, Table D1) plus the extra time (t_{extra}) to respond to a failure. Because the average response time is already subtracted from the total time to solve for t_{extra} (equation D-7), the probability of interest is the probability from t_{extra} to ∞ with μ equal to zero. The explanation for the selection of the standard deviation, σ, can be found in Section 3.4.1.4.