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Interval Management Operations in the Terminal Airspace of Amsterdam Airport Schiphol

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NLR-TP-2016-194

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Problem area

For the Schiphol terminal airspace, a new handling concept is developed with fixed arrival routes and continuous descent approaches. The aviation sector agrees that fixed arrival routes are desired from the TMA boundary to the runway related to predictability and enabling continuous descent approaches. Continuous Descent Approaches will improve fuel efficiency and environmental aspects, such as noise annoyance and emissions, compared to traditional step-down approaches. Fixed arrival routes and CDAs are procedures that inherently have lower capacity than “vectoring”. Given Schiphol’s demand for high peak-hour capacity, application of fixed arrival routes and CDAs is limited to off-peak and night-time hours. However, the Dutch aviation sector has proposed a strategy for increased application of fixed arrival routes and CDAs. For this reason innovations are sought to increase the capacity of these procedures.

Description of work

Interval Management (IM) is seen as one of the promising innovations to support the new handling concept at Schiphol. With IM, aircraft exchange flight information via ADS-B and use this information to control an ATC assigned time interval with a lead aircraft. It is assumed that this close loop control provides the accuracy and predictability that is required to maintain peak hour capacity.

The IM research involves a number of phases. In the first phase requirements were captured. During the second phase fast-time simulations were performed to evaluate the spacing performance. The third phase progressed with IM real-time simulations (RTS) to assess controller acceptance and workload and to evaluate the IM procedures and IM support tools.

Results and conclusions

The outcome of the fast-time simulations is positive: IM can generate the required performance in the Schiphol terminal environment, allowing high-density operations on fixed routes with continuous descents.

The main results of the controller-in-the-loop real time simulations are:

- All controllers readily accepted and appreciated the IM Concept of Operations and were able to safely and efficiently manage the arrival traffic in all scenarios, including non-normal events, with the newly developed HMI.
- Perceived controller workload was generally well within predefined targets in all scenarios.
- The average number of R/T instructions per aircraft did not vary much between IM and non-IM operations.
- The percentage of (unanticipated) IM cancellations by the controller was very low (<3%).

GENERAL NOTE

This report is based on a presentation held at the AIAA SciTech 2016 conference, San Diego, USA, January 2016.

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Contents

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Interval Management Operations in the Terminal Airspace of Amsterdam Airport Schiphol

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For the Schiphol terminal airspace, a new handling concept is developed with fixed arrival routes and continuous descent approaches. The aviation sector agrees that fixed arrival routes are desired from the TMA boundary to the runway related to predictability and enabling continuous descent approaches. Fixed arrival routes however have the tendency to negatively affect capacity and Schiphol can afford no loss of capacity. Therefore, research is done for innovative ways to handle the incoming traffic, to make high capacity combined with fixed arrival routes possible. Interval Management (IM) is seen as one of the promising innovations to support the new handling concept at Schiphol.

With IM, aircraft exchange flight information via ADS-B and use this information to control an ATC assigned time interval with a lead aircraft. It is assumed that this close loop control provides the accuracy and predictability that is required to maintain peak hour capacity. The KDC IM research involves a number of phases. In the first phase requirements were captured. During the second phase fast-time simulations were performed to evaluate the spacing performance. The outcome of these simulations is positive: IM can generate the required performance in the Schiphol terminal environment, allowing high-density operations on fixed routes with continuous descents. The third phase progressed with IM real-time simulations (RTS) to assess controller acceptance and workload and to evaluate the IM procedures and IM support tools. The main results of the RTS are:

- **All controllers readily accepted and appreciated the IM Concept of Operations and were able to safely and efficiently manage the arrival traffic in all scenarios, including non-normal events, with the newly developed HMI.**
- **Perceived controller workload was generally well within predefined targets in all scenarios.**
- **The average number of R/T instructions per aircraft did not vary much between IM and non-IM operations.**
- **The percentage of (unanticipated) IM cancellations by the controller was very low (<3%).**

I. Introduction

IN 2008, the Knowledge & Development Center – Mainport Schiphol (KDC) investigated the potential benefits of ADS-B based applications for the Schiphol Terminal environment [1]. One of the recommendations was to further develop Interval Management (IM) Operations at Schiphol including its airborne component termed Flight Deck Interval Management (FIM). IM as an Airborne Spacing application has the capability to mitigate potential runway throughput reductions as a consequence of introducing fixed arrival routes and Continuous Descent Operations (CDO) during daytime and in particular during peak hours.

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In the KDC research agenda [2] the problem statement is as follows: “There is an urgent call from government and surrounding Schiphol communities to implement Continuous Descent Approaches (CDA) in the upcoming years. Such procedures would be based on partly fixed routes which will be introduced at Schiphol Airport as a result of an agreement between the Dutch regulator and the aeronautical sector (“Alders Advice until 2020”). Continuous Descent Approaches will improve fuel efficiency and environmental aspects, such as noise annoyance and emissions, compared to traditional step-down approaches. However, it is also anticipated that the introduction of CDAs, with a fixed lateral path, will have negative capacity consequences. Reduction of peak hour capacity will hurt network operations and will jeopardize Schiphol’s future. For the Dutch aviation sector the introduction of CDAs without mitigating procedures or technology to alleviate the foreseen capacity drop is unacceptable.”

In order to introduce CDAs with a high hourly capacity (≥ 35-36 landings per hour, per runway) additional measures are required. Interval Management is regarded, according to the current internationally accepted view, to be the most appropriate to address this shortfall. Initial operational trials have been conducted by United Parcel Services (UPS), in co-operation with the FAA, at Louisville Airport in the USA. More operational trials are under way at Philadelphia / US Airways and New York / JetBlue.

The KDC aims to develop the IM Operation and associated procedures and systems, and in particular aims to demonstrate feasibility and validity of an IM concept of operation for the specific operational and environmental conditions of Schiphol.

In principle, an IM Operation has to be validated for each local situation given its specific airspace structure, approach and departure routes, procedures and demand and mix of air traffic. The Schiphol case is unique in the sense that research and development of CDOs in combination with IM has been carried out for large Terminal Manoeuvring Areas only (e.g. Dallas-Fort Worth) [4, 5].

This paper reports on the results of two simulations that support the development of IM Operations in the Terminal Airspace of Schiphol. The first is a fast-time simulation investigating the spacing performance for varying initial conditions and disturbances, e.g., several levels of wind forecast errors and several levels of navigation performance. The second is a real-time controller-in-the-loop simulation addressing procedural, HMI and controller acceptance aspects.

