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Risk Analysis of Runway 16L Category I and II Instrument Landing System Missed Approach Operations with the new Seattle-Tacoma International Airport (KSEA) Control Tower

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Abstract

Probability density curves were determined for five aircraft that participated in a flight test of the Microwave Landing System and had missed approach data in the time period 1982 through 1986. The probability density curves were used to determine the risk of collision with the control tower at the Seattle-Tacoma International Airport during a routine missed approach from a Category I (200-foot decision altitude) missed approach and a Category II (100-foot decision altitude) missed approach. A target level of safety was established so that the acceptability of the risk could be ascertained.
Four of the five aircraft met the target level of safety during a Category I missed approach. The aircraft that met the target level of safety were the Boeing B737, Boeing B727, Lockheed C141, and Convair CV580. The Cessna 172 did not meet the target level of safety.
Three of the five aircraft met the target level of safety during a Catefory II missed approach. The aircraft that met the target level of safety were the Boeing B737, Boeing B727, and Lockheed C141. The Convair CV580 and Cessna 172 did not meet the target level of safety.
Additional flight tracks were collected during a flight test conducted by the University of Oklahoma Departments of Engineering and Aviation. These flight track data were intended to supplement the archived data with data more representative of Category B turbo-prop and Category A twin-engine aircraft flying to Category II minimums. The Turbo Commander AC680 also met the target level of safety for the Category II missed approach, and the Piper Seneca PA-34 did not. Three recommendations were provided for implementation and risk mitigation. This study only considered routine misseed approaches and did not consider misssed approaches with malfunctioning equipment or blunders.

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EXECUTIVE SUMMARY

The control tower of the Seattle-Tacoma International Airport (KSEA) is located 2,935 feet from the threshold of runway 16L and 1,600 feet east from the runway centerline. The tower is 259 feet tall and 86 feet wide at its widest point near the top of the tower. The purpose of this paper is to discuss the probability of a collision with the control tower during a missed approach from an Instrument Landing System (ILS) approach to runway 16L by certain category A, B, C, and D aircraft.

The Seattle TRACON provided radar tracks of actual landing traffic at KSEA; however, no missed approaches were recorded in the data. Therefore, it was necessary to use archived data to conduct the analysis. The initial flight tracks used in the analysis were collected during a study designed to develop approach criteria for the Microwave Landing System (MLS). Therefore, the results of this study based solely on older generation aircraft performance may be considered to be conservative (too large) estimates of the probability of a collision with the control tower (risk) associated with current new-generation aircraft. However, these probabilities can only be considered to be estimates of the actual probabilities, since the number of observations in each data set is considered small.

Additional flight tracks were collected during a flight test conducted by the University of Oklahoma Departments of Engineering and Aviation. These flight track data were intended to supplement the archived data with data more representative of Category B turbo-prop and Category A twin engine aircraft flying to Category II minimums.

In order to ascertain the acceptability of the risk involved with an operation, a target level of safety (TLS) is established for the operation. Often the TLS is established by reference to historical accident data or by comparison to other operations. Since the fatal accident rate due to all causes is on the order of 1×10^{-7} per departure, the probability of a fatal accident during a component or phase of flight must be at least one order of magnitude smaller to maintain the current accident rate. Therefore, the TLS for this operation was chosen to be 1×10^{-8}. If the risk of a collision can be shown to be less than the TLS, then the risk of collision is considered to be acceptable. If the risk of collision is shown to be more than the TLS, then the risk is considered to be unacceptable.

In order to use the aircraft performance data, continuous probability density functions must be fitted to the data. The probability of flying through the vertical area occupied by the control tower during a missed approach from a Category I approach (200-foot decision altitude) was computed for the five aircraft from the MLS study that had missed approach data. The probabilities for three of the aircraft, the Boeing B727, Boeing B737, and Convair CV580, were found to be extremely small and are listed as "$<10^{-9}$". Therefore, the probabilities of collision of the Boeing B727, Boeing B737, and Convair CV580 meet the TLS.

