PD/2 FINAL REPORT

Annex C

Analysis of Traffic Throughput / Quality of Service

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              S Tenoort
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1 Introduction

1.1 General

This annex describes the results of the statistical analysis of the traffic-related data recorded during the second PHARE Demonstration (PD/2). The analysis makes use of two sources of data: the traffic as it was actually observed in the real-time simulations, plus the traffic as it was originally planned by the PHARE Advanced Tools (PATs).

One of the main objectives of PHARE Demonstrations was stated as to determine the effect of PATs and datalink on traffic throughput. The other main objectives, to determine the effect on controller workload, and to assess controller approval, is addressed fully in detail in Annex D and Annex E of the PD/2 final report.

During the discussion of the PHARE Demonstration One en-route trial results in the aviation community another aspect was brought up. It became obvious that airspace users and airlines are strongly interested in assessing the potential benefit of the PHARE concept in terms of the "Quality of Service" which they can expect.

This annex attempts to incorporate quality of service aspects into the analysis of traffic throughput. In the TMA a close relation between the quantity of traffic throughput and the quality of service provided to airspace users can be assumed to exist. For instance, the number of aircraft passing through an airspace per time unit which is often seen as the most straightforward indicator of throughput can be expected to correlate highly with the average flight time of aircraft. That time is immediately relevant for an airline’s perception of quality of service, since it affects delays, fuel consumption, etc.

Therefore, traffic throughput and quality of service are treated together in this annex. PD/2 analysis extracted the following parameters from the simulation traffic data:

- number of landings,
- flight time,
- inbound delays,
- precision of delivery,
- separation.

Sections 2 to 6 will present the results in detail.

1.2 Hypotheses and Tests

The analysis methodology has been described already in Annex A. However, it is important to note again some significant points.

As it was implicitly expected that the introduction of the PATs and datalink would be a positive effect, one-tailed statistical tests of significance were appropriate for the quantitative analysis of traffic throughput/quality of service parameters.

The hypotheses tested for analysing ORG 0 against ORG 1 data were

\[ H_0: \text{There is no difference in traffic throughput/quality of service between ORG 0 and ORG 1 due to PATs and GHMI introduction,} \]
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H₁: Traffic throughput/quality of service is higher/better in ORG 1 than in ORG 0 due to PATs and GHMI introduction.

The Wilcoxon Matched-Pairs Signed-Ranks Test was used, with a significance level of 5%.

The hypotheses tested for ORG 1, ORG 2/30 %, and ORG 2/70 % data were

H₀: There is no difference in traffic throughput/quality of service between ORG 1, ORG 2/30 % and ORG 2/70 % due to different proportions of 4D FMS/datalink aircraft,

H₁: Traffic throughput/quality of service is higher/better with introducing proportions of 30 % to 70 % 4D FMS/datalink aircraft in ORG 2.

The Friedman Analysis of Variance by Ranks was used, again with a 5% level of significance. Note that, by nature of Analysis of Variance tests, a significant result indicates that some difference between ORG 1, ORG 2/30 %, and ORG 2/70 % exists (non-directional). Thereafter the measured parameters can be inspected as to whether that difference is in the hypothesised direction.

The Wilcoxon and Friedman tests were applied in the same way on both the high and the medium traffic load data. However, high and medium traffic data were submitted to two separate strings of analysis independently. The structure of reporting the results will follow this by giving for all parameters first the results obtained under high traffic load, and then the results obtained under medium traffic load.

An important caveat must be mentioned. The results of the PD/2 real-time simulations, in terms of averages and variations measured, are not suitable for generalised interpretation that applies to the large variety of real-life today’s or future situations. The data reported here cannot be transferred directly to every sort of ETMA airspace geometry, route structure, and local constraints, not to speak of weather and traffic samples. Real-time simulations have to be very selective and specific on that in order to produce meaningful results.

What the results can show is the difference in relation between the situations investigated, i.e. between the ORGs of PD/2. Any significant difference, or benefit, due to the advanced ORGs can be taken as an indication of a truly existing potential for improvement. The absolute magnitude of such an improvement that can be expected in real-life situations is also dependent on the characteristics of the situation. Other research instruments, e.g. fast-time simulations, would then be suitable to quantify the effects.

Finally it has to be pointed out that a considerable number of class A aircraft were downgraded from class A during the simulations as a consequence of controller intervention, or because the PATs were unable to compute conflict-free trajectories in time for some aircraft supposed to be class A. In the PD/2 trials there was no functionality to re-negotiate a trajectory and thus to recover class A status (see section 2.1 of the Main Report for the mechanisms of transition between a/c classes). Therefore the actual proportions of class A aircraft, i.e. those aircraft who kept their class A status throughout the ORG 2 simulation runs, were smaller than the defined ratios of 30% and 70%. In fact, the results reported for ORG 2 refer to the following overall ratios actually achieved.

High traffic scenarios
ORG 2 (30%): 19% class A; 81% non-class A,
ORG 2 (70%): 39% class A; 61% non-class A.

