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Collision risk related to the usage of parallel runways for landing

L.J.P. Speijker, M.J.H. Couwenberg and H.W. Kleingeld

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OF PARALLEL RUNWAYS FOR LANDING

by

L.J.P. Speijker, M.J.H. Couwenberg, H.W. Kleingeld

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Summary

Due to space limitations at most airports an increased airport capacity can often only be accomplished by using existing parallel runways more effectively or by building additional parallel runways. This study focuses on the collision risk related to independent parallel approaches and the minimum required parallel runway spacing for which the collision risk may be judged acceptable. The suitability of several risk measures and methods for Target Level of Safety (TLS) assessment is studied. Application of two methods provide a TLS-area, defining a range from which the TLS may be chosen by policy makers. A risk model is developed for determination of the collision risk between aircraft conducting independent parallel approaches under Instrument Meteorological Conditions (IMC), thereby using Instrument Landing System (ILS) procedures. Numerical evaluations show that the collision probability between two aircraft can be considerable under various operational conditions, especially near turn on to the localizer and during a dual missed approach. For trying to maintain the collision risk at a low and acceptable level, three risk reducing measures are identified. Provided that these measures are applied and assuming that a TLS from the specified TLS-area is used, independent parallel approaches may be judged adequately safe if the runway spacing is greater than 1270 m, and unsafe if the spacing is lower than 930 m.



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1 Introduction

The steady increase in air traffic imposes a need for enhanced airport capacity. An increase in runway capacity may be achieved by using existing parallel runways more effectively or by building additional parallel runways. An important factor for both is the reduction of the minimum required distance between parallel runways used for independent parallel approaches [14, 17]. The minimum required runway spacing for independent parallel approaches has already been reduced several times, thereby trying to maintain the same required level of safety. These reductions were induced by improved operational procedures and technological improvements. The latest reduction to 1035 m (3400 ft), approved by the International Civil Aviation Organisation (ICAO) as from November 9th 1995, was initiated by an airport capacity programme developed by the Federal Aviation Administration (FAA), and based on use of the Precision Runway Monitor (PRM) system [6, 7, 18].

Reducing the minimum required runway spacing without taking other measures generally brings along an enlargement of risks which must be avoided. Main risk is the risk of collision between aircraft. In order to properly evaluate the risks related to independent parallel approaches, insight into the collision risk during all approach flight phases, including intermediate approach, final approach, and missed approach, is necessary. This enables the identification of hazardous situations, and the derivation of collision risk reducing measures. A thorough collision risk analysis strongly supports the decision taking about building (additional) parallel runways or requiring specific approach and/or missed approach procedures.

This study describes a probabilistic risk analysis of the collision risk between aircraft conducting independent parallel approaches under Instrument Meteorological Conditions (IMC), thereby using Instrument Landing System (ILS) procedures. The next Section gives the currently prescribed procedures and requirements for simultaneous ILS approaches to parallel runways. Section 3 contains the identification of hazardous flight phases, identification of suitable risk measures, and adoption of the TLS. Section 4 describes the risk model, developed for determination of the collision risk. In section 5, a number of scenarios, with varying runway spacing and under different operational conditions, are numerically evaluated. The worst case scenario is identified, and risk reducing measures are examined. The conclusions are given in Section 6.

2 Requirements and procedures for parallel approaches

2.1 Required runway spacing for parallel approaches

In general, parallel runways can be used for four different modes of operations: independent parallel approaches, dependent parallel approaches, independent parallel departures, and



segregated parallel operations [9]. According to mode of operation and weather condition, different runway spacings are required to obtain the same level of safety. Under IMC, dependent parallel approaches may now be conducted at runways spaced from 2500 ft to 3400 ft, whereas independent parallel approaches are only permitted at runways spaced more than 3400 ft. Over the last 30 years, the minimum required runway spacing for independent parallel approaches has been reduced several times. An overview of these reductions is given in table 1.

Table 1

Minimum required runway spacing for independent parallel approaches (ICAO)

Year	Required runway spacing
- 1962	6200 ft
1963	5000 ft
1974	4300 ft
1995	3400 ft

These reductions were induced by improved operational procedures and technological improvements, such as new navigation and landing systems, and surveillance radar of higher update rate and resolution. ICAO has approved the latest reduction to 3400 ft as from November 9th 1995, provided that certain conditions and requirements are satisfied. One of these requirements is usage of the PRM system, which is a radar monitoring system intended to increase utilization of multiple, closely spaced, parallel runways under IMC [6, 7, 18].

2.2 Required operational procedures for parallel approaches

According to available facilities (e.g. ground and onboard equipment), a variety of instrument approach procedures have been developed to guide aircraft safely to the runways during IMC. In general, an instrument procedure may have five segments: arrival, initial, intermediate, final, and missed approach. This paper only considers usage of ILS, the presently most common procedure. A detailed description of ILS procedures can be found in the PANS-OPS [11]. For now, only the additional requirements for simultaneous ILS approaches to parallel runways are described.

For independent parallel approaches radar separation minima between aircraft on adjacent localizers are not prescribed [9]. The approaches must be flown straight in, with turn on to the localizer separated vertically by at least 1000 ft. This vertical separation has to be maintained until the aircraft intercept their glide path at the Final Approach Point (FAP). Separate radar controllers have to monitor the approaches once the 1000 ft vertical separation is lost during ILS procedures, and must intervene if any aircraft is observed to penetrate the No Transgression

Zone (NTZ). The latter is a corridor of airspace located centrally between the two extended runway centre lines, with width depending on, among other aspects, the surveillance system, responding time of controllers, pilots and aircraft, and lateral track separation [9]. If one aircraft enters the NTZ, the aircraft on the adjacent localizer must be issued appropriate instructions to avoid collision, such as break-out manoeuvres.

