Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Virtual Block Control and Separation Bubbles in ATC Low Visibility Operations

Results of Tower Control Real-time Simulations

Tower Controller Working Position during Rotterdam Evaluation Sessions

Problem area
The EUROCONTROL Airport Operations Programme (APR) is providing stakeholders with documentation and support for safe, cost-effective and efficient airport operations. Within this work programme the potential of Advanced Surface Movement Guidance and Control Systems (A-SMGCS) to increase safety and maintain throughput in all weather conditions is investigated. Currently, airport operations under low visibility conditions are still based on procedures and working methods without automation support.

Description of work
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Author(s)
J. Teutsch
V. Mollwitz

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candidate concepts for advanced operations with A-SMGCS surveillance under low visibility conditions as part of the EUROCONTROL APR. During dedicated interviews and workshops with stakeholders, candidate concepts were selected based on criteria for usability, safety, human factors, and cost-benefit. Two candidate concepts, named Virtual Block Control and Separation Bubble Alerting, emerged and were evaluated in full-scale human-in-the-loop real-time simulations of Rotterdam Airport on the NLR ATM Research Tower Simulator (NARSIM Tower) platform.

Results and conclusions

The study showed that a combination of the two tower control concepts can indeed improve efficiency of operations under low visibility conditions. The designed interface prototypes are flexible and inexpensive tools that should be developed further.

Applicability

This paper was presented at the Ninth Integrated Communications Navigation and Surveillance Conference (ICNS) in Arlington (VA), USA, in May 2009.

Nationaal Lucht- en Ruimtevaartlaboratorium, National Aerospace Laboratory NLR

Anthony Fokkerweg 2, 1059 CM Amsterdam,
P.O. Box 90502, 1006 BM Amsterdam, The Netherlands
Telephone +31 20 511 31 13, Fax +31 20 511 32 10, Web site: www.nlr.nl

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

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Virtual Block Control and Separation Bubbles in ATC Low Visibility Operations

Results of Tower Control Real-time Simulations

J. Teutsch and V. Mollwitz[1]

[1] Deutsches Zentrum fuer Luft- und Raumfahrt

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Contents

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Dipl.-Ing. Jürgen Teutsch, National Aerospace Laboratory (NLR), Amsterdam, Netherlands
Dipl.-Ing. Vilmar Mollwitz, German Aerospace Centre (DLR), Braunschweig, Germany

Abstract

The EUROCONTROL Airport Operations Programme (APR) is providing stakeholders with documentation and support for safe, cost-effective and efficient airport operations. Within this work programme the potential of Advanced Surface Movement Guidance and Control Systems (A-SMGCS) to increase safety and maintain throughput in all weather conditions is investigated. Currently, airport operations under low visibility conditions are still based on procedures and working methods without automation support.

The National Aerospace Laboratory of the Netherlands (NLR) together with their partners from the German Aerospace Centre (DLR) carried out research activities on the selection and evaluation of candidate concepts for advanced operations with A-SMGCS surveillance under low visibility conditions as part of the EUROCONTROL APR. During dedicated interviews and workshops with stakeholders, candidate concepts were selected based on criteria for usability, safety, human factors, and cost-benefit. Two candidate concepts, named Virtual Block Control and Separation Bubble Alerting, emerged and were evaluated in full-scale human-in-the-loop real-time simulations of Rotterdam Airport on the NLR ATM Research Tower Simulator (NARSIM Tower) platform. The study showed that a combination of the two tower control concepts can indeed improve efficiency of operations under low visibility conditions. The designed interface prototypes are flexible and inexpensive tools that should be developed further.

Introduction

ATC Low Visibility Operations

ICAO Annex 3 defines visibility for aeronautical purposes and also provides a definition for the prevailing visibility to account for different values at different locations on the aerodrome surface[1]. Still, such definitions are not clearly addressing operational issues.

For take-off and landing operations, Runway Visual Range (RVR) more appropriately provides pilots, air traffic service (ATS) units and other aeronautical users with information on runway visibility conditions during periods of low visibility. This is thoroughly described in the ICAO RVR Manual[2]. Nevertheless, RVR does not account for separation issues on the remaining airport surface.

Finally, the ICAO A-SMGCS Manual (Appendix A) introduces four visibility conditions (VC), each addressing a certain operational condition rather than a measured visibility value[3]. Even though it will be difficult to determine whether such visibility conditions actually prevail on the airport surface, their definition is important for assessing adequate operational procedures.