Medium traffic scenarios
ORG 2 (30%): 21% class A; 79% non-class A,
ORG 2 (70%): 52% class A; 48% non-class A.
2 Number of Landings

The number of inbound aircraft that completed their flights through the simulated airspace of PD/2 and were brought down to land on either of the two parallel runways was analysed as a first overall indicator of traffic throughput. The landing rates were calculated on an hourly basis. As the individual simulation runs started with an "empty" ETMA into which aircraft were fed from the adjacent sectors it took more than 20 minutes until the first aircraft landed. The time interval between that first landing and the latest landing observed before the end of the 90 minutes simulation time served as the basis to calculate the number of landings per hour.

Figure 2.1 and Figure 2.2 show the number of landings in high traffic and in medium traffic scenarios. The dots represent arithmetical means (M) of eight scores obtained from the eight teams. Vertical bars indicate the standard deviations (SD) of the eight scores, and thus the variability between teams.

Table 2.1 gives the results of the statistical tests. The "ORG 0 vs. ORG 1" part of the table gives the probabilities of the Wilcoxon test under $H_0$. A probability $p < .05$ indicates rejection of $H_0$, and thereby acceptance of $H_1$ saying that the ORG 1 mean is significantly better than the ORG 0 mean. The right hand part of the table describes the results of the Friedman analysis. The scores of each team under ORG 1, ORG 2/30 %, and ORG 2/70 % were put in a rank order from 1.00 to 3.00 to obtain the mean ranks over all teams printed in the table. The chi-square test results based on mean rank comparison are given below. A probability $p < .05$ indicates rejection of $H_0$ and acceptance of $H_1$ which means in that case a significant effect of different proportions of 4D FMS/datalink aircraft in the traffic sample. Non-significant test results are indicated by "n.s.".

In high traffic (Figure 2.1) with the ORG 0 reference system a mean number of 62.2 landings per hour was measured, whereas that number was noticeably higher with the advanced ORGs. 64.6 landings per hour in ORG 1 showed a significant increase over ORG 0 and thus supports the hypothesis of a benefit through PD/2 PATs and GHMI introduction. Under the same traffic demand two more landings per hour were achieved.

Two more things are shown by Figure 2.1:

First, mean landing rates of ORG 1, ORG 2/30 %, and ORG 2/70 % were nearly equal, ranging from 64.0 to 64.6. There was no significant difference between them. In all the advanced ORGs the average landing rate was higher than in the ORG 0 reference mode, regardless if any, or how many class A aircraft were involved.

Second, the standard deviation of the eight teams’ landing rates was highest in ORG 0 (SD= 2.4). The standard deviations which characterise the variability between the teams were smaller in all advanced ORGs (SD between 0.7 and 1.2).

With medium traffic (Figure 2.2) average landing rates close to 42 landings per hour were observed in all ORGs, ranging between 42.5 in ORG 0 and 41.8 in ORG 2/70 %. Any trends confirming superiority of the advanced ORGs over ORG 0 were not found in the data. There was rather a reserve trend found in the Friedman test which indicated that the mean landing rate of 41.8 in ORG 2/70 % was significantly smaller than in any other ORG. In summary, the landing rate showed that there was neither a benefit of PATs and GHMI introduction nor of having additionally some proportion of class A aircraft.
Figure 2.1  Mean number of landings in high traffic scenarios

Figure 2.2  Mean number of landings in medium traffic scenarios

<table>
<thead>
<tr>
<th></th>
<th>ORG 0 vs. ORG 1</th>
<th>ORG 1</th>
<th>ORG 2/ 30%</th>
<th>ORG 2/ 70%</th>
<th>Mean Rank</th>
</tr>
</thead>
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<td>high traffic</td>
<td>p&lt; .05</td>
<td>2.25</td>
<td>2.00</td>
<td>1.75</td>
<td>Mean Rank</td>
</tr>
<tr>
<td></td>
<td>( \chi^2(\text{n=8, d.f.=2}) = 1.00 )</td>
<td></td>
<td>n.s.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>medium traffic</td>
<td>n.s.</td>
<td>2.50</td>
<td>2.25</td>
<td>1.25</td>
<td>Mean Rank</td>
</tr>
<tr>
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<td>( \chi^2(\text{n=8, d.f.=2}) = 7.00 )</td>
<td></td>
<td>p&lt; .05</td>
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<td></td>
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</table>

Table 2.1  Statistical tests of mean number of landings per hour
3 Flight Time

The time that inbound aircraft took for their way through the simulation, i.e. starting from their defined entry point into the simulation down to the threshold, was taken as another parameter for analysing potential benefits from implementing the PD/2 advanced ORGs.

Flight time was defined as "Time over Threshold" minus "Simulation Entry Time". The average flight time of all aircraft that had landed per simulation run was calculated and used for analysis of an overall trend.

Additionally, since the arrival routes were different in their length, and hence particularly aircraft approaching through the ACC West sector which was the only manned ACC sector had a longer way to go, the analysis was also done separately for the West, North, and South arrival routes.

