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Precision Runway Monitor Experiments for Frankfurt/Main International Airport

Final Report

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0 Executive Summary

0.1 Executive Summary (English)

Mission

In close cooperation, the Federal Aviation Administration (FAA) Air Traffic Control Simulation and Support Branch, ACT-510, and the Deutsche-Flugsicherung (DFS) Air Navigation Services (SES, FM/R and FDF) conducted a real-time simulation to investigate the potential benefits of a Precision Runway Monitor (PRM) system at Frankfurt/Main Airport, Germany.

Simulation environment

During the three-week simulation, 12 experienced approach (APP)-controllers from Frankfurt (4 per week) participated as subjects. Original Frankfurt flight-data and radar video maps were used to generate realistic traffic scenarios. In addition to the traditional working positions TR1 (Pick-up) and TE (Feeder), the PRM (precision runway monitor) position was used. The following runway configurations were simulated:

- Dependent parallel runways 25L/25R (Positions: 1 TR, 1 TE, 1 PRM, 1 Coordinator)
- An additional independant runway 26 (1 TR and 1 TE for 25L/R, 1 TR/TE for 26, 1 PRM)

The applied separation varied between 2.5, 2.0 and 1.5 NM considering or disregarding wake vortices (simulated WVWS -„Wake Vortex Warning System“). Although the current Frankfurt airspace structure does not allow for an extensive traffic increase, it was implemented into the facility 1:1. To introduce a heavy traffic workload for testing purposes, airplanes were released extremely close to another, separated by the computer system at the entry fixes PSA, GED and RUD.

Results

The results of the objective and subjective measurements during the simulation runs revealed that, using a PRM in the Frankfurt airspace will attain safety and capacity increasees in different levels:

- Even using the actual runway system the controller will, because of the increased confidence to a very precise radar-display,succeed in getting the absolute minimum separation very often. Rem.: During the simulations it was noticed that PRM could also be used to apply separation between missed approaches and departures.
- Whenever systems become available that allow the controller to invalidate wake vortex separation and have approval to reduce the separation below the current standards because of an improved and reliable radar-display, there will be a considerable capacity increase of traffic for the dual runway system.
- Having a third, independent runway, the expected capacity enhancement will be obtained; and by installing a PRM, the present high safety level will be preserved.
- Using PRM, a much better control of the vertical component of the approach is possible.
- A 1-second update rate of the radar is needed for the expected traffic increase.

Applying 2.5NM and wake vortex separation, the results under simulated „imc conditions“ were in accordance with the „vmc-account“ under real conditions.

Looking at the results in the attached lists, it has to be kept in mind, that these are results of simulations, that could be obtained under optimized conditions only.

Recommendations

Based on the knowledge obtained during the simulations at the FAA, it can be stated, that PRM seems to be a very promising technology, which has decisive advantages face to face with the presently used system. Further investigations regarding the technical realizability, operational requirements, procedures

and phraseology should be done. These analyses can be carried out for additional Airports like München or Düsseldorf.

0.2 Executive Summary (German)

Auftrag

Das Angebot des FAA TEC Center in Atlantic City an FD, den kurzzeitig vakanten PRM-Simulator nutzen zu dürfen, wurde seitens der DFS begrüßt. In Zusammenarbeit zwischen SES, FM/R und FDF wurden kurzfristig Szenarien entwickelt,die sowohl für die Erprobung einer PRM Darstellung, als auch für die Untersuchung von Kapazitätszuwachsmöglichkeiten von Bedeutung waren.

Simulationsablauf

Drei Wochen lang konnten pro Woche 4 erfahrene APP-Lotsen den Simulator nutzen. Originale Flugplandaten und RADAR-Videokarten machten die Arbeit realistisch. Neben den Arbeitsplätzen TR1 (Pick-up) und TE (Feeder) wurde der nach FAA-Vorgaben eingerichtete Arbeitsplatz PRM (precision runway monitor) genutzt. Es wurden folgende Landbahnkonfigurationen simuliert:

- Abhängiges paralleles Zweibahnsystem 25L/25R (Arbeitsplätze: 1 TR, 1 TE, 1 PRM, 1 Koordinator)
- Zusätzlich eine dritte unabhängige Piste 26 (1 TR und 1 TE für 25L/R, 1 TR/TE für 26, 1 PRM)

Die anzuwendende Staffelung variierte zwischen 2.5, 2.0 und 1.5 NM mit und ohne Wirbelschleppenberücksichtigung (simuliertes WSWS -„Wirbelschleppen Warnsystem“).

Obwohl die derzeitige Frankfurter Luftraumstruktur große Verkehrszuwächse nicht zuläßt, wurde sie 1:1 übernommen. Um die erforderliche Verkehrsmenge zu erreichen, wurde an den 3 vorhandenen „Übergabefixes“ PSA, GED und RUD das für die Simulationen erforderliche Verkehrsvolumen rechnergesteuert extrem eng gestaffelt angeliefert.

Ergebnisse

Die aufgrund von objektiven und subjektiven Messungen gewonnenen Simulationsergebnisse zeigen, daß durch den Einsatz eines PRM in Frankfurt ein Sicherheitszugewinn und ein Kapazitätszuwachs in mehreren Ebenen erreichbar sein kann:

- Schon beim heutigen Bahnensystem wird der Lotse durch das angestiegene Vertrauen in eine präzise RADAR-Darstellung seinen mindestmöglichen Staffelungswert weit häufiger erreichen. Anm.: Bei den Simulationen wurde deutlich, daß sich PRM auch hervorragend für die Kontrolle resp. Staffelung von Fehlanflügen und Abflügen einsetzen läßt.
- Durch einsatzfähige Systeme, die eine Wirbelschleppenstaffelung hinfällig machen und einer weiteren, genehmigten Staffelungsreduzierung aufgrund der verbesserten und zuverlässigen Darstellung kann beim Zweibahnbetrieb ein beachtlicher Zuwachs an Landungen erreicht werden.
- Beim Betreiben einer dritten, unabhängigen Landebahn kann der erwartet hohe Zugewinn bei den Landungen erreicht werden; durch PRM bleibt der hohe Sicherheitsstandard erhalten.
- Durch PRM ist eine bessere Überwachung der vertikalen Anflugkomponente möglich.
- Bei der erwarteten Zuwachsrate wird ein RADAR-System mit „1sec. update“-Rate erforderlich.

Die erreichte Landerate beim Zweibahnbetrieb und 2.5NM Staffelung bei „imc“ unter Anwendung von Wirbelschleppenstaffelung entsprach dem heute in der Praxis erreichbaren „vmc-Wert“. Beim Betrachten der in den Tabellen angeführten Werte muß berücksichtigt werden, daß es sich um Simulationsergebnisse handelt, die unter optimalen Bedingungen erreicht wurden.

Empfehlungen

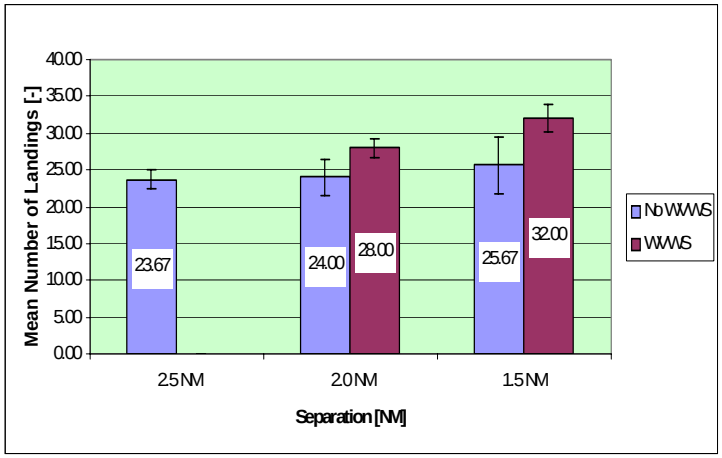
PRM scheint aufgrund der bei der FAA gewonnenen Erkenntnisse eine vielversprechende Technologie zu sein, die gegenüber dem derzeitigen System entscheidende Vorteile bringt. Die positiven Ergebnisse sprechen für eine Einführung des Systems. Neben den Untersuchungen zur technischen Realisierbarkeit

müssen die betrieblichen Anforderungen, Verfahrensfragen und Phraseologien geklärt werden. Diese Analysen können parallel für weitere Flughäfen (z.B. Düsseldorf, München) anlaufen.

1 Summary

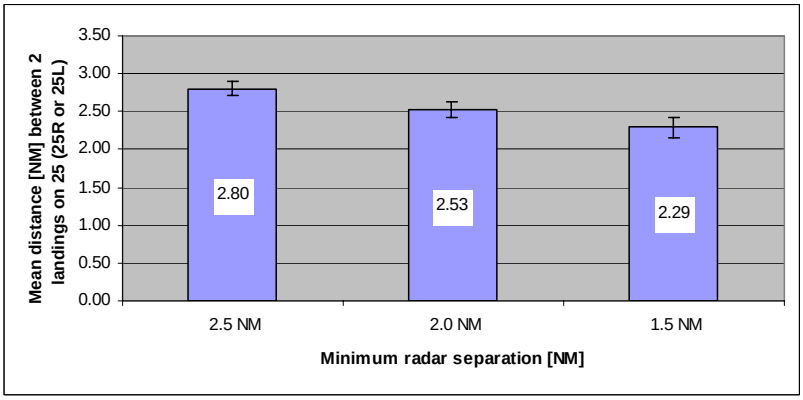
The Federal Aviation Administration's Air Traffic Control (ATC) Simulation and Support Branch (ACT-510) and System Resources Corporation conducted a real-time simulation in cooperation with the Deutsche-Flugsicherung (DFS) Air Navigation Services to investigate potential benefits of a Precision Runway Monitor (PRM) system for capacity enhancement at Frankfurt/Main International Airport. PRM systems provide aircraft position updates at rates of 1 second. For the runway monitor use, the display aspect ratio is adjusted to emphasise lateral movements from the extended runway centerline (details see chapter 2).

A total of 12 experienced tower/approach controllers from Frankfurt/Main approach control participated in the investigation. Four controllers per week carried out extensive simulations at the FAA William J. Hughes Technical Center PRM simulation laboratory in Atlantic City, NJ, USA. They worked as a team of pickup, feeder and PRM controllers for the current dual runway configuration at Frankfurt/M. In addition, a fourth controller worked on an additional pickup/feeder position for the simulated triple runway configuration. The simulated traffic was based on real traffic from 5th of July 1996 at Frankfurt/M. Airport. To avoid non-realistic traffic situation on the runways 25R/25L, no departure were simulated on those runways, although the separation on final would have allowed some. All traffic departed from runway 18. Each team worked the different controller position for a total of about 16 hours of simulation time. The simulation runs varied according to the following parameters : the minimum radar separation for the staggered approach, the runway configuration, the traffic density and mix and the simulation of a Wake Vortex Warning System (WVWS) or not. Subjective data was collected and set into the context of the objective data gathered, e.g. landing rate and separation. During the simulation, aircraft already established on final were intentionally deviated towards the neighbouring centerline to disturb traffic flow. The task of the PRM controller was to assure a safe separation of traffic even at all times for aircraft on final approach.



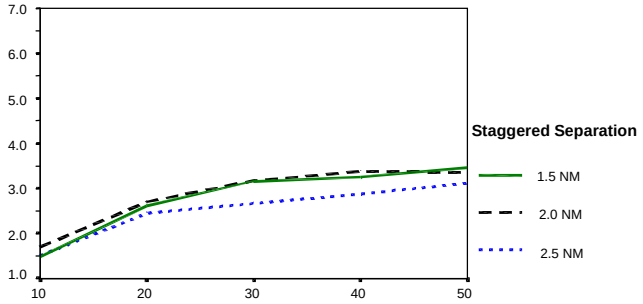
30 minutes arrival rate by minimum radar separation

After the conduct and evaluation of this initial PRM simulation, the DFS team and participating controllers concluded that PRM technology benefits can be realized with both existing and reduced separation standards. According to simulation results, utilizing a PRM system today at Frankfurt/M., with existing minimum radar separation requirements, could reduce the mean distance between two aircraft on final approach from 2.9 nm to the minimum of 2.5 nm. This effect would be actualized more with approach controllers' growing trust of the PRM system.



Actual separation by minimum radar separation

As demonstrated in the simulation, PRM technology also allows for a reduction in radar separation requirements, which results in an increase in average arrival rates. Under the assumption of an operational Wake Vortex Warning System (WVWS), the arrival rate clearly increases (30 minutes arrival rates 23.67 per 2.5 NM, 28.00 per 2.0 NM, 32.00 per 1.5 NM, see figure besides and chapter 3) . Even without a WVWS, the PRM system allows, for a moderate increase of the arrival rate (30 minutes arrival rates 23.67 per 2.5 NM, 24.00 per 2.0 NM, 25.67 per 1.5 NM) while maintaining wake vortex separation. Quantitative data supporting an increase of the arrival rate still needs to be verified in light of only a few subjects participating in this initial investigation. Regarding this fact, an initial increase of 1-2 movements per hours seems to be possible. Further investigation should validate this estimation. Investigation of the data yield the fact that the average separation between two aircraft landing decreased from 2.8 NM to 2.5 NM towards 2.3 NM for a nominal separation of 2.5 NM, 2.0 NM and 1.5 NM, respectively. These results support that an even higher capacity increase (more than 1-2 movements) seems possible. Analyses of the objective and subjective analyses show the importance of the training effect on the subjects. Getting used to the PRM system, the controller tended to reduce the current separation. Evaluations of the separation show that the safety of the traffic on final was not compromised. Even more, compared to the current VMC conditions, safety was improved due to a more precise radar update and display presentation.



Workload for different separation

A controller workload assessment confirmed the benefits of a PRM system. The workload associated with the PRM controller position was consistently rated as the same or lower than the pickup and feeder positions. The workload ratings throughout the runs showed neither an increase nor a decrease of workload for the different radar separation minima on final. The questionnaires and debriefings captured the overall positive impression of the subjects on the PRM system for Frankfurt/M. even for today's operations. However several details, like procedures and responsibilities in a PRM approach environment, have to be discussed and investigated in detail.

To summarize the results, a PRM system seems to be a promising technology for capacity enhancement at Frankfurt/M. Airport in addition to other means already defined. It can even be

considered for other German Airports (e.g. München, Düsseldorf). However, an implementation of the system would require further simulation investigations in Langen. Support from the FAA PRM experts may be of further benefits for those investigations.

2 Experimental setup

2.1 Simulation overview

The main objective of the DFS Deutsche Flugsicherung GmbH is to assure safe, efficient and orderly traffic inside the airspace of the Federal Republic of Germany. This objective aims at providing air traffic services of highest quality and at the best benefit for any airspace user. It implies to envision economical aspects as well as capacity aspects. Due to the predicted growth of air traffic both aspects lead to the fact that more traffic has to be handled at the same or an even better quality as today. The well-known bottle neck of handling more traffic is the runway capacity at the major Airports.

The highest loaded Airport in Germany is the Frankfurt/Main Airport. Identifying the Frankfurt/Main Airport as a major bottle neck led to a program for the Airport's capacity enhancement (Stufenplan 2000), which was established in1996. Inside this program, several means for capacity enhancement were defined, like the *Wake Vortex Warning System (WVWS)*, the *4-D-Planner* or the *High Approach Landing System (HALS)*. Each of the means for its own will come along with only a small benefit for the objective of capacity enhancement. But taken together, there will be a significant benefit for the capacity – i.e. the departure and arrival rate – of the Frankfurt/Main Airport.

One of the pieces of this mosaic may be a *Precision Runway Monitoring System (PRM)*. This system helps to shorten down the final approach separation. Use of a PRM system requires an additional working position (the *Final Monitor Position* or PRM position) to ensure adequate separation on final. To support this task, a radar system with high radar update rate of 1 second is necessary. PRM systems offer potential benefits, but additional costs for personnel and for technical infrastructure would be required.

The objective of the simulation study reported here was to gain an initial insight of the potential for capacity enhancement and the shortcomings of the PRM system from an operational point of view. It has to be stated, that due to the design of this study as a first exploration, no final recommendations can be expected. Instead, the study tried to support a decision to further investigate PRM or not as a part of the capacity enhancement program for Frankfurt/Main Airport.

To implement this study, DFS obtained support from the US Federal Aviation Administration (FAA). The FAA has extensive experience in the field of Precision Runway Monitoring simulations. Simulation experiments were carried out for different Airports in the US. Configurations tested were always designed for independent parallel approaches and landings on up to four parallel runways at various runway spacing. The minimum separation between two runways used for independent parallel approaches, as determined by the FAA is 3000 ft with a 2.5-degree localizer offset. The FAA has not conducted PRM simulations, however, to investigate reduced dependent approach separation minima. The DFS simulation was the first of this type of experiment.

For the current configuration of the Frankfurt/Main Airport (25R, 25L distance 518 m or 1726 ft), the FAA PRM experiments already conducted were not directly applicable. At the Frankfurt/Main Airport, according to ICAO regulation, staggered approaches have to be

performed. The minimum staggered separation between two aircraft of the same weight category has to be 3.0 NM. In case of a runway occupation time of less than 50 seconds, this minimum separation can be reduced to 2.5 NM.

The simulation experiment reported here was conducted in a joint effort of the DFS research & development division, subdivision simulation (DFS SES), and the FAA ACT simulation & support division (FAA ACT-510). In three weeks of simulation with several DFS subjects the benefits of an additional PRM position for the Frankfurt/M. approach unit were tested. These tests included simulated minimum staggered separation of 2.0 NM and 1.5 NM for a dual and a triple runway configuration at Frankfurt/Main Airport.

The simulation was conducted at the FAA William J. Hughes Technical Center in Atlantic City, NJ, over a three-week period between the 4th and the 22nd of May. The experiments were designed for a one week duration, so that each week reproduced the same experiments with a different team of four controllers from the DFS Frankfurt/M. approach unit and one simulation supervisor (SES).

2.2 Outline of the PRM system

The Precision Runway Monitoring system (PRM) consists of two major parts: a secondary surveillance radar system with an update rate of 1 second and the final monitor aid as the display (PRM position). It provides controllers with high–precision secondary surveillance radar data and more frequent aircraft target update rates for monitoring aircraft on final approaches. PRM systems allow simultaneous ILS approaches and ILS approaches with reduced staggered separation to be conducted where they were previously restricted due to existing runway spacing and radar error.

A high-precision radar system is the technical prerequisite for the final monitor aid. It allows for displaying reliable aircraft position information and with sufficient time to alert the controller for potential conflicts on final. Those conflicts are called *blunders* or *deviations*, as detailed below.

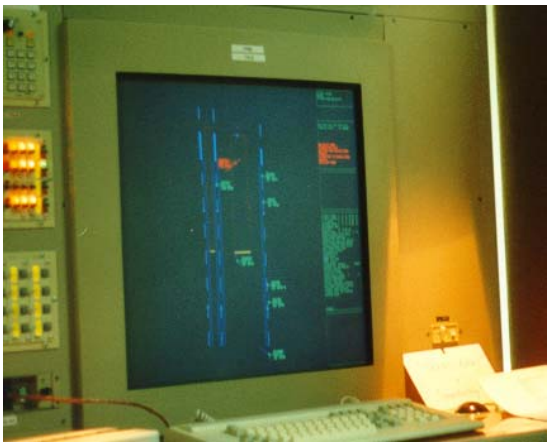


Figure 1: A Final Monitor Aid Display as used in the investigation reported

The Final Monitor Aid is a high resolution color display equipped with a controller alert system hardware / software that is used in the Precision Runway Monitoring system. The display includes alert algorithms providing target predictors, a colour change alert when a target penetrates or is predicted to penetrate the no transgression zone (NTZ) or the protection zone (PZ), a colour change alert if the aircraft transponder becomes inoperative, synthesized voice alerts and digital mapping.

The final monitor aid display shows the final from about 10-12 miles to the runway threshold (see Figure 1). Dashed lines and spaces indicate distances of 1 mile each - which for this simulation, were displayed as such on both the PRM and feeder displays. Several finals next to each other can be displayed at the same time. The core idea of the final monitor aid

display is a stretched x-axis in the presentation of the traffic. The stretching used in this investigation was a 4:1 ratio for x:y axis. The stretching leads to a much more obvious presentation of traffic deviating laterally from the centerline. In addition a visual and aural alert supports the situation awareness of the PRM controller and the urgency of the situation.