VC1 and VC2 are defined as good visibility conditions where separation responsibility still rests with the pilots. Visibility from the tower is reduced in VC2. In VC3, visibility further deteriorates such that pilots cannot avoid collision with other traffic on taxiways and at intersections by visual reference. However, pilots are able to taxi by visual reference, meaning that they can discern guidance elements or specific locations on the airport surface. This condition is usually referred to as low visibility and more or less corresponds to a RVR between 400 and 75 meters. In VC4, visibility is insufficient for the pilot to taxi by visual guidance only. This condition occurs at RVR values below 75 meters.

Low Visibility Research Focus

According to the A-SMGCS Manual (Appendix A), visibility conditions, traffic density and aerodrome layout are decisive factors when making a choice on which A-SMGCS level should be implemented at an airport[3]. Clearly, improvements in VC4 will only be brought about by cockpit technology (moving map with ground traffic display, traffic conflict monitor, etc.). Such technology is only foreseen for advanced levels of A-SMGCS. Furthermore, it is doubtful whether such technology will be available and implemented in all commercial aircraft any time soon.

As a consequence, EUROCONTROL started investigating A-SMGCS (Level 1) surveillance improvements. Traditional non-cooperative surveillance systems at the airport, such as the surface movement radar (SMR), are enhanced with cooperative surveillance systems, such as multilateration (MLAT). This will not only provide unambiguous identification of the targets and provide the controller with a labelled display of the traffic situation but also lead to improved accuracy.

Several airports, such as London Heathrow, Amsterdam Schiphol, and Zurich Airport, already introduced such surveillance technology. This only led to small changes in the procedures for VC1 (visually perceived traffic picture is confirmed) and VC2 (mandatory position reports become obsolete with the exception of initial identification) as pilots or vehicle drivers are still able to avoid collision. Thus, they are also still responsible for separation on the ground. Procedures at airports are essentially the same as with SMR according to ICAO[4], and in consequence, they are the same as without MLAT.

In VC3, when pilots or vehicle drivers can navigate on the airport surface but visibility is not sufficient to avoid collision, controllers switch over to procedural control. Therefore, on most airports aircraft or vehicles will only move in one defined section of the airport at a time and will be controlled as such. An aircraft or vehicle will only be permitted to enter a clearly defined airport section (e.g. taxiway segment separated by stop bars) after this section has been cleared by all other traffic. This leads to an enormous reduction in efficiency and airport capacity.

Thus, EUROCONTROL initiated a project for procedural improvements in VC3. NLR with support from the German sister institute DLR carried out this research project under the AT-One framework, which was set up to facilitate and bundle ATM research efforts in the Netherlands and Germany. The following chapters show the results of a feasibility study for several candidate concepts, as well as further evaluation and initial validation activities for the two most promising concepts.

Candidate Concepts

As part of the EUROCONTROL APR, operational experts from European industry and research institutes discussed numerous approaches for finding operational solutions to the negative effects of low visibility conditions at airports. They tried to investigate ways to improve efficiency and capacity of operations given the current restrictions that apply in these conditions. Input was received from ANSPs, ICAO[3], and the EMMA[5] project, which is the major European A-SMGCS research initiative, co-sponsored by the European Commission.

As a result of the discussions and the input provided, EUROCONTROL and AT-One experts set up a list of candidate concepts that were considered viable options for further research. These concepts are shortly introduced.

Multiple Line-up (ML)

ANSPs considered the possibility of using multiple line-ups for take-off during low visibility conditions provided that the A-SMGCS enhanced surveillance allows controllers to determine all aircraft positions. It was assumed that this procedure could lead to more capacity in low visibility conditions when applied in mixed-mode runway operations.

Virtual Block Control (VB)

The Human-Machine Interface (HMI) of the Ground and Runway Controller could be enhanced with virtual stop bars in the taxiway structure. Virtual stop bars do not exist on the airport surface but are displayed to the controller on a surveillance display. Aircraft could be controlled in sequence from one virtual stop bar to the next in analogy of the block control procedure used in the UK. The VB procedure could be investigated in combination with several alerting functions (e.g. for minimum separation, stop bar crossing, runway entry).