3.1 Flight Time In High Traffic Scenarios

The means and standard deviations of flight time under high traffic load are depicted in Figure 3.1 to Figure 3.4. Table 3.2 summarises the results of their statistical tests.

Figure 3.1 shows that the average flight time for the pooled data over all arrivals routes observed under reference condition (ORG 0) decreased from 25.2 minutes to 24.4 minutes in ORG 1 where the PD/2 concept of PATs and GHMI support was introduced. The difference indicated an overall saving of about 0.8 minutes (48 seconds) per aircraft which is equivalent to about three per cent of the flight time characteristic for the PD/2 simulations. The decrease was statistically significant (see Table 3.2) whereas no significant effect on the overall flight time was found in the ORG 1 versus ORG 2 data; thus no further benefit from having traffic flying as class A aircraft was observed.

Figure 3.2 to Figure 3.4 show the flight time means of the individual arrival routes. Note that the vertical axes have different scaling due to different route (and thus time) length.

The pattern is similar to the overall data, although a decrease of flight time from ORG 0 to ORG 1 was verified as statistically significant only in case of the northern arrival route. Among the ORG 1 vs. ORG 2 comparisons there were again no significant indications of any further reduction of flight time with an increasing proportion of class A aircraft. Rather, the significant outcome of the Friedman test for differences between the ORG 1 vs. ORG 2/ 30 % vs. ORG 2/ 70 % data of the West route showed that there was even a slight effect in the reverse direction as hypothesised (here mean flight time with the 70 % class A traffic sample was about 0.3 minutes higher than with the 30 % class A sample and the 0 % class A sample of ORG 1).

As can be further seen from Figure 3.1 to Figure 3.4, the standard deviations of the eight teams’ mean flight time were in all cases considerably higher under ORG 0 than under any of the advanced ORGs. That variability has been drastically reduced by introducing the PD/2 advanced ORGs.
Figure 3.1 Mean Flight Time per aircraft in high traffic scenarios, all arrival routes combined

Figure 3.2 Mean Flight Time per aircraft from arrival route West in high traffic scenarios

Figure 3.3 Mean Flight Time per aircraft from arrival route North in high traffic scenarios
3.2 Flight Time In Medium Traffic Scenarios

The medium traffic data, as depicted in Figure 3.5 to Figure 3.8 and in Table 3.3, did not show a significant trend in parallel to the high traffic data. In particular, no overall benefit of the PD/2 advanced ORGs to reduce mean flight time could be verified under medium traffic load. No ORG 0 vs. ORG 1 difference towards a hypothesised benefit of PATs and GHMI, nor any significant difference between ORG 1 and ORG 2 flight time as an effect of introducing class A aircraft, were present in the overall data pooled from all arrival routes.

Analysis of flight time data per arrival route shows that, except for the North route, mean flight time tended to be even smaller under ORG 0. This suggests that with the ORG 0 reference system under medium traffic load the controllers succeeded to deploy their basic skills in such a way that an equivalent or sometimes even slightly more efficient guidance of inbound aircraft resulted than in the advanced ORGs with strict observance of the system-generated advisories, respectively with strict adherence to the trajectories.
In the ORG 1 against ORG 2 statistical tests of flight time under medium traffic load the only significant differences were found for the West and the North arrival routes, indicating that particularly in the case of ORG 2 (70%) a slight re-distribution of flight time between these routes took place.

Figure 3.5  Mean Flight Time per aircraft in medium traffic scenarios, all arrival routes combined

Figure 3.6  Mean Flight Time per aircraft from arrival route West in medium traffic scenarios
Figure 3.7  Mean Flight Time per aircraft from arrival route North in medium traffic scenarios

Figure 3.8  Mean Flight Time per aircraft from arrival route South in medium traffic scenarios

<table>
<thead>
<tr>
<th>Route</th>
<th>ORG 0 vs. ORG1</th>
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<th>ORG 2/ 30%</th>
<th>ORG 2/ 70%</th>
<th>Mean Rank</th>
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<td>Overall</td>
<td>n.s.</td>
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<td>2.50</td>
<td>Mean Rank</td>
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<td>West</td>
<td>n.s.</td>
<td>1.50</td>
<td>1.63</td>
<td>2.88</td>
<td>Mean Rank</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\chi^2(n=8, d.f.=2) = 9.25$ p&lt; .05</td>
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<tr>
<td>North</td>
<td>n.s.</td>
<td>2.13</td>
<td>2.75</td>
<td>1.13</td>
<td>Mean Rank</td>
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<td>$\chi^2(n=8, d.f.=2) = 10.75$ p&lt; .05</td>
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<tr>
<td>South</td>
<td>n.s.</td>
<td>2.50</td>
<td>1.50</td>
<td>2.00</td>
<td>Mean Rank</td>
</tr>
<tr>
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<td>$\chi^2(n=8, d.f.=2) = 4$ n.s.</td>
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</table>

Table 3.3  Statistical tests of mean flight time per aircraft in medium traffic scenarios
4 Inbound Delay

An inbound delay was measured as the difference between an aircraft’s preferred time against the actually observed time of Gate overflight. The preferred time results from an estimate derived from the aircraft’s "user preferred trajectory" along the arrival route that could be flown if there were no other aircraft in the area.