The paper is organized as follows. Section II discusses the IM concept envisaged for the Schiphol Terminal Airspace. The experimental set-up, results and conclusions of the fast-time simulation are given in Section III. And the real-time simulation is described in Section IV. General conclusions and next steps are summarized in Section V.

II. IM Operations in the Schiphol Terminal Manoeuvring Area

For Schiphol, IM Operations start with Amsterdam Area Control (ACC) using an Arrival Manager (AMAN) or other means to build up a properly spaced sequence of aircraft to the designated runway. From this planned sequence, aircraft pairs can be determined. Each pair consists of an IM aircraft and a Target aircraft. The Target aircraft may initially be on a different route. Air Traffic Control (ATC) furthermore needs to assure that both aircraft arrive at their IAFs in time in order to be able to adhere to the fixed arrival routes and to start IM Operations. ATC uses a ground automation tool, e.g., the Speed And Route Advisor (SARA) tool [3]. This tool helps ACC to deliver the aircraft on their designated Initial Approach Fixes (IAF) time with a tolerance of +/-30 sec (99%) around the planned schedule time.

Prior to or just after entering the Terminal Manoeuvring Area (TMA), the IM aircraft will receive an IM Clearance. ATC determines the IM Clearance parameters and assesses these to ensure that applicability parameters are met. The IM Clearance, which will be communicated over voice, includes amongst others the aircraft to follow (Target Aircraft Identification), the spacing requirement - both its value (Assigned Spacing Goal) and location (Achieve-by Point), and the Intended Flight Path Information of the Target aircraft. The Achieve-by Point is located at the Final Approach Point (FAP) of the runway in use and the clearance limit, the Planned Termination Point, is co-located with the Achieve-by Point. The IM Operational Tolerance of approximately 10 seconds (95%) is fixed and is not communicated over voice.

Upon reception of the IM Clearance, the flight crew acknowledges reception and enters the clearance parameters into the FIM Equipment. The FIM Equipment checks the input to see if the data of both the Target and IM aircraft is of sufficient quality. When it determines that all execution requirements are met, an initial IM speed is calculated and displayed in the cockpit. The flight crew now determines if this speed is feasible and stays within any applicable regulatory and/or performance limits, and assesses the overall feasibility of the IM Clearance. When the result of this assessment is positive, the flight crew starts the execution of the IM Operation.

The flight crew now executes the IM Operation, either by manually inputting IM speeds to the auto flight system or by activating the automatic execution of the IM speeds. During the IM Operation both the flight crew and the

FIM Equipment will monitor conformance with the IM Clearance. The flight crew may terminate the IM Operation, at any time, if unable to continue the IM Operation for whatever reason. If this occurs ATC is notified. ATC in the meantime monitors the progression of both flights. When separation, spacing or other issues are identified, ATC determines whether to intervene. In some instances tactical adjustments to the Target aircraft may resolve the problem without impacting the IM aircraft. However modifications to the target aircraft's path or speed will cause the IM aircraft to react by changing speeds. In other instances ATC may suspend the IM Clearance so that it can be amended or ATC may terminate it altogether.

Upon reaching the Planned Termination Point, the FIM Equipment will notify the flight crew of the termination and removes the IM speed information from the cockpit displays. The flight crew will now fly speeds as instructed by ATC or as published by the final approach procedure. This will be similar to today's operational procedures, resulting in a stabilized approach condition at 1000 ft AGL.

A full description of the concept is provided in the Operational Service and Environment Definition (OSED) document [2], which describes the services, intended functions and associated procedures of the Schiphol IM Operation, along with the assumptions about the environment in which the application is specified to operate.

III. A fast-time simulation study: Does IM deliver?

A. Performance Requirements

The operational goals of achieving precise inter-aircraft spacing, while maintaining string stability, together with controller needs for the IM Operation are translated into spacing metrics. These metrics, called the Operationally-Required Tolerances (ORTs), are described using two quantities [7]:

1) the Nominal Spacing Bounds, which relate the nominal spacing performance to the operational goals for the IM Operation, and
2) the Controller Intervention Threshold, which describes a threshold on the deviation from the Assigned Spacing Goal where the controller will intervene if crossed by the IM aircraft.

The Nominal Spacing Bounds are chosen such that the Spacing Intervals of at least 95% of IM Aircraft meet the operational goals. The IM Operational Tolerance then corresponds to this 95% value. The Controller Intervention Threshold is based on the minimum distance spacing requirement in that the Spacing Interval (in distance) cannot come within the required minimum separation.

1. Allocation of IM Operational Tolerance

In order to meet the operational goals the IM Operational Tolerance for the specific operating environment needs to be defined. In the allocation of the IM Operational Tolerance all uncertainties need to be taken into account. The allocation process for determining the IM Tolerance for Schiphol is based on the method described in the RTCA/EUROCAE FIM SPR [7] and is defined in [8] from which this summary is derived.

The analysis showed that the operational tolerances differ depending on the time of day, mainly because of traffic mix and runway throughput requirements. The minimum IM Operational Tolerance is required during the morning inbound peak. The results from the IM Operational Tolerance derivations are shown in Table 1.

Table 1. IM Operational Tolerance for SPL IM Operations

Time of day	IM Operational Tolerance (seconds)
7:00-8:00	13.6
8:00-9:00	10.4
9:00-19:00	21.5
19:00-20:00	15.9
20:00-22:00	35.6
22:00-7:00	36.0

A budget for the performance of the spacing algorithm in the assumed operating environment has to be considered. This budget is based on analysis of prior simulations and field tests of trajectory based spacing algorithms [4, 5]. This yielded that an IM spacing performance of ±10 seconds, 95%, can be achieved. Given the applicable IM Operational Tolerance this provides insight into the allowable Measured Spacing Interval Uncertainty (Table 2).

Table 2. Initial Allocations of the IM Operational Tolerances for the Schiphol TMA

IM Operational Tolerance	Initial FIM Equipment Tolerance	Budgeted Measured Spacing Interval Uncertainty
10.4 seconds	10.0 seconds	2.86 seconds

The final allocation is based on the State Data errors that results from the choice in State Data Performance Level and operational velocities. State Data Quality compatible with the European Implementing Rule that specifies ADS-B OUT has been assumed for both IM and Target Aircraft. This results in requirements on IM and Target aircraft state data and the update rate of Target aircraft state data, e.g., a horizontal position accuracy of 0.1 NM.