Other requirements for simultaneous ILS approaches to parallel runways are a maximum intercept angle with the localizer course of 30°, and nominal missed approach tracks diverging by at least 30°, with turns 'as soon as practicable' [9].

For dependent parallel approaches an in-between distance of 2 nautical miles (nmi) between aircraft on adjacent localizers is prescribed. This diagonal separation brings along a minimum required longitudinal separation of about 4 nmi between aircraft on the same runway track. As the minimum longitudinal separation for independent parallel approaches is about 3 nmi, the runway capacity when using dependent parallel approaches is significantly less than that for independent approaches [18]. This clearly shows the importance of reducing the minimum required runway spacing for independent parallel approaches (see also figure 1).

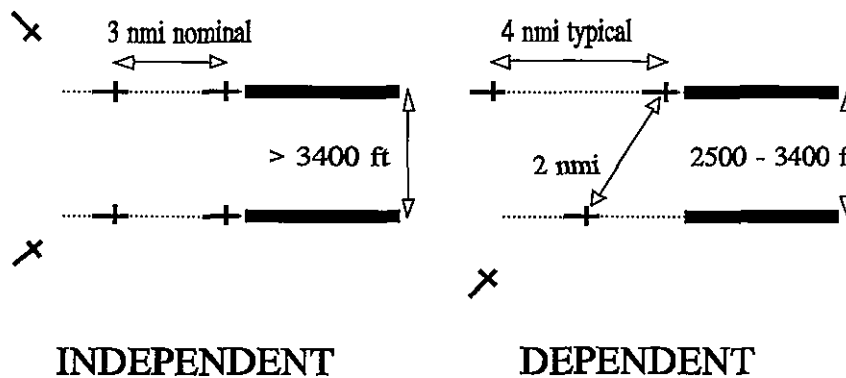


Figure 1. Independent and dependent parallel approaches. Derived from source [18].

3 Risk analysis

3.1 Identification of hazardous flight phases

This study considers the risks related to independent parallel approaches. Risks also present during approaches to single runways are not taken into account. Such reference implies focusing on the collision risk *between aircraft*. The consequences may be catastrophic: probably loss of both aircraft and death of passengers and crew. The lives of people living in the vicinity of an airport may even be endangered.



Evidently, hazardous situations may exist during flight phases containing a relative high uncertainty about the nominal flight trajectory if the runways are closely spaced. Two hazardous flight phases emerge:

- Alignment with the localizer:
A hazardous situation may exist if one (or both) approaching aircraft overshoots the localizer and deviates towards the adjacent runway, with possibly an endangered aircraft in its path.
- A dual missed approach:
A hazardous situation may exist if both approaching aircraft initiate a missed approach, especially if the missed approaches are to be initiated along runway direction and/or if there are strong crosswinds.

An aircraft might also be seriously endangered by a wake vortex developed by an aircraft nearby. Up to now, the wake vortex has been ignored in the risk analysis of independent parallel approaches. The gradual reduction of the minimum required parallel runway spacing may raise concerns, especially in case of strong crosswinds. In this study, the wake vortex problem is still not taken into account.

3.2 Identification of suitable risk measures

There is no single common measure of risk (or safety). There are many different risk measures which may be used for quantification of the risk of collision with an obstacle or between aircraft. Some of the risk measures that can be applied for assessing the risk related to air traffic operations are given in figure 2.

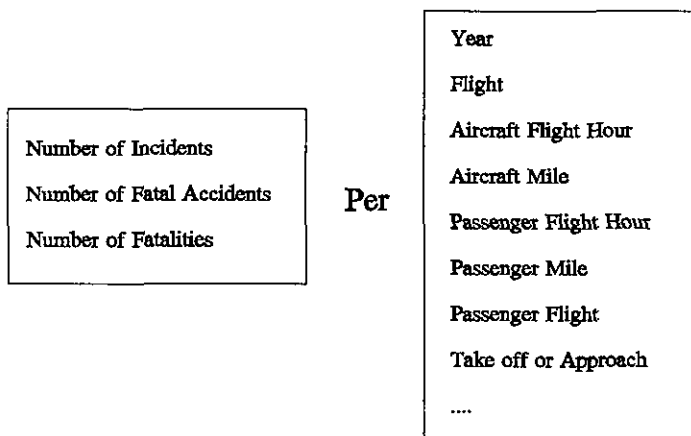


Figure 2. Risk measures for air traffic operations. Source [3].

Note that, in general, a collision may be regarded as a fatal accident, losing adequate separation may be seen as an incident, and the number of fatalities per collision will likely involve all passengers and crew.



Other risk measures can often be derived. In this respect, two types of commonly used risk measures are individual risk measures which are based on the risk to an individual being exposed to a risk on a regular basis, and societal risk measures which take into account the number of persons to be killed in a single event.

