DEVELOPMENT OF REQUIRED NAVIGATION PERFORMANCE (RNP) REQUIREMENTS FOR AIRPORT SURFACE MOVEMENT GUIDANCE AND CONTROL

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ABSTRACT

This paper presents the application of a relatively new concept, Required Navigation Performance (RNP), as a method to determine requirements for aircraft surface movement guidance and control. Currently, navigation standards do not exist for low visibility aircraft operations on runway and taxiway surfaces. Whereas there are enabling technologies under evaluation for aircraft guidance and Air Traffic Control surveillance on the airport surface, there are no performance requirements available to judge the suitability of specific systems. A top-down process is applied, starting with a target level of safety for each surface operation. RNP requirements are allocated to ground and airborne equipment and an approach is presented to validate the RNP allocations using a Functional Hazard Assessment (FHA).

INTRODUCTION

RNP is a relatively new concept that has been developed over the past few years and has been applied to several systems, most notably aircraft landing systems. RNP gives the design engineer flexibility in budgeting different navigation system parameters to meet an overall target level of safety. Previously, requirements would have been specified as allocated to different system components; e.g., the accuracy of the aircraft receiver and ground transmitter. In contrast, the RNP method allows the design engineer to make the tradeoffs. This has been a significant development for aircraft landing systems.

In this paper we propose the application of RNP to surface movement guidance and control, an area of aviation where aircraft performance standards and requirements do not currently exist. We expand the concept from navigation only to an overall system level, the Required System Performance (RSP). The system level functions include navigation, surveillance, control, and routing.

Under contract to the Low Visibility Landing & Surface Operations (LVLASO) Element of NASA Langley's Terminal Area Productivity Program, Rannoch is developing the RNP requirements for surface movement guidance and control.
 Rannoch is coordinating the development of these standards with NASA, FAA and the International Civil Aviation Organization All Weather Operations Panel (ICAO AWOP). ICAO is developing operational requirements for Advanced Surface Movement Guidance and Control Systems (A-SMGCS). This paper contains only the understanding and views of the authors and is not intended to represent the official position of NASA, FAA or ICAO.

CONCEPT OVERVIEW

The objective of the analysis is to demonstrate that we achieve an overall target level of safety, which is normally expressed in units of fatal accidents per aircraft flight hour or operation. As shown in Figure 1, the Target Level of Safety (TLS) risk is allocated to the RSP. The RSP in turn consists of four separate functions. The guidance function is defined by the RNP and surveillance by Required Surveillance Performance (RSVP). Similarly, control and routing are defined in terms of Required Control Performance (RCP) and Required Routing Performance (RRP). The four functions shown are based on the surface movement functions identified by ICAO [1]. Guidance is the function that provides navigation information to the aircraft on the airport surface. The surveillance function provides a position report of all aircraft within the movement area. The ATC control function provides all of the conflict resolution, stopbar lighting, and aircraft sequencing on the tarmac. The routing function designates the route for each aircraft or vehicle on the movement area.