For a design groundspeed at the Achieve-by Point of 170 kt, the spacing error contribution due to the uncertainty in state data is then calculated to be 3.04 seconds [7]. Given the IM Operational Tolerance and the uncertainty in state data, the FIM Equipment Tolerance can now be computed using the Root Sum Squared method:

$$\text{FIM Equipment Tolerance} = \text{SQRT}[\ (\text{IM Operational Tolerance})^2 - (\text{Measured Spacing Interval Uncertainty})^2\ ] \quad (1)$$

The results of the final allocation are provided in Table 3 below.

Table 3. Final Allocations of the IM Tolerances for SPL IM Operations

IM Operational Tolerance	Measured Spacing Interval Uncertainty	FIM Equipment Tolerance
10.4 seconds	3.04 seconds	9.9 seconds

This means that in order to meet IM operational goals, the FIM equipment needs to meet the spacing interval to within ± 9.9 sec of the Assigned Spacing Goal.

B. Experimetal Set-up

In order to evaluate the performance of the IM concept at Schiphol and investigate the robustness of the concept against operational uncertainties an off-line simulator batch study was performed.

1. Experiment Design

Arriving traffic for Schiphol's runway 18R was simulated under various wind and traffic density conditions. The aircraft were initiated at one of the four IAFs to Runway 18R, merging at three possible merge points, EH600, EH606 and EH608, see Figure 1. The Intermediate Approach Fix (IF) EH608) was selected as the Achieve-by Point, while the Final Approach Point (FAP) EH621 was selected to be the Planned Termination Point. The spacing algorithm used to generate IM speeds is a trajectory based algorithm developed by NASA Langley Research Center (LaRC), called ASTAR (Airborne Spacing for Terminal Arrivals) [6]. ASTAR uses nominal speed profiles with a control space (allowable deviation) of ±10% from the nominal speed to make up for spacing errors.

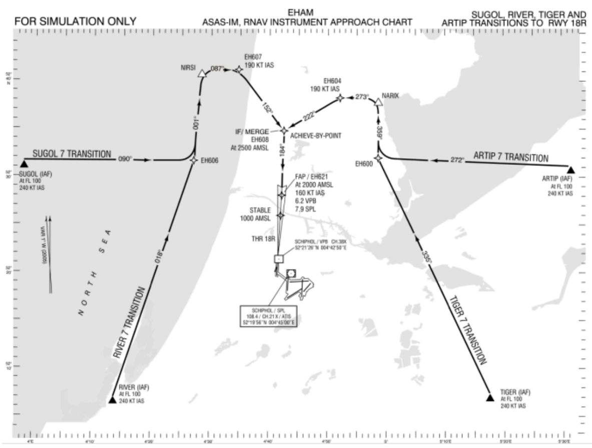

Figure 1. Batch study route design

2. Independent variables

Five independent variables were selected to introduce realistic disturbances into the simulations. For each combination of the independent variables 1600 IM operations were simulated.

1) Time of Day

Two inbound peaks were simulated: one including the largest inbound peak between 8-9AM when the throughput is 35 aircraft per hour per runway, and one between 7-8AM with a throughput of 30 aircraft per hour. The 7-8AM scenario has a 45% Heavy, 55% Medium traffic mix, while the 8-9AM scenario has a 14% Heavy, 86% Medium traffic mix. For the 7-8AM time period, aircraft coming from all four IAFs are directed to runway 18R. But during the inbound peak of 8-9AM only two IAFs are in use for runway 18R, as the airport typically switches to two landing runways.

2) Aircraft Navigation

To research the effect of the aircraft navigation, three levels of Actual Navigation Performance (ANP) were used: ANP0.0, ANP0.15, and ANP0.3. Navigation inaccuracies were modeled by aircraft flying a sinusoidal ground track along the route, with the maximum lateral deviation given by the ANP value, e.g. 0.3 NM for ANP0.3. The ANP0.0 and ANP0.15 scenarios included Radius-to-Fix (RF) legs, thus prescribing an exact ground track during turns, while the ANP0.3 scenario used fly-past waypoints, where the flown ground track depends on ground speed, bank angle and track change.

3) Wind Field

To incorporate the effect of wind forecast uncertainty on the FIM performance, three wind field profiles were included. The forecast wind (WindField 0) consisted of a 15 kts headwind at 3,000ft on final approach for runway 18R, see Table 4. Two more wind fields were constructed from this profile to introduce prediction errors between truth and predicted wind. These wind fields simulate a headwind at 3,000ft on final of 20 kts and 25 kts, respectively.

Table 4. Wind profiles used in the batch study

WindField	*0 ft*	*1,000 ft*	*3,000 ft*	*7,000 ft*	*10,000 ft*
0, SW wind profile	210/12	220/17	230/22	240/32	240/42
1 (+5 kts HW on final)	195/16	205/20	215/24	225/34	225/44
2 (+10 kts HW on final)	195/21	205/25	215/29	225/39	225/49

4) CTA Error

To research the ability of the spacing algorithm to close initial spacing errors, the accuracy with which the aircraft meet the Controlled Time of Arrival (CTA) over the IAF was varied. Three levels of accuracy were chosen to investigate the required delivery accuracy: 30 seconds to indicate expected performance with the use of SARA [3], 15 seconds to incorporate future requirements as laid down by SESAR and 0 seconds for reference. This means that in the worse condition an IM aircraft could have an initial spacing error of 60 sec.

5) Level of automation

Two FIM implementations were simulated: one in which all speed selections had to be made by the flight crew through the Mode Control Panel (MCP)/Flight Control Unit (FCU). This included the use of a Pilot Model with varying time delays (mean=8 sec, ± 4 sec (3-sigma normally distributed)); and one where the IM Speed was directly coupled to the aircraft Speed Control System.

3. Performance Metrics

In order to assess the effect of the independent measures on the IM performance, a number of performance metrics were defined. The most important one was the Spacing Error. This parameter looks at the accuracy with which the ASTAR algorithm was able to achieve the required spacing at the ABP. The spacing error is defined as:

$$\epsilon_{spacing} = \left(t_{(ABP)_{IM}} - t_{(ABP)_{Target}}\right) - spacing\ goal \qquad (2)$$

Where $t_{(ABP)IM}$ $t_{(ABP)_{IM}}$$t_{(ABP)_{IM}}$ and $t_{(ABP)Target}$ are the crossing times overhead the ABP of the IM aircraft and the Target aircraft, respectively, and the spacing goal is the time interval in seconds that the IM aircraft should be spaced behind the Target aircraft. Acceptable performance was set to 95% of the aircraft meeting their assigned spacing goal within the FIM equipment tolerance of ±9.9 sec.