The suitability of a risk measure depends on, among other aspects, the system under consideration, the available data and the required results. In this respect, some considerations leading to the selection of an appropriate risk measure are:

- The risk measure must be attractive and useful for involved policy makers.
- The risk measure must be able to represent the consequences of possible decisions in an appropriate way. In view of the steady increase in air traffic, this means that the collision probability per year might be more suitable than, for example, the collision probability per approach.
- The risk measure must, if possible, not include risks which are outside the scope of the problem under consideration. The risk measure must therefore be restricted to the risk of collision between aircraft, during the approach part of a flight only. Risk measures defined in terms of accidents per flight hour or per mile travelled are not suitable, as the approach takes only a relative small amount of time.
- The risk measure must be used to derive the minimum required parallel runway spacing for independent parallel approaches. For this usage, it is presently not clear if and how to take into account the risk to people living in the vicinity of an airport, as airport surroundings vary widely.
- The risk measure must fit in with present safety requirements. However, these are not yet established for independent parallel approaches. Note that the ICAO single runway approach safety requirement is defined in terms of maximum probability of collision with an obstacle *per approach* [10], and that the FAA use the collision probability per approach for independent parallel approaches [6].
- It seems not appropriate to apply societal risk measures for quantification of the risk related to *one* part of a flight, as passengers and crew are exposed to risks during *all* parts of a flight. Societal risk measures for aircraft passengers seem only suitable for quantification of the overall collision risk of a flight.
- In other fields (e.g. the fields of surface public transport, hydraulics and civil engineering, chemical processes, and the nuclear field) there is a tendency to use risk measures related to a period of time more often.
- Use of the collision probability per year brings along the possibility that, by conducting a small number of approaches, two parallel runways with a high collision probability per approach can be judged adequately safe. Especially for pilots or crew, this high peak level of risk will be unacceptable.

Considering the above, there may not be *one* most appropriate risk measure. Two suitable risk measures evolve for the safety analysis of two parallel runways used for landing. Both are defined with respect to the risk of collision *between aircraft* only:

- The collision probability per approach:
Commonly used, up to now, for evaluation of the risk during the approach part of a flight. It fits well within the present safety requirements for air traffic operations, but does not take into account an increase in runway capacity.
- The collision probability per year (or its reciprocal, the expected average time interval between two collisions):
Easy to interpret. It takes into account the runway capacity, and consequently the steady increase in air traffic. As an aid to planning or decision making, it may therefore be easier to use.

Both risk measures will therefore be used in this study.

3.3 Adoption of the Target Level of Safety

To determine the minimum required parallel runway spacing, a Target Level of Safety (TLS) needs to be adopted. The TLS represents the level of risk which is considered acceptable. The acceptability of risk depends, naturally, highly on the magnitude of the consequences. In general, safety requirements are based on the principle that an inverse relationship should exist between the probability of occurrence and the magnitude of its consequences. In our case, the consequences are severe. A collision between aircraft mostly results in loss of both aircraft and death of all passengers and crew, and may even endanger the lives of people on the ground. Evidently, a zero collision probability can not be realized. As, up to now, a worldwide accepted TLS for independent parallel approaches has not yet been established, the question arises how to assess the level of risk which may be considered acceptable.

Several methodologies for TLS assessment have been proposed up to now. Some methods worth mentioning for air traffic operations are [3, 8, 16]:

- 1 Air transport as safe as surface public transport (e.g. railway or bus);
- 2 Expected passenger fatality rate in air traffic comparable with population fatality rate due to all causes;
- 3 Air crew risk of accidental death comparable with other occupations;
- 4 Current air traffic accident rates with a factor of improvement;
- 5 Maintaining current air traffic accident statistics;
- 6 Fitting in with present safety requirements for air traffic operations.

Applying these methods does not necessarily lead to the same TLS. Moreover, they depend on the selected risk measure. As a result, several methods are difficult to apply in our situation. The

first three methods are usually based on the number of fatalities per distance or per time travelled, which are both not suitable for the approach part of a flight. With regard to the fourth, the problem arises *which* size of the target factor of improvement must be used. From the above methods, the fifth and sixth seem most suited for this paper. Note that different actor groups (e.g. airlines, airport authorities, controllers, crew, passengers or policy makers) may support different methods. Airlines often support the first, passengers the second, crew the third, whereas policy makers often support one of the last three methods.

Maintaining current air traffic statistics

Accident data regarding collisions between aircraft during parallel approaches is not available. We develop a method consisting of three steps:

- Assessment of the *accident* probability per approach:
The historical accident ¹⁾ probability per approach at 'reasonable safe' mainports, with more than about 150000 movements per year, is estimated at $7 \cdot 10^{-7}$ [15].
- Assessment of the *fatal* accident probability per approach:
The ratio fatal accidents : non-fatal accidents is of the order 1:4 [13]. This implies a historical fatal accident probability per approach of about 10^{-7} .
- Account for the *number of fatalities*, and the loss of *two* aircraft:
The n^c -criterion ²⁾ is based on the assumption that accidents with an n -times greater number of fatalities must correspond to an n^c times smaller probability. Assuming that a collision may bring along about five times more fatalities than an average fatal accident [1], and using the n^c -criterion leads to a TLS for the collision probability per approach of $1 \cdot 10^{-8}$ if $c=1.5$ and $4 \cdot 10^{-9}$ if $c=2$.

Fitting in with present air traffic safety requirements

Safety requirements for independent parallel approaches are not yet defined. We develop a method based on the JAR risk categorisation for ATC *systems*, which relates a number of hazard categories (catastrophic, hazardous/severe, major, minor, no effect) to a maximum probability of occurrence [12]. A collision between aircraft fits in the catastrophic category, for which the maximum probability of occurrence *per flight hour* is 'extremely improbable', and defined at 10^{-9} *per initial cause*. Safety requirements specified per flight hour are however not suitable for the approach part of a flight. The method now consists of three steps:

¹⁾ An accident is defined as the occurrence of an unintended ground contact outside the runway

²⁾ The parameter c can be used to quantify the degree of (in)voluntariness of the people being exposed to a risk, thereby assuming that an involuntary risk requires a larger value of c

- Assess the maximum probability of collision per flight:
Depending on the world region, the mean flight time may be estimated at 2 to 4 hours [13]. This implies a maximum probability of collision between aircraft of $2 \cdot 10^{-9}$ to $4 \cdot 10^{-9}$ per initial cause.
- Account for the number of initial causes:
Assuming that there could be 1 to 5 initial causes leading to a collision, implies a maximum probability of collision between aircraft of $2 \cdot 10^{-9}$ to $2 \cdot 10^{-8}$ per flight.
- Assess the TLS for the collision probability per approach:
Dividing the risk of collision equally between the three main parts of a flight (i.e. take off, en-route, and approach) leads to a TLS of about 10^{-9} to 10^{-8} .