2.3 Hypotheses

As explained above, the experiment is to be seen in the context of capacity enhancement for the Frankfurt/Main Airport. Due to this, the major hypotheses for this experiment are related to the arrival rate. An increase is expected for any of the conditions in comparison to the control condition. The following hypotheses describe the expected results of the study:

1. The arrival rate for a 2.0 NM staggered separation on a dual runway system (dual runway configuration 25L, 25R) will increase compared to the control condition with a staggered separation of 2.5 NM on a dual runway system (dual runway configuration 25L, 25R).
2. The arrival rate for a 1.5 NM staggered separation on a dual runway system (dual runway configuration 25L, 25R) will increase compared to the control condition with a staggered separation of 2.5 NM on a dual runway system (dual runway configuration 25L, 25R).
3. The arrival rate for a 1.5 NM staggered separation on a dual runway system (dual runway configuration 25L, 25R) will increase compared to the arrival rate for a 2.0 NM staggered separation on a dual runway system (dual runway configuration 25L, 25R).
4. The arrival rate for a 2.0 NM staggered separation on the dependent runways and parallel approaches on a third independent runway (triple runway configuration 25L, 25R, 26) will increase compared to the control condition with a staggered separation of 2.5 NM on a dual runway system (dual runway configuration 25L, 25R).
5. The arrival rate for a 1.5 NM staggered separation on the dependent runways and parallel approaches on a third independent runway (triple runway configuration 25L, 25R, 26) will increase compared to the control condition with a staggered separation of 2.5 NM on a dual runway system (dual runway configuration 25L, 25R).
6. The arrival rate for a 1.5 NM staggered separation on the dependent runways and parallel approaches on a third independent runway (triple runway configuration 25L, 25R, 26) will increase compared to the arrival rate for a 2.0 NM staggered separation on the dependent runways and parallel approaches on a third independent runway (triple runway configuration 25L, 25R, 26).
7. The experimental induced loss of separation (blunders, deviations[1]) will not lead to critical incidents (less than 500 ft lateral separation or less than 1000 ft vertical separation) at any time.

[1] Terminology see below

2.4 Methods

2.4.1 Key words related to the simulations

For a better understanding of the experimental setup it is necessary to define some terms used later on in this report. The terms are : *No Transgression Zone*, *Protection Zone*, *Blunder* and *Deviation*.

2.4.1.1 No Transgression Zone (NTZ) and Protection Zone (PZ)

The final approach airspace includes either a Protection Zone or a No Transgression Zone (NTZ). The Protection Zone is used in the Two Runways Configuration (runways 25R, 25L) at Frankfurt/M. (Figure 2). This area intends to provide a visual alert to the controller while conducting staggered approaches 25 R, 25 L at Frankfurt/M. Airport.

The No Transgression Zone is used in the Three Runways Configuration (runway 25R, 25L, 26) at Frankfurt between runways 25R and 26 (Figure 3). Since these runways are separated by 6000 ft, they will be controlled as independent runways. The NTZ is a 2000 ft wide area equidistant between center lines where aircraft are not permitted to enter. If an aircraft enters the NTZ, the monitor controller is required to react on this event in an adequate manner to assure separation between the aircraft on final.

2.4.1.2 Blunder and Deviation

For simulation purposes, a *blunder* is a scripted event intended to qualify the ability of the system to maintain adequate separation between aircraft on final approach during critical situations.

A blunder occurs as an aircraft already established on the final approach course turns unexpectedly towards another aircraft on an adjacent approach and enters a *No Transgression Zone*. Blundering aircraft are scripted to turn 30 degrees towards adjacent approach courses, and may either maintain altitude or descent. The blunder is considered resolved if the minimum distance between the blundering aircraft and the evading aircraft at the closest proximity is 500 ft or greater. Any blunder that results in a miss distance of less than 500 ft between aircraft is considered as a Test Criterion Violation (TCV). A valid TCV is one that could occur in the operational environment and is not the result of a simulation anomaly (simulation hardware and software failure).

An aircraft already established on the final approach course, turning unexpectedly towards another aircraft on an adjacent approach and entering a *Protection Zone* is considered not as a *blunder* but as a *deviation*. Deviating aircraft are scripted to turn 10 degrees towards adjacent localizer courses. This terminological difference is due to the ICAO vocabulary on independent or dependant runways.

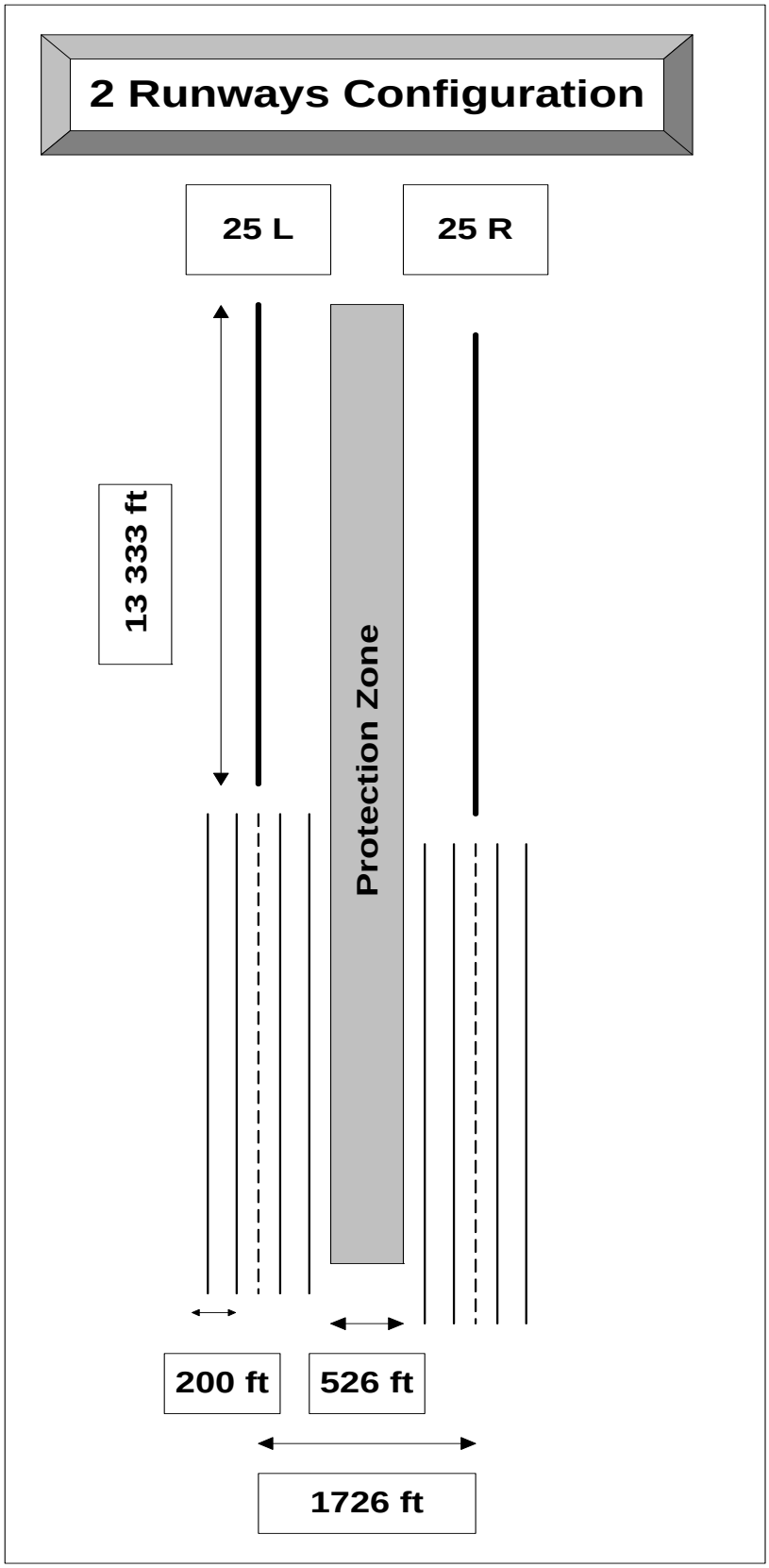


Figure 2: Protection Zone with Runways 25 R and 25 L

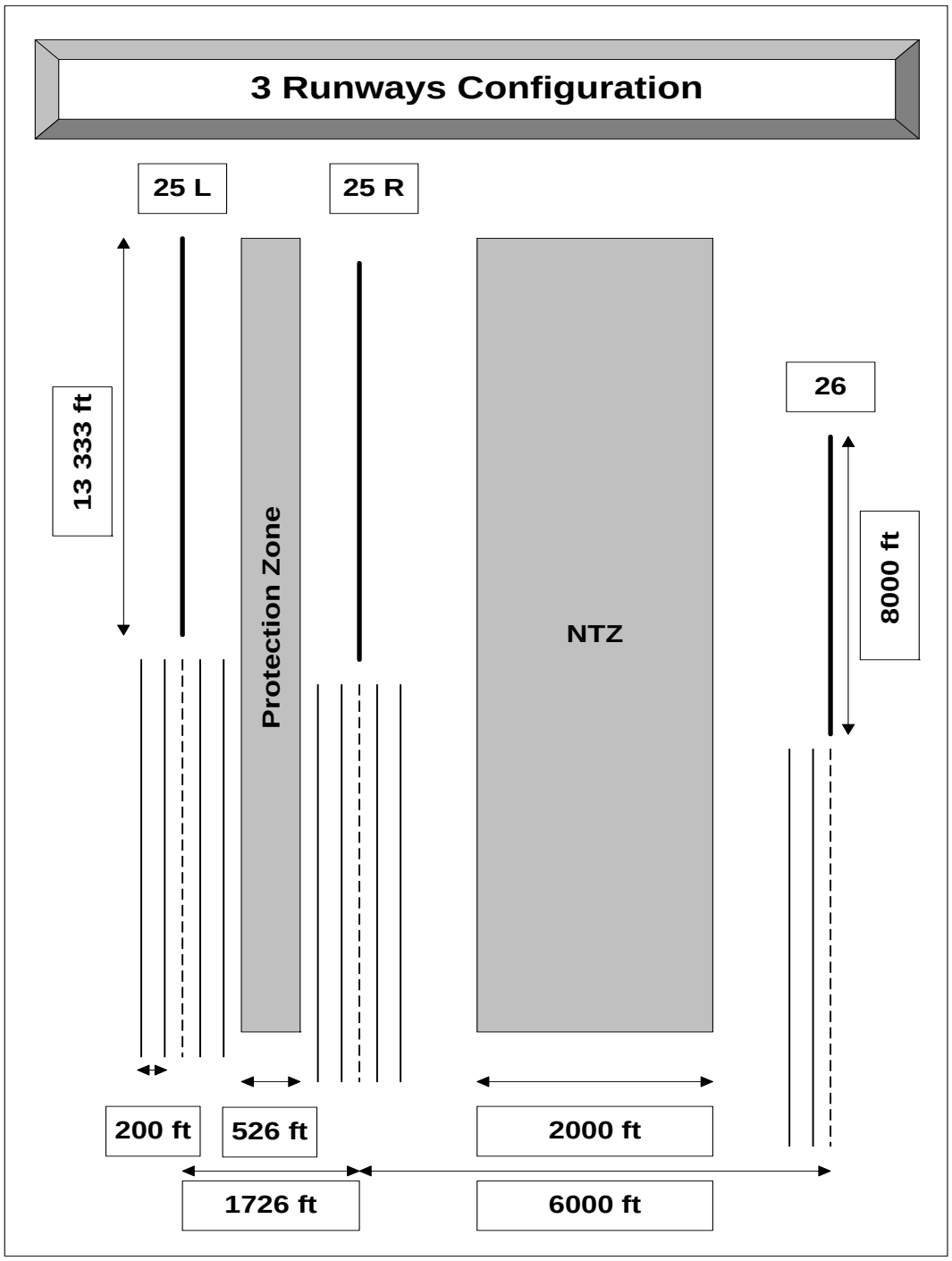


Figure 3: Protection Zone and NTZ with Runways 25L, 25 R and 26

2.4.2 Experimental design

According to the hypotheses (see section 2.3) the experiment was divided into several conditions. The idea was to vary the minimum separation on final with two runway configuration and three runway configurations. In addition, the presence of a reliable wake vortex warning

system was assumed for a part of the runs, while for the other part a normal wake vortex separation as exists today was to be delivered by the subjects.

For testing the workability of the PRM position, several experimental events were implemented to force a PRM controller interaction to the system. These events were unpredictable for the subjects. A number of blunders or deviations (see section 2.4.1) occurred in most of the simulation runs. These blunders or deviations differed according to a scheme described below. The task of the PRM controller was to assure the separation on final even in the case of blundering or deviating aircraft. In addition, it was possible for the PRM controller to adopt speed control on final in accordance to an ad hoc teaming agreement between the PRM controller and the pick-up controller.

All blundering or deviating aircraft in the simulation were scripted to have certain response conditions, responding or non-responding, (see section 2.4.2.1). In addition, blunders and deviations were distributed along the localizer courses and initiated towards certain types of aircraft according to predetermined percentages.

For achieving a more readable text, the terms blunder and deviation are used as synonyms in the rest of this section. Wether the term blunder or the term deviation is to be applied depends on the runway configuration of the concrete simulation run. Further on, the term blunder is used, while the term deviation is implied for a two runway configuration simulation run.

2.4.2.1 Response condition

In order to simulate worst-case situations where blundering aircraft are not able to correct their deviations, in some cases pilots of blundering aircraft were instructed not to respond to the controller anymore. Thus, the blunder was not corrected. This leads to a blunder which is referred to as a non-responding blunder. Throughout the simulation 80% of the blundering aircraft were scripted to be non-responding.

2.4.2.2 Blunder distribution along localizer course

In order to be able to track the blunder along the localizer course, the blunders were regrouped into distances from the runway threshold :1-4 NM, 4-8 NM and 8-12 NM. The blundering aircraft were distributed on the localizer as follows: 20 % of the blunders occurred in the first bin, 30 % in the second bin and 50 % in the last bin.

2.4.2.3 Procedure

PRM controllers monitored the flight paths of the aircraft on their assigned runways and ensured that the aircraft maintained the required separation. Aircraft blunders were initiated to test the ability of the ATC system to maintain adequate distances between aircraft during critical situations. The blunders always occured without warning to the controllers. During blunders event, controllers issued control instructions to attempt to resolve the situation. The number of blunders occurring during the run depended on the scenario which was simulated (see sections 2.4.3.1 and 2.4.6).

2.4.2.4 Controller working positions

The runs were conducted with the help of three to four different positions :

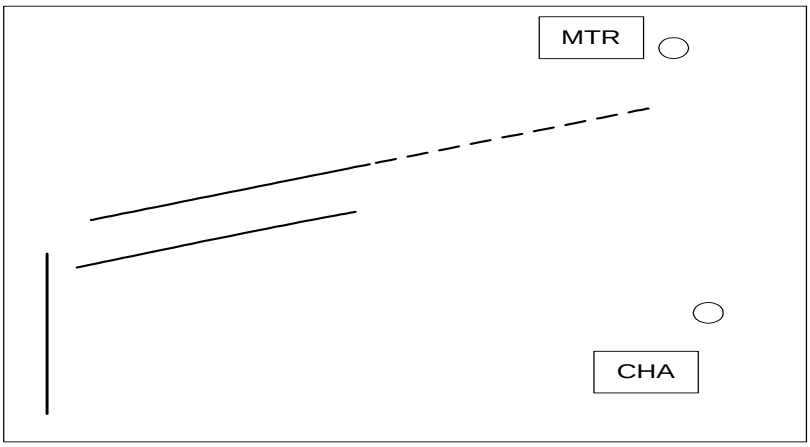


Figure 5: Feeder Position

- Pick-up Position (Figure 4)
- Feeder Position (Figure 5)
- „PRM Position“ (Figure 6)
- for three runway configuration runs an additional Pick-up/Feeder North Position

The following figures provide an overview of the three different positions mentioned above (case of the Two Runway Configuration).

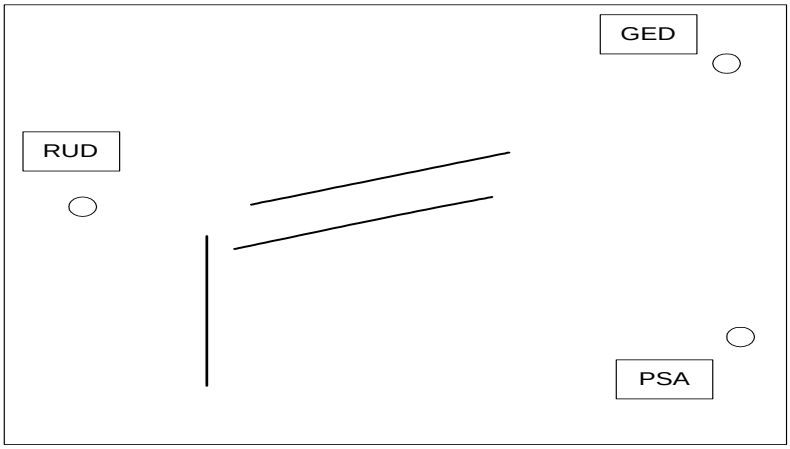


Figure 4: Pick-up position

A more precise description of the PRM Position is provided in [1]. Figure 6 only represents a schematic view on the display of the PRM Controller.

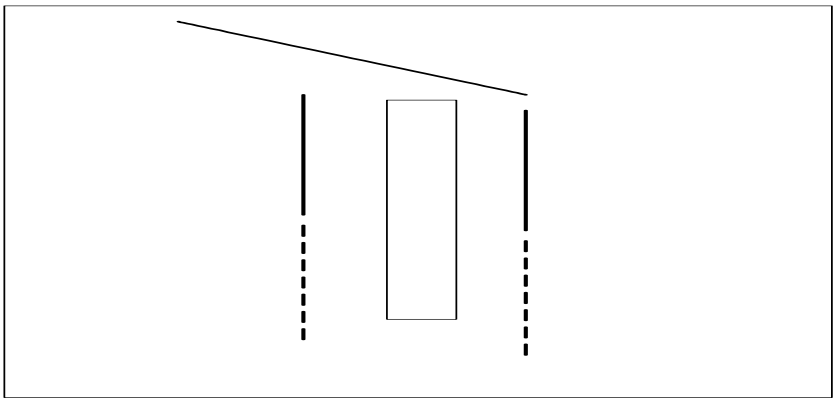


Figure 6: PRM Position

2.4.2.5 Occupation of the Controller working position

Depending on the runway configuration, a different occupation of the controller working positions is defined.

Two Runway Configuration (see Figure 2): staggered approach

- 1 Controller Position **TR1** (Pick-up) Frequency **120.800**

  Pick-up and sequence planning of the aircraft coming via PSA, GED and RUD.

- 1 Controller Position **TE 1** (Feeder) Frequency **124.200**

  Regulation of the traffic sent to TE1 by TR1, in order to establish the appropriate landing sequence and the required separation between the aircraft for RWY 25R and 25L.

- 1 Controller Position **PRM** (Final Monitoring Aid) monitoring TWR-Frequency **119.900** and giving corrections/advisories if necessary.

  Regulation of the traffic in case when an aircraft is deviating from its centerline.

- 1 Controller Coordinator/Supervisor

Three Runway Configuration (Figure 3): staggered approach 25R, 25L and independent traffic on 26.

- 1 Controller Position **TR1** (Pick-up) Frequency **120.800**

  Pick-up and sequence planning of the aircraft coming from the South (PSA) and the East, and integration into the south-downwind of all the aircraft coming from RUD (sent by TR4).

- 1 Controller Position **TE1** (Feeder) Frequency **124.200**

Regulation of the traffic sent to him by TR1 (exceptionally by TR4, if co-ordinated), in order to establish the appropriate landing sequence and the required separation between the aircraft for RWY 25R and 25L.

- 1 Controller Position **TR4** (Pick-up + Feeder North) Frequency **118.500**

  Pick-up and sequence planning of the aircraft coming from the North (GED) and the West (RUD). Aircraft coming from the West and flying a north-downwind to land on RWY 26 are integrated into the „GED-flow“. Aircraft coming from the West and have flying via the Frankfurt VOR (FFM) because of the traffic situation, are sent shortly before FFM to TR1.TR1 will integrate these aircraft into the traffic flow for RWY 25R and 25L .

- 1 Controller Position **PRM** monitoring TWR-Frequency 119.900 and giving advisories for „deviating“ a/c (entering the PZ), traffic warnings and deconflict actions in case of a/c „blunders“ (entering the NTZ).

The control room layout is depicted schematically in Figure 9.

2.4.3 Experimental variables

For this experiment, independent and dependent variables were defined. The independent variables define the variation of conditions the subjects have to face. They reflect the hypotheses and the experimental design. The dependent variables define the measurements taken to validate these hypotheses inside the experimental design.

2.4.3.1 Independent variables

For this experiment, six independent variables were defined. They are listed below with their associated values.