C. Results

The spacing error results for all experimental conditions are given in Table 5. The metric is the percentage of IM Aircraft for which the spacing error at the Achieve-by Point was within +/-9.9 seconds. Green means more than 95% of the aircraft meet the goal, red means less than 95% meet the goal. As can be seen in this table, manual implementation of the IM Speed, through flight crew entries in the Mode Control Panel, in combination with the worse wind forecast error for the 7-8AM timeframe gives results that are not complying with the desired tolerance of 9.9 seconds. It should be noted that the use of speedbrakes and sensed winds were not taken into consideration. A re-run of the simulation with the use of speedbrakes showed that also these 'non-complying' conditions then comply with the 9.9 second tolerance.

Table 5. Percentage of IM aircraft for which the spacing error was within ±9.9 seconds

Spacing Error	Time of Day: 7-8 o'clock								
	Wind Field 0			Wind Field 1			Wind Field 2		
		MCP	AT		MCP	AT		MCP	AT
ANP 0.0	CTA 0	99.69	100.00	CTA 0	99.00	100.00	CTA 0	90.88	99.63
	CTA 15	99.81	100.00	CTA 15	98.75	100.00	CTA 15	89.38	99.75
	CTA 30	99.63	100.00	CTA 30	98.75	100.00	CTA 30	89.31	99.38
ANP 0.15	CTA 0	99.38	100.00	CTA 0	98.44	100.00	CTA 0	89.63	99.63
	CTA 15	99.06	100.00	CTA 15	97.44	100.00	CTA 15	89.69	99.44
	CTA 30	99.00	100.00	CTA 30	97.50	100.00	CTA 30	89.56	99.00
ANP0.30	CTA 0	98.69	100.00	CTA 0	97.06	99.94	CTA 0	90.88	98.75
	CTA 15	98.38	100.00	CTA 15	97.06	99.94	CTA 15	90.69	98.50
	CTA 30	98.19	100.00	CTA 30	97.19	99.94	CTA 30	89.94	98.06

Spacing Error	Time of Day: 8-9 o'clock								
	Wind Field 0			Wind Field 1			Wind Field 2		
		MCP	AT		MCP	AT		MCP	AT
ANP 0.0	CTA 0	100.00	100.00	CTA 0	99.63	100.00	CTA 0	98.13	100.00
	CTA 15	100.00	100.00	CTA 15	99.81	100.00	CTA 15	98.38	99.88
	CTA 30	100.00	100.00	CTA 30	99.19	100.00	CTA 30	97.75	99.75
ANP 0.15	CTA 0	100.00	100.00	CTA 0	99.50	100.00	CTA 0	97.44	100.00
	CTA 15	100.00	100.00	CTA 15	99.13	100.00	CTA 15	98.13	99.88
	CTA 30	100.00	100.00	CTA 30	99.00	100.00	CTA 30	96.88	99.81
ANP0.30	CTA 0	100.00	100.00	CTA 0	98.38	100.00	CTA 0	95.56	99.94
	CTA 15	99.81	100.00	CTA 15	98.00	100.00	CTA 15	96.06	99.63
	CTA 30	99.69	100.00	CTA 30	97.94	99.94	CTA 30	96.06	99.56

Figure **2** shows the aggregated spacing errors (μ +/- 2σ) for all combinations of Time of Day, Wind Forecast Errors and IM implementation method. This again shows the worse performance for the combination 7-8AM, Wind Field 2 and MCP. Furthermore, both the impact of wind forecast errors and in particular IM implementation method is clearly shown. Best spacing performance is achieved with direct coupling to the aircraft speed control system. The navigation performance and initial spacing error did not reveal noticeable differences in spacing performance.

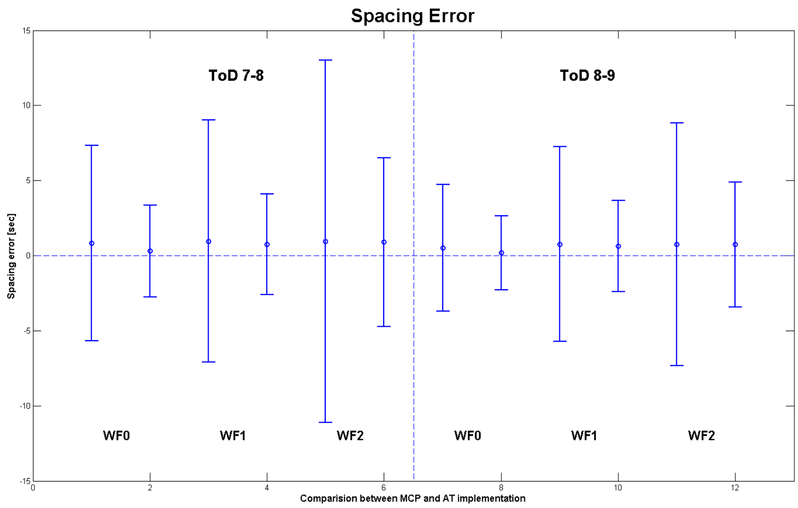

Figure 2. The means and two times standard deviations for the spacing error among all Wind Forecast (WF) errors and both Time of Day (ToD) conditions. For each condition the left bar indicates MCP usage, and the right bar direct coupling to the aircraft speed control system.

D. Discussion and conclusions

First of all it is concluded that IM works. The simulation batch study shows that strings of up to forty (40) aircraft can be safely spaced, while arriving at 35 aircraft per hour. For the chosen levels of wind forecast errors, aircraft navigation and IAF delivery, IM spacing performance is good when using the ASTAR algorithm to control the spacing interval. Keeping in mind that this batch study did not aim to find the limits of the IM concept, but merely researched the feasibility of introducing the IM concept to the Schiphol operation, no conclusions on minimum requirements for aircraft navigation, IAF delivery or wind forecast can be given. However, given that the simulated levels of accuracy caused the algorithm to use up to 80% of its control space for the most unfavorable combinations, it can be assumed that the least restrictive conditions form a good lower limit.

It is apparent that coupling the IM Speeds directly to the aircraft speed control system yields far better performance, compared to setting the IM Speeds manually through the MCP. This performance benefit could be used to trade-off other conditions, e.g. wind forecast errors. No effects on spacing performance were found for the different levels of aircraft navigation and the delivery accuracy over the IAF.