4.1 Inbound Delay In High Traffic Scenarios

For the high traffic load simulations, means and standard deviations of inbound delay are shown in Figure 4.1 to Figure 4.4; statistical tests are summarised in Table 4.4.

The shapes of the figures look very much like those found for flight time, showing at first glance again a benefit, i.e. a reduction of delays from reference (ORG 0) down to a lower level in the advanced ORGs, and again no further benefit resulting from an increasing percentage of class A aircraft as it was originally hypothesised for ORG 2.

However, other than for flight time, in the pooled data over all routes no significance was found for the mean delay reduction of about 37 seconds between ORG 0 and ORG 1, presumably because of the high variability among the eight teams which could be observed again particularly in ORG 0. That variance was significantly reduced in the advanced ORGs (cf. the vertical standard deviation bars). The only significant effect (p < .05) of introducing PATs and GHMI was found for the North arrival route, where a mean delay reduction from about 35 seconds in ORG 0 down to about 5 seconds in ORG 1 was observed.

Note that, although a uniform trend developed, the absolute numbers for mean delay were different for the arrival routes:

- West: -05 to -45 seconds,
- North: +35 to +5 seconds,
- South: +80 to +30 seconds.

Therefore different scaling was used again for the different figures.

Generally delays were on the average smallest for the West route, followed by the North, and finally by the South route. Aircraft flying the West route used to reach the Gate even earlier than estimated. There appeared to be some kind of a general, underlying effect of the route geometry: the longer the actually simulated route was, respectively the more flight time was required on average, the higher was the chance to keep delays generally small. To recall the mean flight times reported in the previous section, they were about

- 27 to 28 minutes on the West route,
- 24 to 25 minutes on the North route,
- 23 to 24 minutes on the South route.

The manoeuvring space, or time available to the controllers and to their supporting tools, being either conventional or PATs-driven, seemed to play the key role in determining the delays, whereas the introduction of the PD/2 advanced system only indicated some additional trend which was superimposed to that basic effect of route length. Remember that the West route was the longest...
one, and that aircraft on that route were under control of the only manned ACC sector in the PD/2 simulations.

**Figure 4.1**  Mean Inbound Delay per aircraft in high traffic scenarios, all routes combined

**Figure 4.2**  Mean Inbound Delay per aircraft from arrival route West in high traffic scenarios
Inbound Delay

Figure 4.3  Mean Inbound Delay per aircraft from arrival route North in high traffic scenarios

Figure 4.4  Mean Inbound Delay per aircraft from arrival route South in high traffic scenarios

<table>
<thead>
<tr>
<th>Sector</th>
<th>ORG 0 vs. ORG1</th>
<th>ORG 1</th>
<th>ORG 2/ 30%</th>
<th>ORG 2/ 70%</th>
<th>Mean Rank</th>
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<td>1.63</td>
<td>Mean Rank</td>
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<td></td>
<td>$\chi^2(n=8, d.f.=2) = 2.25$</td>
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<tr>
<td>West</td>
<td>n.s.</td>
<td>2.13</td>
<td>1.63</td>
<td>2.25</td>
<td>Mean Rank</td>
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<td>$\chi^2(n=8, d.f.=2) = 1.75$</td>
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<td>North</td>
<td>p&lt; .05</td>
<td>2.25</td>
<td>2.25</td>
<td>1.50</td>
<td>Mean Rank</td>
</tr>
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<td></td>
<td></td>
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<td>$\chi^2(n=8, d.f.=2) = 3.00$</td>
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<td>South</td>
<td>n.s.</td>
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<td>1.88</td>
<td>2.00</td>
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<td>$\chi^2(n=8, d.f.=2) = .25$</td>
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Table 4.4  Statistical tests of mean inbound delay in high traffic scenarios
4.2 Inbound Delay In Medium Traffic Scenarios

The medium traffic delay data, shown in Figure 4.5 to Figure 4.8 and Table 4.5, continued to display trends in parallel to the flight time figures as discussed in the previous section. Again, any benefit from the advanced ORGs could not yet be observed for that traffic sample, and, again with the exception of the North route, inbound delays tended to be even less favourable for the advanced ORGs. The only result of the statistical tests that is reported significant in Table 4.5 applies for the South route where a slight benefit through stepwise increasing the proportion of class A aircraft was found. However, this cannot be operationally relevant, in the light of even smaller delays observed under ORG 0 reference conditions.