Separation on staggered approach (dependent runway system 25L, 25R)

The required minimum staggered separation between aircraft on the localizer courses of the dependent runway system (25L, 25R) was varied systematically. Three different values were defined. Valid values are:

- Type A = 2.5 NM separation between 25R and 25L, staggered approach (today’s situation)
- Type B= 2.0 NM separation between 25R and 25L, staggered approach
- Type C= 1.5 NM separation between 25R and 25L, staggered approach

Complexity of the traffic samples

The complexity of the traffic samples was varied systematically. This variation serves two purposes. First for an increase of the arrival rate to occur, more traffic than exist today had to be available in the traffic samples. Second, more traffic was a prerequisite to validating controller activities in light of high traffic, high stress situations. Three different values were defined. Valid values were:

- Level 1 = about 55 A/C planned to land in an hour
- Level 2 = about 70 A/C planned to land in an hour

- Level 3 = about 90 A/C planned to land in an hour

Traffic mix

Depending on the time of the day, the traffic mix regarding the wake vortex categories changes in Frankfurt/M. Airport. Due to this, the traffic mix varied throughout the different scenarios. Two different values were defined. Valid values were:

- 30% of the traffic in the category heavy, 70% of the traffic in the category medium
- 40% of the traffic in the category heavy, 60% of the traffic in the category medium

Runway configuration

In addition to simulating today's runway system a synthetic third runway was tested. This item served the purpose of evaluating a parallel ILS approach on independent runways (as investigated by FAA in earlier experiments) together with the reduced staggered approach to two closely spaced parallel runways. Two different values were defined. Valid values were:

- 2 Runway Configuration: 25R and 25L (see Figure 2)
- 3 Runway Configuration: 25R, 25L and 26 (see Figure 3)

Wake Vortex Warning System

The use of a wake vortex warning system significantly influences the arrival rate for any condition. A wake vortex warning system indicating ideal conditions allows for utilising the minimum staggered radar separation defined above. If no wake vortex warning system is assumed to be operational, wake vortex separation has to be applied. This means, for example, a 5 nm staggered separation would be applied to a medium aircraft following a heavy aircraft instead of 2.5 NM, 2.0 NM or even 1.5 NM. Due to that fact, the presence of a reliable wake vortex warning system (WVWS) was assumed in some runs and not in others. Two different values were defined. Valid values were:

- Simulated WVWS
- No simulated WVWS

Update Rate of the PRM radar system

The update rate for the PRM display is of vital interest for the task of ensuring separation on final. A 1.0 second update rate provides more frequent aircraft information updates that a 4.8 seconds update rate (as it is used for the operational ASR8- and ASR9-systems). To demonstrate that, one scenario was run with that update rate, i.e. two different values were defined. Valid values were:

- 4.8 seconds
- 1 second

The Pick-up and Feeder controllers always worked with a 4.8 second update rate. The PRM controller ran a 1 second update rate. Only for scenario 1A (see section 2.4.5.2), the 4.8 seconds update rate for the PRM display was demonstrated.

Number of blunders/deviations

The number of blunders resp. deviations changed depending on the scenario and the runway configuration. Three different values were defined. Valid values were:

- 3 deviations for dual runway configuration runs
- 6 blunders/deviations for triple runway configuration runs
- blunders app. Every 3 minutes for the advanced PRM scenario (see below)

2.4.3.2 Dependent variables

Several measurements were taken during the experiments. They can be divided into subjective and objective data. The objective data were generated from automatic recordings inside the simulation system. The subjective data were gathered by means of questionnaires, observations and ratings. Data were collected while simulation runs were in progress, directly after a particular simulation run and at the end of the whole simulation program.

Computer generated data files

The generation of data files by the Target Generation Facility (TGF, see section 2.5) allowed a detailed examination of the performance of the ATC system in resolving blunders. Data files included information on parallel conflict frequencies, parallel conflict miss distances and aircraft position/track data.

Audio and Video recordings

Video and audio data were recorded at each controller position for all simulation runs, except for the warm-up runs. These video tapes were used for analyses of the identification of No Transgression Zone or Protection Zone entries and the verification of computer generated files.

Subjective analyses

Two different subjective analyses tools were used in order to assess the workload and stress of the controllers.

One system used was the NASA TLX system made available by the FAA. At the completion of each run, each controller was given a NASA Task Load Index (TLX) Rating Sheet. This sheet asked the controllers to evaluate their experiences during the run on six different dimensions that have been shown to contribute to workload. These dimensions are: Mental demand, physical demand, temporal demand, performance, effort and frustration (refer to Table 1). After the simulation was completed, the controllers were then asked to determine which NASA TLX factors contributed to their workload the most. This data was used to determine weights for the ratings given on the rating scale sheets. NASA TLX scores range from 0 to 100.

Dimension	Endpoints	Description
Mental Demand	Low/High	How much mental and perceptual demand was required during this task?
Physical	Low/High	How much physical activity was required for this task?

Demand		
Temporal Demand	Low/High	How hurried or rushed was the pace of this task?
Performance	Good/Poor	How successful were you in accomplishing your task?
Effort	Low/High	How hard did you have to work to accomplish your level of performance?
Frustration	Low/High	How insecure, frustrated, and annoyed were you during this task?

Table 1 : NASA Task Load Index Description

The second system was the WAK (Workload Assessment Keypad). The WAK is a device with keys labelled 1 through 7 on its surface, corresponding to a rating scale of 1 to 7, with 1 meaning minimal workload and 7 meaning maximum workload. The purpose of the WAK is to obtain workload information from test participants at specified intervals throughout a test scenario, or run. It allows for analyses of workload on a more continuous basis than that obtained from post-run workload assessment tools. The WAK is programmed to illuminate the scale of numbers and sound an aural alarm at each specified period of time. For this simulation, the WAKs were programmed to light and sound at 10-minute intervals during each one-hour run. At each prompt, the controllers responded by pressing numbers corresponding to the workload they perceived at that moment in time. Since most runs ended just short of one hour, data were collected on five intervals (i.e., 10, 20, 30, 40, and 50 minutes into scenarios), and in some cases, four intervals. The intent of the WAKs was to improve the evaluation of controller workload during the simulation. If the subject missed a cue to answer in about 20 seconds, the rating was automatically set to 7. By this rating, a quasi continuous rating f a simulation run in progress was possible.

Questionnaires

Questionnaires used were a post simulation questionnaire to assess the subjective impression of all subjects after finishing the simulation program and a biographical questionnaire for a classification of the subjects. Both questionnaires were submitted in the final debriefing at the end of each simulation week.

Debriefings

Extensive debriefings were carried out after each of the simulation runs. All remarks were noted, and for analyses purposes, the relevant remarks were extracted and correlated qualitatively to other subjective and objective findings.

2.4.4 Subjects

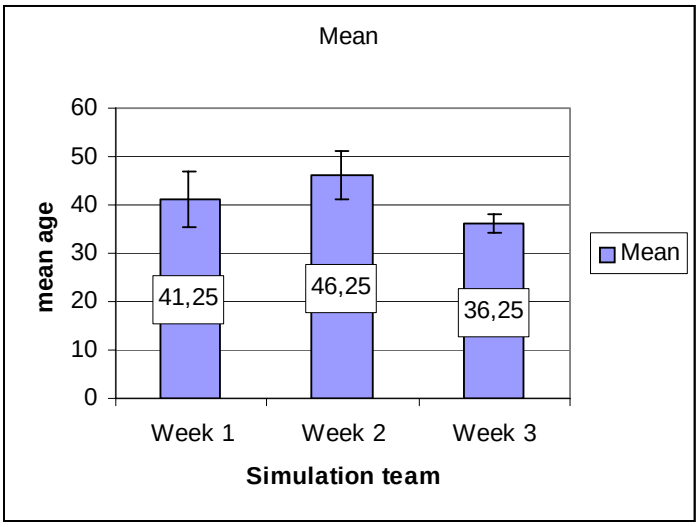


Figure 7: Average age of the test teams

A total of 12 air traffic controllers with experience in simultaneous parallel approach operations participated as subjects. They were selected from the FMF2 subdivision of the DFS Central Region (Frankfurt Approach Control Office). They had experience both for tower and approach control. The average age was 41,25 years (S.D. = 9,23).

The 12 controllers were randomly grouped to three simulation teams. Each of the teams performed a one week simulation program as described in section 2.4.6.1. The average age of each of the teams is depicted in Figure 7. It shows that the average varied significantly. The team of week 3 was the most homogenous and the youngest team according to age. The week 2 team was the oldest one.

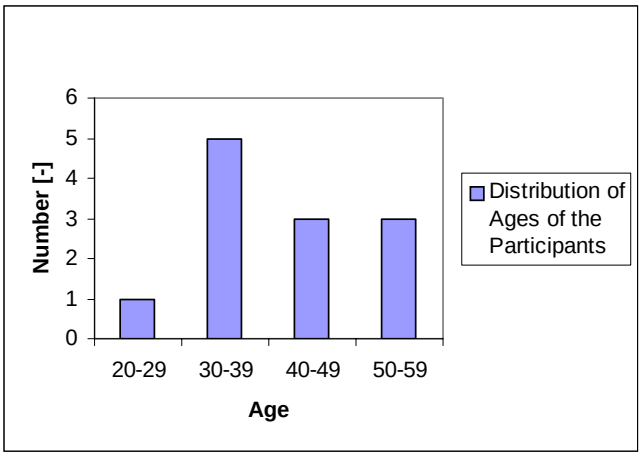


Figure 8: Distribution of Ages of the Participants

Grouping the subjects by age independently from their grouping to the team order results in the variation depicted in Figure 8. This figure demonstrates, that most of the subjects were older than 30 years. In addition, 9 of the 12 subjects had a background as controllers for Frankfurt Approach and Tower only, whereas three of the controllers had experiences at other DFS locations as well as at the Frankfurt approach site. Taken together, these facts imply two important points:

1. The subjects have a long experience in controlling the Frankfurt approach and tower airspace.

2. The subjects were trained initially before the DFS COMPAS system[2] was introduced. It indicates, that all subjects were able to work without the presence of a sequencing tool, which is available at Frankfurt approach. This system was not available for these experiments at the FAA.

2.4.5 Airspace and scenarios

2.4.5.1 Airspace

The Frankfurt TMA airspace structure was used for the simulation. Original airspace video maps were taken and analyzed for implementation into the TGF simulation system. They were presented on all pick-up and feeder positions. In a fine-tuning phase at the FAA, together with DFS experts, the airspace video maps were optimized. As a result, video maps similar to the maps used in operation at Frankfurt approach were presented to the controllers. This was validated in the initial debriefings of the warmup runs as well as in the post simulation questionnaires.

For the PRM Scope the localizer course for both runways and the runways themselves were presented. On the localizer course, dashed lines and space lines with lengths of 1 NM each were used (see Figure 6). No additional airspace structure was presented on this position.

2.4.5.2 Traffic Samples

The traffic samples were based on data recorded by the DFS Lage- und Informationszentrum LIZ. The data was recorded in summer 1996 and 1997. Some modifications were introduced in order to meet the requirement of having 30% resp. 40% of heavy aircraft (see section 2.4.3.1). Departing aircraft from RWY 18 were also programmed into the traffic scenarios to generate a more realistic ATC environment. Departing traffic was assumed to be clear by procedures from arrival traffic, it was not under control. No overflights were included in the scenarios.Basically, two scenarios were generated: a scenario with 90 aircraft and 30% heavy traffic and another one with 90 aircraft and 40% heavy traffic. Derived from these two scenarios, the scenarios with 70 and 55 aircraft (see section 2.4.3.1) and the warmup scenarios were generated. The advanced PRM scenario was a hypothetical scenario were only the callsigns and the aircraft parameters were taken from the original LIZ data. Table 2 provides an overview of the different scenarios performed during the simulation phase, counterbalanced specifically to measure the independent variables of interest.

Duration [min.]	Name	Description	Scenario code
60	Reference run	Separation 2.5 NM, RWY 25L+25R, no simulated WVWS, Level 1, scenario duration 60 minutes, radar update rate:4.8 s	1A

[2] The *Computer-oriented Metering and Spacing system COMPAS* is an approach sequencing tool introduced in 1989 as test system. It is used at Frankfurt approach and tower since 1991 operationally.

Duration [min.]	Name	Description	Scenario code
60	PRM run 1	Separation 2.0 NM, RWY 25L+25R, no simulated WVWS, Level 1, scenario duration 60 minute, radar update rate:1s	1B
60	PRM run 2	Separation 1.5 NM, RWY 25L+25R, no simulated WVWS, Level 1, scenario duration 60 minutes, radar update rate:1s	1C
60	PRM run 3	Separation 2.0 NM, RWY 25L+25R, simulated WVWS, Level 2, scenario duration 60 minutes, radar update rate:1s	2B
60	PRM run 4	Separation 1.5 NM, RWY 25L+25R, simulated WVWS, Level 2, scenario duration 60 minutes, radar update rate:1s	2C
60	PRM run 5	RWY 25R+25L+26, separation 2.0 NM between 25L and 25R and independent traffic on the runway 26, simulated WVWS, Level 3, scenario duration 60 minutes, radar update rate:1s	3B
60	PRM run 6	RWY 25R+25L+26, separation 1.5 NM between 25L and 25R and independent traffic on the runway 26, simulated WVWS, Level 3, scenario duration 60 minutes, radar update rate:1s	3C
45	Warm up run A	Separation 2.0 NM, RWY 25L+25R, simulated WVWS, Level 1, scenario duration 45 minutes, radar update rate:1s	4B
45	Warm up run B	Separation 2.0 NM, RWY 25L+25R+26, simulated WVWS, Level 2 , scenario duration 45 minutes, radar update rate:1s	5B
30	Advanced PRM scenario	Separation 2.0 NM, , RW 25L+25+26, blunder every 3 minutes, Level 1, scenario duration 30 minutes, radar update rate:1s	6B

Table 2:Description of the scenarios related to the experimental design and the independent variables

For scenarios 1A, 1B, 1C, 2B, 2C, 3B, 3C, 4B and 5B, six blunders were scripted per 1 hour run. This scenario aimed at studying the reaction of the PRM controller under the occurrence of unexpected blunders. Scenario 6B intended to focus on the extreme workload of the PRM controller under the pressure of a large number of blunders. In this scenario blunders occured approximately within 3 minutes of each other.

2.4.6 Procedure of the experiments

The simulation was conducted with 3 groups of 4 controllers from Frankfurt (APP) (see section 2.4.4). One group of 4 controllers was working per week. Each scenario defined in Table 2 was carried out twice, once with 30% heavy traffic and once with 40% heavy traffic.

2.4.6.1 Example of Time Schedule

Time	Action (scenario code)	Run Number	Subjects	Responsible
	Briefing ***Separation 2.0 NM***		Controllers	Test manager DFS, Test manager FAA

Time	Action (scenario code)	Run Number	Subjects	Responsible
8:00-8:30				
8:30-9:30	PRM run 1 (**1B**) 30% Heavy 3 deviating A/C from centerline	4	Controllers Pilots	Test manager DFS, Test manager FAA
9:30-9:45	Controller Questionnaire		Controllers	
9:45-10:45	PRM run 3 (**2B**) 30% Heavy 3 deviating A/C from centerline	5	Controllers Pilots	Test manager DFS, Test manager FAA
10:45-11:00	Controller Questionnaire		Controllers	
11:00-12:00	Lunch break			
12:00-12:15	Briefing ***Three runways***		Controllers	Test manager DFS, Test manager FAA
12:15-13:15	PRM run 5 (**3B**) 40% Heavy 6 blunders	6	Controllers Pilots	Test manager DFS, Test manager FAA
13:15-13:30	Controller Questionnaire		Controllers	
13:30-14:30	PRM run 1 (**1B**) 40% Heavy 3 deviating A/C from centerline	7	Controllers Pilots	Test manager DFS, Test manager FAA
14:30-14:45	Controller Questionnaire		Controllers	
14:45-15:00	Break			Test manager DFS, Test manager FAA
15:00-16:00	PRM run 3 (**2B**) 40% Heavy 3 deviating A/C from centerline	8	Controllers Pilots	Test manager DFS, Test manager FAA
16:00-16:15	Controller Questionnaire		Controllers	

Table 3 : Day 2 of the Simulation

2.5 Simulation system

2.5.1 Experimental Apparatus.

The William J. Hughes Technical Center in Atlantic City, NJ, provides an environment for performing real time simulations using a Precision Runway Monitoring System (PRM). Tests can be conducted to collect data on controller and pilot performance issues that cannot be measured in the operational environment.

2.5.1.1 Target Generation Facility (TGF) Laboratory

The TGF is an advanced simulation system designed to support testing of current and future ATC systems at the William J. Hughes Technical Center. For this simulation, the functionality of

the TGF was divided into three subsystems: *pseudo pilot*, *target generation*, and *development and support*.

The *pseudo pilot workstations* (PPW) are computer workstations containing a communication system that provide an audio interface with the monitor controllers. Pseudo pilots use the PPWs to fly the simulated aircraft and command them in accordance with the controller instructions.

The *target generation* (TG) subsystem consists of a TG chassis and an external interface (EI) chassis. The TG performs with known flight plans all modelling within the TGF and correlated dynamic data, such as aircraft state vectors and radar performance. The EI is responsible for creating the exact form and content of the digitised radar messages sent to the ATC system. The TGF includes long and short range radar sensors, controlled airspace, weather conditions, air traffic, and aircraft performance.

The *development and support* subsystem provides the post-exercise data reduction and analyses capabilities.

2.5.1.2 Radar System and Controller Displays

The controller displays for the pick-up and feeder position were SONY 2kx2k rasterscan displays. The appearance of the display software was to be made as similar to the Frankfurt/M. approach conditions as possible. However, some differences remained. While it was possible to adopt the airspace video maps, the display logic of the software showed a significant difference to the Frankfurt/M. approach conditions. A data block for a target was presented only if the aircraft was under control of the particular position. If an aircraft was transferred to the next position (pick-up ➔ feeder, feeder ➔ PRM), the data block was no longer displayed. This difference caused some anxiety for the subjects. However by training it was possible to overcome this shortcoming more or less.

The PRM Controller used a prototype of the components of the PRM system located in the System Display Laboratory at the William J. Hughes Technical Center. The components consisted of final monitor aid (FMA) displays and a simulated electronic scanning beacon sensor with a 1.0 second update rate.

The control room layout indicating the different positions is depicted schematically in Figure 9.

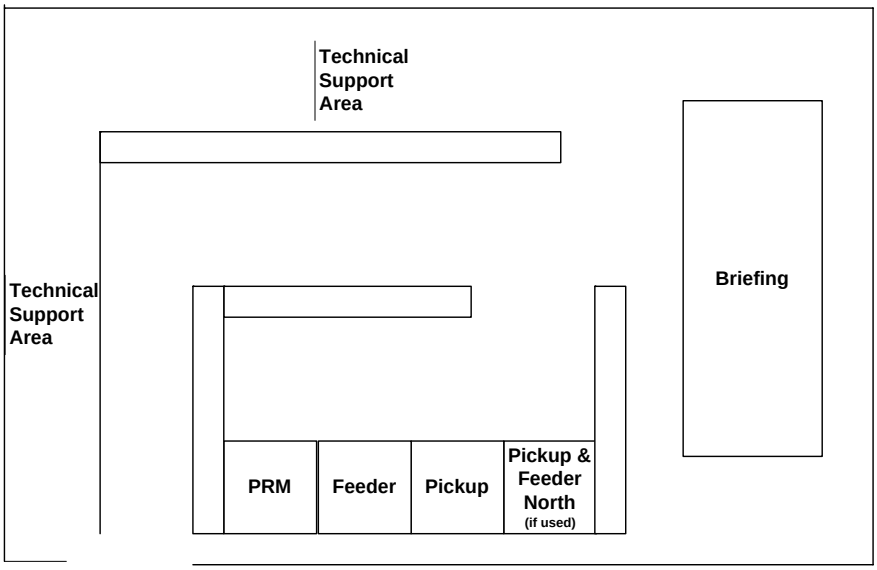


Figure 9: Schematic view on the control room layout

2.5.2 Support personnel

2.5.2.1 Test Manager

The test manager FAA and the test manager DFS together were responsible for a smooth and successful execution of the simulation program. The test manager DFS was provided by the DFS simulation subdivision (SES) and was supported by the head of the controller DFS team.

2.5.2.2 Pseudo-Pilots

The FAA provided, at no cost, the FAA pseudo pilots (8-10). The pilot operational advisor took part in the briefings, in order to become familiar with the procedures used in each scenario and to avoid errors made by the pseudo-pilots.

The pseudo pilots controlled blundering aircraft at the instruction of the test manager and responded to controller instructions (except during non-responding blunders) by entering aircraft headings and/or altitude changes.

2.5.2.3 Blunder Test Manager

The blunder test manager was responsible for initiating blunders based upon the information provided by the experimental design and his own judgement.

2.5.2.4 Controller technical observer

The controller technical observer documented discrepancies between issued control instructions and actual aircraft responses, alerted responsible parties to any problems that occurred during the runs (computer failure, stuck microphone), and prepared a controller technical assessment at the end of the runs.

2.5.2.5 Pseudo-Pilot technical observer

The pseudo-pilot technical observer documented errors made by the pseudo pilots during the runs and participated to the controller technical assessment at the end of the runs.

3 Simulation analyses

It should be kept in mind that the results of this study should not be extrapolated to situations that contain variables other than those tested in this study.

3.1 Simulation Execution Evaluation

Thanks to a minutely detailed preparation of the simulations by the FAA Team and the DFS Team, the schedule was respected, the different runs planned each day were executed on time and the motivation of the different partners was at the highest. Regarding the fact that the pseudo pilots had to be trained especially for the Frankfurt/Main approach procedures and phraseology, one will understand that the reaction of the pseudo pilots was not without a few errors. Nevertheless, no scenario was significantly modified by those mistakes.

3.2 Objective analyses

The objective analyses was based on data collected by the TGF Team. The data provided by the TGF team were recorded during all runs made over the three weeks of tests. The runs used for the evaluations, which exclude the warm-up runs and the advanced PRM scenarios, had duration of about 60 minutes. About 15 minutes were necessay at the beginning of each scenario to build up the planned amount of traffic on the displays. Consequently, most of the analyses were carried out over a period of 30 minutes, beginning with the first aircraft landing at Frankfurt/Main (25R or 25L or 26).