The main results of the fast-time simulation study indicate that:

1) The IM concept works for the scenarios with an initial metering error of <= 30 s;
2) The IAF delivery accuracy as aimed for by SARA (~30 s) is therefore sufficient for implementing IM Operations, but a more accurate delivery at the IAF will improve the robustness of the system;
3) The IM concept works for the currently assumed level of navigation performance: ANP 0.3 with fly-by turns. A better navigation (e.g., ANP 0.15 and RF-legs) will improve the robustness of the system;
4) Wind forecast errors have a large influence on the spacing performance and should be considered with great care when implementing IM Operations.
5) Direct coupling of the IM Speeds through an aircraft speed control system greatly improves performance over manual MCP/FCU selections of the IM Speeds; and
6) The ability to use speedbrakes as a control method greatly improves performance.

IV. A real-time simulation study: Is trust built in IM?

A. Introduction

The objective of the initial IM real-time simulation (RTS) study is to develop and validate working procedures and support tools, and to assess controller workload and acceptance.

B. Experimental Set-up

Three “independent” variables were selected for the IM RTS.

1) Controller tools (two levels)
    - Basic APP controller HMI + “need to have information for IM” + Merge tool
    - Basic APP controller HMI + “need to have information for IM” + Merge tool + Controller Spacing symbology
2) FIM equipage (three levels)
    - 5% FIM equipped
    - 50% FIM equipped
    - 95% FIM equipped
3) Wind field (two levels)
    - Light wind conditions
    - Moderate wind conditions

Disturbances were added to the experiment environment to create variety in the operations and increase the level of realism. The disturbances included:

1) Metering accuracy: Inbound traffic towards their assigned IAF were scripted to represent an organized flow that is sequenced and arrives within +/- 30 sec (99%) of their assigned time, Expected Approach Time (EAT), at the IAF.
2) Traffic mix: ~12% Heavies, ~2% Boeing 757s, and ~86% Mediums, based on the average traffic mix of the defining peak hour (8-9AM).
3) Traffic distribution: distribution of traffic over the four IAFs differed between scenarios

4) Pilot performance varied as a result of variance in the pilot model reaction time, which is used for IM speed selection.
5) Non-normal events were included, distributed among the experiment runs:
   - Incorrect Target Aircraft selection (correct readback);
   - Incorrect readback of Target Aircraft;
   - Unable Target Aircraft selection (e.g. out of ADS-B range);
   - Unable to accept IM Operations (e.g. equipment failure, data quality);
   - Unable to continue with IM Operations (e.g. equipment failure, IM Speed too low/too high);
   - Delivery at IAF well outside +/- 30 seconds;
   - Incorrect spacing (e.g. aircraft flies profile speeds instead of IM speeds);
   - Incorrect spacing (e.g. aircraft follows different spacing goal than the assigned one); and
   - Unable to continue the transition (e.g. RNAV equipment failure).

1. HMI - Radar display

The radar display shows the aircraft position of all flights, which is identified as one of the necessary IM data elements. As aid for the controller the RNAV transitions in the TMA can be displayed on the radar display. This display feature can be switched on and off by the individual controller.

Track labels on the radar display typically contain in the first line the aircraft identification; in the second line mode C and instructed flight level; in the third line aircraft type and RNAV Instrument Approach Procedure (IAP), Standard Instrument Departure (SID) or heading; and in the last line ground speed, Wake Turbulence Category (if not medium) and instructed speed.

Figure 3. Typical track label.

The track label field for instructed speed is also used as IM status indicator, the IM-status indicator is one of the “need to have information for IM” data elements. Currently this field shows the instructed speed or the characters ‘SPD’ if no speed has been instructed.

During the IM set-up phase the field indicates if all conditions with regard to equipment, positions and routes for IM Operation have been met. The character ‘#’ is used to indicate to the controller that the aircraft is eligible for IM Operations.

During the execution phase the field shows ‘IM’ to indicate that the speed is the flight’s responsibility controlled by the agreed spacing goal. On passing the Planned Termination Point ‘IM’ is automatically removed from the track label. Also, controller inputs like speed instructions terminate an IM Operation and update the label with the instructed speed.

Figure 4. Track labels showing aircraft eligible for IM Operations (#, left) and aircraft engaged in IM Operation (IM, right).

The radar display also contains an Interaction Area, located in the bottom right hand corner of the screen. This area consists of: an on-request line (1), Mode S-block (2), status block (3), clock (4), message area (5) and input templates (6).

Figure 5. Interaction Area, displayed in the lower right corner of the plan view display.

The on-request line (ORL) shows information of the flight selected on the radar display. The first line of the ORL contains: aircraft identifier, SSR-code, departure aerodrome and runway, RNAV IAP or SID, arrival runway and aerodrome; while the second line contains items like aircraft type, true airspeed, requested flight level (RFL), exit flight level (XFL) and entry - exit sector numbers.

A third line is added to the on-request line to present the active or suggested IM target identifier, RNAV IAP of the target aircraft (i.e., the intended flight path information) and spacing goal. This information supports the controller in issuing the IM Clearance and represents the other “need to have information for IM” data elements. The format used is ‘[#]IM <aircraft identification> <RNAV instrument approach> <spacing goal>; the ‘#’ is not shown during the execution phase. For example ‘#IM KLM1094 S2X 96’ indicates the suggested IM Clearance to cross the standard Achieve-by Point, VENEP, 96 seconds behind the KLM1094, who is on the SUGOL2X (S2X) transition. In the illustrated example below the selected flight, KLM1830, is on the ARTIP2X (A2X) transition. During IM execution ‘IM KLM1094 S2X 96’ is displayed, without the ‘#’.

Figure 6. On-request line with active / suggested target aircraft information and spacing goal.

2. HMI - Merge tool

Controllers have indicated that a concept involving the merge of two fixed RNAV IAPs on a single runway requires support. The merge tool provided by the ground system shows markers (also called ‘ghost’ plots) in the shape of yellow lines perpendicular to the corresponding segment of the RNAV IAP on which the marker is displayed. The ghost plot’s position is calculated using a distance based projection. Flights for one RNAV IAP are displayed on the other RNAV IAP for the same runway and vice versa. In the example above, ghosts of the KLM1148 and KLM1830 are displayed on the (extended) SUGOL2X transition, while the ghost of the KLM1094 is displayed on the ARTIP2X transition (in front of KLM1830).