Application of both methods does not motivate the adoption of *one particular* TLS. Problems arising are a large number of numerical assumptions and lack of statistical accident data, leading to considerable uncertainty in TLS assessments. The methods suggest adopting a TLS ranging between one collision in 10^8 and 10^9 approaches, i.e.

$$TLS_{per\ approach} \in [1 \times 10^{-9}, 1 \times 10^{-8}]$$

The TLS-area for the collision probability per year is derived by assuming on average 200000 approaches per runway per year. This leads to a TLS ranging between one collision in 500 years and one collision in 5000 years, i.e.

$$TLS_{per\ year} \in [2 \times 10^{-4}, 2 \times 10^{-3}]$$

As a consequence of the difficulties in TLS assessment, the usage of a TLS as an absolute boundary-line between safe and unsafe is hard to justify. Besides, the uncertainty in collision risk assessments is often high, and sensitive to variations in model parameters. The determination of a safe separation standard is therefore also subject to uncertainty. The TLS concept does not really provide the means for taking this uncertainty into account. It is recommended to examine the possibility of broadening the TLS concept, by investigating the development of the ALARP (As Low As Reasonably Practicable) approach for use in aviation risk management [8].

3.4 Definition of collision risk judgement scheme

In order to set *the* TLS and/or broaden the TLS concept, policy makers must be consulted. In order to already judge the acceptability of calculated collision risk, a "collision risk judgement scheme" is defined for usage in this study:

- A scenario for which the collision risk is lower than the lowest boundary of the TLS-area, is judged adequately safe.

- A scenario for which the collision risk is higher than the highest boundary of the TLS-area, is judged unsafe. Collision risk reducing measures must be taken.
- A scenario for which the collision risk falls in between both boundaries of the TLS-area, is judged *tolerable* until the TLS has been set by policy makers. Besides, it is recommended to investigate the feasibility of risk reducing measures.

4 Risk model

4.1 Overview of the risk model

A risk model is developed for the determination of the selected collision risk measures. The airspace around the airport where the collision risk is evaluated is restricted to the intermediate, final, and missed approach flight phases, thereby assuming that the arrival and initial phases bring along a negligible risk of collision.

The risk model consists of three parts. The first part, the *conditional* collision probability model, developed by Couwenberg [5], describes how to calculate the conditional collision probability between two aircraft *given* the localizer interception times and types of aircraft operation (landing or missed approach). The second part describes the nominal flight trajectories and the probability distributions for the deviations from the nominal flight trajectories. The third part takes into account the missed approach rate, dependency between aircraft operations at adjacent runways, initiation altitude of a missed approach, localizer interception times, and air traffic density in order to derive the selected risk measures (collision probability per approach and per year). The remainder of Section 4 describes these three parts. A more detailed description of the risk model is given in Speijker [17].

The possibility of intervention when blunders occur is not taken into account. In reality, the collision risk might therefore be somewhat smaller than calculated.

4.2 The conditional collision probability model

The time dependent conditional collision probability between two aircraft A and B given their localizer interception times, t_A and t_B , and types of aircraft operation (landing or missed approach at a fixed altitude) is denoted by

$$P_{\text{collision},i}$$

where i , $1 \leq i \leq 4$, indicates the four possible combinations of type of operations.

Let the flight trajectories of aircraft A and B be represented by $\{(x_A(t), Y_A(t), Z_A(t))\}$ and $\{(x_B(t), Y_B(t), Z_B(t))\}$, where the three vector components give the longitudinal, lateral, and vertical

coordinates of the geometric centres of the rectangular bounding boxes about the aircraft, with sizes $\lambda_{Ax} \times \lambda_{Ay} \times \lambda_{Az}$ and $\lambda_{Bx} \times \lambda_{By} \times \lambda_{Bz}$. On basis of the CRM [10], the longitudinal speed (and coordinate) is taken deterministic.

Let the stochastic movement $\{(x(t), Y(t), Z(t))\}$ represent the relative position between the centres of the involved aircraft, i.e.

$$\begin{aligned} x(t) &= x_B(t) - x_A(t) \\ Y(t) &= Y_B(t) - Y_A(t) \\ Z(t) &= Z_B(t) - Z_A(t) \end{aligned}$$

Define

$$\lambda_x = \frac{\lambda_{Ax} + \lambda_{Bx}}{2}, \quad \lambda_y = \frac{\lambda_{Ay} + \lambda_{By}}{2}, \quad \lambda_z = \frac{\lambda_{Az} + \lambda_{Bz}}{2}$$

Using the fact that a collision occurs when there is a simultaneous overlap of the bounding boxes in all of the three coordinate directions, it follows that:

$$P_{collision,i} = P[|x(t)| < \lambda_x \wedge |Y(t)| < \lambda_y \wedge |Z(t)| < \lambda_z]$$

With the assumption that the stochastic aircraft movements in the three directions are independent, the conditional collision probability is equal to

$$P_{collision,i} = P[|x(t)| < \lambda_x] \times P[|Y(t)| < \lambda_y] \times P[|Z(t)| < \lambda_z]$$

Using the deterministic character of the longitudinal coordinate, the following expression for the conditional collision probability between two aircraft is stated:

$$P_{collision,i} = P[|Y(t_p)| < \lambda_y] \times P[|Z(t_p)| < \lambda_z], \quad x(t_p) = 0$$

where the passage time t_p is determined from the localizer interception times and the deterministic velocities of both aircraft. Of course, $P_{collision,i} = 0$ if $x(t) \neq 0, \forall t$.