3.2.1 ILS loading

3.2.1.1 Two Runway Configuration

This evaluation allowed for the assessment of the number of landings which occured during the different runs. An important point is to compare the number of landings per week (Simulation Team 1, 2 or 3) and per minimum radar separation (2.5 NM, 2.0 NM or 1.5 NM). The minimum radar separation is the separation the controllers aimed at implementing between two aircraft landing on 25 (25R or 25L). As mentioned in section 3.2,. the analyses were carried out over a period of 30 minutes from the time the first aircraft landed in the scenario.

The first set of analyses show the mean number of landings and the standard deviations during weeks 1, 2 and 3 considering the different separation between the aircraft established on final (2.5 NM, 2.0 NM or 1.5 NM). Run 03 of each week corresponded to a separation of 2.5 NM. Only 1 run was simulated with the reference separation 2.5 NM which means that no standard deviation was calculated for the 2.5 NM separation. The run 04, 05, 07 and 08 (see Table 3) corresponded to a separation of 2.0 NM and the run 13, 14, 15 and 16 corresponded to a separation of 1.5 NM . For the simulation team 1, the mean number of landings ranged from 25 (2.5 NM) to 26.75 (2.0NM) and to 31.25 (1.5 NM), with a standard deviation of 0.83 for 2.0 NM and 1.79 for 1.5 NM. For the simulation team 2, the mean number of landings ranged from 24 (2.5 NM) to 25.75 (2.0NM) and to 28.25 (1.5 NM), with a standard deviation of 2.28 for 2.0 NM and 3.56 for 1.5 NM. For the simulation team 3, the mean number of landings ranged from 22 (2.5 NM) to 25.5 (2.0 NM) and to 27 (1.5 NM), with a standard deviation of 4.15 for 2.0 NM and

5.61 for 1.5 NM. Figure 10 depicts the mean number of landings and the Standard Deviation respectively for Week 1, Week 2 and Week 3.

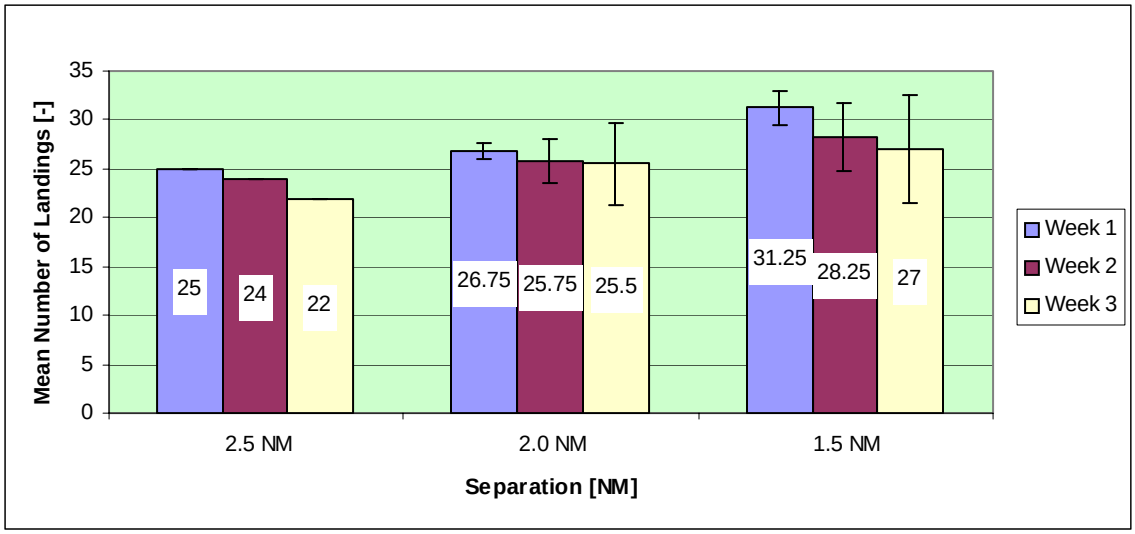
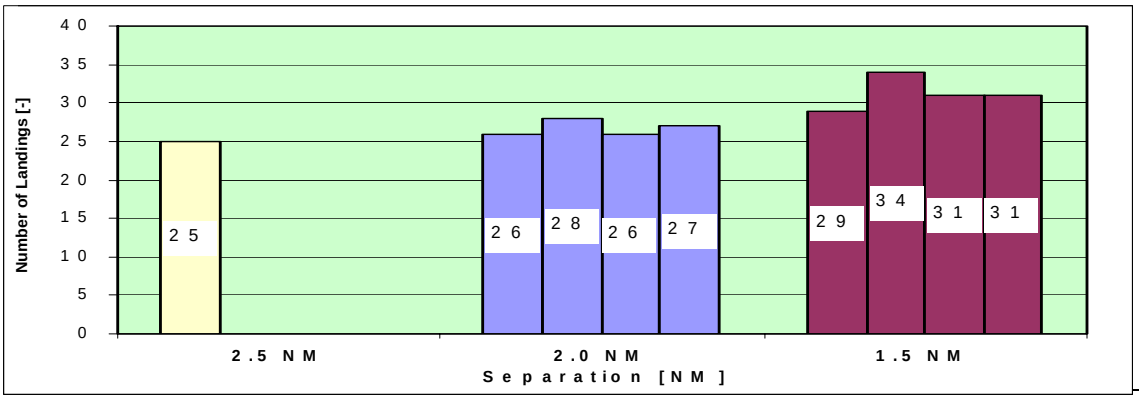


Figure 10 : Mean number of landings and Standard Deviation (Week 1, Week 2,and Week 3) (30 Min. analysis)

The following set of analyses provide the number of landing per week and per run. It aims at giving a more detailed overview of the previous results. As mentionned before, only one scenario (reference scenario) was conducted with a 2.5 NM separation. In this scenario, the traffic mix contained 30% heavy and no Wake Vortices Warning System (WVWS) was simulated This means that the controller had to establish additional separation between the aircraft from the same runway related to their weight class. In the 1st and 3rd runs with 2.0 NM separation and with 1.5 NM separation, no Wake Vortices Warning System was simulated (see Table 2). In the 1st and 2nd runs with 2.0 NM and with 1.5 NM, the traffic mix contained 30% heavy, and in the 3rd and 4th run with 2.0 NM and 1.5 NM, the traffic mix contained 40% heavy . Figure 11 shows that for the simulation team 1, the number of landings in the 2.0 NM separation configuration varied from 26 to 28 and in the 1.5 NM separation configuration, the number of landings varied from 29 to 34. Figure 12 shows that for the simulation team 2, the number of landings in the 2.0 NM separation configuration varied from 22 to 28 and in the 1.5 NM separation configuration, the number of landings varied from 23 to 33. Figure 13 shows that for the simulation team 3, the number of landings in the 2.0 NM separation configuration varied from 20 to 30 and in the 1.5 NM separation configuration, the number of landings varied from 21 to 34.



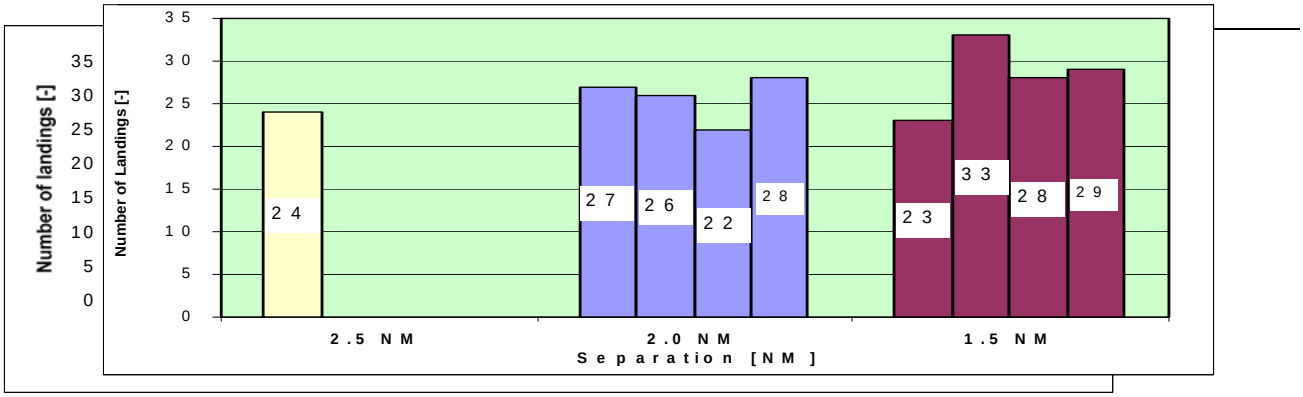


Figure 11: Number of landings per Run (Week 1) (30 Min. analysis).

Figure 12 : Number of landings per Run (Week 2) (30 Min. analysis)

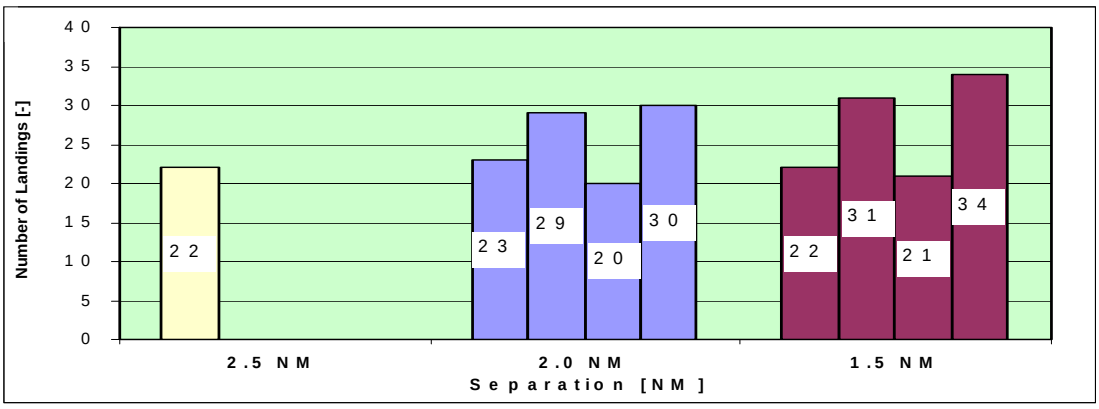


Figure 13 : Number of landings per Run (Week 3) (30 Min. analysis)

In order to compare the influence of the different separation (2.5 NM, 2.0 NM or 1.5 NM) on the different teams, the following analyses shows the number of landing per week at each given separation. Figure 14 shows that for a separation equal to, 2.5 NM (reference scenario), the number of landings varied from 25 (week 1) to 24 (week 2) to 22 (week 3). Figure 15 shows that for a separation equal to 2.0 NM, the number of landings varied from a mean value of 26.75 (week 1) to 25.75 (week 2) to 25.5 (week 3). Figure 16 shows that for a separation equal to 1.5 NM, the number of landings varied from a mean value of 31.25 (week 1) to 28.25 (week 2) to 27 (week 3). The following figures depict the number of landings for the separation 2.5 NM, 2.0 NM and 1.5 NM.

Figure 14 : Number of landings (separation=2.5 NM) (30 Min. analysis)

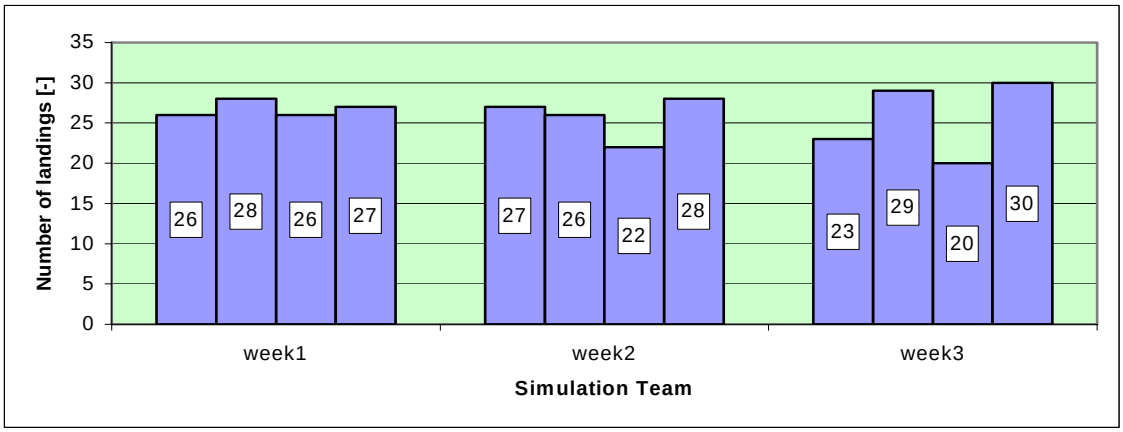


Figure 15 : Number of landings (separation=2.0 NM) (30 Min. analysis)

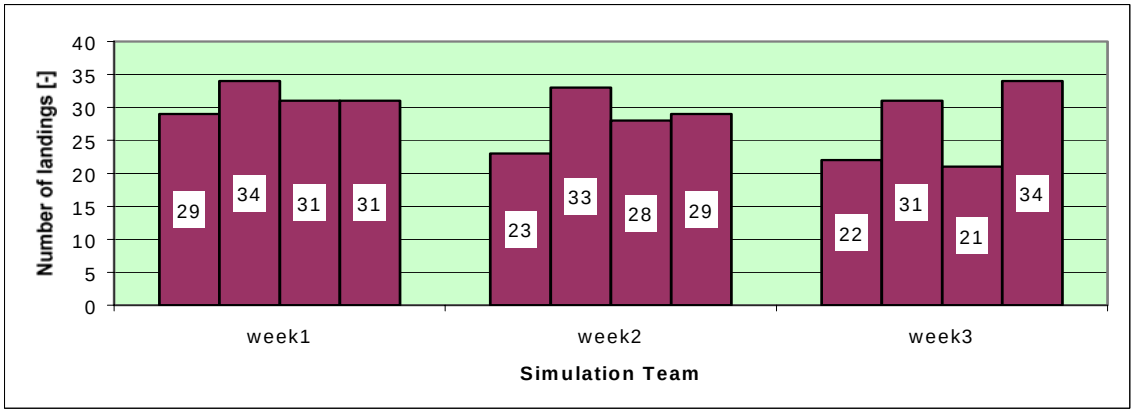


Figure 16 : Number of landings (separation=1.5 NM) (30 Min. analysis)

Taking the mean values over the 3 weeks for each separation, it appears that the mean number of landings in the 2.5 NM configuration was 23.67 with a standard deviation over the three simulation teams of 1.25. The mean number of landings in the 2.0 NM configuration was 26.00 and the standard deviation over the three simulation team was 0.54. Finally, the mean number of landing in the 1.5 NM configuration was 28.83 and the standard deviation over the three simulation team was 1.78. This means that with a 2.0 NM configuration the increase in the number of landings compared to the reference scenario (2.5 NM) was 9%, and with the 1.5 NM configuration, the increase was 18%. The Figure 17 depicts the mean number of landings for each separation over the three weeks.

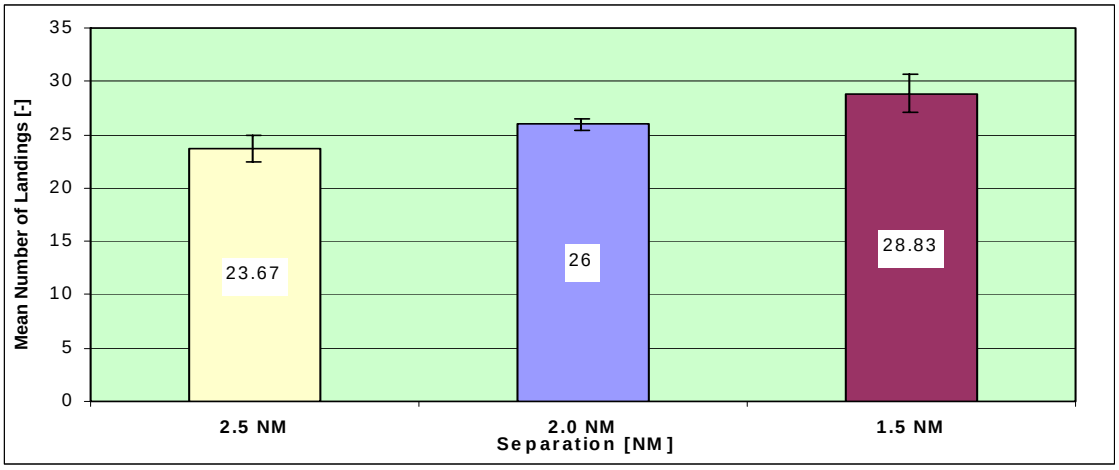


Figure 17 : Mean number of landings for each separation over the 3 Weeks (30 Min. analysis)

During the analyses, it was noted that the number of landings observed under the use of a Wake Vortex Warning System (WVWS) appeared to be higher than without the WVWS. While further investigation is necessary to confirm the influence of the Wake Vortex Warning System on the number of landings under the use of a PRM system, one can consider the results of the evaluation to be worth being analyzed. Figure 18 depicts the mean number of landings over the three weeks with the WVWS and without WVWS.

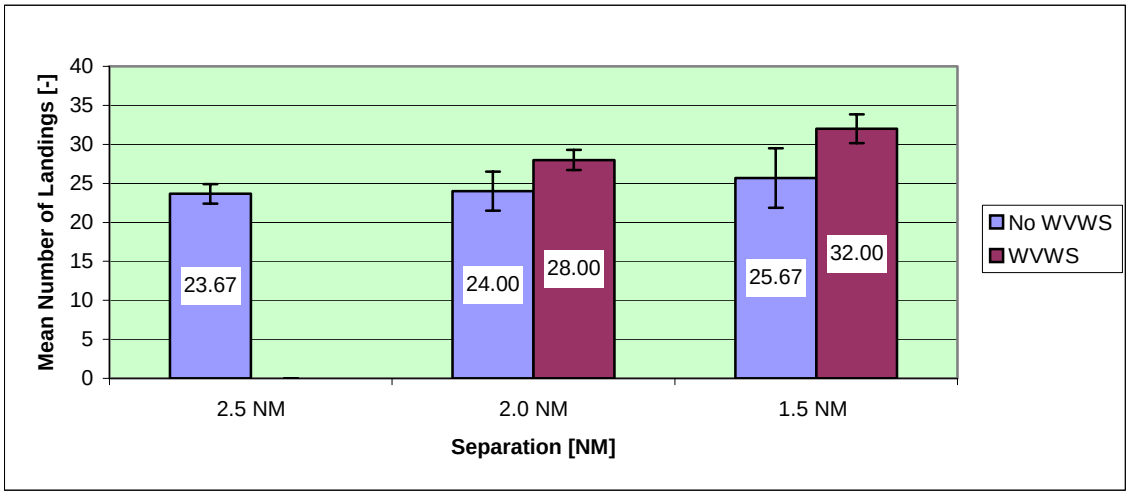


Figure 18 : Influence of a WVWS on the landing rate (30 Min. analysis)

As can be seen in Figure 18, without a WVWS the mean number of landings increased with each reduction in the separation from 23,67 for 2.5 NM (reference scenario), to 24,00 for 2.0 NM to 25.67 for 1.5 NM. With the use of a WVWS, the increase in the number of landings is even more outstanding. Analyses revealed that the number of landings increased from 23.67 for 2.5 NM (reference scenario without WVWS) to 28.00 for 2.0 NM to 32.00 for 1.5 NM. Thus, in the case of 2.0 NM separation, the number of landings with the WVWS was **16.67%** higher than without the WVWS, and in the case of 1.5 NM separation, the number of landings with the WVWS was **24.66%** higher than without the WVWS.

As could be seen in all the previous figures, the runs were split into 3 categories : 2.5 NM, 2.0 NM, and 1.5 NM minimum radar separation between the aircraft on final approach at Frankfurt/Main. This separation was made by the controllers alone, without the help of any arrival management system[3]. The following figures depict the mean values of the time duration between two landings on 25 (either 25R or 25L) and an approximate evaluation of the separation between two aircraft landing on 25 (either 25R or 25L) compared with the minimum radar separation assuming that the speeds of the aircraft from the scenario in short final were 140 kts .

The minimum radar separation is the separation the controllers aimed at implementing between two aircraft landing on 25 (25R or 25L). Figure 19 shows that for Simulation Team 1, in the case of a 2.5 NM minimum radar separation, the mean duration between 2 landings was 1:07 minutes. In the case of a 2.0 NM minimum radar separation, the mean duration between 2 landings ranged from 0:59 minutes to 1:07 minutes. And, in the case of a 1.5 NM minimum radar separation, the mean duration between 2 landings ranged from 0:50 minutes to 1:00 minutes. Figure 20 depicts for the Simulation Team 1, the calculated mean distance between 2 landings on 25. In the case of a 2.5 NM minimum radar separation, the mean distance between 2 aircraft landing on 25 was 2.72 NM, in the case of a 2.0 NM minimum radar separation, the mean distance ranged from 2.21 NM to 2.7 NM. And in the case of a 1.5NM minimum radar separation, the mean distance ranged from 1.93 NM to 2.33 NM. The mean distance between 2 aircraft landing on 25 over all the runs per minimum radar separation (2.5 NM, 2.0 NM and 1.5 NM) is depicted in Figure 26.