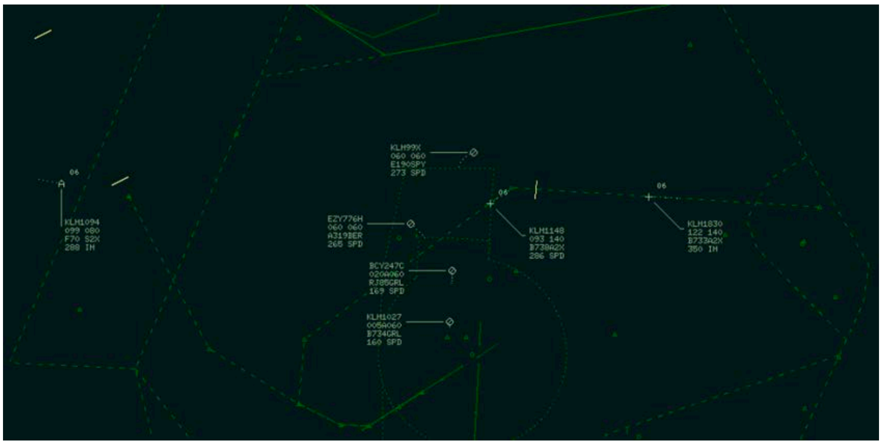

Figure 7. Merge tool display

3. HMI - Spacing marker

The spacing marker is depicted as a solid circle. The spacing marker indicates where the aircraft should have been, if it were to fly the RNAV instrument approach using the nominal speed profile through the forecasted wind field. An aircraft flying in the middle of its spacing marker will achieve the required in-trail spacing at the Achieve-by Point when it continues flying the nominal speed profile given a perfect wind forecast. The radius of the circle is determined by the nominal ground speed at the location of the Spacing Marker multiplied by the IM Tolerance (=10 sec). The spacing marker together with an indication of the actual spacing, which is displayed after the spacing goal in the third line of the ORL, forms the so-called controller spacing symbology. This controller spacing symbology is the main discriminator of the independent variable “controller tools”.

4. Arrival/Departure Configuration

Figure 8 shows the general route structure of the Schiphol TMA that was used in the RTS. It is based on published day-time SIDs for take-off runway 36L and newly defined RNAV IAPs from the four IAFs to the runways 06 and 36R. An RNAV IAP includes both a transition and an ILS approach procedure. It should be noted that these transitions are defined for this research study.

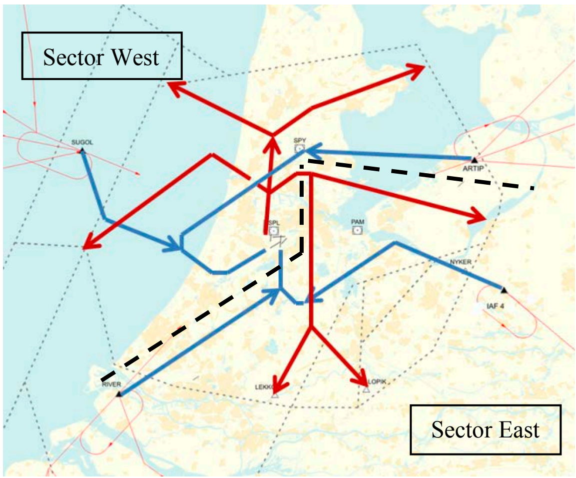

Figure 8. RNAV IAPs RWY 06 and RWY 36R, SIDs RWY 36L (Blue arrivals, Red departures)

5. Altitude Profile

The FIM algorithm uses speed control by means of thrust to minimize the spacing error. In order for this to be effective, it is required that speed deviations from the nominal speed profile are allowed, to gain or lose time during the approach. Full idle CDOs eliminate the possibility for an aircraft to slow down by means of thrust and are therefore unsuitable for use with ASTAR. A 2°, fixed-geometric angle CDO is used as a compromise between noise benefits and speed control-space [2]. Control-space on a 2° CDO is available since the aircraft is not flying full-idle, i.e., the descent angle is such that limited thrust is required to maintain speed.

Therefore, deceleration while on the profile is still possible by reducing thrust further to idle, which may be required if the aircraft needs to slow down in IM Operations. Noise benefits are inferred to come from the reduced thrust and an altitude profile which is higher than ordinary step down profiles, see Figure 9.

Figure 9 shows the altitude profile used for the RTS. The vertical profile from the runway back up to the IAF crossing altitude is equal for all four transitions. The IAF crossing altitude differs according to the path distance to the runway. After passing the intermediate top of descent point, a 2° continuous descent path is followed up to the Final Approach Point (FAP) at an altitude of 2000 ft where the 3° ILS glideslope will be intercepted. From the FAP onwards the aircraft follow a standard ILS approach to the runway. In this study the FAP is both the Achieve-By Point as well as the Planned Termination Point.

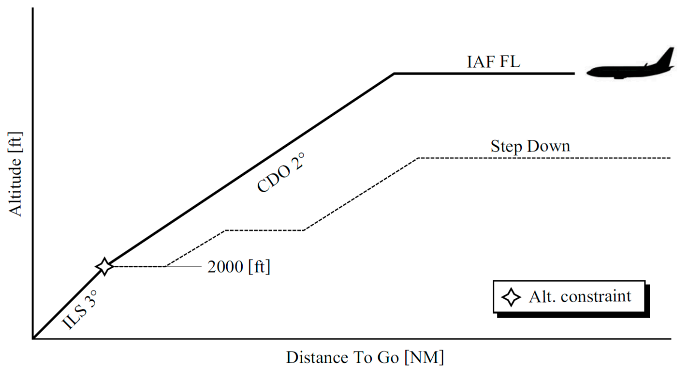

Figure 9. Vertical profile, the profiles are similar for each transition, the only difference is the IAF entry FL

6. Speed Profile

The speed profile is illustrated in Figure 10. All speeds in the figures are in Calibrated Airspeed (CAS). Requirements for the speed profile are operational feasibility and good control-space margins for all types of aircraft. The speed profile for the transition may differ concerning the TMA entry speed, but below 10,000 ft a similar nominal profile of 240/220/190/180 is defined. The speed control-space is illustrated in Figure 10 with a grey fill colour and is defined as 10% around the nominal speed with a max of 250 kts below 10,000 ft.

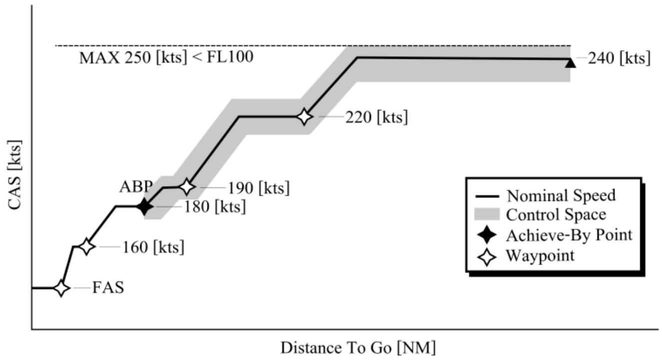

Figure 10. Speed profiles are equal for the four transitions, this is the nominal profile, ASTAR commanded speeds are within 10% of this profile

7. Pilot-Controller Phraseology

The following examples provide the typical phraseology used by the APP controllers in the RTS.