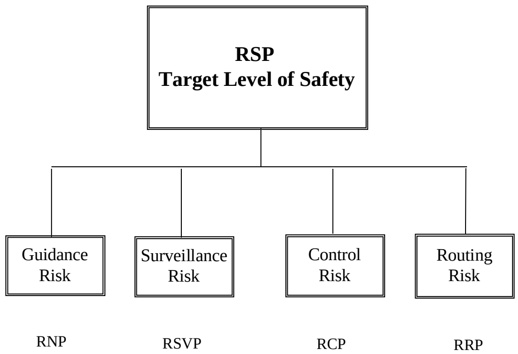

Figure 1. Relationship Between RSP and Function Requirements

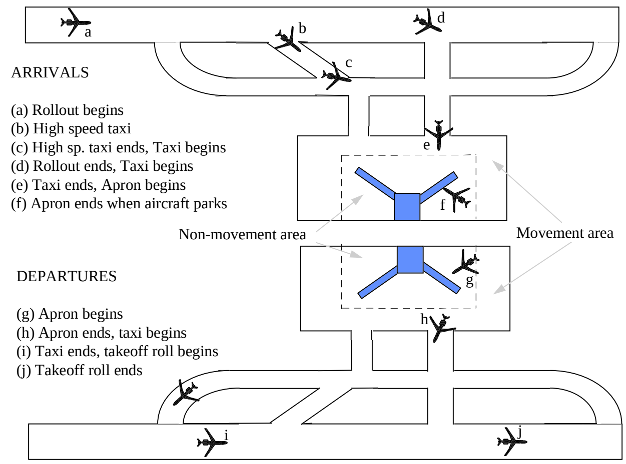

Figure 2. Phases of Operation

The parameters that make up each function of the RSP are the same as those currently used for aircraft approach and landing: accuracy, integrity, continuity, and availability. Accuracy is the ability of the system to maintain the aircraft within a Total System Error (TSE) limit with a 95% probability at each point along the specified procedure and to keep it within an outer performance boundary with a specified probability. For surface procedures, the accuracy requirement applies only to the lateral boundary (vertical requirements do not apply as the aircraft is on the ground). Integrity relates to the trust that can be placed in the correctness of the information supplied by the total system. Integrity includes the ability of a system to provide timely and valid warnings to the user when the system must not be used for the intended operation. Continuity is the ability of the total system to perform its intended function without interruption during the intended operation. Availability is the ability of the total system to perform its function at the initiation of the intended operation. For more detailed discussion on the concept of RNP, readers are directed to the extensive work of Kelly and Davis [2].

PHASES OF OPERATION

Before developing RSP requirements for ground based operations, we first had to define those operations. Consider as an analogy the well defined and documented landing procedures for Category I, II, and III landing operations and aircraft departure operations. Figure 2 summarizes each A-SMGCS operational phase for an arriving and departing aircraft. We also identify where A-SMGCS operations connect to landing and departure operations.

From the existing AWOP definition, rollout is defined as touchdown to the point where the aircraft decelerates below 60 kts [3]. Operationally, rollout is considered to be a part of the aircraft landing, therefore we do not need to develop an RNP for that phase of A-SMGCS as it already exists. After completing rollout the aircraft will enter into the taxi phase, which is defined as either high speed or normal taxi. High speed taxi is when the aircraft taxis at a speed between 30 and 80 kts. The airport would, of course, need to have high speed taxiways in place to support this, as shown in Figure 2 between points b and c. Normal taxi speeds range from 5 - 30 kts.

The 30 kts maximum for normal taxi is based upon a study that found 95% of aircraft taxi speeds to be less than 30 kts, with the average being slightly under 20 kts [4]. When the aircraft leaves the movement area and enters the non-movement area, it enters the apron phase of A-SMGCS, and will have a ground speed between 0 and 5 kts.

For the departing aircraft, the order of each phase of operation is reversed. The aircraft will move from the gate (apron phase) to normal taxi and will begin its takeoff roll. The takeoff roll is covered in the standards for aircraft departure and is therefore not included as part of A-SMGCS RNP.

RNP DEVELOPMENT PROCESS

An overview of the RNP development process is provided in this section of the paper. There are essentially six main elements in the process:

- RNP Classification
- TLS Risk Allocation
- Accident/Incident Ratio Determination
- RNP Parameter Computation

- Accuracy Considerations
- Functional Hazard Assessment Validation

RNP Classification

The RNP is classified according to the phase of the operation and the prevailing visibility condition. Visibility conditions are based on ICAO terminology and are numbered 1- 4 [1]. For conditions 1 & 2, the pilot can taxi using visual references. For condition 3, the Runway Visual Range (RVR) is between 75 m and 400 m, and for 4 is less than 75 m. The difference between conditions 1 and 2 is ATC's ability to perform visual surveillance, so for the purpose of determining RNP these conditions are essentially similar, however, they will cause different RSVPs. This will result in a matrix set of RNP values determined by phase of operation and visibility condition.

TLS Risk Allocation

Figure 3 shows the ICAO accident statistics for commercial aircraft over a 30 year period [3]. Taxi accidents, including loading and unloading, account for 2% of all accidents. The current overall accident risk is approximately 1.5 x 10^{-6} per operation. If we apply the 2% value to the overall accident risk, we get an estimate of 3.0 x 10^{-8} for the accident risk during taxi operations. The TLS for surface operations should be better than the historical data. As the TLS used for landing operations is 1 x 10^{-8}, we have selected this value for A-SMGCS TLS as well, to apply to all visibility conditions.