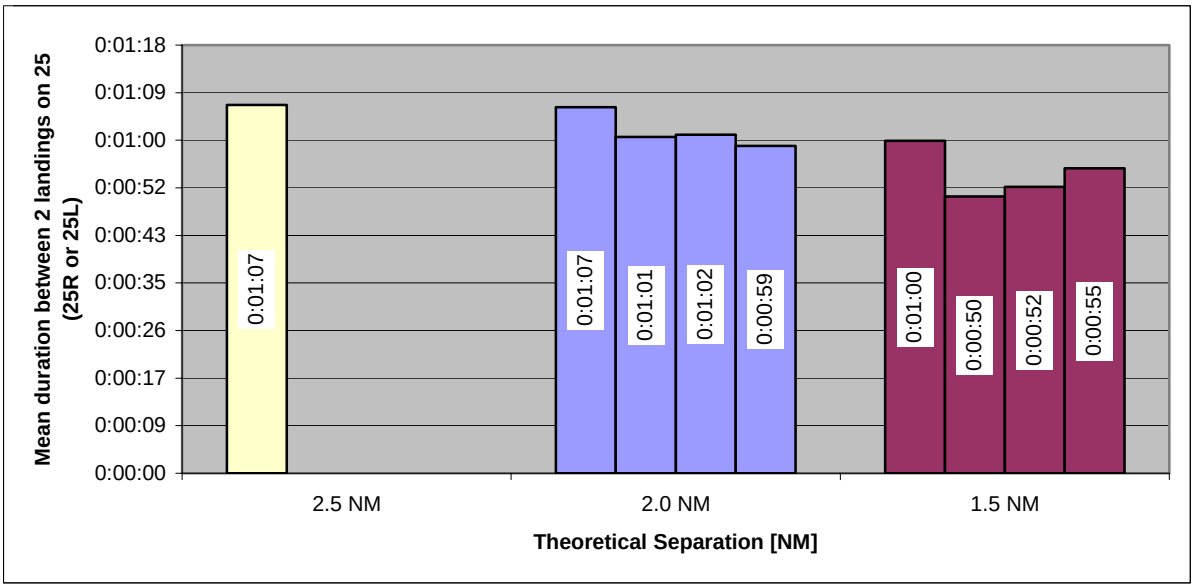


Figure 19 : Mean duration between 2 landings on 25 (Week 1) (30 Min. analysis)

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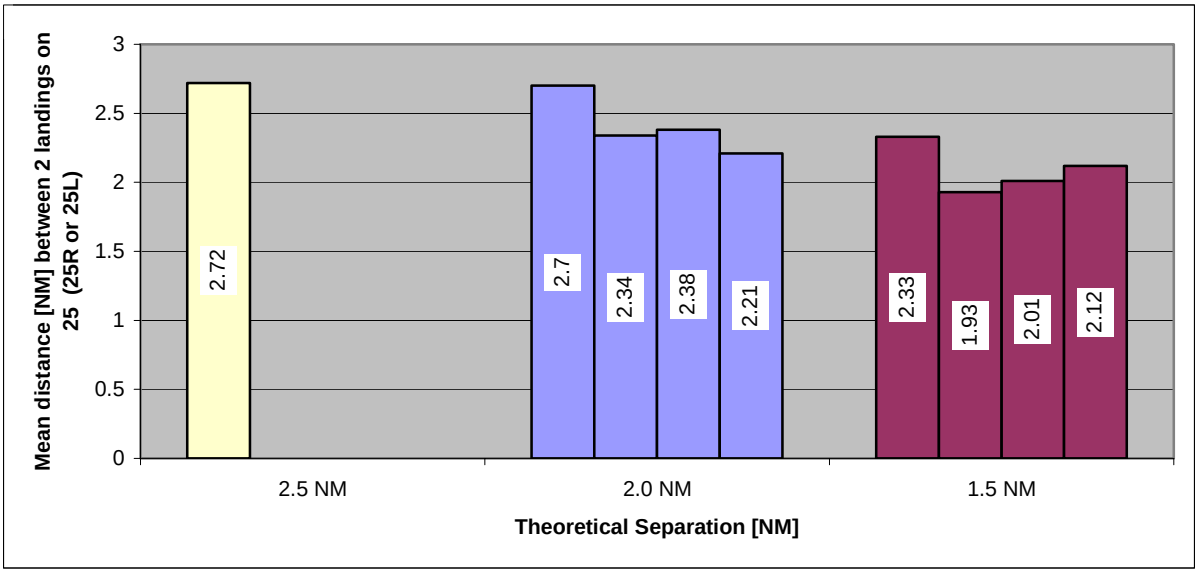
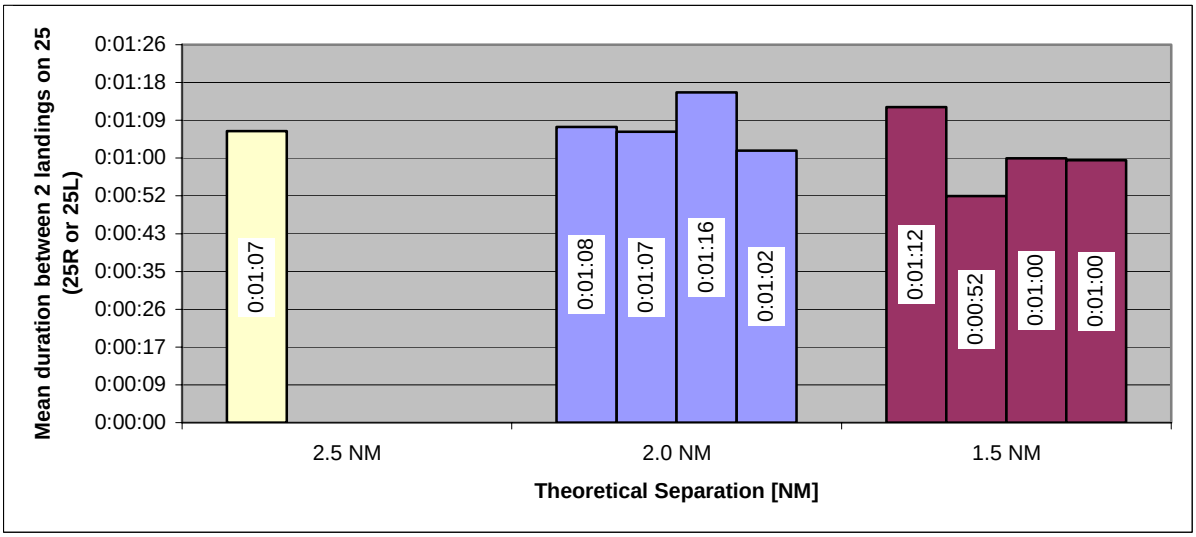


Figure 20 : Mean distance [NM] between 2 landings on 25 (week1) (30 Min. analysis)

Figure 21 shows that for Simulation Team 2, in the case of a 2.5 NM minimum radar separation, the mean duration between 2 landings was 1:07 minutes. In the case of a 2.0 NM minimum radar separation, the mean duration between 2 landings ranged from 1:02 minutes to 1:16 minutes. And in the case of a 1.5 NM minimum radar separation, the mean duration between 2 landings ranged from 0:52 minutes to 1:12 minutes. Figure 22 depicts for the Simulation Team 1, the calculated mean distance between 2 landings on 25. In the case of a 2.5 NM minimum radar separation, the mean distance between 2 aircraft landing on 25 was 2.72 NM. In the case of a 2.0 NM minimum radar separation, the mean distance ranged from 2.34 NM to 2.83 NM. And in the case of a 1.5NM minimum radar separation, the mean distance ranged from 2.01NMto 2.79 NM. The mean distance between 2 aircraft landing on 25 over all the runs per minimum radar separation (2.5 NM, 2.0 NM and 1.5 NM) is depicted in Figure 26.



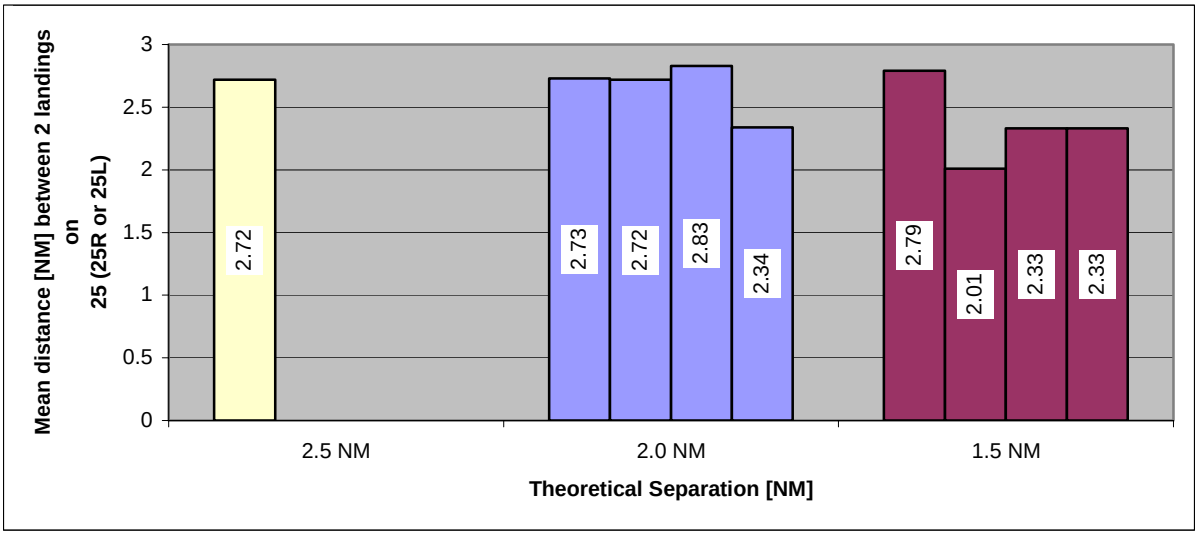
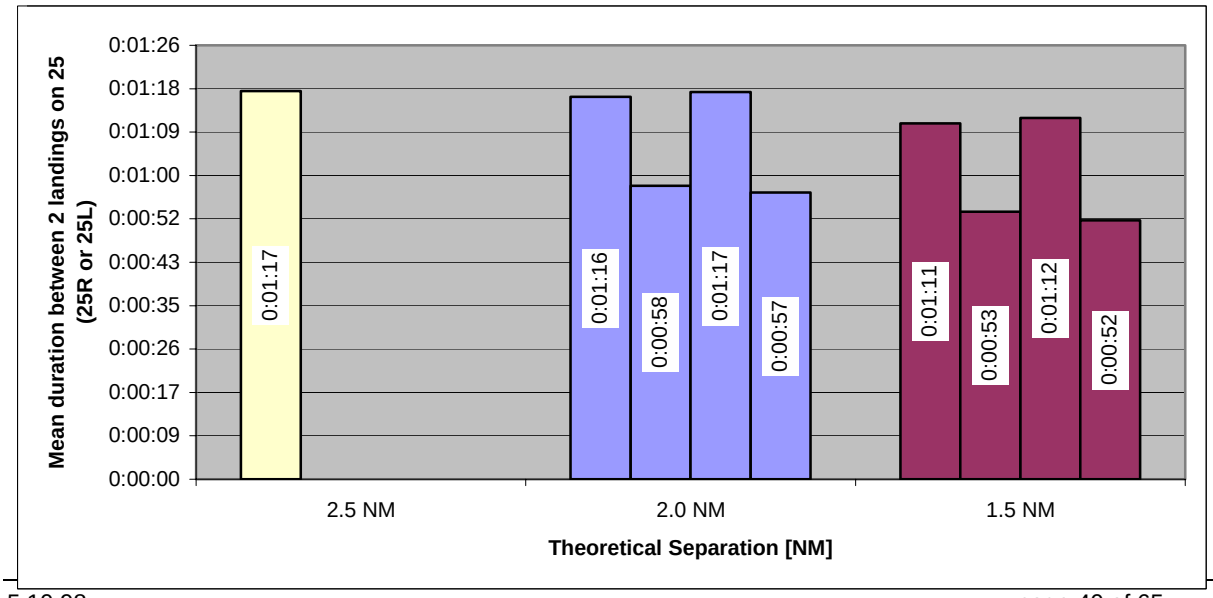


Figure 21 : Mean duration between 2 landings on 25 (Week 2) (30 Min. analysis)

Figure 22 : Mean distance [NM] between 2 aircraft landing on 25 (Week 2) (30 Min. analysis)

Figure 23 shows that for Simulation Team 2, in the case of a 2.5 NM minimum radar separation, the mean duration between 2 landings was 1:07 minutes. In the case of a 2.0 NM minimum radar separation, the mean duration between 2 landings ranged from 0:57 minutes to 1:17 minutes. And in the case of a 1.5 NM minimum radar separation, the mean duration between 2 landings ranged from 0:52 minutes to 1:12 minutes. Figure 24 depicts for the Simulation Team 1, the calculated mean distance between 2 landings on 25. In the case of a 2.5 NM minimum radar separation, the mean distance between 2 aircraft landing on 25 was 2.93 NM. In the case of a 2.0 NM minimum radar separation, the mean distance ranged from 2.18 NM to 2.93 NM. And in the case of a 1.5NM minimum radar separation, the mean distance ranged from 2.01 NM to 2.79 NM. The mean distance between 2 aircraft landing on 25 over all the runs per minimum radar separation (2.5 NM, 2.0 NM and 1.5 NM) is depicted in Figure 26.



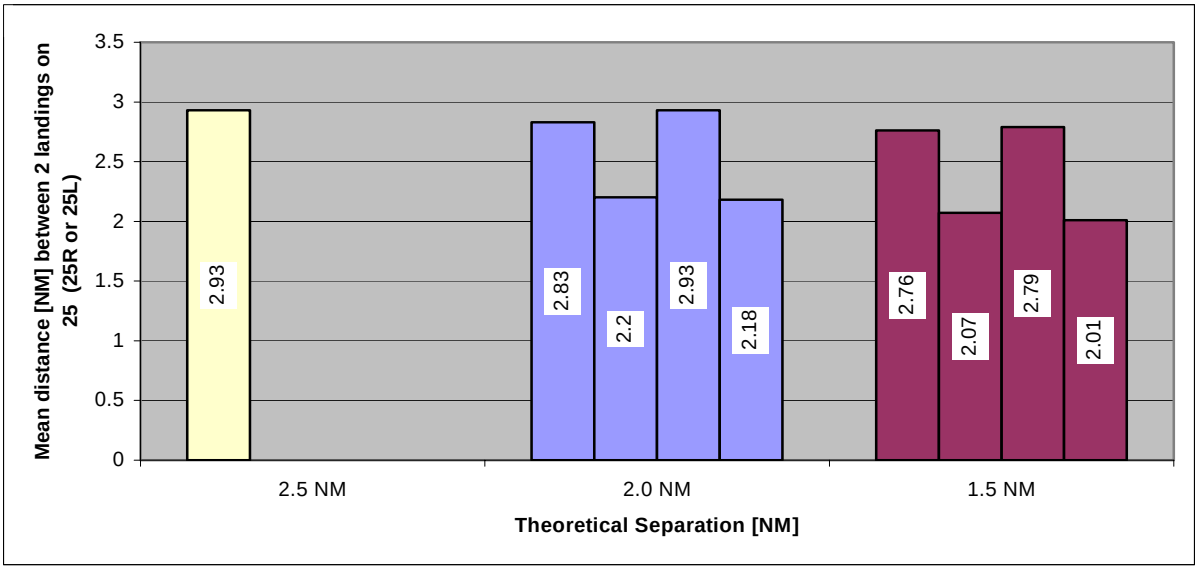


Figure 23 : Mean duration between 2 landings on 25 (Week 3) (30 Min. analysis)

Figure 24 : Mean distance between 2 aircraft landing on 25 (Week 3) (30 Min. analysis)

Figure 25 depicts the mean distance between 2 landings on 25 per week. Analyses of the data revealed that for the 3 Simulation Teams, the mean distance between 2 aircraft landing on 25 decreased with each reduction in minimum radar separation. For the Simulation Team 1, the mean separation ranged from 2.72 NM, to 2.41 NM to 2.10 NM. For the Simulation Team 2, the mean separation ranged from 2.76 NM to 2.66 NM to 2.37 NM. For the Simulation Team 3, the mean separation ranged from 2.93 NM to 2.54 NM to 2.41 NM.

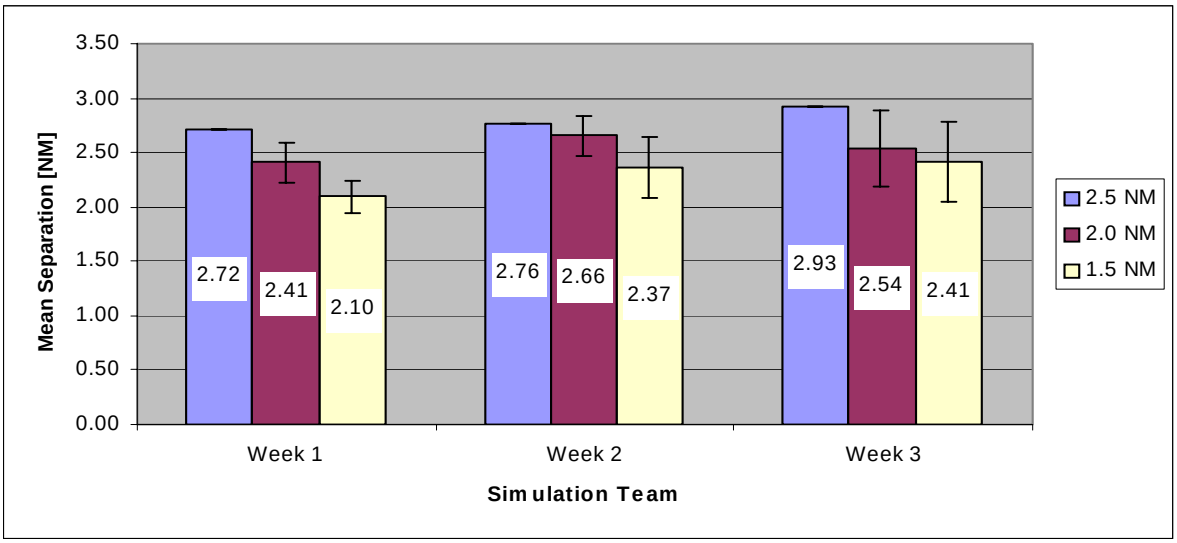


Figure 25 : Mean distance between 2 landings on 25 (per Week) (30 Min. analysis)

Figure 26 shows that the mean distance between 2 landings on 25 per minimum radar separation ranged from 2.72 NM to 2.93 NM when the minimum radar separation was 2.5 NM, from 2.41 NM to 2.66 NM when the minimum radar separation was 2.0 NM and from 2.10 NM to 2.41 NM when the minimum radar separation was 1.5 NM. Figure 27 shows the mean values of the mean distances between 2 landings on 25 over the 3 Simulation Teams. For a minimum radar separation of 2.5 NM, the mean distance between 2 landings on 25 was 2.80 NM with a standard deviation of 0.09 NM. For a minimum radar separation of 2.0 NM, the mean distance between 2 landings on 25 was 2.53 NM with a standard deviation of 0.10 NM. And for a minimum radar separation of 1.5 NM, the mean distance between 2 landings on 25 was 2.29 NM with a standard deviation of 0.14 NM .