Figure 4.5  Mean Inbound Delay per aircraft in medium traffic scenarios, all routes combined

Figure 4.6  Mean Inbound Delay per aircraft from arrival route West in medium traffic scenarios
Figure 4.7  Mean Inbound Delay per aircraft from arrival route North in medium traffic scenarios

Figure 4.8  Mean Inbound Delay per aircraft from arrival route South in medium traffic scenarios

<table>
<thead>
<tr>
<th>Sector</th>
<th>ORG 0 vs. ORG1</th>
<th>ORG 1</th>
<th>ORG 2/ 30%</th>
<th>ORG 2/ 70%</th>
<th>Mean Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>n.s.</td>
<td>2.25</td>
<td>2.13</td>
<td>1.63</td>
<td>Mean Rank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\chi^2(n=8, d.f.=2) = 1.75$</td>
</tr>
<tr>
<td>West</td>
<td>n.s.</td>
<td>1.88</td>
<td>1.63</td>
<td>2.50</td>
<td>Mean Rank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\chi^2(n=8, d.f.=2) = 3.25$</td>
</tr>
<tr>
<td>North</td>
<td>n.s.</td>
<td>1.75</td>
<td>2.50</td>
<td>1.75</td>
<td>Mean Rank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\chi^2(n=8, d.f.=2) = 3.00$</td>
</tr>
<tr>
<td>South</td>
<td>n.s.</td>
<td>2.63</td>
<td>2.00</td>
<td>1.38</td>
<td>Mean Rank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\chi^2(n=8, d.f.=2) = 6.25$</td>
</tr>
</tbody>
</table>

Table 4.5  Statistical tests of mean inbound delay in medium traffic scenarios
5 Precision Of Delivery

Since flight time and inbound delay are, in principle, common products of both the planning tool performance and controller performance, precision of delivery is considered as a useful indicator of how precisely the tools-generated plans were actually implemented.

Precision of delivery is calculated from the observed differences between actual time over Gate and planned time over Gate. Note that the planned time over Gate may already include a delay because the planning algorithm accounts for the overall traffic situation either by using merely arrival time estimates in ORG 0, or by using conflict-free trajectories in ORG 1 and ORG 2.

As aircraft can be delivered earlier or later than exactly at planned time, positive and negative deviations might cancel each other when averaged. To avoid this, precision of delivery was measured by the absolute magnitude of the time difference between planned and actual Gate overflight of an aircraft (Equation 1).

\[
\text{absolute mean} = \frac{\sum |t_a - t_p|}{n}
\]

where \( t_a \) = an aircraft’s actual time over Gate,
\( t_p \) = an aircraft’s planned time over Gate,
\( n \) = number of aircraft.

Precision of delivery was analysed again separately for the high traffic load and the medium traffic load simulation runs.

5.1 Precision of Delivery In High Traffic Scenarios

The high traffic load simulations results of precision of delivery are displayed in Figure 5.1. Table 5.7 gives the summary of the statistical tests.

The mean precision of delivery for the data pooled from all arrival routes dropped from 91 seconds in ORG 0 to 21 seconds in ORG 1 where the PATs trajectory-based planning and GHMI support was introduced. This effect was of course significant (\( p < .05 \)).

The enormously high deviations from the planned times as they are expressed in the ORG 0 precision of delivery resulted from frequent changes of the arrival sequences. As there were no system-generated control advisories available in the reference system (ORG 0) the entirely manual guidance with it’s inherent larger variability often resulted in ad-hoc controller decisions to rearrange initially planned sequences later on. An example will illustrate the effect of this: a controller team decides to change the sequence of a particular pair of aircraft against the planned arrival sequence. When doing their job perfectly then and delivering the two aircraft exactly 3 NM spaced with 180 kts at the Gate, one aircraft is then 60 seconds earlier, the other one 60 seconds later than originally planned. This impairs the mean precision of delivery considerably.

For the effect of having class A aircraft in the sample, Figure 5.1 shows the improvement in precision of delivery with increasing proportions of class A aircraft. The ORG 1 mean of 21 seconds decreased to 15 seconds in ORG 2/ 30 % and to 11 seconds in ORG 2/ 70 %. This effect was also statistically significant at the required level of \( p < .05 \) (as can be seen from Table 5.7).
Figure 5.2 provides more detailed information. For the interval of +/- 60 seconds deviation from planned time the distributions of precision of delivery are shown for the different ORGs. The graphs are based on collations of data from all measured runs with high traffic load, thereby integrating the data from all teams.

The two graphs on top of Figure 5.2 illustrate the transition from ORG 0 to ORG 1. With the reference (ORG 0) type of arrival sequence planning which provided no further information to the controller about what control strategy to select for implementing the plan a flat distribution over a wide range of plan deviations emerged. Less than five per cent of the aircraft were delivered exactly (i.e. +/- 2.5 seconds) at their scheduled Gate time. With support of trajectory-based PATs planning and the PD/2 GHMI in ORG 1 more than ten per cent of the aircraft were delivered exactly on time.