The probability for one other aircraft, the Lockheed C141, was also found to meet the TLS. The probability for the Cessna 172 was found to be too large and does not meet the TLS.

The nominal decision altitude (DA) for a Category II ILS approach is 100 feet. The probabilities for four of the aircraft during a missed approach from a Category II ILS approach, the Boeing B727, Boeing B737, Lockheed C141, and Turbo Commander AC680, were found to be extremely small and are listed as "$<10^{-9}$." Therefore, the probability of collision of the Boeing B727, Boeing B737, Lockheed C141, and Turbo Commander AC680 meet the TLS. The probability for the Convair CV580 was found to be too large and does not meet the TLS. The probabilities for the Piper Seneca PA-34 and the Cessna 172 are very close to the TLS and are considered marginal.

For Category II missed approaches, the lateral dispersion is much smaller in the area of the control tower resulting in generally lower probabilities of a fly-over than for Category I missed approaches. The one exception is the Convair CV580. The probabilities for the Boeing B737, Boeing B727, Lockheed C141, and Turbo Commander AC680 are all on the order of 10^{-9} or less. Events with probabilities that low are called "extremely improbable" and may not ever be experienced, but they are possible. The probability for the Cessna 172 and the Piper Seneca PA-34 is on the order of 10^{-8}. Events with probabilities on the order of 10^{-8} are called "extremely improbable" and may never be experienced, but they are possible. The probability for the Convair CV580 is on the order of 10^{-6}. Events with probabilities that low are called "extremely remote" and are unlikely to occur but are possible.

The analysis of this report indicates that the risk of collision with the control tower at KSEA meets the TLS for Category B, C, and D aircraft executing a missed approach at DA of a Category I or II ILS approach to runway 16L. Therefore, the following recommendations are made based upon this analysis:

1. Restrict Category I approaches with a 200-foot decision altitude to Category B, C, and D aircraft.
2. Restrict Category II approaches with a 100-foot decision altitude to Category B, C, and D aircraft.
3. Chart the control tower as an obstacle on the approach chart.

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PROBABILITY OF COLLISION WITH SEATTLE CONTROL TOWER DURING A MISSED APPROACH

1.0. INTRODUCTION

The control tower of the Seattle-Tacoma International Airport (KSEA) is located 2,935 feet from the threshold of runway 16L and 1,600 feet east from the runway centerline. The tower is 259 feet tall and 86 feet wide at its widest point near the top of the tower. The purpose of this paper is to discuss the probability of a collision with the control tower during a missed approach from an Instrument Landing System (ILS) approach to runway 16L by certain category A, B, C, and D aircraft. Figure 1 is a drawing of the KSEA runway configuration and the location of the control tower.

Figure 1. Diagram of Seattle-Tacoma International Airport.

The Seattle TRACON provided radar tracks of actual landing traffic at KSEA; however, no missed approaches were recorded in the data. Therefore, it was necessary to use archived data to conduct the analysis. The initial flight tracks used in the analysis were collected during a study designed to develop approach criteria for the Microwave Landing System (MLS). The study involved seven different aircraft representative of speed Categories A, B, C, and D. The Category A aircraft was a Cessna 172P. The Category B aircraft were a Beechcraft 200 and a Convair CV580. The Category C aircraft were a Sabre-80, a Boeing B727, and a Boeing B737. The Category D aircraft was a military Lockheed C-141A. Missed approach data were not available for this study from the Sabre-80 or the Beechcraft 200. The FAA in cooperation with NASA and the United States Air Force conducted the MLS data collection during the years 1982 through 1986.

Three sites were used to conduct the flight tests: the NASA/Wallops Flight Center, Chincoteague Island, VA; the FAA Technical Center, Atlantic City, NJ; and the NASA/Ames Research Center, Crows Landing, CA. The aircraft were tracked using an infrared laser tracker. The 1-sigma (standard deviation) accuracy of the laser tracker over the runway threshold was approximately 0.3 meters.