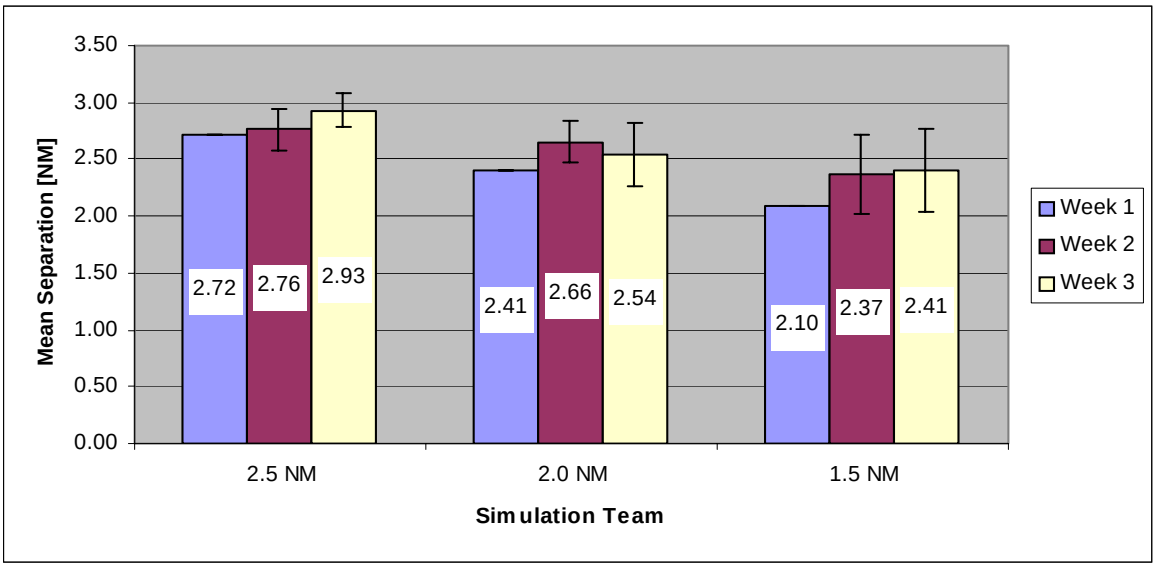


Figure 26 : Mean distance between 2 landings on 25 (per Minimum radar separation) (30 Min. analysis)

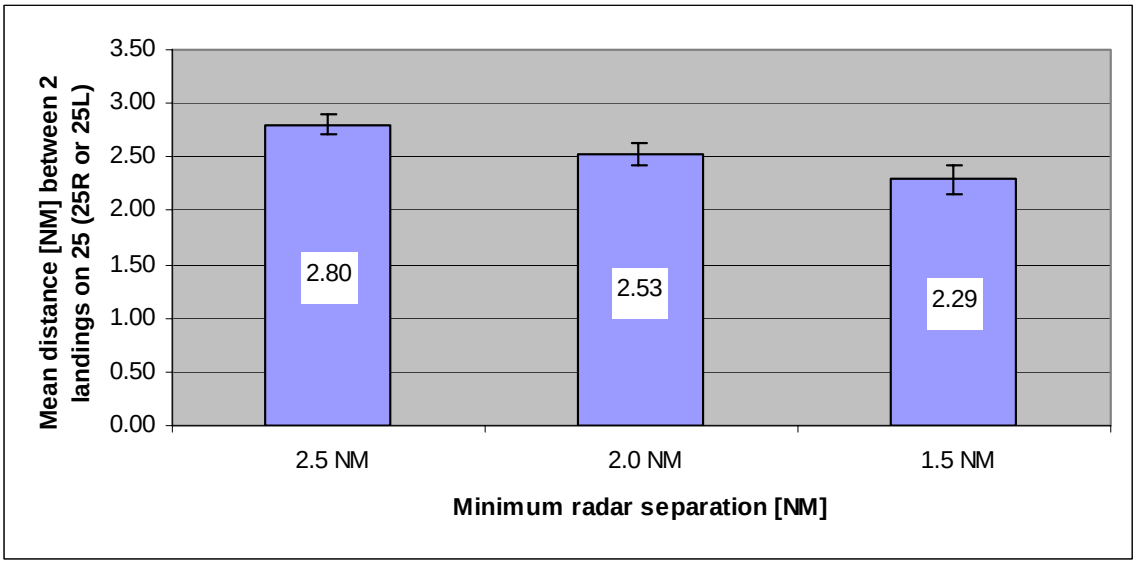
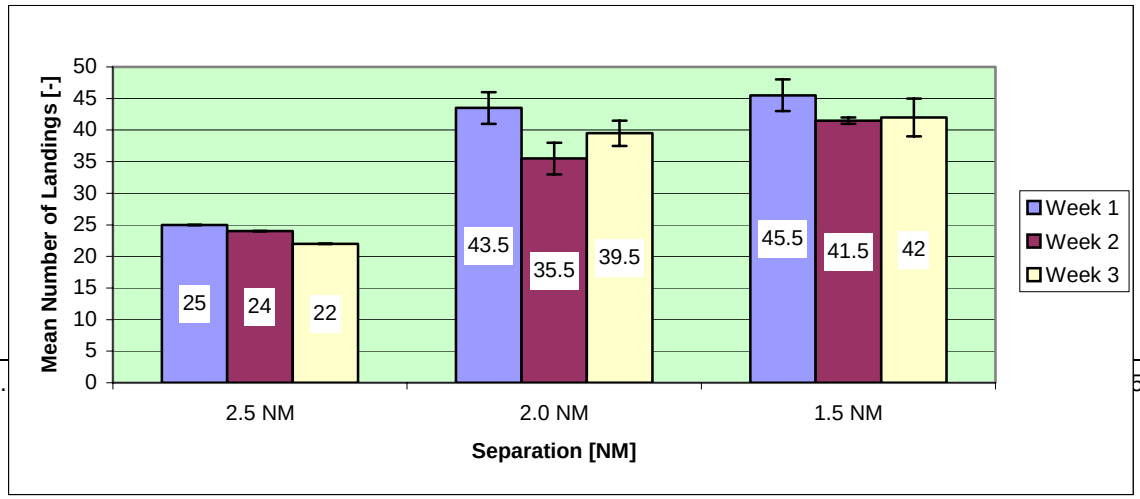


Figure 27 : Mean distance between 2 landings on 25 (mean value over the 3 Simulation Teams) (30 Min. analysis)

3.2.1.2 Three runways configuration

Four runs were conducted to evaluate the increase in the landing rate at Frankfurt/Main Airport by having a Three runways configuration (see Figure 3). The analyses are based on 2 runs with 2.0 NM separation between 25R and 25L and independent traffic on 26 and 2 runs with 1.5 NM separation between 25R and 25L and an independent traffic on 26. The three runway configuration analyses always incorporate the reference scenario (2 Runways 25R and 25L and 2.5 NM separation) to highlight potential capacity enhancements provided by the use of a 3rd runway. As mentioned in the section 3.2. the analyses were carried out over a period of 30 minutes starting with the time the first aircraft landed in the scenario.

Analyses of the data collected at the simulator site revealed that the capacity could significantly be increased with the use of a 3rd runway 26. For the simulation team 1, the mean number of landings increased from 25 landings (reference scenario) to 43.5 with 2.0 NM separation to 45.5 with 1.5 NM separation. The Standard Deviation was 2.5 both for 2.0 NM separation as for 1.5 NM separation. For the simulation team 2, the mean number of landings increased from 24 landings (reference scenario) to 35.5 with 2.0 NM separation to 41.5 with 1.5 NM separation. The Standard Deviation was 2.5 with 2.0 NM separation and only 0.5 with 1.5 NM separation. For the simulation team 3, the mean number of landings increased from 22 landings (reference



scenario) to 39.5 with 2.0 NM separation to 42 with 1.5 NM separation. The Standard Deviation was 2.0 with 2.0 NM separation and 3.0 with 1.5 NM separation. Those results are depicted in the

Figure 28.

Figure 28 : Mean Number of landings and Standard Deviation (Week 1, Week 2 and Week 3) (30 Min. analysis)

Taking the mean values over the 3 weeks for each separation, the mean number of landings in the 2.5 NM configuration was 23.67 with a standard deviation over the three simulation teams of 1.25. The mean number of landings in the 2.0 NM configuration was 39.50 and the standard deviation over the three simulation team is 3.27. Finally, the mean number of landings in the 1.5 NM configuration is 43.00 and the standard deviation over the three simulation teams was 2.89. This means that with a 2.0 NM configuration the increase in the number of landings compared to the reference scenario (2 runways, 2.5 NM) was **66,88%**, and with the 1.5 NM configuration, the increase was **81.66%**. Figure 29 depicts the mean number of landings for each separation over the three weeks.

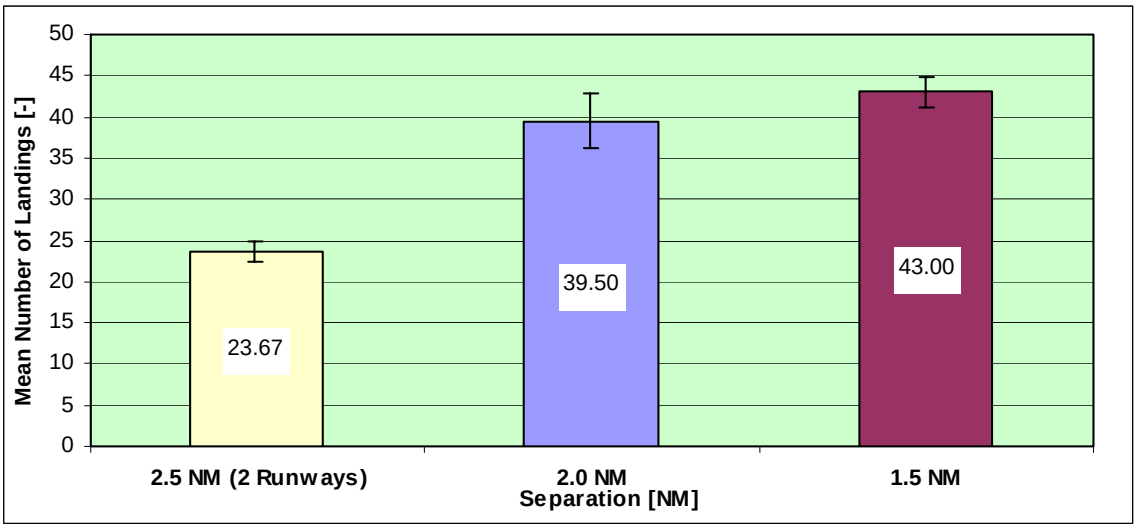


Figure 29 : Mean Number of landing for each separation over the 3 weeks (30 Min. analysis)

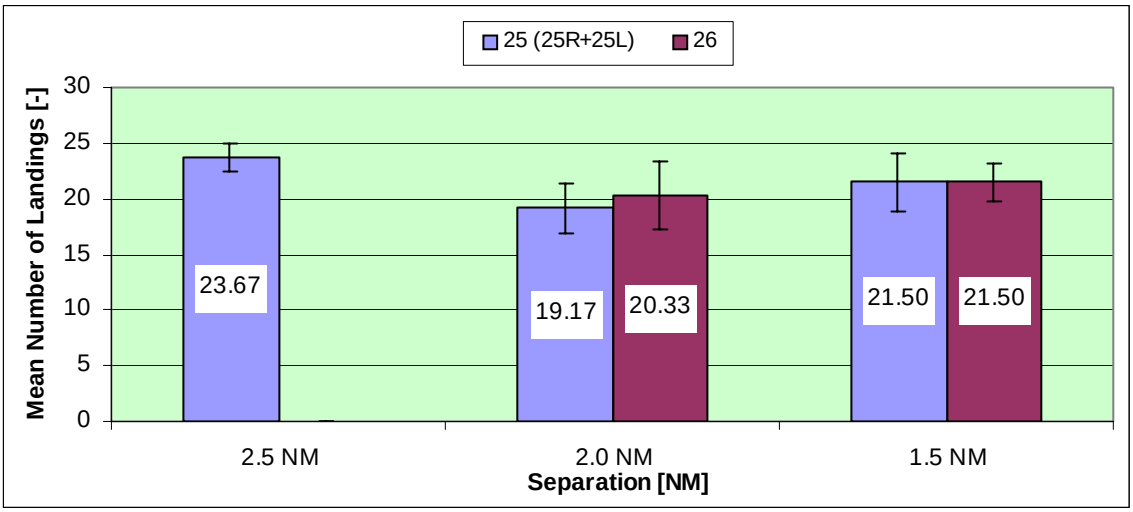


Figure 30 : Repartition of the landings on 25 (25R+25L) and 26. (30 Min. analysis)

Figure 30 shows that an additional runway 26 allows for significantl increase in the number of landings. Figure 30 shows that whil the total number of landings increased with the additional runway, the number of landings on 25 decreased (both with 2.0NM and 1.5 NM separation). Analyses of the data collected in the case of duals (25R and 25L) and depicted in Figure 17 show that for 2.0 NM separation, the number of landings on 25 was 26, and for 1.5 NM, the number of landings was 28.83. Compared with Figure 30, for 2.0 NM the number of landing on 25 decreased 26,3%. And for 1.5 NM separation, the number of landings decreased 25,4%. This decrease could have allowed more departure to be made on 25 while the total number of landing on 25 plus 26 increased. (The number of departures was not part of the tests).

3.2.2 Number of No Transgression Zone (NTZ) and Protection Zone (PZ) entries

The No Transgression Zone (NTZ) and Protection Zone (PZ) are depicted in Figure 3. In the case of duals sceanrios (25R and 25L), only the PZ between 25R and 25L was of importance. In the case of triples scenarios (25R, 25L and 26), the number of aircraft entering the NTZ also has to be taken into consideration. When aircraft entered the NTZ or PZ, it never led to a miss distance of less than 500 ft between 2 aircraft. Thus no Test Criterion Violation (see chapter 2.4.1.2) occurred during the real-time simulations. The NTZ or PZ entries were only registered for aircraft which were not blundering. (see blundering definition section 2.4.1.2).

Figure 31 depicts the number of entries of the PZ, in the case of duals scenarios. No aircraft entered the PZ in the reference scenarios .In the case of a 2.0 NM minimum radar separation, 1 aircraft entered the PZ during Week 3. In the case of 1.5 NM minimum radar separation, 1 aircraft entered the PZ during Week 2 and 1 aircraft entered the PZ during Week 3. During Week 2, the entry of the PZ was due to the fact that the pilot was instructed to land on 25R whereas it was on final for 25L,and during Week 3, the entry of the PZ occured while the aircraft was turning to intercept the localizer.

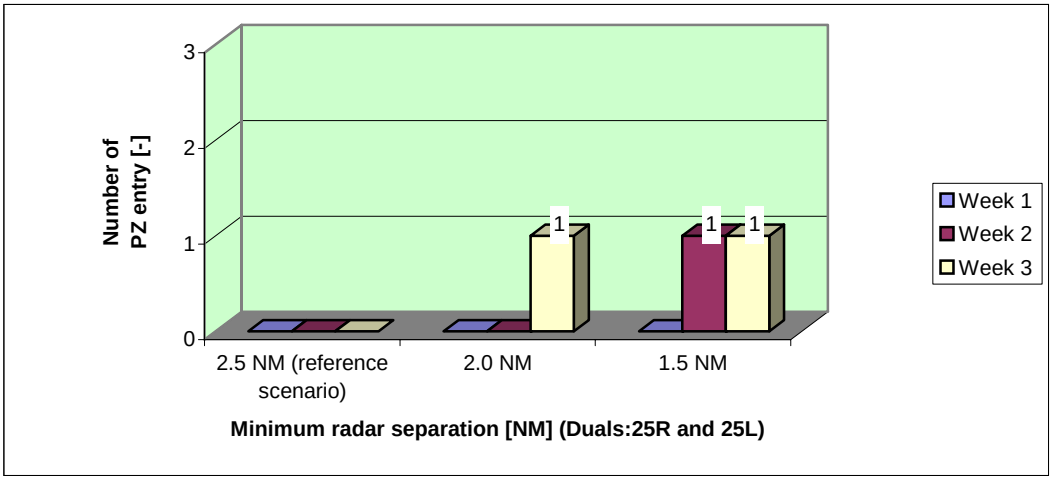


Figure 31 : Number of Protection Zone (PZ) Entries (Duals:25R and 25L)

Figure 32, depicts the number of PZ and NTZ entries in the case of triples scenarios. In order to be able to compare with the reference scenario, this scenario (Dual scenario) was also depicted in the following figure. In the case of a 2.0 NM minimum radar separation, during week 1, 2 aircraft entered the PZ because they had missed the localizer and during week 2, 1 aircraft entered the PZ . In the case of a 1. 5NM minimum radar separation, during the week 1, 2 aircraft entered the PZ, and 1 aircraft entered the NTZ. One of the PZ entries occured while the aircraft was turning to intercept the localizer. During the week 2, 1 aircraft entered the PZ.

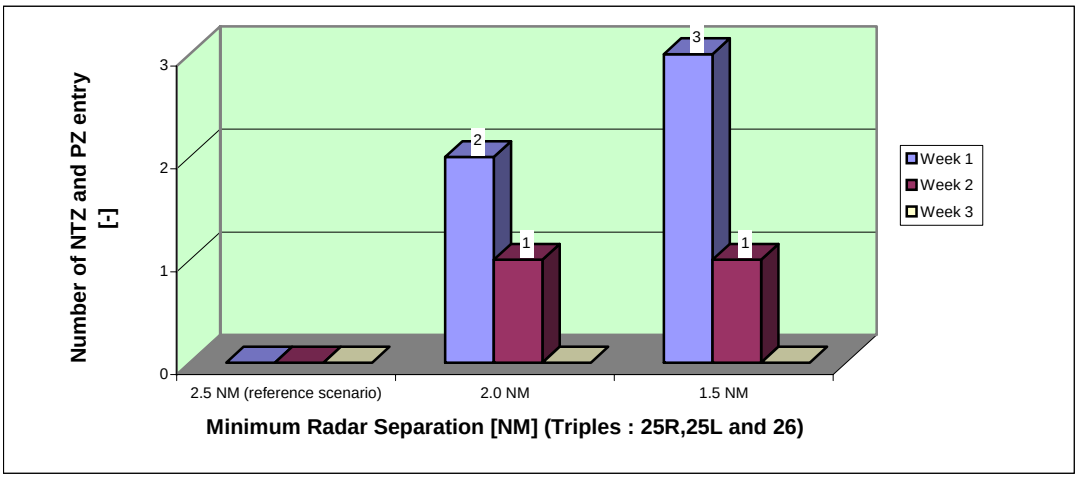


Figure 32 : Number of Protection Zone (PZ) and Non Transgression Zone (NTZ) Entries (Triples:25R, 25L and 26)

Analyses of the data revealed that of the 10 NTZ and PZ entries in the Dual and Triple configurations were due to aircraft having missed the localizer. Based on this, and knowing that

there was a non-negligible delay factor between the pilots and the controllers, most of the NTZ and PZ entries due to aircraft having missed the localizer, are actually due to the delay in the transmission between the controller instruction and the pilot command.

3.3 Subjective Analyses

3.3.1 NASA Task Load Index

Several Analyses of Variance (ANOVA) tests were conducted to determine the effects of traffic level, controller position, and staggered separation distance on controller workload.

The first analyses focused on determining the effect of increased traffic and separation on workload. A three-way ANOVA was conducted to answer this question. This ANOVA analyzed controller postion (i.e., TR1, TE1, and PRM), and separation (i.e., 1.5 nm and 2.0 nm) for levels 1 and 2. Since level 3 was the only scenario to utilize triple runways, it was excluded from this analyses.

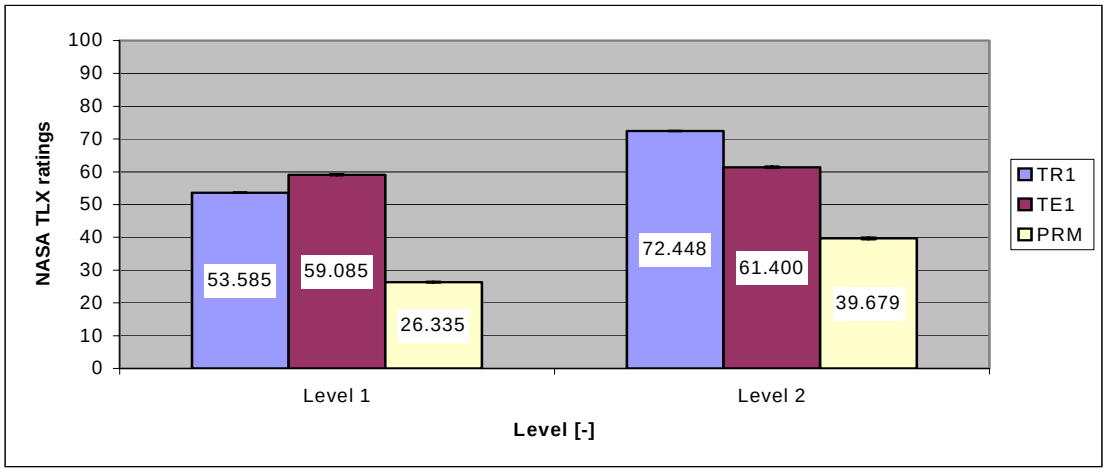


Figure 33: Mean workload ratings by position for levels 1 and 2.

The data revealed that both the level and position variables had a significant effect on NASA TLX workload ratings. The mean for level 2 (M= 57.842) was higher than the mean for level 1 (M=48.795). PRM controller ratings were the lowest of all three controller positions (M_{PRM}=34.067, M_{TE1}=62.194, M_{TR1}=63.082). Figure 33 displays the means for each controller position under 1.5 nm, 2.0 nm and 2.5 nm separation conditions. Since the number of aircraft per scenario (level) variable had a significant effect on workload ratings, it was decided that the number of aircraft in each run would be used as a covariate in the following analyses. This ensures that the results are not confounded by the number of aircraft, and that any significant effects are due only to the variables being studied.A two-way ANOVA was conducted on each of the three levels to determine the effect of position and separation on controller workload. The number of aircraft that landed in each condition was used as a covariate for this analyses. Since only one PRM controller provided a rating for the 2.5nm separation condition, the same rating was used for the other two controllers. Figure 34 displays the means for each controller position under 1.5 nm, 2.0 nm and 2.5 nm separation conditions.