- KLM 602, FOLLOW THE SUGOL 2X TRANSITION, ILS RUNWAY 06, CONTINUE DESCENT FLIGHT LEVEL 70 ACCORDING PROFILE, WEATHER INFORMATION CHARLIE
- KLM 602, FOR INTERVAL SPACING, SELECT TRAFFIC ARKEFLY 838 (” TFL838”) ON THE ARTIP 2X TRANSITION
- KLM 602, CROSS VENEP 96 SECONDS BEHIND TRAFFIC
- KLM 602, DESCEND TO 2000 FEET ACCORDING PROFILE, QNH 1013, CLEARED FOR THE APPROACH
- KLM 602, CANCEL INTERVAL SPACING, MAINTAIN 240 KNOTS

C. Results

Controller acceptance, confidence and workload of the KDC IM RTS study are presented below. More detailed results of this research study can be found in [9].

1. Controller Confidence and Acceptance Ratings

The participating controllers were asked to fill out questionnaires post-training (before the experiment) and after the experiment. As can be seen in Table 6, the controllers had confidence in the system, although Controller 1 showed a slightly reduced confidence after the experiment. This controller indicated that the runs where he had to cope with non-conforming traffic had been difficult to complete and he had initially expected more support from the system than he had encountered.

Table 6. Controller confidence in the system. Scale of 1 to 10, where 10 is perfect

	Post-training	Post-experiment
Controller 1	8	7
Controller 2	7	8
Controller 3	9	10

As part of the post-experiment questionnaire, the controllers were asked to indicate their level of acceptance of the IM concept and the IM procedure as presented during the experiment. Table 7 shows that the three controllers felt very confident that the IM concept is viable and can be implemented in the future.

Table 7. Controller acceptance of the IM concept and procedure. Scale of 1 to 10, where 10 is perfect

	IM Concept	IM Procedure
Controller 1	9	9
Controller 2	8	8
Controller 3	8	8

2. Controller Workload

After each simulation run, the controllers were asked to fill out a NASA Task Load Index (TLX) to give an indication of the perceived workload for each scenario.

As can be seen in Figure 11, the effect of the traffic sample shows a slight increase in workload with increasing traffic density. Traffic scenario A has an average throughput of 36.3 aircraft per hour, scenario B has 25.7 and scenario D has 32.6 aircraft per hour on the landing runway 06. The effect of FIM equipage level is less prominent, but seems to indicate a slight increase for the 50% scenario. One possible explanation might be that having to deal with both IM and non-IM aircraft is more difficult for the controller than a predominantly IM (95%) or non-IM (5%) traffic mix. This is something to take into account when implementing IM operations.

The effect of HMI seems negligible on TLX, indicating that the extra tools available for the controller did not lower the workload. The tool that controllers found most useful, the merge tool, was available in both HMI configurations, so its effect cannot be measured. As expected, the effect of introducing non-nominal events has a detrimental effect in workload, but not a very large effect, as can be seen in Figure 11 (*yes* means non-nominal aircraft were introduced into the scenario, no means no non-nominals were present).

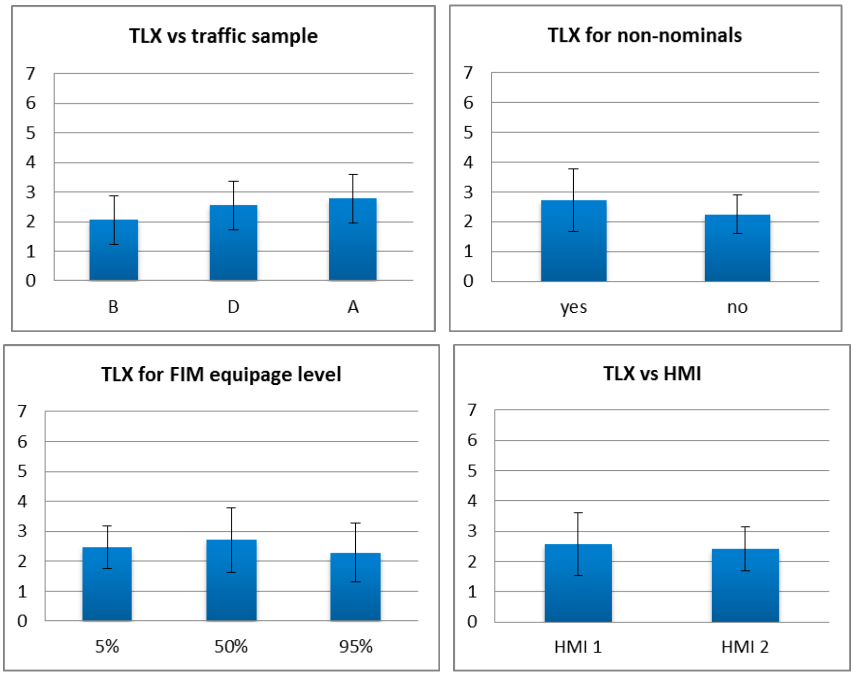

Figure 11. Means and standard deviations (in units on a scale 1-7) of the NASA TLX scores

D. Conclusions and recommendations

1. Main Conclusions

The main conclusions of the KDC IM RTS study are given for a number of key indicators [9]

Controller acceptance

- All controllers readily accepted and appreciated the IM Concept of Operations and were able to safely and efficiently manage the arrival traffic in all scenarios with the newly developed HMI.
- All controllers showed a high level of trust for the IM concept, working procedures and HMI.

Controller workload (NASA TLX metric)

- Perceived controller workload was well within predefined targets in all scenarios, with the exception of one of the six workload components (frustration) during one run.
- There appears to be a trend that workload slightly increases in scenarios with non-normals.
- For 50% FIM equipage level, perceived workload seems to be slightly higher than for 5% and 95% FIM equipage.
- Perceived controller workload seems to slightly increase with increased traffic density.
- For all other experimental variables, no effect on perceived workload has been observed.

Number of R/T transmissions

- The average number of R/T instructions per aircraft does not vary much between IM and non-IM operations. However, if an IM-aircraft is taken off the IM-operation and has to continue with radar vectors, the average number of instructions effectively doubles.