The two bottom graphs display what happened when 4D FMS/datalink aircraft entered the game. Larger portions of aircraft were delivered perfectly on time. In ORG 2/30% more than 35 per cent of all aircraft in the traffic sample were delivered on time. That percentage was composed of the 19 per cent class A aircraft who kept their class A status plus another 17 per cent of the aircraft in the traffic sample. In ORG 2/70% about 62 per cent of all aircraft were delivered on time. Here the percentage was composed of 39 per cent of aircraft remaining class A plus another 23 per cent of aircraft. Broadening the view onto an interval of no more than ten seconds early or late delivery at the Gate (which of course includes delivery exactly on time) shows that

- 16% of all aircraft were delivered within +/- 10 seconds in ORG 0,
- 60% of all aircraft were delivered within +/- 10 seconds in ORG 1,
- 71% of all aircraft were delivered within +/- 10 seconds in ORG 2/30%,
- 79% of all aircraft were delivered within +/- 10 seconds in ORG 2/70%.

Figure 5.1 Mean precision of delivery in high traffic scenarios, all arrival routes combined

<table>
<thead>
<tr>
<th>ORG 0 vs. ORG1</th>
<th>ORG 1</th>
<th>ORG 2/30%</th>
<th>ORG 2/70%</th>
</tr>
</thead>
</table>
| p<.05          | 2.63  | 2.00      | 1.38      | Mean Rank
| $\chi^2(n=8, d.f.=2) = 6.25$ | p<.05 |

Table 5.7 Statistical tests of precision of delivery in high traffic scenarios
Figure 5.2  Distributions of precision of delivery in high traffic scenarios
5.2 Precision Of Delivery In Medium Traffic Scenarios

The medium traffic load simulation results about precision of delivery are displayed in Figure 5.3. Table 5.8 gives the statistical tests summary. In addition to this, Figure 5.4 shows the distributions of precision of delivery in the different ORGs, for the interval of +/− 60 seconds deviation from planned time.

The Wilcoxon test for ORG 0/ORG 1 differences in precision of delivery showed a significant benefit when PATs and GHMI support were used in medium traffic load. The ORG 0 mean of 41 seconds was reduced to 22 seconds in ORG 1.

In the mixed class A/non-class A traffic samples of ORG 2 there was also an improvement going along with increasing the class A proportion. The precision of delivery mean dropped from 22 seconds in ORG 1 to 17 seconds in ORG 2/30%, and further down to 8 seconds in ORG 2/70%. An overall precision gain due to the growing proportion of 4 D FMS/datalink aircraft was again significant (p < .05).

![Figure 5.3](image-url)

*Figure 5.3   Mean precision of delivery in medium traffic scenarios, all arrival routes combined*

<table>
<thead>
<tr>
<th></th>
<th>ORG 0 vs. ORG1</th>
<th>ORG 1</th>
<th>ORG 2/30%</th>
<th>ORG 2/70%</th>
</tr>
</thead>
<tbody>
<tr>
<td>p&lt;.05,</td>
<td>2.63</td>
<td>2.13</td>
<td>1.13</td>
<td>Mean Rank</td>
</tr>
<tr>
<td>(\chi^2) (n=8, d.f.=2) = 10.75</td>
<td>p&lt;.05</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 5.8    Statistical tests of precision of delivery in medium traffic scenarios*
Figure 5.4  Distributions of precision of delivery in medium traffic scenarios
6 Separation

Separation over the Gate was taken as an indicator of whether potential benefits in terms of traffic throughput were possibly achieved at the expense of separations less than published wake vortex separation standards. The Gate, located 10 NM ahead of the runway threshold, was chosen as an appropriate reference point for assessing separations since this was the planning target for the tools’ support to the controllers as well as the end of active controller guidance in the PD/2 simulations. Near the Gate the Feeder (TC-F) had to “transfer” the aircraft to the Tower which was not included as a manned position in PD/2.

The separations were calculated on a time basis, referring to the ICAO wake vortex categories minimum separation standards based on weight classes, i.e. 3 NM for Medium/Heavy and Medium/Medium aircraft sequences, 4 NM for Heavy/Heavy, and 5 NM for Heavy/Medium sequences. A simple algorithm, assuming an average speed of 180 kts at that flight phase, counted the number of aircraft pairs for which the distances were less than 3 NM (equivalent to 60 seconds), or 4 NM (80 seconds), or 5 NM (100 seconds). The calculations were done for each runway independently, then the data from both runways were pooled.

The average numbers of separations less than standard are displayed in Figure 6.1 and Figure 6.2. Table 6.9 gives a summary of the performed statistical tests.

In the high traffic load simulations (Figure 6.1) a significant decrease of the number of separations less than standard was found for ORG 1 as compared to ORG 0. Some further decrease in ORG 2/30 % and ORG 2/70 % was not statistically significant.

In the medium traffic load simulations (Figure 6.2) no significant effects at all were observed. The average number of separations smaller than standard was below 1.5 per hour in all ORGs.

It must be pointed out that the observed numbers of smaller separations should not be interpreted in terms of safety-related minimum separation infringements. On purpose, the simulations aimed quite specifically at minimum separations to allow for tight arrival sequences, and thus high traffic throughput. Making permanently use of minimum separation requires that certain meteorological, specifically visibility requirements must be met. When they are met the controller has, on the other hand, justification to allow pilots to keep their own visual separation which then indeed may be smaller than the published standards. In a real-life situation it would not make sense to apply an arrival sequence planning which is very tight in terms of separation, and to penalise at the same time any inaccuracy resulting in a violation of a separation standard.