Convoy Operations (CO)

The idea of convoy operations was introduced although, strictly speaking, the definition of VC3 would not allow for such a procedure. In convoy operations, aircraft follow each other on a taxiway segment. While the first aircraft in the convoy would receive guidance instructions from the controller, the aircraft in sequence would follow their predecessor at a distance that is judged safe by the pilots. Such a procedure is already applied in better visibility conditions at some airports. In VC3, the procedure could additionally be monitored by A-SMGCS enhanced surveillance and alerting functions or a combination thereof.

Parallel Push-backs (PP)

Another procedure considered by ANSPs for VC3 was the parallel push-back procedure, which is frequently applied in good visibility. If two aircraft that are parked next or opposite to each other leave at the same time, they could be pushed back or pulled simultaneously. As the tower cannot see the push-back in VC3 and the pilots cannot avoid collisions, responsibility would need to shift to the ground staff performing pushing and towing operations. Thus, procedures would require close co-ordination between platform operators, airlines and the tower. The procedure could provide higher airport throughput and could form the starting point for convoy operations and virtual block control.

Separation Bubbles (SB)

A significant increase in airport throughput under low visibility conditions could be achieved when procedural separation by means of segmented taxiways is replaced with longitudinal spacing by so-called separation bubbles. Aircraft would maintain a specific minimum distance to each other ensured by an imaginary safety bubble around the aircraft. The algorithm for that bubble and the minimum distances should be determined according to ICAO[3] (Ch. 3.4.4.3 and Ch. 3.4.4.4). Other applicable parameters could be the initial speeds and decelerations of aircraft, pilot and controller reaction times, and system reaction times. The controller would conduct longitudinal spacing using the tool, which issues a warning when aircraft bubbles touch and separation minima are violated.

Taxiway Conflict Monitoring (TCM)

In addition to receiving warnings of longitudinal spacing minima violations, controllers should also be warned well in advance of other possible conflicts which can easily be overlooked when concentrating on a specific aircraft pair or convoy. A Taxiway Conflict Monitor that warns controllers of head-on conflicts and potential infringements of on-ground separation was prototyped by NLR in early A-SMGCS studies. It is based on a taxiway structure with virtual blocks (not displayed on the controller screen) and works as a safety net in the background. The software is extrapolating surveillance data across the block boundaries to detect potential conflicts.

Selection Process

Based on initial concept descriptions of abovementioned candidate concepts, AT-One carried out a feasibility study[6] incorporating the results of stakeholder interviews and workshops, an initial safety analysis, a procedure analysis, and cost-benefit considerations. The study derived at conclusions regarding the practicability of each concept and gave recommendations regarding the concepts that should be considered for further evaluation and validation.

Additional Concept Options

In the course of the feasibility study, it was realized that separation bubbles and taxiway conflict monitoring were actually two safety nets sharing common issues and features. Therefore, it was decided to merge the two options and look at the separation bubble concept as a concept for both conflict monitoring in the maneuvering area and longitudinal spacing. This reduced the number of concept options to five. These options were ordered according to perceived complexity of the solution and discussed with an emphasis on human role and HMI. Thus, the new list reads as follows:

- Virtual Block Control
- Separation Bubbles
- Multiple Line-up
- Convoy Operations
- Parallel Push-back

For the VB concept, it was suggested to increase the situational awareness of pilots by marking position references on the ground, such as block numbers or signs next to the taxiway.

Additional monitoring software could watch aircraft passing stop bars without clearance. However, it would still have to be determined whether the available surveillance data would provide sufficiently stable and precise position values.

For the SB concept, it was suggested that the bubbles should be fixed to the aircraft symbol and displayed on the radar screen to assist controllers in the separation task. Lateral separation could be indicated by the bubble width. This needed further investigation for crossing traffic, though. Also proper training and tuning of the tool would be required

For the ML concept, an important remark was that a pilot should always be able to visually identify the aircraft lined up in front. Clearly, in low visibility, it would be difficult to meet this requirement, as there might be too much distance between the different runway entry points. Control procedures would not have to change, as it was expected that aircraft and other traffic are presented clearly and unambiguously on the surveillance screen. Generally, however, safety concerns were quite high.

For convoy operations, it was considered unnecessary to develop an HMI. In order to establish a convoy, aircraft would have to be guided to taxi in or out simultaneously. While the first aircraft in the convoy would receive the guidance information, other aircraft would be required to establish visual contact and follow the preceding aircraft. An obvious weakness of the concept in low visibility would be the uncertainty whether distances can be accurately judged by pilots to guarantee safe operations. Also fallback procedures would need to be in place in case pilots lose visual contact. Finally, convoy operations would be limited to an appropriately simple airport layout with long and uninterrupted taxiway stretches.