The lateral and vertical overlap probabilities can be determined from the probability density functions f_{Y_A} and f_{Y_B} by convolution. For the lateral overlap holds:

$$P[|Y(t)| < \lambda_y] = \int_{-\lambda_y}^{\lambda_y} f_Y(y) dy = \int_{-\lambda_y}^{\lambda_y} \int_{-\infty}^{\infty} f_{Y_A}(y+u) f_{Y_B}(u) du dy$$

A similar expression can be derived for the vertical overlap probability. Since the lateral overlap probability is very small, it may be approximated by:

$$P[|Y(t)| < \lambda_y] \approx 2\lambda_y f_Y(0) = 2\lambda_y \int_{-\infty}^{\infty} f_{Y_x}(u) f_{Y_s}(u) du$$

The vertical overlap probability can be considerable, and needs to be estimated by numerical integration (e.g. using Simpson's rule).

4.3 Determining the flight trajectories

The airspace around the airport where the collision risk is evaluated is restricted to the intermediate, final, and missed approach flight phases. The arrival and initial flight phases are assumed to bring along a negligible risk and are therefore left aside.

The aircraft intercept their localizer at the Intermediate Fix (IF). From the IF, the aircraft are expected to fly along runway direction. During intermediate approach the flight trajectory is kept horizontal. From the Final Approach Point (FAP), an aircraft descends with a glide path angle of about 3°. Several reasons may cause an aircraft to initiate a missed approach at any altitude between the FAP and Decision Height (DH). The missed approach path consists of a curved part and a climb out part. From the Climb Out Point (COP), the aircraft climb under a constant climb out gradient. The missed approach track direction can only be changed from a certain altitude, above the COP. The nominal flight trajectories of aircraft approaching the adjacent parallel runways are sketched in figure 3, and satisfy the requirements for independent parallel approaches, which are described in section two.

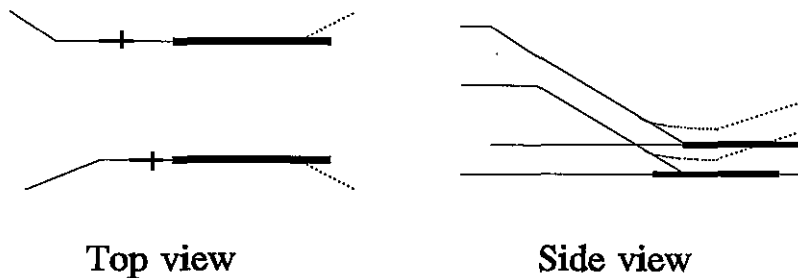


Figure 3. Top-view and side-view of the nominal flight trajectories.

The probability distributions for the deviations from the nominal flight trajectories during intermediate approach are determined with data collected with the FANOMOS flight trajectory registration system in August 1995 at Schiphol runway 06. The probability distributions for the deviations from the nominal flight trajectory during final approach and missed approach are determined with a method developed by ICAO [10]. For an extensive description, see Speijker [17] and Couwenberg [5].



The deterministic aircraft speed, depending on aircraft category and position, is given in table 2, and satisfies the requirements defined in the PANS-OPS [11].

Table 2

Deterministic aircraft speed in knots (kt)

Aircraft Category	Intermediate Approach	Final Approach		Missed Approach	
		2000-1000 ft	1000 ft-DH	DH-1000 ft	1000-2000 ft
A	120	95	70	90	100
B	150	120	90	110	140
C	190	150	120	140	200
D	230	170	140	160	230

4.4 Determining the identified risk measures

To obtain the collision probability between two aircraft, the missed approach rate, dependency between aircraft operations at adjacent runways, initiation altitude of a missed approach, and localizer interception times are taken into account.

The conditional collision probability between two aircraft A and B given their localizer interception times, t_A and t_B , is defined by

$$P_{collision}(t_{Loc}) = \sum_{i=1}^4 P_i \cdot P_{collision,i}$$

with $t_{Loc} = t_B - t_A$ the time difference between the localizer interception times. The probabilities P_i , $1 \leq i \leq 4$, give the probabilities of the occurrence of the four combinations of type of aircraft operations. These are based on the missed approach rate and the dependency between aircraft operations at adjacent runways. Denote the stochastic missed approach rate by R , and let ρ represent the extent to which the operations of aircraft A and B are dependent, where $0 \leq \rho \leq 1$. Full independency is given by $\rho = 0$, and full dependency by $\rho = 1$. In the latter case there are only two possibilities: a dual landing or a dual missed approach. The probabilities P_i , $1 \leq i \leq 4$, given both realisation r of R and ρ , are estimated by

$$\begin{aligned} P_1(r, \rho) &= (1-\rho)(1-r)^2 + \rho(1-r) \\ P_2(r, \rho) &= (1-\rho)(1-r)r \\ P_3(r, \rho) &= (1-\rho)(1-r)r \\ P_4(r, \rho) &= (1-\rho)r^2 + \rho r \end{aligned}$$



Let f_R denote the probability density function of the missed approach rate and \bar{p} the best estimate of the dependency parameter. The probabilities P_i may now be stated as

$$P_i = \int_{r=0}^1 P_i(r, \bar{p}) f_R(r) dr \quad , \quad 1 \leq i \leq 4$$

In the absence of statistical data, the missed approach rate must be represented by a (subjective) probability distribution elicited through the use of expert opinion [4]. In this paper, R is assumed to be Beta distributed with shape parameters p and q : $R \sim \text{Beta}(p, q)$. For a motivation see Speijker [17]. The parameters p and q can be determined with a procedure based on elicitation of two percentiles [2].