To simulate instrument flight rules (IFR) weather, a special view-limiting device was used during the test identified as the Instrument Meteorological Conditions (IMC) Simulator series 1020 that permitted clouding goggles on the top and side to limit pilot view to the cockpit instruments. At Decision Altitude (DA), the observer pilot either cleared the goggles for landing or left the goggles clouded for a missed approach.

Although approximately three-fourths of the approaches ended in a missed approach, only a small number of missed approaches were recorded. No electronic signals were used to provide guidance during the missed approach. The pilots were instructed to maintain runway heading and climb to an altitude of 2,000 feet Mean Sea Level (MSL) before executing a turn. Therefore, most of the results of this study are based on older generation aircraft performance and may be considered to be conservative (too large) estimates of the probability of a collision with the control tower (risk) associated with current new-generation aircraft.

During subsequent analysis, the lateral dispersion of the aircraft lateral positions was found to be statistically equivalent to that of an ILS at DA. Since electronic guidance signals were not used during the missed approaches, the dispersion of the missed approaches during the MLS flight test is considered to be equivalent to the dispersion of missed approaches conducted from an ILS approach. The missed approaches for this study were initiated at 200 feet DA. The flight test data were collected at 50-meter intervals, or slices, starting at 1141 meters (3,742 feet) from the glideslope point of intersection (GPI) with the ground or 850 meters (2,789 feet) from the runway threshold. The glideslope height at 1,141 meters from GPI is 196 feet. Each data record included the lateral deviation of the aircraft center of gravity from the centerline of the runway and the height of the navigation system antenna above the runway threshold.

Additional flight tracks were collected during a flight test conducted by the University of Oklahoma (OU) Departments of Engineering and Aviation. The flight-testing was conducted at Norman Westheimer Field (KOUN) during September and October 2004 using a Piper Seneca PA-34 and a Turbo Commander AC680. The flights were ILS Category II approaches to runway 17 with a DA of 100 feet. The Piper Seneca PA-34 was flown at Category A approach speeds and the Turbo Commander AC680 was flown at Category B speeds. The flight track data of the Turbo Commander AC680 were intended to supplement the Category B Convair CV580 data with data more representative of Category B turbo-prop aircraft flying to Category II minimums. Similarly, the Piper Seneca PA-34 would provide Category A twin engine aircraft data.

A view-limiting device was used to simulate IFR weather. At DA, the observer pilot either advised the pilot the runway was in sight for landing or called for a missed approach. No electronic signals were used to provide guidance during the missed approach. The pilots were instructed to maintain runway heading and climb to an altitude of 1,000 feet MSL before executing a turn.

The OU flight test data were collected at 10-meter intervals starting at 291 meters (954 feet) from the runway threshold near the missed approach point. Positive ranges indicate the data were collected between the missed approach point and the runway threshold. Negative range values indicate the data were collected over the runway. Zero range was assigned to the runway threshold. The data were separated into two classes, the data collected during the Piper Seneca PA-34 approaches and the data collected during the Turbo Commander AC680 approaches.

The OU flight test data were collected using a differential Global Positioning System (GPS) based position truth system. This system consists of two modified Ashtech Z-12 receivers operated in the differential GPS mode. The stationary receiver was placed at a reference position on the University campus, and the mobile receiver was placed in the test aircraft. The differential data was post processed and time synchronized with the analog data taken during the mission. The Ashtech Precision Navigation (PNAV) software was used to produce highly accurate (<1 m) track data for each of the flight missions.

2.0. TARGET LEVEL OF SAFETY

In order to ascertain the acceptability of the risk involved with an operation, a target level of safety (TLS) is established for the operation. Often the TLS is established by reference to historical accident data or by comparison to other operations. Since the fatal accident rate due to all causes is on the order of 1×10^{-7} per departure, the probability of a fatal accident during a component or phase of flight must be at least one order of magnitude smaller to at least maintain the current accident rate. Therefore, the TLS for this operation was chosen to be 1×10^{-8}. If the risk of a collision can be shown to be less than the TLS, then the risk of collision is considered to be acceptable. If the risk of collision is shown to be more than the TLS, then the risk is considered to be unacceptable.