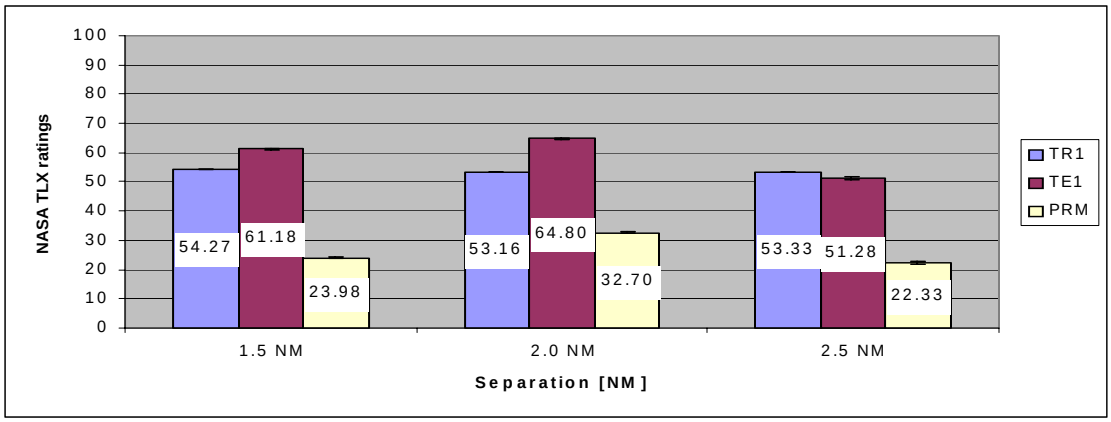
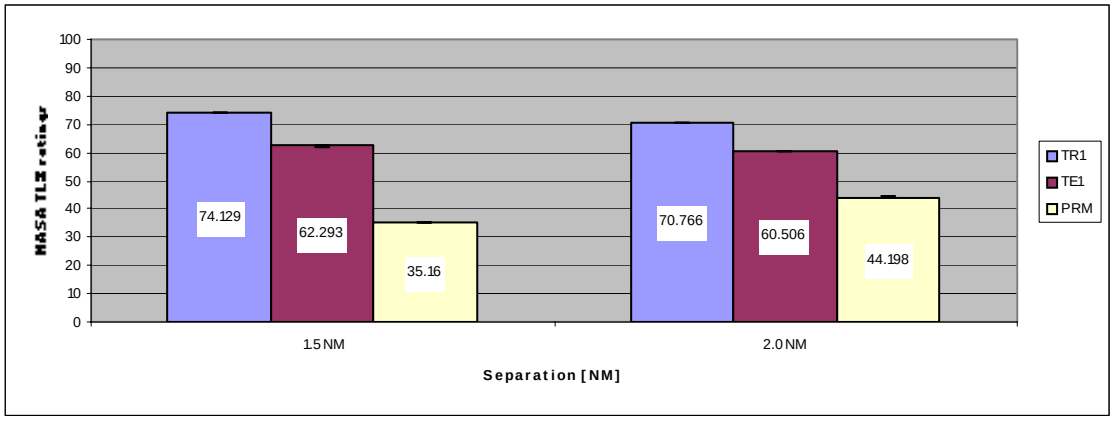


Figure 34: Level 1 mean workload ratings by position and staggered separation distances.

The two-way ANOVA for level 2 revealed that the number of aircraft landings was significant. Therefore, the number of aircraft that landed in each condition would have confounded the results if it were not taken as a covariate in this analyses. The position by separation interaction did not reach significance for this level. The PRM controllers (M =39.679) had significantly lower workload ratings than the TR1 (M=72.448) and TE1 controllers (M=61.400). Refer to Figure 35 for a graphical depiction of the means of controller ratings for each separation



condition

Figure 35: Level 2 mean workload ratings by position and separation distances.

Controllers rated the 1.5nm separation condition (M=73.502) as significantly more workload intensive than the 2.0nm (M=42.183) condition

Figure 36 displays the means for each condition for both 1.5 nm and 2.0 nm staggered separation conditions.

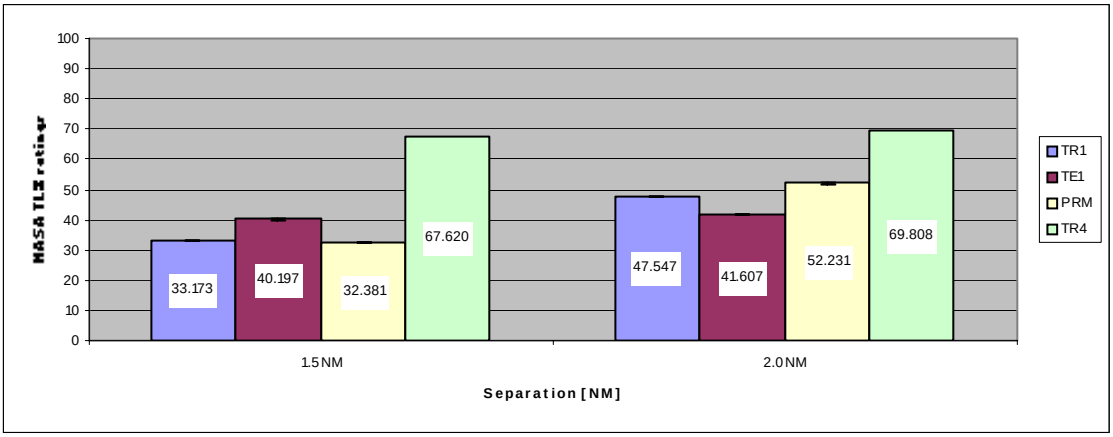


Figure 36: Level 3 mean workload ratings by position and staggered separation distances.

3.3.2 Workload Assessment Keypad (WAK)

For the simulation, Workload Assessment Keypads, or WAKs, were placed at each controller position (i.e., PRM, TE1, TR1, TR4). The TR4 controller only responded during triple runway scenarios.

Several Analyses of Variance (ANOVA) tests were conducted to determine the effects of traffic level, controller position, and staggered separation distances on perceived workload. Since the WAK collected data every 10 minutes, it was first necessary to determine if the traffic volume and/or complexity fluctuated during scenarios enough to affect different interval ratings. If traffic complexity varied to a great degree during the runs, then analyses would require that traffic counts be computed at each 10-minute interval. The resultant data, however, showed that this step was, in fact, not necessary. As can be seen in Figure 37, the mean workload rating trend if fairly consistent over the course of the runs and at varying separation conditions. The lower workload ratings in the beginning of the runs can be expected considering the first aircraft usually landed about twelve minutes into the run. The volume of aircraft slowly increased within the first ten minutes of every scenario. The data in Figure 37 also show that mean workload ratings for all runs were minimal to, at most, moderate. Although further statistics and graphs will be presented and significant effects noted, it should be kept in mind that the workload associated with the tested procedures was not excessive. Had workload been perceived as high at any time, a more in-depth analyses of contributing factors would be necessary. Controllers participating in this simulation, however, did not report anything more than moderate workload.

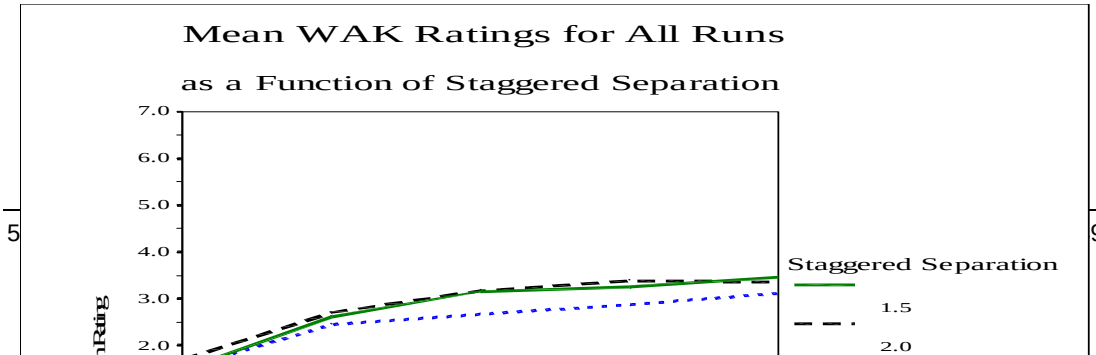


Figure 37 : Mean WAK ratings during all runs by staggered separation distance

The first statistical analyses focused on determining the effect of increased traffic (level) and staggered separation distance on workload. A three-way ANOVA was conducted to address this question. Controller position (i.e., PRM, TE1, TR1, and TR4) and separation (i.e., 1.5 nm, 2.0 nm) for levels 1 and 2 were analyzed. Since level 3 conditions were different than levels 1 and 2, namely, triples versus duals, level 3 was excluded from this analyses.

The mean for level 2 (M_{lev2}= 3.04) was higher than the mean for level 1 (M_{lev1}= 2.64). PRM controller ratings were the lowest of all three controller positions (M_{PRM}= 1.67, M_{TE1}= 3.11, M_{TR1}= 3.64). One interaction, position*separation*level, was significant. Refer to Figure 38 and Figure 39 for a graphical depiction of mean ratings and main effects of controller position.

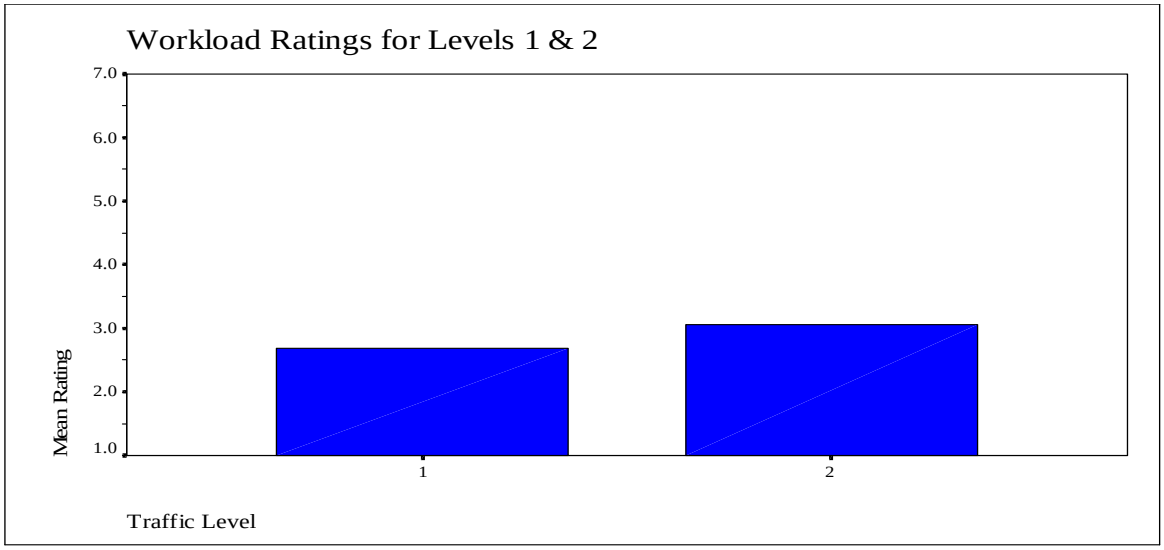


Figure 38 : Mean workload ratings by traffic level.

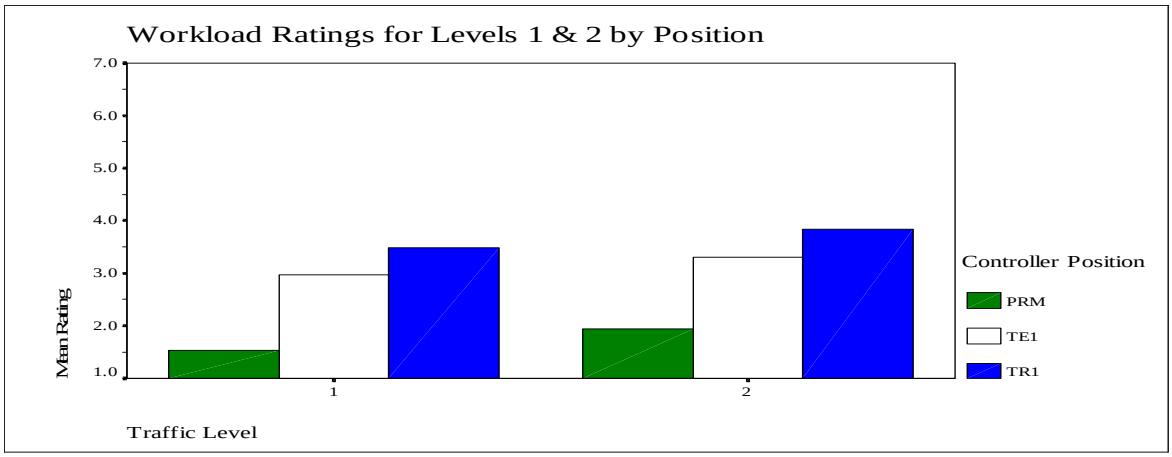


Figure 39: Mean workload ratings by position for levels 1 and 2.

A two-way ANOVA was conducted on each of the three traffic levels to determine the effect of position and separation on controller workload. Since the traffic level was found to have a significant effect on the workload ratings, as demonstrated in the previous analyses, it was decided to use the number of aircraft that actually landed in each run as a covariate. This ensures the results are not confounded by the number of aircraft that landed and that any significant results found are due only to the independent variables tested.

The PRM controllers had lower mean workload ratings (M= 1.46) than the TE1 (M= 2.97) and TR1 (M= 3.50) controllers. Figure 40 depicts the means for each controller position under 1.5 nm, 2.0 nm, and 2.5 nm separation conditions. This analyses revealed that the number of aircraft landings was significant. Therefore, had this factor not been included as a covariate, the results would have been confounded. No interactions were significant in this analyses.

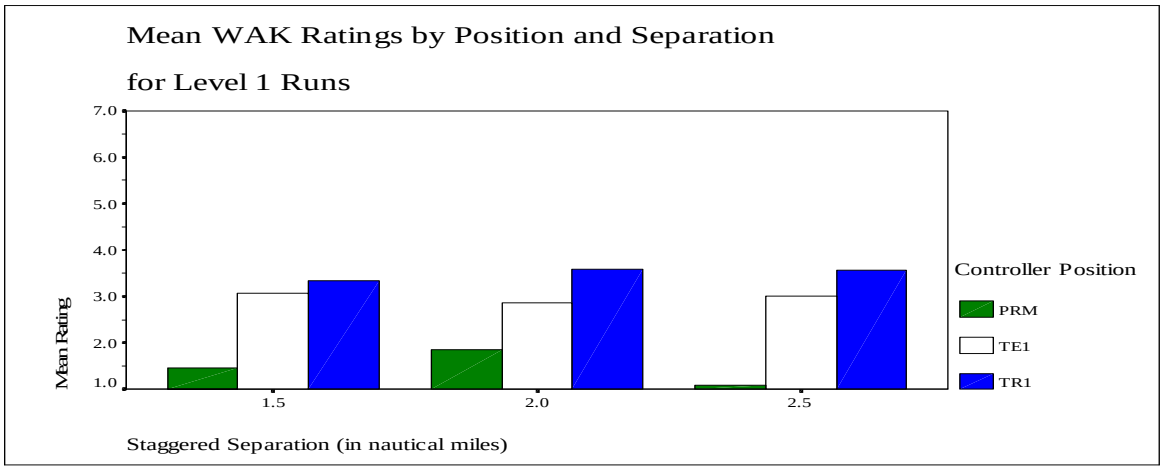


Figure 40 : Level 1 mean workload ratings by position and staggered separation distances.

The position * separation interaction was not significant. PRM controllers again had significantly lower workload ratings (M= 1.98) than the TE1 (M= 3.30) and TR1 (M= 3.85) controllers. Refer to Figure 41 for a graphical depiction of the mean workload ratings for each separate condition.

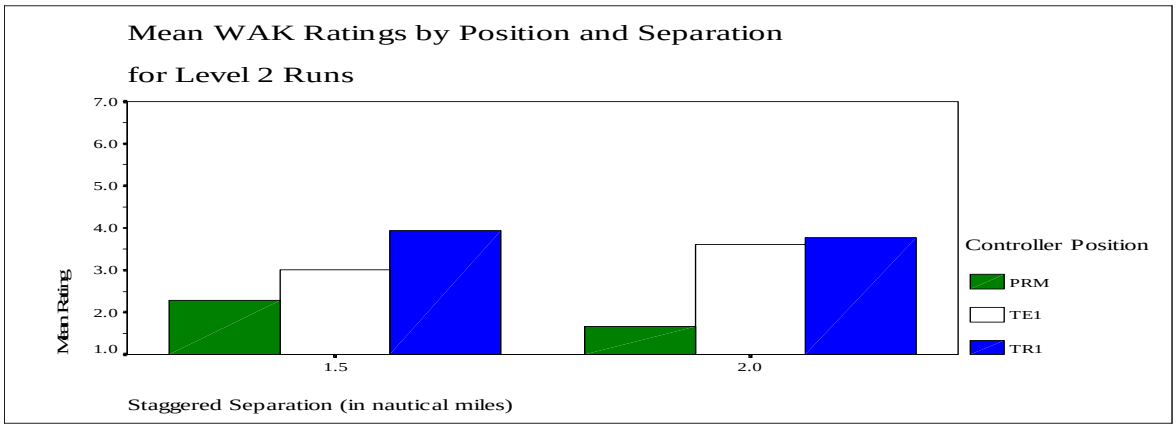


Figure 41 : Level 2 mean workload ratings by position and staggered separation distances.

The number of aircraft landings, or, the covariate, was also significant. No interactions were significant. TR4 reported a significantly higher workload than all other positions. None of the other positions (i.e., PRM, TE1, TR1), however, were significantly different from each other. The overall mean workload ratings for each controller position were as follows: M_{TR4}= 3.90, M_{TR1}= 2.69, M_{TE1}= 2.47, and M_{PRM}= 2.13. Figure 42 displays the means for each position for both 1.5 nm and 2.0 nm staggered separation distances.

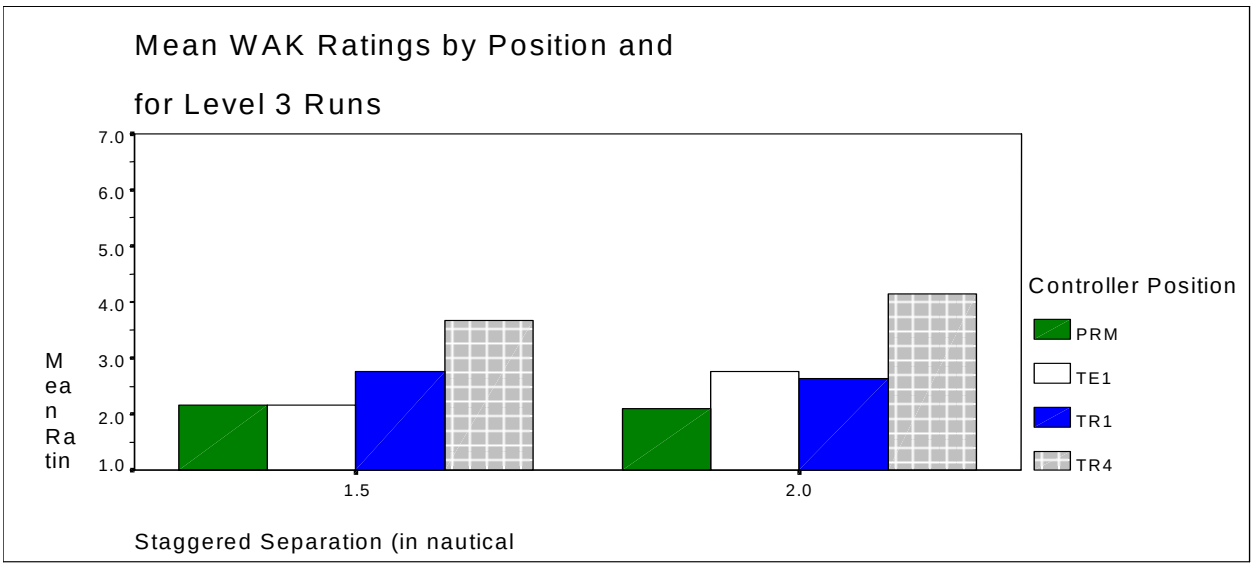


Figure 42 : Level 3 mean workload ratings by position and staggered separation distances.

3.3.3 Post Simulation Questionnaires

In addition to the daily debriefings and the verbal statements, the controllers were asked to fill out the „post simulation controller questionnaire“ at the end of the simulation week.

In summary it can be stated, that

- the simulation environment was fully accepted and fulfilled the demands.
- the traffic samples in most runs were well accepted. The workload in some scenarios was extremely high (because of the airspace structure and the reduced number of working positions). Two controllers mentioned „this traffic was not workable“.
- the PRM-display and the functionality was well accepted, with significant positive response distribution.
- the entire team concerned with the PRM-simulation was commented for a „great attitude and proficiency“ by most of the controllers.

The 12 questions on the post-sim questionnaire and the comprehensive answers in detail are provided below:

Question 1: *Do you think, that staggered approaches 2,0 NM can be safely conducted as simulated?*

Question 2: *What improvement could be incorporated into the above mentioned procedure?*

Question 3 and 4 were corresponding to 1 and 2, but for a 1,5 NM separation.

The controllers answered unanimously YES on 2,0 NM separation, having the following suppositions and requirements to the system:

- the RADAR-system has to be reliable (no mirror targets, no target failures) and redundant.
- the RADAR update rate should be 1 sec., at 1,5NM separation it is a must.
- the working positions and the airspace structure (FIR and TMA) have to be revised and simulated in order to get the high traffic amount into the TMA.
- the PRM-controller must have an additional ASR- display of the feeder-scenario. or a „window“ if it is on his screen.
- important obstacles and the MRVA (minimum RADAR vector altitude) should be portrayable in the RADAR scope.
- the possibility of displaying different colors should be used.

Further recommendations to the a.m. questions were:

- new procedures and coordination phraseologies have to be defined (within APP and between APP/TWR).
- controllers and pilots have to be trained, the urgency of the word „traffic alert“ has to be made known.
- TWR and Airport procedures have to be adjusted in order to get the runways vacant.
- further tests and/or simulations have to be conducted for departing aircraft.