Next aspect is the initiation altitude of a missed approach. As most missed approaches are initiated at or near DH [10], it is assumed that missed approaches are to be initiated at 200 ft, the DH for ILS Category I.

To obtain the collision probability between two aircraft, the localizer interception times are now taken into account. Considering the *independent* use of the runways, it is assumed that the localizer interception times are uniformly distributed.

Consequently,

$$P_{\text{collision}} = \frac{1}{T} \int_{t=0}^T P_{\text{collision}}(t) dt$$

with T such that each possible passage point is taken into account.

The collision probability per approach, $P_{\text{collision, per approach}}$, can be determined in a similar way by taking into account the air traffic density as well. A method for determining the collision probability per approach is described in Speijker [17].

The collision probability per year, $P_{\text{collision, per year}}$, can be determined from the collision probability per approach by taking into account the number of approaches per runway per year, n . Assuming mutual independence between runway approaches,

$$P_{\text{collision, per year}} = 1 - [1 - P_{\text{collision, per approach}}]^n$$

If $P_{\text{collision, per approach}} \ll 1$, this may be simplified by using first order approximation:

$$P_{\text{collision, per year}} \approx n \times P_{\text{collision, per approach}}$$

which is equal to the expected number of collisions per year.

5 Numerical evaluations

5.1 Definition of a baseline scenario

In order to obtain a first, most likely, estimation of the collision risk related to independent parallel approaches, a baseline scenario is defined which satisfies the currently prescribed operational procedures. Its main characteristics are:

- Distance between runway thresholds, (x_d, y_d) : The most interesting scenario is specified by $x_d=0$ and $y_d=1035$ m (the minimum required parallel runway spacing).
- Traffic density: The time interval between aircraft approaching a runway is 75 s, corresponding to 4 nmi longitudinal distance.
- Average number of approaches per runway per year: 200000, reflecting the fact that, in general, during the night only part of runway capacity may be utilized.
- Aircraft speed categories: C and D, for aircraft approaching the adjacent runways.
- Aircraft sizes, $\lambda_x \times \lambda_y \times \lambda_z$: 70.51×59.64×19.33 m, corresponding to a Boeing 747.
- ILS Category: I, bringing along the largest uncertainty about the glide path.
- Localizer interception: The angle with the localizer course is between 0° and 30°.
- Intermediate approach altitudes: The aircraft approaching the adjacent runways are expected to fly at altitudes of 2000 ft (right runway) and 3000 ft (left runway).
- Intermediate segment length: 5.0 km, in accordance with the collected flight data.
- Glide path angle, ψ : 3°.
- Climb out gradient, $\tan \alpha$: 4.0 %.
- Missed approach initiation altitudes: 200 ft, which is the minimum required Decision Height (DH) for ILS category I.
- Missed approach turns: 30° angle of divergence between the nominal missed approach tracks, with turns at an altitude of 500 ft.
- Missed approach rate: Beta distributed stochastic variable with shape parameters $p=1.17$ and $q=84.66$, corresponding to elicited median (50-th percentile) and 5-th percentile of 0.01 and 0.001 respectively. A value of 0.01 (one missed approach in 100 approaches) is also used in the CRM [10] and in the PANS-OPS [11].
- Dependency parameter, ρ : 0.30, derived by assuming that the main reasons for a dual missed approach are turbulence and windshear (see Speijker [17]).

5.2 Numerical results for the baseline scenario

Based on the risk model, a computer program has been implemented in FORTRAN-77 running under UNIX on the NLR mainframe computer. With this computer program the baseline scenario has been numerically evaluated. The main results are:



- The calculated collision probability per approach is $3.6 \cdot 10^{-9}$.
- The calculated collision probability per year is $7.2 \cdot 10^{-4}$.
- The numerical values of both risk measures fall within the defined TLS-areas, and may therefore be judged 'tolerable' until *the* TLS has been set by policy makers.
- The probability of a near miss ³⁾ is $7.44 \cdot 10^{-5}$ per approach, which implies that about 15 near misses are expected to occur per year, which is relative high and therefore somewhat worrying.
- The maximum conditional probability of an aircraft entering a 2000 ft NTZ during final approach is considerable, and equal to $1.47 \cdot 10^{-2}$ near glide path interception.
- The collision probability during intermediate approach is highest when passage occurs near turn on to the localizer (magnitude about 10^{-7}).
- The collision probability during final approach maximally reaches a magnitude of about 10^{-9} to 10^{-10} , which is relative low compared with the most hazardous phases during intermediate approach and a dual missed approach.
- The collision probability during the larger part of a dual missed approach is of magnitude 10^{-10} to 10^{-11} , and may be judged acceptable. The collision probability is relative high when passage occurs near the turn altitude of 500 ft (magnitude 10^{-6}).

The collision probability *during final approach* is already relative low. Technological improvements and improved operational procedures, leading to further increased safety during final approach, do therefore not significantly lower the collision probability per year. To increase the safety related to independent parallel approaches, the relative high collision probability near both turn on to the localizer and near the turn altitude must be lowered.