What the separation figures allow to conclude is that the positive effects on traffic throughput of the PD/2 concept which were particularly observed in high traffic load, were definitely not achieved at the expense of separation. Quite the reverse appeared to be true. With the introduction of PATs and GHMI there was even less need to use final approach spacing closer than the published standards.
Figure 6.1  Mean number of separations smaller than wake vortex categories in high traffic scenarios

Figure 6.2  Mean number of separations smaller than wake vortex categories in medium traffic scenarios

<table>
<thead>
<tr>
<th></th>
<th>ORG 0 vs. ORG1</th>
<th>ORG 1</th>
<th>ORG 2/ 30%</th>
<th>ORG 2/ 70%</th>
</tr>
</thead>
<tbody>
<tr>
<td>high traffic</td>
<td>p = .05</td>
<td>2.25</td>
<td>1.88</td>
<td>1.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>medium traffic</td>
<td>n.s.</td>
<td>2.06</td>
<td>1.94</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table 6.9  Statistical tests of mean number of separations smaller than wake vortex category
7 Summary and Discussion of Results

Several indicators of traffic throughput and quality of service were analysed in this annex and reported one by one. In this final section the results will be discussed in context, thereby referring to the main objectives of

- analysing the effect of introducing PD/2 PATs and GHMI by comparison of ORG 0 against ORG 1, and
- analysing the effect of introducing additionally portions of 4D FMS/datalink aircraft by comparison of ORG 1 against ORG 2/ 30% and ORG 2/ 70%.

Table 7.10 compiles the results of the statistical tests of the parameters analysed under both, high and medium traffic load. The '=' indicates that there was no statistically significant difference of an analysed parameter between compared ORGs, whereas the '+' indicates a significant positive effect.

<table>
<thead>
<tr>
<th></th>
<th>medium traffic</th>
<th>high traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>From ORG 0 to ORG 1</td>
<td>From ORG 1 to ORG 2</td>
</tr>
<tr>
<td>number of landings</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>flight time</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>inbound delays</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>precision of delivery</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>separation</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>variability between teams</td>
<td>=</td>
<td>=</td>
</tr>
</tbody>
</table>

Table 7.10 Summary of results: effects on traffic throughput/quality of service

This table summarises the data in total whereas Figure 7.1 to Figure 7.4 exemplify typical patterns of traffic guidance which were observed in singular simulation runs. The radar plot examples given in this figure illustrate horizontal flight paths of aircraft in all ORGs of PD/2 and were taken from one controller team’s measured runs under high traffic load. They are displayed here to visualise directly some of the effects which will be discussed below.
Figure 7.1  Radar plot of ORG 0 run of one controller team in high traffic scenario

Figure 7.2  Radar plot of ORG 1 run of one controller team in high traffic scenario
Figure 7.3  Radar plot of ORG 2/ 30% run of one controller team in high traffic scenario

Figure 7.4  Radar plot of ORG 2/ 70% run of one controller team in high traffic scenario
7.1 Traffic Throughput/ Quality of Service Differences Between ORG 0 and ORG 1

The reference, or baseline, ORG 0 system represents the functionality of a today’s ATC system with paper strips and conventional arrival sequence planning. It leaves decisions about tactical control measures that are suitable to implement the proposed sequences completely to the controller. Transition to ORG 1 introduces as a key element ground-based 4D trajectory planning of inbound traffic. The system supports the controller by generating 4D advisories and by providing a stripless advanced GHMI for interacting with the system.

The unique set of PD/2 PATs tools and functions, together with the GHMI display and interaction mechanisms offered, can be seen as a first step towards an advanced system for traffic guidance in the Terminal Area in a future 4D FMS/datalink environment. This required that controllers were briefed adequately to adopt a specific role in the experiment. They accepted a role which expected them not to test a pre-operational system that goes into service soon but to try their best to work with the advanced system, thereby keeping in mind that a concept rather than a final system was to be assessed.

All controllers participating as subjects in PD/2 were highly qualified. They passed the training successfully, and were then able to work with the PD/2 system in the ORG 0 baseline mode as well as the advanced ORGs.

As a general observation found from nearly all measured parameters, there was the highest variance in the data of ORG 0, indicating that work styles differed largely between controller teams. This is not a surprise when the type of ORG 0 planning support is considered. The proposed arrival sequences were displayed, but no information on particular tactical control measures how to implement the planned sequences was provided. In ORG 1, with control advisories generated that apply to individual trajectories, the variance between the teams’ data was generally smaller. Work styles and performances of the different controller teams became more homogeneous, and thus more predictable.