Situation Awareness (EUROCONTROL SASHA metric)

- Perceived situation awareness was rated as good by all controllers. One controller had difficulties coping with some non-normals which resulted in a lower perceived situation awareness and a higher perceived workload for those runs.

IM Usage / Success rate

- The percentage of IM clearances as function of FIM equipped aircraft is very high (>90%).
- The percentage of (unanticipated) IM cancellations by the controller is very low (<3%).

Excessive Distance Spacing at the Achieve-by Point – Safety

- The number of violations of the separation distance (4%) is relatively high, they only occur in the higher density scenarios (32 and 36 ldg/hr).
- Out of the twelve cases, five were related to IM performance, three were related to IM usage, and five were not related to IM Operations.
- During three runs (out of twelve) a total of seven losses of separation (<2.5 NM) occurred.
- Two losses of separation occurred near the merge point (once between two IM aircraft in combination with an incorrect target selection and once between two non-IM aircraft)
- All five losses of separation on final approach were related to an aircraft performing IM and an aircraft not performing IM. In 3 out of 5 cases in combination with vectoring. In all of these cases IM Operation was continued where it should have been cancelled (due to vectoring and a very low speed instruction to the target aircraft). In 2 out of 5 cases a non-IM aircraft trailing an IM aircraft did not reduce speed in time, due to a 'late' instruction in combination with a slow deceleration on the continuous descent path.

2. Secondary Conclusions

- The R/T phraseology to initiate IM Operations should be improved to make the target selection a shorter and more naturally spoken phrase. Suggestions for improvement were provided.
- The speed limit of 250 kt below FL100 in relation to the nominal speed of 240 kt had an impact on the spacing performance, either waiving the speed limit (at least for IM Operations) or applying a lower nominal speed (e.g., 230 kt) should be considered.
- The lower bound of the IM speed range at the Achieve-by Point, co-located with the Planned Termination Point, was too low. Aircraft sometimes crossed the Planned Termination Point at 160 KIAS, and subsequently maintained this speed, where normally they still would fly 180 KIAS. This behaviour has the risk to potentially reduce throughput.
- The capability to suspend and later on to resume an IM Operation was used a number of times (without explicit discussion or requests).
- The working method in which the target selection and IM Clearance were separated in time regularly caused confusion about whether or not the target selection or IM Clearance had been given. It is recommended to use a working method in which the target selection is immediately followed by the IM Clearance itself.
- The spacing marker was hardly used because it showed jumping behavior on the radar screen and resulted in a cluttered display. Though, in principle it was considered a good feature to monitor the IM (and non-IM) Operations.

3. Recommendations

- Improvements are needed in terms of guidance (and training) to the controllers on when to suspend or terminate IM Operations, especially in relation to vectoring operations and (very) large speed reductions of a target aircraft.
- Additional controller support with respect to their monitoring task may in some situations be helpful (e.g., continuous display of the spacing marker and/or continuous display of the actual IAS). Special attention in terms of controller support is deemed necessary for non-IM aircraft behind an IM aircraft.
- Traffic was normally handed over to the tower near the Intermediate Approach Fix (IF) instead of the FAP. The FAP was the anticipated handover point and was selected as the Achieve-by Point. Placing the Achieve-by Point at the IF seems to be more in line with the working method of the APP controllers. Moreover, the handover procedures need to be readdressed when IM is continuing after the handover.
- Controllers strongly recommended getting a confirmation of the correct selection of the Assigned Spacing Goal and Target Aircraft Identification. These are included in the IM Clearance and could be set incorrectly without the controller knowing it. This recommendation is related to traffic flow efficiency, and not to safety.

V. Summary and next steps

A. Background

The Dutch aviation sector (KLM, Amsterdam Airport Schiphol, LVNL) together with the Department of Infrastructure and Environment have jointly committed to develop a new concept for flight operations in the Schiphol terminal airspace. This concept consists of RNAV instrument approaches procedures (i.e., a fixed route network) and continuous descent operations. It is expected that the current night operations at Schiphol will gradually be expanded into daytime off-peak hours, provided that new support tools become available to manage the inbound traffic.

B. New technological solutions will open new doors

For Schiphol TMA operations a new handling concept is developed with RNAV instrument approaches and continuous descent approaches. The aviation sector agrees that fixed routes are desired from the TMA boundary to the runway due to improved predictability and as an enabler for continuous descent operations. However, RNAV instrument approaches have the tendency to negatively affect capacity and Schiphol can afford no loss of capacity. Therefore, research is done for innovative ways to handle the incoming traffic, to make high capacity combined with RNAV instrument approach procedures possible.

C. Interval Management is precise and predictable

One of the pillars is Interval Management (IM). With IM, aircraft exchange flight information via ADS-B and use this information to control an ATC assigned time interval (spacing goal) with a lead aircraft. It is assumed that this close loop control provides the precision and predictability that is required to maintain peak hour capacity. For the Schiphol terminal airspace, IM is expected to become an enabler to expand the RNAV instrument approaches (i.e., fixed routes from TMA boundary to runway threshold) and CDOs into peak hour operations.

D. Results of IM fast-time simulation studies

KDC IM research has been performed in a number of phases. In the first phase requirements were captured. During the second phase fast-time simulations were performed to evaluate the IM performance. The outcome of the study is positive: IM can generate the required spacing performance in the Schiphol terminal airspace, allowing high-density operations on fixed routes.

E. IM real-time simulations

The third phase of the IM concept for Schiphol progressed with IM real-time simulations (RTS) to assess controller acceptance and workload and to evaluate the IM procedures and IM support tools. The RTS study was performed at NLR's ATC Research Simulator (NARSIM). The main conclusions of the RTS are:

- All controllers readily accepted and appreciated the IM Concept of Operations and were able to safely and efficiently manage the arrival traffic in all scenarios, including non-normal events, with the newly developed HMI.
- Perceived controller workload was generally well within predefined targets in all scenarios.
- The average number of R/T instructions per aircraft did not vary much between IM and non-IM operations.
- The percentage of (unanticipated) IM cancellations by the controller was very low (<3%).

F. IM continues!

KDC and the Dutch aviation sector continue to develop the Schiphol IM concept. The next step is to develop an on-board IM system and run a series of flight trials to test this system in real life. The objective is to develop and demonstrate technical feasibility of the on-board IM system. The initial flight trial will be performed with the use of NLR's Citation II test aircraft and is supported by an international team of experts.

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