Parallel push-backs in visibility condition three could be performed under the supervision of platform marshals, supposed that visibility on the apron is good enough to visually identify other traffic and obstacles. However, concerns about safety of the procedure and clear responsibilities were quite high. Again, the procedure would depend on an appropriate airport layout that allows for this kind of operation. Procedure or HMI changes for controllers were not foreseen.

Conclusions of the Feasibility Study

One of the major conclusions of the feasibility study was that, considering the different kinds of benefits that could be expected for the different concepts, it would only make sense to look at appropriate combinations of concepts into an overall concept. This quickly led to the formation of two groups of concepts, namely VB as a control concept in combination with SB as a safety net, and the combination of PP, CO, and ML as a concept for outbound operations with most control activities being reduced to traffic monitoring.

In spite of the obvious advantages of the combined PP, CO, and ML concept regarding cost and development work, the combined VB and SB concept was considered the most promising concept for improved VC3 operations and was suggested for further research activities after completion of all analyses and stakeholder consultation activities. This was mainly due to the uncertainties for the PP, CO, and ML procedures regarding roles and responsibilities of involved actors and expected safety concerns. Above that, these procedures were based on conditions closer to VC2 than VC3. They were not expected to lead to large improvements in VC3 when compared to VB and SB.

At the end of the feasibility study, it was recommended to further investigate the Virtual Block and Separation Bubble concepts. For the VB concept, it was suggested to also look at aspects of dynamically placing block boundaries and to particularly study workload issues. For the SB concept, several options could be studied, such as the use as control tool or use as a safety net. The combination of VB and SB in a single concept was seen as a promising option. According to the study, highest priority for follow-on research had to be given to testing HMI solutions and a-priori user acceptance (pilots and controllers). Demonstrations and real-time simulations should validate the concepts and give guidelines for further conceptual development. Procedures should be subject to further and more detailed safety assessments. As part of future investigations, it was also considered interesting to validate separation standards for aircraft on the airport and study pilot reactions in flight simulators in VC3.

Detailed Concept Description

The project following the feasibility study had to define VB and SB concepts in more detail and prepare and carry out evaluation and initial validation exercises in a real-time simulation environment[7].

When applying Virtual Block Control the Traffic Situation Display (TSD) of ground and runway controllers is enhanced with so-called virtual stop bars, which means that these stop bars are additionally introduced for controller reference but do not exist on the airport surface (Figure 1). Thus, the concept aims to reduce block sizes thereby improving taxiing throughput. Like in ordinary block control, which ensures spacing between aircraft in VC3 and is described in the SMGCS Manual[8], an aircraft needs to leave its block before another aircraft is allowed to enter that same block.

Figure 1. Virtual Block Control

Virtual stop bar violations (illegal crossings) were to be indicated by visual and aural alerts, which would require a certain accuracy of the surveillance system. In the simulations, it was assumed that the surveillance system had sufficient accuracy.

During stakeholder workshops and interviews it was eventually determined that virtual stop bars should be positioned statically at predetermined locations, not dynamically at random locations. Dynamic aspects of virtual stop bars could be better implemented as so-called Watch Dogs. The last aspect should be seen as a replacement of the possibility of placing stop bars on the airport layout at unknown locations and, thus, without position reference. Placing stop bars dynamically would make it rather impossible for pilots to navigate to the clearance limit as long as no other technology (such as a moving map display) was involved. Instead, controllers had the possibility to attach a so-called Watch Dog to an aircraft needing special attention. As soon as such an aircraft started to move, the Watch Dog produced the same alarm as a virtual stop bar violation.

The basic idea of Separation Bubbles is to create an artificial bubble around an aircraft the size of which primarily depends on aircraft speed (Figure 2). That bubble can function as a buffer zone to prevent collisions on taxiways. Depending on whether the bubble is shown to the controller or not, the controller could use this tool for either enhanced control as in the case of virtual blocks or as an additional safety net. When the bubbles are shown they would indicate separation as do the blocks. The controller then has to monitor the bubbles of all aircraft taxiing on the movement area and has to advise aircraft to stop or taxi slower whenever two bubbles are about to touch. This would allow more than one aircraft in one block at a time (given that the block is bigger than the safe separation indicated by the bubbles) and thus would increase capacity. The disadvantage of the bubbles being shown permanently would be that they could clutter the controller display. Above that, clearance limits would be missing by definition.