Apart from this various gains of the PD/2 concept were found in terms of traffic throughput and quality of service, as compared to the ORG 0 baseline. Significant benefits for the number of landings per hour, average flight time of aircraft, precision of delivery, and separation were reported. As a matter of fact the positive effects were mainly present under high traffic load, whereas the data obtained under medium traffic load suggested that the controllers could make use of their basic skills in such a way that an equivalent, or sometimes even slightly more efficient guidance of inbound traffic resulted than with observance of the system-generated advisories in ORG 1.

Under the higher traffic load which was in the PD/2 simulations equivalent to increasing the traffic volume by about one third, the ORG 0 type planning reached its limits, and advantage could be taken from introducing the PATs and GHMI in ORG 1. Nearly all traffic throughput and quality of service parameters analysed were better than in ORG 0. The improvements were statistically significant, only the observed reduction of inbound delay failed to reach the five per cent significance level.

The benefit in terms of flight time, number of landings achieved, and precision of delivery must be seen in conjunction with each other. For instance the stated decrease of average flight time taken in isolation might raise a certain suspicion because flight time calculation was based on the data of aircraft that actually had landed within the 90 minutes of a simulation run. It could be suspected that less flight time of that aircraft was achieved at the expense of some, or even many other aircraft that
had not landed within the data collection period. However, this can definitely be excluded by also considering the number of landings which was equally favourable.

In total it can be concluded that a benefit of the introduction of PATs and GHMI in ORG 1 was observed such that particularly higher traffic demand could be handled more smoothly and more efficiently. That efficiency gain was achieved without any detrimental effect on separation measured over the approach gate, there was even a significantly positive effect on separation going along with the ORG 1 introduction.

It should be emphasised again that generalisation of the PD/2 simulation results such as “three per cent flight time gain” are not realistic because they cannot be applied to every sort of TMA geometry, route structure, etc. However, the example quoted can be taken as a serious indication that the PD/2 concept provides the means to reduce flight times to the controllers. The absolute magnitude of such benefit in future real systems is difficult to quantify.

An interesting observation was made from the analysis of inbound delays. The earlier the aircraft came under control of the actively simulated part of the ATC system, the more time seems to be given for optimising individual flight paths, and thus for keeping delays small. This could be seen already in ORG 0 as well as with the PD/2 advanced system. It was an observation only, and was not the matter of the PD/2 study. However, it would certainly be worth to verify such a general effect. This would require more specific systematic studying.

7.2 Traffic Throughput/Quality of Service Differences Between ORG 1, ORG 2/30%, and ORG 2/70%.

The transition from ORG 1 to ORG 2 with its increasing proportions of class A aircraft did not change anything about the functionality of the PD/2 system. The basic principles of tools and GHMI support remained unchanged, the difference was in the use of mixed class A/non-class A traffic in ORG 2. While all traffic in ORG 1 was handled as non-class A, in ORG 2 some portions of aircraft in the traffic sample were supposed to make use of on-board 4-D FMS/datalink equipment and thus to proceed automatically along their trajectories which had been established upon entry into simulation. The controllers’ only interaction with that aircraft was to assume control, establish initial radio contact, and transfer them later to the next sector, or the tower. Without any control advisories the aircraft followed their plan and arrived at the Gate exactly at their scheduled time, by definition in the simulation. In case of a tactical intervention of a controller, such an aircraft lost the class A status.

The main question was, did throughput and quality of service in the ETMA, for the traffic sample as a whole, benefit from having class A aircraft in that traffic sample? The simulation results showed significant gains in precision of delivery of the aircraft at the Approach Gate. All other improvements over the baseline system were achieved by the controllers with using the advanced PD/2 system in either case, no matter if any, or how many 4D FMS/datalink aircraft were involved.

This needs some further explanation. By nature of the PD/2 trials the 'optimal' traffic guidance will theoretically be reached when all aircraft (class A and class B) follow their trajectories in a perfect manner. Then the actual mix of class A and class B aircraft would not matter at all; no further benefit could be expected since all aircraft adhere strictly to their 4-D trajectories. The simulation data suggest that already under ORG 1, with trajectory-based guidance entirely implemented via controllers' R/T advisories a result close to that optimum could be achieved. Of course, this optimum is very specific for the trajectories actually used in PD/2, and it does not tell anything about how optimal the trajectories in itself are. Without any doubt there is still room for further improvement of trajectories, e.g. by using parallel routes and shortcuts, or by calculating generally for higher
airspeeds, or by increasing the inbound traffic flow rate through reducing minimum separation, all these measures leading towards a capacity gain. However, it must be emphasised that those capacity issues were not within the scope of PD/2.

Another question of utmost relevance to aircraft operators is whether there could be expected some specific benefit for class A aircraft from using their on-board 4D FMS/datalink capabilities. The answer from the PD/2 simulations to that question is clear but perhaps too simplistic. Of course there is a benefit, the precision of delivery figures have illustrated this impressively. However, by nature of the simulations, for class A aircraft which frequently were downgraded from class A there was no renegotiation foreseen. The lack of system functionality to allow for recovering the class A status certainly underestimates the potential benefit of 4D FMS/datalink equipment. Therefore, more research is necessary to fully address this question and to quantify that benefit exactly.