3.0. RISK ANALYSIS

Flight track data always represents the flight track of the navigation system antenna. If probability curves are fitted to the data, then the curves provide measures of the probability of the location of the navigation system antenna. However, an aircraft is not just a point, but has physical dimensions.

The aircraft physical dimensions can be accounted for by adding the aircraft wheel height (from navigation system antenna to bottom of wheels) to the top of the obstacle and adding the aircraft semispan to each of the lateral edges of the obstacle. A collision will occur if the point representing the aircraft navigation system antenna penetrates the adjusted area. This is illustrated in figure 2.

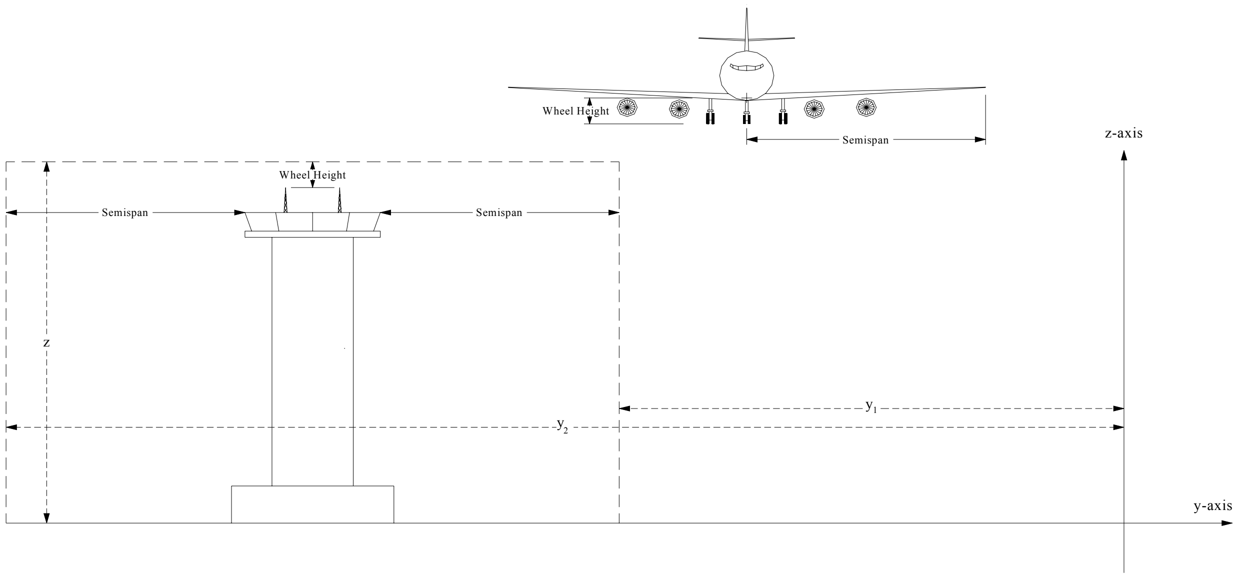

Figure 2. Diagram Illustrating Obstacle Modeling.

Suppose that $f_x(y,z)$ is the two-dimensional probability density function describing the dispersion of the aircraft navigation system antenna mounting points about the intended flight path in the (y,z) plane at distance *x* from the runway threshold. Then the probability of collision $P(O)$ with a certain obstacle *O* at distance *x* from the runway threshold is given by:

$$P(O) = \int_0^z \int_{y_2}^{y_1} f_x(y,z)dydz \qquad (1)$$

Previous analysis of flight track data has shown that aircraft dispersion about the intended flight path can be considered to be independent. Therefore, there exist probability density functions $g_x(y)$ and $h_x(z)$ describing the dispersion of aircraft along the *y* and *z* axes respectively at distance *x* such that:

$$f_x(y,z) = g_x(y) \times h_x(z) \qquad (2)$$

By substituting equation 2 into equation 1, equation 1 becomes:

$$P(O) = \int_{y_2}^{y_1} g_x(y)dy \times \int_0^z h_x(z)dz \qquad (3)$$

4.0. DETERMINATION OF PROBABILITY DENSITY FUNCTIONS

Examination of the lateral data at each of the ranges indicates that the probability curves are generally unbounded but have thicker tails than a normal or Gaussian distribution. The vertical data generally exhibits properties of a bounded distribution, while the normal or Gaussian distribution is unbounded. Therefore, numerical methods were employed to compute appropriate probability density functions for the lateral and vertical data sets at 50-meter increments for each of the aircraft: Boeing B737, Boeing B727, Lockheed C141, Convair CV580, and Cessna 172. Probability density functions for the lateral
and vertical data sets of the Piper Seneca PA-34 and Turbo Commander AC680 were computed at 10-meter increments.

In order to use the aircraft performance data, continuous probability curves must be fitted to the data. The Johnson family of curves, developed by N. L. Johnson in 1949, was used to fit probability curves to the data sets. The Johnson family includes three types of curves: the Johnson S_L family, the Johnson S_B family, and the Johnson S_U family (see Hahn et.al.). The curves of the S_L family are bounded at one end with an infinite tail at the other end. The curves of the S_B family are bounded at both ends. The curves of the S_U family are unbounded, i.e., have infinite tails at both ends. Each family of curves is based on a transformation of the observed data into a set of data that could be generated by a normal N(0,1) distribution. A test based on the statistics of the data determines which type of curve will best fit the data. It was found that only two of the Johnson families, the S_B and $S_{U,}$ were required to fit curves to the data sets.

Each Johnson family is a transformation of the normal or Gaussian curve. Therefore, probabilities defined by a particular realization of a Johnson curve are easily computed from the standard normal probability density curve. The transformation that determines the Johnson S_B family of curves is given by the following equation:

$$z = \gamma + \delta \ln\left(\frac{x-\varepsilon}{\lambda+\varepsilon-x}\right), \ \varepsilon < x < \lambda + \varepsilon \qquad (4)$$

The transformation that determines the Johnson S_U family of curves is given by the following equation:

$$z = \gamma + \delta \sinh^{-1}\left(\frac{x-\varepsilon}{\lambda}\right), \ -\infty < x < \infty. \qquad (5)$$

In equations 4 and 5, *x* represents a sample observation such as a lateral deviation from runway centerline or vertical distance above threshold, and *z* represents the transformation of *x* into a number from a normal N(0,1) distribution. The variables γ, δ, λ, and ε represent parameters that "fit" the curve to the data. The parameters γ, δ, λ, and ε are determined from the data via an iterative numerical process.

5.0. COMPUTATION OF COLLISION PROBABILITIES

A collision with the control tower can only occur if two successive events occur. First, a missed approach must occur, and afterward the aircraft must fly through the area occupied by the control tower. The situation can be expressed mathematically by letting *A* stand for the event "a missed approach occurred", *B* stand for the event "the aircraft flew through the vertical area occupied by the tower", the symbol $\cap$ represent "and", and the symbol | represent "given". The probability equation becomes:

$$P(Collision) = P(A \cap B) = P(B|A) \times P(A)\,. \qquad (6)$$

The equation shows that the probability of collision can be found by computing the probability that an aircraft flies through the vertical area occupied by the tower and multiplying by the probability that a missed approach occurs. The probability of a missed approach is internationally (International Civil Aviation Organization) accepted to be 1×10^{-2}; therefore, the probability that an aircraft performing a missed approach flies through the vertical area occupied by the control tower must be less than 1×10^{-6} in order to meet the TLS of 1×10^{-8}. Recent studies (see Lankford and Greenhaw) have suggested that the probability of a missed approach is smaller than 1×10^{-2}, perhaps as low as 1×10^{-3}. However, in order to present a conservative picture of the risk, the larger 1×10^{-2} value will be used.