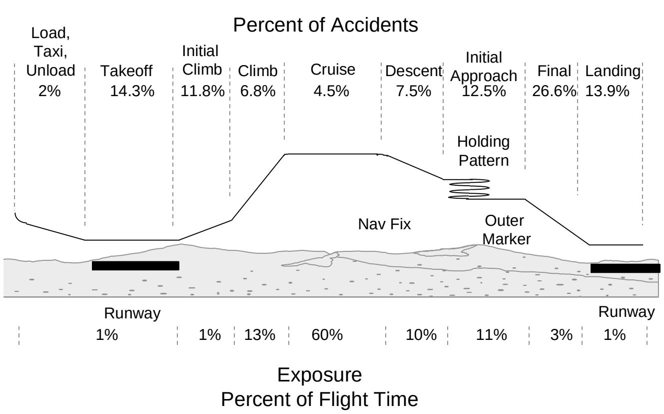

Figure 3. Accident Percentages by Phase of Flight

Figure 4 shows how the guidance risk and RNP is allocated. Using the accident/incident ratio the guidance incident risk is divided into departures and arrivals and into RNPs for each of the operational phases described previously (apron, normal taxi, high speed taxi). The incident risk for each surface movement phase of operation is then allocated to each of the RNP parameters, integrity, accuracy, and continuity. After factoring in the ability of the pilot to correct or stop the aircraft, the result is performance requirements for each of the parameters.

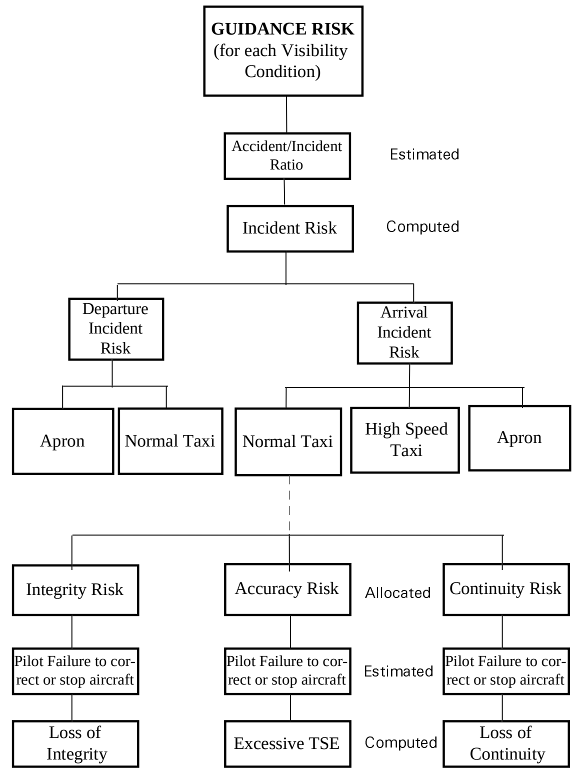

Figure 4. Guidance Risk & RNP Allocation

Accident/Incident Ratio Determination

An incident is defined as any occurrence of the aircraft exceeding the outer boundaries. Only a fraction of the total number of incidents actually result in accidents. For the approach and landing RNP, the ratio of accidents to incidents is 1/10. We propose to use the same value for A-SMGCS at least as a preliminary value. The argument could be made that the ratio should be smaller than 1/10 for runway surface operations, due to the lower aircraft speeds involved. However, at this time it is difficult to select and substantiate a lower value. Therefore, we consider the preliminary selection of 1/10 to be a conservative estimate.