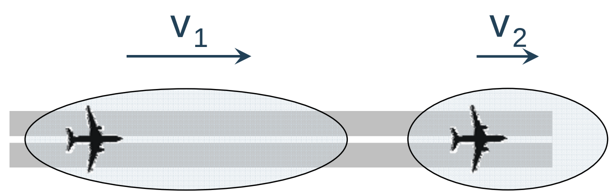

Figure 2. Separation Bubbles

Thus, after a workshop at EUROCONTROL and first evaluation sessions with controllers, it was decided not to display bubbles and use them as a safety net only. This meant that audio and visual alerts were given when two bubbles touched.

The original idea was to base the bubble size on different parameters such as speed, deceleration, pilot and controller reaction times, jet blast and braking margins, in accordance with ICAO[3]. Nevertheless, during implementation of the separation bubble software and during stakeholder workshops it was found that the same safety net effect could be accomplished by considering a static bubble size for a taxi speed of 15 knots and projecting it to a future position by multiplying a look-ahead time with the current speed. In that way, bubbles were also adapted to the taxiway layout, i.e. they followed the taxiway structure and divided into branches at intersections. It was also mentioned during the stakeholder workshops that the bubble parameters will need fine-tuning for each airport depending on the actual taxiway layout and that their application on the apron area will need even more careful fine-tuning because of the density of the route net. Therefore, the separation bubbles were not applied in the apron area during the evaluations exercises.

Furthermore, a number of decisions and assumptions relevant for executing the real-time simulations were made:

- Rotterdam Airport (EHRD, RWY06/24, 2200 x 45 m), as implemented on the NARSIM Tower platform, was chosen as simulation environment
- On-board guidance was not simulated
- Pilots were assumed to be able to identify virtual stop bar locations visually
- No additional R/T phraseology was used
- No system input was given with clearances
- Controllers decided on activated stop bars
- Automatic re-illumination of stop bars

The last aspect needs some explanation. Automatic re-illumination of a virtual stop bar means that as soon as an aircraft crossed the stop bar it was illuminated again as an additional safety precaution. However, there was no automatic switching for convoy operations in a runway queue (if an aircraft has passed a virtual stop bar and left the block, the stop bar re-illuminates and the next stop bar in the queue would be switched off, and so forth). This was considered unsafe.

A number of important functionality requirements were determined during initial HMI evaluations and led to the following decisions concerning the two concepts:

- Virtual stop bars were implemented for both runway configurations (even if only configuration RWY 24 was used)
- Different audio alerts were used for the different types of stop bars (runway and taxiway/watch dog) and separation bubbles
- A conflict list was implemented presenting conflict information for all tools (type, involved call signs and acknowledge field)

Simulation Environment

Simulation Platform

The simulation platform for the evaluation of low visibility procedures for Virtual Block Control and Separation Bubbles and for an initial validation of operational improvements was the NARSIM Tower environment. NARSIM Tower is a highly realistic and flexible simulation environment and is used for training Dutch air traffic controllers and for prototyping of new tools. NARSIM Tower was considered an ideal platform for prototyping, evaluation and initial validation.

Alerting services for Taxiway Conflicts (Hermes: patron of travellers), Stop Bar Violations (Cerberus: guard of Hades) and Watch Dog Functionality (Pallas: goddess of strategic warfare) were running at the experiment leader position. Actual alerts, however, were presented on the Surface Movement Radar (SMR) display at both controller positions (including audio). Apart from the SMR, the runway controller had a Terminal Approach Radar (TAR) screen and the emulated display of instruments with meteorological and communication information. The ground controller had an SMR available that is identical to the one used by the runway controller (virtual bars could be switched at both positions). Additionally, the ground controller had a Closed Circuit Information System (CCIS) display (with ATIS and meteorological information) and an Electronic Data Display (EDD) with flight information.

Experiment Participants

The main actors in the real-time simulation exercises were the tower controllers, i.e. the ground controller for the apron area and the taxiways and the runway controller for RWY 24. Clearance delivery (start-up) was pre-scripted and simulated by the NARSIM Tower validation platform. The overall objective for the ground controller was to ensure the safe and efficient conduct of ground maneuvering. The overall objective for the Runway Controller was to ensure the safe and efficient conduct of flights on the runway and in the air within the area of responsibility of the tower.