The probability that an aircraft performing a missed approach flies through the vertical area occupied by the control tower is found by applying equation 3 using the derived Johnson distributions at the distance of the control tower from threshold. The width and height of the tower were adjusted appropriately for each type of aircraft. Therefore, the probability of a collision, given that a missed approach occurred, is given by:

$$P(B|A) = \int_{y_2}^{y_1} g_x(y)dy \times \int_0^z h_x(z)dz \qquad (7)$$

6.0. PROBABILITIES FOR CATEGORY I APPROACHES

The nominal DA for a Category I ILS approach is 200 feet. Assuming a 3-degree glide slope, the missed approach point (MAP) will be located 2,862 feet (872 meters) from threshold. The control tower is located an additional 2,935 feet (895 meters) from the threshold along the runway. The control tower is located 5,797 feet (1,767 meters) from the MAP. At that point, the missed approach aircraft are climbing and on average are well above the level of the top of the control tower. The lateral dispersion about the runway centerline is relatively large and increasing, because the aircraft are flying runway heading without any electronic guidance.

The nearest data slice to the tower location is 609 meters from GPI. The derived probability density functions for this slice were used to extrapolate probability estimates of a collision with the control tower. These probabilities can only be considered to be estimates of the actual probabilities, since the number of observations in each data set is considered small.

Table 1 summarizes the computed probability of flying through the vertical area occupied by the control tower for each of the five MLS aircraft. The probabilities for three of the aircraft, the Boeing B727, Boeing B737, and Convair CV580, were found to be extremely small and are listed as "$< 10^{-9}$." Therefore, the probabilities of collision of the Boeing B727, Boeing B737, and Convair CV580 meet the TLS. The probability for one other aircraft, the Lockheed C141, was also found to meet the TLS. The probability for the Cessna 172 was found to be too large and does not meet the TLS. Note that if the missed approach rate is actually 1×10^{-3}, then the Cessna 172 meets the TLS. Note also that the sample sizes are small, with the sample size of the Boeing B727 being the smallest. Note that the Piper Seneca PA-34 and Turbo Commander AC680 are not included in this table, since they were flown to Category II minimums.

Aircraft	Sample Size	$P(B \mid A)$	$P(A)$	$P(A \cap B)$	Meets TLS?
Boeing B737	192	$< 10^{-9}$	1×10^{-2}	$< 10^{-9}$	Yes
Boeing B727	82	$< 10^{-9}$	1×10^{-2}	$< 10^{-9}$	Yes
Lockheed C141	195	1.4×10^{-8}	1×10^{-2}	1.3×10^{-9}	Yes
Convair CV580	103	1.2×10^{-8}	1×10^{-2}	$< 10^{-9}$	Yes
Cessna 172	129	5.8×10^{-6}	1×10^{-2}	5.8×10^{-8}	No

Table 1. Summary of Category I Collision Risk

7.0. PROBABILITIES FOR CATEGORY II APPROACHES

The nominal DA for a Category II ILS approach is 100 feet. Assuming a 3-degree glideslope, the MAP will be located 954 feet (291 meters) from threshold. The control tower is located an additional 2,935 feet (895 meters) from the threshold along the runway. The control tower is located 3,889 feet (1,186 meters) from the MAP. At that point the missed approach aircraft are climbing and on average are below the top of the control tower. The lateral dispersion about the runway centerline is still rather tight but is increasing since the aircraft are flying runway heading without any electronic guidance.

To translate the MLS data to ILS Category II (100 feet) usage, the data slice nearest to the tower location was selected. That slice was the 9-meter slice from GPI for the Category I (200 feet) MAP.

The derived probability density functions for this slice were used to extrapolate probability estimates of a collision with the control tower after the means of the distributions were adjusted 100 feet downward to compensate for the 100-feet minimum DA. These probabilities can only be considered to be estimates of the actual probabilities, since the number of observations in each data set is considered small. However, they may be conservative estimates since the entry dispersions, both vertical and lateral, are larger for Category I approaches at the MAP compared to Category II approaches at the MAP. Note that the Piper Seneca PA-34 and Turbo Commander AC680 were flown to Category II minimums.