RNP Parameter Computation

The RNP for A-SMGCS will not necessarily divide equally between different phases of operation, as more stringent requirements may be allocated to more critical phases of operation. Also, the RNP will not necessarily divide equally between each of the RNP parameters (accuracy, integrity and continuity). Larger allocations may be made to undetected failures than to detected failures due to the pilot's ability to deal more readily with the latter. Detected failures are those in which the pilot has feedback available to indicate that an abnormal condition exists. These pertain to failures of continuity and accuracy. Undetected failures are those in which the pilot has no indication that an abnormal condition exists, and pertain to integrity failures. Quantitative values for pilot failures will be based on relevant available data, which will likely require additional validation. Future plans include the use of NASA aircraft simulators for validation of pilot factors. Our initial analysis takes into account guidance only and does not include surveillance and separation from other aircraft.

Outer Boundary and Accuracy Considerations

One of the key concepts of RNP is the determination of inner and outer performance boundaries. The inner performance boundary defines the 95% performance (lateral only for surface guidance) of the aircraft, meaning that less than 5% of the aircraft deviations from the nominal path are allowed to exceed this boundary. The outer performance boundary defines the probability of an incident. For approach it is defined as a 10^{-7} surface, meaning that the aircraft is allowed to exceed this boundary less than 1 in 10^{7} approaches. For surface movement it is proposed that the probability of exceeding the outer boundary not exceed the risk assigned to each phase of surface operations. As will be shown later, the preliminary allocation of this value is 0.6×10^{-8}. The proposed definition of the outer boundary is 15 meters from the taxiway centerline. Figure 5 illustrates the safety margins for taxiways designed to accommodate the largest aircraft (the B-747 is shown as an example). References 5 and 6 contain the ICAO and FAA taxiway design requirements, respectively. The safety margin for the wingtip to an object is 16 m, while the margin for the main wheels to the edge of the taxiway shoulder is 15.5 m. Therefore the proposed outer boundary limit of 15 m is within these safety margins. Similar margins exist for parallel taxiways and curved sections of taxiways. Accuracy performance is defined in terms of Total System Error (TSE). The TSE is a combination of Navigation System Error (NSE) and Flight Technical Error (FTE). The FTE in this case, of course, is not a flight error but rather is during taxi, and refers to the ability of the aircraft to follow the desired path.

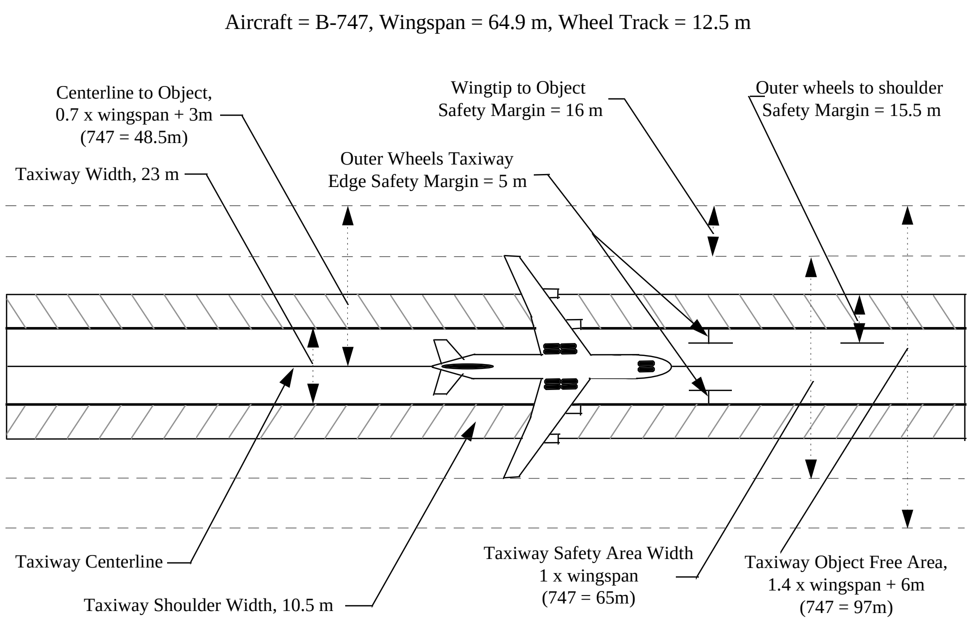

Figure 5. Single Taxiway Design Standards

The proposed 95% value, or inner boundary, is 2.0 m. The relationship between the inner and outer boundary values depends upon the distribution. The study referred to earlier of aircraft taxi performance [4] found an exponential distribution of taxi deviation. For the large commercial aircraft for which data was collected, the 95% deviation values were all less than 2.0 m. Therefore, this initial analysis indicates that the TSE accuracy requirement for positioning the aircraft wheels during taxi is 2.0 m (95%). This is based on the principle that performance during low visibility operations should be as good as during visual conditions. Longitudinal performance, as it applies to the aircraft's speed and position must also be taken into account. Longitudinal accuracy is of interest when determining the ability of the aircraft to navigate turns.