On question 3 (1,5 NM) there was just one NO, because of the high traffic amount and the problem to transmit important clearances just in time (high frequency load).

Question 5: *Assess the communications workload for NTZ (non transgression zone between RWY 25R and 26) and PZ (protection zone between RWY 25L and 25R) –entries and breakouts relative to current operations. Please explain. Which phraseology do you think, should be used in case of blunders?*

- the communication workload, under normal conditions, is very low, whilst the entire workload (especially when watching three finals) is rated to be high, by most of the controllers.
- experiences during further simulation runs will show the best phrases, reactions in different scenarios and working position arrangements.
- to allow the best necessary coordination, the PRM working position should be located close to the feeder-position.
- regarding the phrases, the words „traffic alert“, and „immediately“ shall be used, the rest should be up to controllers decision and the current traffic situation. The phrase has to be short and pregnant and harmonized with pilot´s associations.

Question 6: *Did you develop specific control strategies for the simulated approach operations?*

- new general procedures, like inbounds from the north down to 5000 feet and from the south down to 4000 feet (or vice versa) were created by most of the controllers.
- „teamwork“, extremely good and precise (elbow-) coordination is essential.
- the procedures for PRM need some more examination and simulation.

Question 7 concerned with the obtained pre-briefing and was considered to be adequate and sufficient by all controllers.

Question 8: *Rate the realism of the traffic (e.g. aircraft type, density) for each level (level 1, 2 and 3). Please explain.*

The traffic mixes (heavies and mediums) were rated to be all right by all controllers. Regarding the traffic density, level 1 was valued to be realistic (just two controllers said, it would be too much traffic); on level 2 42% felt it acceptable, 33% had the opinion, the amount was too high and 25% didn´t comment it. Level 3 was considered to be too extreme for the present airspace and number of controllers, just one controller was satisfied with the traffic amount in this level.

Question 9: *How did you react in case of blunders? Please describe.*

- fast reaction is mandatory. A lot of training is required.

- only at the beginning it looked very unsafe and dramatic. Once you get used to the 1:4 scale display, it is much easier.
- most simulated blundering a/c were lost communication; so the only chance was, to turn away the succeeding a/c on staggered approaches (25L/R) or the parallel approach (25R and 26).
- with more training, the level of „good“ decisions increases rapidly.
- The following means were used: climb, descent, turns (into all directions), traffic infos.

Question 10 covered the duration of the training for the PRM controller position. The answers were very different. While one controller didn´t need any training at all, 2 required 20 – 30 hrs., most of them 50 – 60 hrs. or two weeks and one controller 200 – 300 hrs. It was stated numerous times, that additional „fitness/refresher“-training will be necessary after the system is in operation.

Question 11: *Please describe any items in the simulation which you believe were not realistic or whose realism should be improved. (equipment, displays, communication, etc.)*

- most of the controllers stated, that the simulator and the surroundings were excellent, the pilots were in a very good condition, typical „simulation-mistakes“ were very seldom.
- the feature „automatic label delete“ after a frequency change, caused some problems; it should be changed to an „automatic label dim“, so that the callsign will remain readable.
- two controllers assessed the aircraft performance not to be realistic, speed reduction was too immediate, turns sometimes too tight.
- ~50% grieved about too much traffic.
- in order to communicate to all the aircraft, the phraseology was reduced dramatically (e.g. no inital call, no QNH or additional information).

Question 12: *Do you have any additional comments? Explain.*

- numerous controllers praised the PRM display, the reliability, the altitude display and the possibility for separating aircraft precisely with speed control.
- as the controllers had no flight progress strips, they needed a possibility to mark the label with, for example the „cleared RWY“, by means of electronic input.
- new systems have to relieve the pressure of the controller. Capacity enhancement must not include a rise in of workload.

PRM is needed, in order to maintain the present level of safety even under extreme traffic situations.

3.3.4 Debriefing

After each simulation run a NASA TLX rating and a debriefing discussion finished the test. The extensive debriefings tried to capture the spontaneous ideas of the subjects on problems and advantages in the specific simulation run. The information gathered here is partly redundant to the post simulation questionnaire. However, trying to capture almost any of the comments needs a redundant methodology as implemented here.

3.3.4.1 General discussion

Some of the discussions were related to problems in the simulated environment. Due to the size of the simulation the constraints were not compliant to the at-home-conditions the ATCO's are used to for 100%. E.g. a data tag was displayed only for those targets currently under control. It could be toggled in and out for any other target as well. In fact, this procedure put a lot of extra effort on the subjects. Besides these discussions, several items related to the PRM system itself were covered in the debriefings. The most important ones are listed below.

The realism of the simulation was considered as very good. Several subjects had experience with other simulation systems inside Europe. They were impressed by the stability and the performance modelling of the system. In addition, the quality of the pseudo pilot responses – both auditory read back and system input – were stated as extremely positive for realistic simulation exercises. The subjects appreciated the pseudo pilot's ability to combine instructions[4].

3.3.4.2 Discussion related to the PRM system

Related to the PRM system it was noted that the subjects had to get used to the overshoot behaviour on the PRM scope. Due to the ratio of 4:1 in the x:y scaling, an overshoot in the x-axis (i.e. vertical to final approach course) was displayed much more drastically than in the y-axis.

An update rate of 4.8 seconds for the PRM scope was simulated in the reference scenario where no PRM system was in service inside the simulation scenario. The 4.8 update rate was judged as fully unacceptable. In contrast, the controllers expressed the wish to extend the 1 second update rate of the PRM display to the pickup and feeder displays. This would increase the accuracy of these positions even in today's environment.

Presentation of the targets – after getting used to it – was rated as rather positive. It was stated as a clear and unambiguous presentation of the aircraft and data tags. Due to the update rate of 1 second, a quasi-continuous presentation was achieved.

The aural alert was stated as improvable. If an aircraft entered the NTZ or PZ, the callsign was called out by a synthetic voice output. Nevertheless, two single points were criticised. First, several alarms occurred for overflights crossing Frankfurt VOR for entering the southern downwind. Due to their altitude of 8000 ft these targets were filtered out in the PRM display. In contrast, an aural alarm was given. This led to an aural alert for a target which could not be identified, due to the display filtering. Second, the latency for an aural alert has to be discussed and tested further. In the system tested an aural alert was issued for any target's speed vector entering the NTZ or PZ for more than 2 seconds. This led to a lot of false alerts as well. However, the need for an aural alert was not discussed at all. Especially for low traffic situations, such an additional, multi-modal alert system is strongly required. The training of ATCO's comes along with the result that a callsign called out by the aural alert is listened up to the end of the message (i.e. the complete callsign). About 1 seconds reaction can be gained, if the alert just calls out the word "TRAFFIC" or something similar.

In a video tape the FAA test team demonstrated reaction times of cockpit crews to be much slower than the pseudo pilots' inputs inside the simulation environment. While a pseudo pilot needs about 4-5 seconds to implement any change, a cockpit crew surprised by a "TRAFFIC

[4] E.g. heading, altitude and speed in one transmission.

ALERT" needs 20-30 seconds to react in the intended way. For capturing that problem, the subjects suggested to include a full flight cockpit simulator into further investigations. In addition, critical traffic like east European airlines have to be simulated as well in a follow up investigation.

Departures on runway 25 would increase realism. They would provide more reliable landing rates than the measurements in this simulation where no departing aircraft were simulated.

The PRM position is a high workload position regardless to the responsibilities attributed in final approach to the PRM controller. PRM controllers have to be changed quite often. Times between 30 and 60 minutes of continuous work on the PRM position were discussed. More than 60 minutes seems not to be appropriate.

For a presentation of the wake vortex separation necessary, a temporary history line in the length of the required separation could assist feeder and PRM controller. This line could be accessed e.g. via right mouse button in a mouse-driven system environment. It could last between 10 and 30 seconds and disappear afterwards automatically.

3.3.4.3 Discussion related to procedures

Related to the procedures it was stated that specific procedures have to be established for blunders or deviations thath have been separated. So far it is not clarified how to proceed with those aircraft to re-introduce them into the approach traffic flow. It was recommended for any PRM system to support the PRM display with an additional Feeder display. This second display could significantly help the PRM controller to re-introduce blunders into the traffic flow. In addition to the blunder handling, published missed approach procedures have to be applicable as well.

Task allocation between different control positions and procedures for a PRM system control have to be redefined. This applies both for a two runway configuration as for a three runway configuration. The key element of this discussion is the task for the PRM controller. It can vary between pure monitoring and full speed control from about 15 miles final down to threshold. For a three runway configuration the additional pickup and feeder positions have to be spread on a minimum of two physical positions. Due to the difficulties of the feeder to provide traffic with 1.5 miles of separation, the final spacing should be applied by the PRM controller. If this is done – and implemented via speed control by the PRM controller – the situation awareness of the PRM controller can be raised significantly.

The phraseology for blunders is very important for an unambiguous handling of the situation. In the experiments, the phrase "TRAFFIC ALERT! DLH..." was used. This shifts the attention of the cockpit crews on the alert. In addition, a second radio frequency can be used by the PRM controller to avoid radio garbling while transmission of a traffic alert. For critical situation it is even recommended to turn out the endangered traffic before trying to capture the blunder.

There may be a problemwith the availability of radio frequencies. The feeder frequency was more or less saturated in some of the simulation runs. By this, a bottle neck is identified which can not be overcome even by a PRM system.

Due to the absence of paper flight progress strips, a strip marking system was discussed. In fact, an initial implementation will definitely include paper flight progress strips as they are used

today. To shorten down the writing times, a flight progress strip chain *pickup – feeder – PRM controller* was suggested.

Last not least, a discussion was held on whether a PRM system would be a good choice for other Airports in Germany as well. In this discussion, Munich Airport was pointed out as the relevant candidate for investigations on PRM systems in addition to Frankfurt/M.

4 Discussion on the results

This evaluation allowed the assessment of the number of landings which occurred during the different runs, the mean calculated distance between 2 landings (without the use of a 4D-Planner) and the number of entries in the Protection Zone (PZ) and No Transgression Zone (NTZ) (see Figure 31 and Figure 32 for a description of the PZ and NTZ).

ALL the analyses were carried out over a period of 30 minute starting with the time when the first aircraft landed in the scenario. ALL the landing numbers mentioned in this report refer to an analyses period of 30 minutes.

Number of landings

Analyses of the data revealed three major parameters which influenced the number of landings : the minimum radar separation, the use of a simulated WVWS and the use of a third fictious runway independent from 25R and 25L.

- Having the minimum radar separation varying from 2.5 NM (reference scenario) to 2.0 NM and to 1.5 NM, the number of landing on 25 (25R or 25L) increased respectively from 23.67 to 26 and to 28.83 landings for 30 minutes analyses in the case of the 2 Runway configuration (see Figure 17). In case of the 3 Runway configuration (see Figure 28), the number of landings increased from 23.67 (2.5 NM minimum radar separation: reference scenario, 2 Runway configuration), to 39.50 (2.0 NM minimum radar separation) to 43 (1.5 NM minimum radar separation). Thus, the reduction of the minimum radar separation led to a significant improvement in the number of landings. For the 2 Runway configuration, the number of landings increased by 9% for 2.0 NM minimum radar separation, and by 18% for 1.5 NM minimum radar separation. For the 3 Runway configuration, the the number of landings increased by ca. 67% for 2.0 NM minimum radar separation, and by ca. 81,7% for 1.5 NM minimum radar separation.
- While some scenarios - only in the 2 Runway configuration - were run without a simulated WVWS, others were run simulating a WVWS. The results of the data (see Figure 18) analyses indicate that the number of landings observed under the use of a WVWS was higher than without WVWS. With a 2.0 NM minimum radar separation, the number of landings increased from 24 without WVWS to 28 with WVWS, representing an increase of 16.7 %. With a 1.5 NM minimum radar separation, the number of landings increased from 25.67 without WVWS to 32 with WVWS, representing an increase of 24.6 %. While further investigation are necessary to confirm the influence of the WVWS on the number of landings under the use of a PRM system, the results of those simulations are worth being taken into consideration.
- The simulations with a third fictious runway 26 independent from 25R and 25L, showed two major improvements. First, the number of landings increased significantly. The number of landings varied from 26 in a 2 runway configuration to 39.50 in a 3 runway configuration for a minimum radar separation of 2.0 NM, and the number of landings varied from 28.83 in a 2 runway configuration to 43 in a 3 runway configuration for a minimum radar separation of 1.5 NM. This represents an increase of 52% for a 2.0 NM minimum radar separation, and an increase of 49% for a 1.5 NM minimum radar separation. Second, whil the number of

landings globally increased (on 25 and 26), the number of landings on 25 decreased from 26 in the 2 runway configuration with 2.0 NM minimum radar separation to 19.17 in the 3 runway configuration with 2.0 NM minimum radar separation, and from 28.83 in the 2 runway configuration with 1.5 NM minimum radar separation to 21.50 in the 3 runway configuration with 1.5 NM minimum radar separation. Based upon this information, additional departures could be executed on runway 25 (25R or 25L). Departures were not tested in this simulation, but could be part of future simulations.

Distance between two landings

As mentioned in Chapter 2.4.5.2 the runs were split into 3 categories : 2.5 NM, 2.0 NM, and 1.5 NM minimum radar separation between the aircraft on final approach at Frankfurt/Main. This separation was made by the controllers alone, without the help of any 4D-planner system. Thus, the minimum radar separation was the separation the controllers aimed at implementing between two aircraft landing on 25 (25R or 25L). A comparison of the minimum radar separation with the calculated separation between two aircraft landing on 25 (either 25R or 25L) assuming that the speed of the aircraft from the scenarios on short final was 140 kts revealed the following results. The mean distance between 2 aircraft landing on 25 over all the runs per minimum radar separation (2.5 NM, 2.0 NM and 1.5 NM) shows that for a mimimum radar separation of 2.5 NM, the calculated mean distance between 2 aircraft landing on 25 was 2.8NM with a standard deviation of 0.09 NM. For a mimimum radar separation of 2.0 NM, the calculated mean distance between 2 aircraft landing on 25 was 2.53 NM with a standard deviation of 0.10 NM. And for a mimimum radar separation of 1.5 NM, the calculated mean distance between 2 aircraft landing on 25 was 2.29 NM with a standard deviation of 0.14 NM. These results showed that even if the calculated distance between 2 aircraft landing on 25 did not reach the minimum radar separation, the calculated separation decreased with each reduction in minimum radar separation.

Consequently, analyses of the data revealed that a reduction of the separation between 2 aircraft landing on 25 seemed to be feasible. Without definition of precise landing procedures, and without training of the controllers, the mean distance between 2 landings on 25 could be reduced to 2.29 NM.

NTZ and PZ entry

The results of the NTZ and PZ entries showed that when aircraft entered the NTZ or PZ, it never led to a miss distance of less than 500 ft between 2 aircraft . Thus no Test Criterion Violation (see section 2.4.3.1) occurred during the real-time simulations. The NTZ or PZ entries were only registred for aircraft which were not blundering. (see blundering definition section 2.4.1.2). In the 2 runway configuration, 1 PZ entry occured with a 2.0 NM minimum radar separation and 2 PZ entries occurred with a 1.5 NM minimum radar separation. In the 3 runway configuration, 3 PZ entry occurred with a 2.0 NM minimum radar separation and 3 PZ entries and 1 NTZ entry occurred with a 1.5 NM minimum radar separation. Analyses of the data revealed that 4 from the 10 PZ/NTZ entries in the 2 Runway and 3 Runway configuration were due to aircraft having missed the localizer.

Based on this, and knowing that there is a non-negligible delay factor between the pilots and the controllers, a large part of the NTZ and PZ entries were actually due to the delay in the

transmission between the controller instruction and the pilot command. Consequently, pilot training and controller training have to be enhanced in order to cope with the pilot/aircraft response times and to reduce the NTZ and PZ entries during the conduct of closely spaced approach operations.

Subjective Analyses

Analyses of the subjective data supports the results from the objective analyses. The overall workload for the PRM position was rated lower than workload for pickup or feeder position. However, it has to be taken into account that the PRM position is a heavy workload position in high stress situations: in contrast to the pickup or feeder position where a continuous flow of traffic has to be tackled, on the PRM position most of the time workload is lower. But if a blunder or deviation occures, the controller has to react quickly and precisely.The overall continuous workload (see Figure 37) for reduced staggered separation is comparable to the control condition of today's operation. Analysing these data in detail shows a medium to high subjective workload at several points of measure depending on the traffic situation. This result indicates that further investigations should focus as a major part on workload in specific situations as well.

Hypotheses

As a result of the simulations, the hypotheses made in thesection 2.3. can be verified :

1. The arrival rate for a 2.0 NM staggered separation on a dual runway system (dual runway configuration 25L, 25R) increased compared to the reference scenario with a staggered separation of 2.5 NM on a dual runway system (dual runway configuration 25L, 25R).
2. The arrival rate for a 1.5 NM staggered separation on a dual runway system (dual runway configuration 25L, 25R) increased compared to a staggered separation of 2.5 NM on a dual runway system (dual runway configuration 25L, 25R).
3. The arrival rate for a 1.5 NM staggered separation on a dual runway system (dual runway configuration 25L, 25R) increased compared to the arrival rate for a 2.0 NM staggered separation on a dual runway system (dual runway configuration 25L, 25R).
4. The arrival rate for a 2.0 NM staggered separation on the dependent runways and parallel approaches on a third independent runway (triple runway configuration 25L, 25R, 26) increased compared to a staggered separation of 2.5 NM on a dual runway system (dual runway configuration 25L, 25R).
5. The arrival rate for a 1.5 NM staggered separation on the dependent runways and parallel approaches on a third independent runway (triple runway configuration 25L, 25R, 26) increased compared to a staggered separation of 2.5 NM on a dual runway system (dual runway configuration 25L, 25R).
6. The arrival rate for a 1.5 NM staggered separation on the dependent runways and parallel approaches on a third independent runway (triple runway configuration 25L, 25R, 26) increased compared to the arrival rate for a 2.0 NM staggered separation on the dependent

runways and parallel approaches on a third independent runway (triple runway configuration 25L, 25R, 26).

7. The experimental induced loss of separation (blunders, deviations[5]) did not lead to critical incidents. There were no miss distance between two aircraft less than 500 ft lateral separation or less than 1000 ft vertical separation.

Conclusion

This simulation ***FAA PRM Experiments for Frankfurt/M.*** tested staggered ILS approaches to 2 dependent parallel runways 25R and 25L spaced 526 ft and staggered ILS approaches on the dependent runways with simultaneous ILS approaches on a third independent runway (fictious runway 26), using the PRM System with a 1.0 second radar update. The data collected at the Target Generation Facility (TGF) showed that the number of landings can be significantly increased using the PRM System, maintaining the current level of safety. Nevertheless, in order to have more precise figures on the number of landings, on the separation between 2 aircraft landing on 25, on the number of entries in the NTZ and PZ and finally on the increase of the landing and departing rate further simuations are needed. Based upon these evaluations, the post simulation questionnaires and the debriefings, future simulations are necessary and should mainly focus on the following points : new procedures and coordination phraseologies have to be defined (within APP and between APP/TWR)., controllers and pilots have to be trained, phraseology in case of an aircraft deviating from the centerline has to be defined, TWR and Airport procedures have to be adjusted in order to get the runways vacant and finally, further simulations have to be conducted including departing aircraft.

[5] See definition section 2.4.1.2

5 References

[1] Ozmore, R. E. & Morrow, S.L. (1996): *Evaluation of Dual Simultaneous Instrument Landing System Approaches to Runways spaced 3000 feet apart with one localizer offset using a Precision Runway Monitoring System*. DOT/FAA/CT-96/2, Final Report. Washington, DC: Federal Aviation Administration.

6 Abbreviations

ANOVA	Analyses of variance
APP	Approach
ASR	Aerodrome Surveillance Radar
CHA	Final Approach Fix VOR Charlie
CPA	Closest point of approach
DFS	DFS Deutsche Flugsicherung GmbH (German Air Navigation Services)
EI	External interface
FAA	Federal Aviation Administration
FFM	VOR Frankfurt/M.
FM/R	Office for regional affairs of the DFS Deutsche Flugsicherung GmbH
FMA	Final monitoring aid
GED	VOR Gedern
HALS	High approach landing system
ICAO	International Civil Aviation Organisation
MTR	VOR Metro
NASA	National aerospace and space agency
NASA TLX	NASA Task Load Index
NM	Nautical miles
NTZ	Non transgression zone
PPW	Pseudo pilot workstations
PRM	Precision runway monitoring
PSA	Navigational Aids Spessart
PZ	Protection zone
RUD	VOR Rüdesheim
RWY	Runway
S.D. or SD	Standard deviation
SE	Research & Development division of the DFS Deutsche Flugsicherung GmbH
SES	Simulation subdivision of the DFS Deutsche Flugsicherung GmbH
TCV	Test criterion violation
TE1	Abbreviation for the Frankfurt/M. feeder position

TG	Target generation
TGF	Target generation facility
TR1	Abbreviation for the Frankfurt/M. pickup position
TR4	Abbreviation for the simulated Frankfurt/M. combined pickup and feeder north position
TWR	Control Tower
WAK	Workload assessment keypad
WVWS	Wake vortex warning system