Table 2 summarizes the computed probability of flying through the vertical area occupied by the control tower for each of the five MLS study aircraft and the two additional OU aircraft. The probabilities for four of the aircraft, the Boeing B727, Boeing B737, Lockheed C141, and Turbo Commander AC680, were found to be extremely small and are listed as "$< 10^{-9}$." Therefore, the probabilities of collision of the Boeing B727, Boeing B737, Lockheed C141, and the Turbo Commander AC680 meet the TLS. The probability for the Convair CV580 was found to be too large and does not meet the TLS. The probabilities for the Piper Seneca PA-34 and the Cessna 172 are very close to the TLS and are considered marginal. Again, note that the sample sizes are small. The Turbo Commander AC680 is more representative of the Category B turbo-prop aircraft that may perform Category II approaches.

Aircraft	Sample Size	$P(B \mid A)$	$P(A)$	$P(A \cap B)$	Meets TLS?
Boeing B737	192	6.5×10^{-8}	1×10^{-2}	$< 10^{-9}$	Yes
Boeing B727	82	$< 10^{-9}$	1×10^{-2}	$< 10^{-9}$	Yes
Lockheed C141	195	$< 10^{-9}$	1×10^{-2}	$< 10^{-9}$	Yes
Turbo Commander AC680	48	$< 10^{-9}$	1×10^{-2}	$< 10^{-9}$	Yes
Convair CV580	103	2.6×10^{-5}	1×10^{-2}	2.6×10^{-7}	No
Piper Seneca PA-34	47	1.7×10^{-6}	1×10^{-2}	1.7×10^{-8}	Marginal
Cessna 172	129	1.5×10^{-6}	1×10^{-2}	1.5×10^{-8}	Marginal

Table2. Summary of Category II Collision Risk

8.0. CONCLUSION

Probability density curves were determined for five aircraft that participated in a flight test of the MLS in the time period 1982 through 1986. The probability density curves were used to determine the risk of collision with the control tower at KSEA during a routine missed approach from a Category I (200 feet DA) missed approach. A TLS was established so that the acceptability of the risk could be ascertained. Four of the five aircraft were found to meet the TLS.

The aircraft that met the TLS were the Boeing B737, Boeing B727, Lockheed C141, and Convair CV580. The Cessna 172 did not meet the TLS. This study only considered routine missed approaches and did not consider missed approaches with malfunctioning equipment or blunders.

The MLS data were then translated, so that probabilities of collision with the control tower during a Category II missed approach could be estimated. These probabilities may be considered to be conservative (i.e. too large), since they are derived from Category I missed approach data. The probability estimates for the Boeing B737, Boeing B727, and Lockheed C141 were all less than 1×10^{-9} and met the TLS. The estimated probability for the Cessna 172 was 1.5×10^{-8} and was slightly larger than the TLS. The probability estimate for the Convair CV580 did not meet the TLS.

Additionally, probabilities were computed for Category II missed approaches for the Piper Seneca PA-34 and Turbo Commander AC680 data. The probability estimate for the Turbo Commander AC680 was less that 1×10^{-9} and met the TLS. The estimated probability for the Piper Seneca PA-34 was 1.7×10^{-8} and was slightly larger than the TLS.

The analysis of this report indicates that the risk of collision with the control tower at KSEA meets the TLS for Category B, C, and D aircraft executing a missed approach at DA of a Category I or II ILS approach to runway 16L. Therefore, the following recommendations are made based upon this analysis:

1. Restrict Category I approaches with a 200-foot decision altitude to Category B, C, and D aircraft.
2. Restrict Category II approaches with a 100-foot decision altitude to Category B, C, and D aircraft.
3. Chart the control tower as an obstacle on the approach chart.

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