Validation using Functional Hazard Assessment (FHA)

The FHA is a method used to quantify the severity of failure effects, and is used throughout the aviation industry. The U.S. and Europe have aviation standards citing FHA methods. For our research we are using the FHA to validate our allocations from the RSP process. This essentially is an independent order of magnitude check on the results we get from the allocation process.

For each RNP parameter the consequences of failures will be identified and classified as specified in Federal Aviation Regulation (FAR) 25-1309, FAA Advisory Circular 25.1309-1A [7] and Joint Aviation Requirement (JAR) 25 [8]. These standards are used to relate the severity of effects to quantitative values, and extracts are shown in Figure 6.

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 cannot 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 cope 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

Figure 6. Relationship Between Probability & Severity of Effects

These guidelines were established for determining the level of risk to be assigned to an event based upon the consequences of the failure. The figure illustrates this relationship between the severity of the effects on the aircraft and the required level of probability. As an example, the most severe consequence of failure is a catastrophic one, which usually results in an accident and loss of the aircraft. The probability of such a failure occurring must be on the order of 10^{-9} or less. This category applies to the final phase of a Category III approach and landing, because the aircraft at that point is totally dependent upon the guidance system, due to the lack of visibility preventing the pilot from obtaining guidance cues. As a result, all aircraft systems designed to support Category III approaches must have probabilities of failure of 10^{-9} or less.

For each RNP parameter, operational phase, and level of visibility we will assign a quantitative probability using this process. The allowable risk determined by the FHA will be compared with risk previously allocated by the process shown in Figure 4, thereby using the FHA to validate our RNP allocations.

PRELIMINARY ALLOCATIONS

Having explained the process in some detail, we now present results of our preliminary analysis. We divide the TLS of 1.0×10^{-8} between each of the risk areas (see Figure 7). Surveillance risk, guidance risk, and control risk can be considered as equal contributors to TLS and are assigned equal values. At this time there is no rationale or data to support different allocations to the three functions. Routing is assigned a lower allocation because it is not as complex as the other three functions. The other three are more safety critical and have more severe effects, whereas routing is more of a planning function. A three to one ratio in allocations between the functions seems reasonable.

Taking the guidance risk, we now effectively work from the bottom up. Each of the accident risks for apron and taxi movements are assigned equal values regardless whether or not the aircraft is on arrival or departure, equating to incident risks of 0.6×10^{-8}. The subsequent total for departure is 1.2×10^{-8} and for arrival is 1.8×10^{-8}.

Figure 8 leads on from Figure 7, and shows the expansion of the risk for normal taxi (visibility conditions 1 and 2) which applies equally to departure and arrival. The incident rates are allocated equally between each of the three RNP parameters.