Varying the lateral distance between the two parallel runways, while keeping the other parameters according to the baseline scenario, shows that the collision risk increases with a gradually higher rate if the lateral distance decreases (figure 3). Important numerical results, valid under baseline operational conditions, are:

- Below about 600 m, a collision is most likely to occur every year. The collision probability per year is at least 0.833, and increases further if the lateral distance reduces.
- Below 930 m, the collision risk reaches a high and unacceptable level of at least one collision in 100 million approaches (or one collision in 500 years).
- Above 1270 m, the collision risk attains a low and acceptable level of at most one collision in 1000 million approaches (or one collision in 5000 years).

Note that the currently required minimum parallel runway spacing of 1035 m (or 3400 ft) falls within the 'tolerable area' of the 'collision risk judgment scheme'.

³⁾ A near miss is defined as losing 500 ft vertical and lateral separation *without colliding*

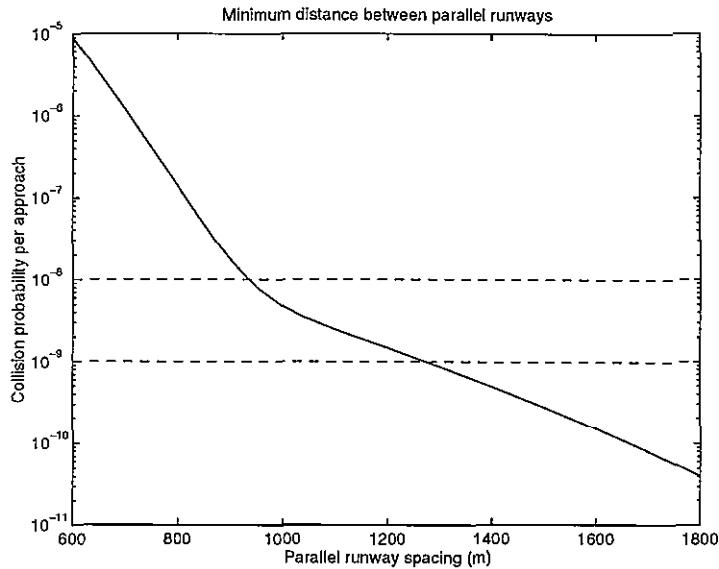


Figure 3. Collision probability per year versus parallel runway spacing. Source: [17].

5.3 Sensitivity analysis

Sensitivity analysis shows to which model parameters the risk measures (collision probability per approach and per year) are sensitive. Varying model parameters, while keeping the other conditions in accordance with the baseline scenario, indicates that the risk measures are sensitive to, especially, the nominal vertical separation during intermediate approach, the angle of divergence between the nominal missed approach tracks, and the missed approach turn altitude. The influence of other missed approach parameters on the collision risk is relative low, but will be larger if the angle of divergence decreases or the missed approach turn altitude increases. It may even be considerable if missed approaches are to be initiated along runway direction. A detailed sensitivity analysis, including numerical computations, is found in Speijker [17].

5.4 Collision risk reducing measures

The following measures are currently prescribed by ICAO for simultaneous and independent parallel approaches, for trying to maintain the required level of safety:

- At least 1000 ft nominal vertical separation during intermediate approach;
- At least 30° angle of divergence between the nominal missed approach tracks, with turns 'as soon as practicable';
- A maximum intercept angle with the localizer course of 30°.

In the following, the effectiveness of each of the first two measures is numerically evaluated, while keeping the other conditions according to the baseline scenario. The impact of staggered parallel runways on the collision risk is also determined.



- Nominal vertical separation during intermediate approach:
According to table 3, the risk decreases rapidly if the nominal vertical separation increases. With less than 500 ft, a collision is likely to occur within 1 to 3 years.

Table 3

Effectiveness of increasing nominal vertical separation during intermediate approach

Vert. separation	P _{collision, per approach}	P _{collision, per year}
0 ft	$6.59 \cdot 10^{-5}$	1.00
500 ft	$1.85 \cdot 10^{-6}$	$3.09 \cdot 10^{-1}$
750 ft	$2.75 \cdot 10^{-8}$	$5.48 \cdot 10^{-3}$
1000 ft	$3.60 \cdot 10^{-9}$	$7.20 \cdot 10^{-4}$

Evidently, at least 1000 ft nominal vertical separation is required. A separation of more than 1000 ft will reduce the risk even further. However, the feasibility of this is rather questionable as it probably lowers runway capacity significantly.

- Diverging nominal missed approach tracks, with turns 'as soon as practicable':
Table 4 shows that the risk decreases with a gradually higher rate if the turn altitude decreases. A turn altitude above 500 ft may be judged unacceptable.

Table 4

Effectiveness of decreasing turn altitude

Turn altitude	P _{collision, per approach}	P _{collision, per year}
500 ft	$3.60 \cdot 10^{-9}$	$7.20 \cdot 10^{-4}$
1000 ft	$1.68 \cdot 10^{-7}$	$3.30 \cdot 10^{-2}$
1500 ft	$1.84 \cdot 10^{-6}$	$3.08 \cdot 10^{-1}$
2000 ft	$4.48 \cdot 10^{-6}$	$5.92 \cdot 10^{-1}$

Table 5 shows that the risk decreases with a gradually smaller rate if the angle of divergence increases. Worth noticing is that increasing the angle of divergence to more than 20° to 30° hardly reduces the collision risk any further.

Clearly, at least 20° to 30° angle of divergence is required, with turns 'as soon as practicable', and not above 500 ft.