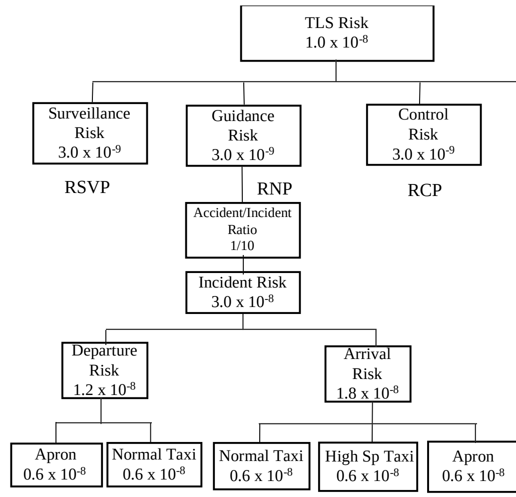

Figure 7. RSP Allocations -- Guidance Function

A lower pilot risk is assigned to continuity risk, than to the other two RNP parameters, because a continuity failure would be detected almost immediately by the pilot (i.e., loss of guidance) whereas, for the other two parameters, a failure could go undetected for some period of time. The results are as shown; the risk allocation for a loss of integrity is 2×10^{-5} , excessive TSE and loss of continuity are 1×10^{-5}. A similar process is used to develop the RNP for the other phases of A-SMGCS, the results of which are not presented here. Completion of the allocation process will also entail definition of the exposure times for each phase of A-SMGCS. The exposure time will define the amount of time over which each of the RNP parameters must be met during the operation.

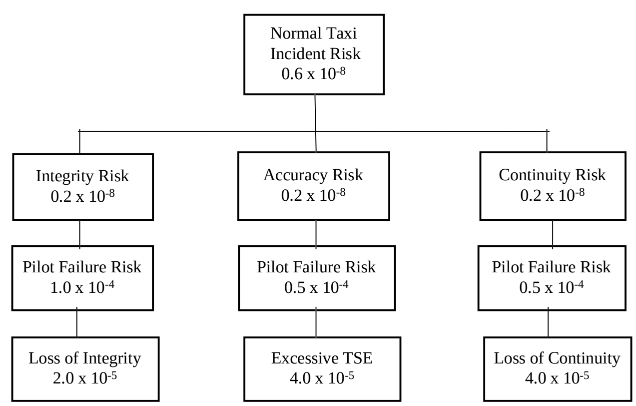

Figure 8. RNP Allocation for Normal Taxi

Allocation Validation

Figure 9 shows the results of our preliminary FHA for normal taxi in visibility conditions 1 and 2. For continuity (the parameter listed in the first row), we identify 3 failure condition effects. As stated earlier, the pilot will detect a continuity failure and will react to stop the aircraft. For this failure condition, we assume that at a speed between 5 - 30 kts and in visibility conditions 1 and 2, the pilot should be able to maintain course without exceeding the taxiway boundary. The classification of this failure condition is therefore minor corresponding to a required probability of between 10^{-3} to 10^{-5}. Refer to Figure 9 for the same process to establish probabilities for integrity and accuracy. These values compare favorably to our allocated values for each of the RNP parameters in Figure 8. In fact, the preliminary allocations can be considered conservative as they are more stringent than the values determined by the FHA.

CONCLUSIONS

This paper represents part of an ongoing development activity that is being coordinated with the aviation community through NASA, FAA, and ICAO. A methodology has been defined for developing the RNP requirements for aircraft surface movement. This method has been used to develop a preliminary set of requirements. The allocated requirements have been validated using the FHA methodology, and have produced general agreement with both methods. Future work will include completing the RNP allocations for all phases of surface operation.

ACKNOWLEDGMENTS

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A-SMGCS Phase	Failure Condition	RNP Parameter	Failure Condition Effects	Comments	FAR /JAR Category	Required Probability
Normal taxi (5-30 kts) Visibility Conditions 1 & 2	Detected failure: Loss of guidance	Continuity	1. Pilot detects failure and must react to stop aircraft 2. Crew actions well within capabilities (slight increase in crew workload) 3. Some inconvenience to occupants	Pilot should be able to maintain course and stop aircraft prior to exceeding boundaries of taxiway (visibility conditions 1 & 2 allow visibility of taxiway)	Minor/ Minor	10^{-3} -10^{-5}
	Detected failure: Total System Error approaches outer boundary	Accuracy	Same as for continuity (both are detected failures)	Same as for continuity	Minor/ Minor	10^{-3} -10^{-5}
	Undetected failure: Erroneous guidance	Integrity	1. Pilot must detect failure by visual reference 2. Crew actions well within capabilities (slight increase in crew workload) 3. Some inconvenience to occupants 4. May have to initiate emergency procedures	Pilot should be able to intervene prior to exceeding taxiway, but less likely than for detected failures since failure is detected by visual reference only	Minor/ Minor	10^{-3} -10^{-5}

Figure 9. Preliminary FHA Assignments

REFERENCES

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