Table 5
Effectiveness of increasing angle of divergence between missed approach tracks

Angle of divergence	$P_{\text{collision, per approach}}$	$P_{\text{collision, per year}}$
0°	$4.48 \cdot 10^{-6}$	$5.92 \cdot 10^{-1}$
10°	$2.45 \cdot 10^{-8}$	$4.89 \cdot 10^{-3}$
20°	$3.75 \cdot 10^{-9}$	$7.50 \cdot 10^{-4}$
30°	$3.60 \cdot 10^{-9}$	$7.20 \cdot 10^{-4}$

- Staggered parallel runways:

Table 6 shows the risk for three longitudinal distances between runway thresholds, x_d , where a positive sign indicates that the 'left runway' is located 'farthest away', and a negative sign the opposite. The collision risk decreases if x_d increases.

Table 6
Effectiveness of staggering the parallel runways

x_d	$P_{\text{collision, per approach}}$	$P_{\text{collision, per year}}$
-2000 m	$1.38 \cdot 10^{-7}$	$2.72 \cdot 10^{-2}$
-1000 m	$1.25 \cdot 10^{-8}$	$2.50 \cdot 10^{-3}$
0 m	$3.60 \cdot 10^{-9}$	$7.20 \cdot 10^{-4}$
+1000 m	$1.32 \cdot 10^{-10}$	$2.64 \cdot 10^{-5}$
+2000 m	$1.53 \cdot 10^{-11}$	$3.06 \cdot 10^{-6}$

Parallel runways should, if possible, be build with some - as large as possible - longitudinal distance between runway thresholds. Independent parallel approaches must then be performed such that the aircraft with the highest located FAP (usually at 3000 ft) approach the runway located farthest away.

It turns out that all three numerically evaluated measures are effective in reducing the collision risk. Besides, although not numerically evaluated, it is reasonable to expect that the collision risk decreases if the localizer intercept angle decreases, especially with lacking nominal vertical separation during intermediate approach.

5.5 Worst case scenario

The worst case scenario is specified on basis of a large number of numerically evaluated scenarios. Besides 1035 m parallel runway spacing, its main characteristics differing from the baseline scenario are:

- Aircraft size: 95.0×80.0×20m, which is about the size to be used in the near future.
- Traffic density: The time interval between aircraft approaching a runway is 60 s.
- Intermediate approach altitudes: The aircraft approaching the adjacent runways are expected to fly at equal altitudes of 2000 ft.
- Climb out gradient, $\tan \alpha$: 2.5%.
- Missed approach tracks: along runway direction (i.e. no turns specified).

Under these worst case operational conditions, the collision probability per approach is $1.38 \cdot 10^{-4}$, which is definitely unacceptable. A collision is even most likely to occur a couple of times per year! Especially the lacking nominal vertical separation during intermediate approach, and the insufficient nominal lateral distance during a dual missed approach are responsible for this unacceptable high risk of collision. The collision probability is considerable when passage occurs near turn on to the localizer (magnitude about 10^{-4} to 10^{-3}) or, in case of a dual missed approach, when passage occurs above about 1000 ft (magnitude about 10^{-4} to 10^{-2}).

Numerical evaluations show that the collision risk reduces into the specified *tolerable* area of [1×10^{-9} , 1×10^{-8}] by application of the following two measures:

- 1000 ft nominal vertical separation during intermediate approach;
- 30° angle of divergence between the missed approach tracks, with turns at 500 ft.

Varying the lateral distance between the runways shows that increasing the parallel runway spacing is not practicable in reducing the risk under worst case conditions. Increasing the runway spacing to 4240 m reduces the collision probability per approach to $1.0 \cdot 10^{-8}$, and increasing to 5140 m is necessary for reduction to $1.0 \cdot 10^{-9}$!

6 Conclusions

In this study a probabilistic risk analysis regarding the risk of collision between aircraft performing independent parallel approaches has been described. Two suitable risk measures evolved for the risk analysis of two parallel runways used for landing: the collision probability per approach and the collision probability per year, defined with respect to the risk of collision between aircraft. Application of two methods for TLS assessment provided *TLS-areas*, defining ranges for the TLS used in this study:



$$TLS_{per\ approach} \in [1 \times 10^{-9}, 1 \times 10^{-8}] \quad or \quad TLS_{per\ year} \in [2 \times 10^{-4}, 2 \times 10^{-3}]$$

Because of problems arising in assessment and usage of the TLS, it is recommended to examine the possibility of broadening the TLS concept. In order to set *the* TLS and/or broaden the TLS concept, policy makers must be consulted.

A risk model was developed and implemented for determination of the collision risk between aircraft conducting independent parallel approaches under IMC, thereby using ILS procedures. Application of the risk model to a number of scenarios, with varying parallel runway spacing, and under different operational conditions, showed that:

- The collision probability between two aircraft can be considerable and unacceptable under certain conditions, especially near turn on to the localizer and during a dual missed approach;
- Technological improvements and improved operational procedures, leading to an increased safety *during final approach*, do not significantly lower the collision probability per approach.

Numerical evaluations showed that the following measures are essential, and must be prescribed, for trying to maintain the collision risk at a low and acceptable level:

- At least 20° to 30° angle of divergence between the nominal missed approach tracks, with turns 'as soon as practicable', and not above 500 ft;
- At least 1000 ft nominal vertical separation during intermediate approach;
- Some - as large as possible - longitudinal distance between the runway thresholds of the parallel runways. Besides, the approaches must then be performed such that the aircraft with the highest FAP approach the runway located 'farthest away'.

Provided that these measures are applied and assuming that a TLS from the specified TLS-areas is used, independent parallel approaches may be judged adequately safe if the runway spacing is greater than 1270 m, and unsafe if the spacing is lower than 930 m.

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