There were two controller teams consisting of two controllers each. Two controllers came from

Rotterdam Airport and were employees of LVNL, the Dutch Air Navigation Service Provider. They had experience with the Rotterdam Tower working environment. Two other controllers came from Stockholm Arlanda Airport and were employees of LFV, the Swedish Air Navigation Service Provider. They had no experience with the Rotterdam Tower working environment but received familiarization training by the Rotterdam controller team.

The Stockholm controllers had previously worked with parts of an A-SMGCS (MLAT). The Rotterdam team had no working experience with an A-SMGCS, but took part in evaluation sessions as part of this project and also had experience with the NARSIM Tower validation platform. They used it and worked with it as instructor for basic and recurrence training for Rotterdam Airport.

The pseudo-pilots participating in the simulations were pilots in training from the KLM Flight Academy (KLS).

Relevant Human-Machine Interfaces

Virtual blocks were created by virtual stop bars on the SMR display, also called Traffic Situation Display (TSD). Figure 3 shows part of the SMR screen that was available at both controller positions. Active virtual stop bars were indicated in red and green (stop and cleared) and inactive virtual stop bars were grayed out. Virtual stop bars could be switched from red to green and vice versa by left-clicking on the pan handles and activated or deactivated with the context menu by right-clicking on the pan handles. Locations for virtual stop bars were chosen during earlier evaluation sessions. Only a single real stop bar exists at Rotterdam Airport at high speed exit V3. This stop bar was indicated by a thick red bar at the exact position.

Runway stop bars were unidirectional, meaning that they only caused an alert when an aircraft tried to cross an illuminated (red) virtual bar to enter the runway. This also applied for the real stop bar. Runway stop bars were under responsibility of the runway controller.

Taxiway stop bars, which were used for virtual block control, were under responsibility of the ground controller (depending on the procedures used and the point of transfer of responsibility this could change, though). Stop bar violations were indicated by a red label and an audio alert.

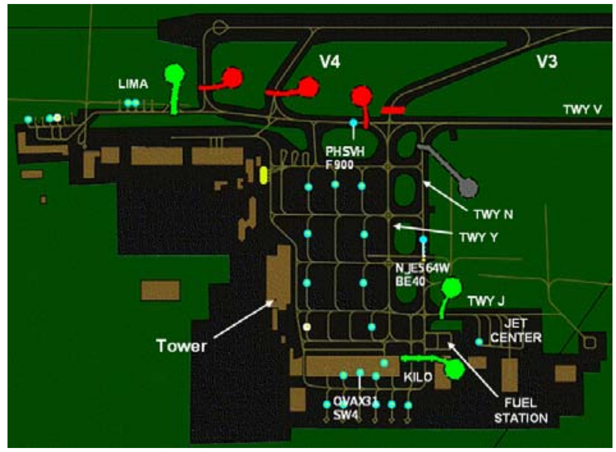

Figure 3. Virtual Stop Bars on the SMR

The Watch Dog functionality monitors an aircraft that is instructed to hold its position. It could be activated and deactivated by left-clicking on the respective aircraft label (or alternatively through the context menu).

The Watch Dog had four different states: activated, guarding, alarm, and resolved. An activated Watch Dog is indicated by a white circle around the aircraft. The Watch Dog starts guarding (orange circle) an aircraft when it stands still but can be activated while it is still rolling. If it continues to roll or starts to move, there is an alarm which is indicated by a red circle and an orange label (Figure 4) as well as an audible alert. If the problem is resolved (aircraft stops moving), the alarm disappears (green circle).

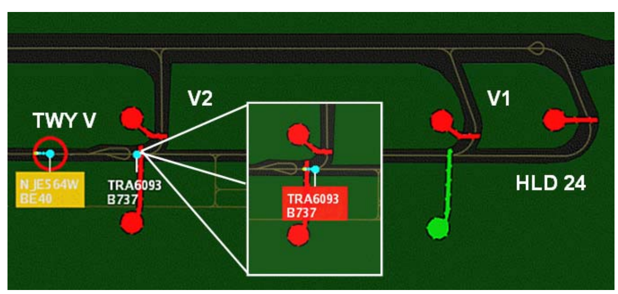

Figure 4. Watch Dog and Stop Bar Violation

The orange label color for Watch Dog violations was chosen after the training exercises as controllers felt that stop bar violations needed more attention (red label color) than Watch Dog violations or taxiway conflicts (orange label color).

Watch Dog and stop bar violations are shown in Figure 4.

Taxiway conflict monitoring was performed by the Hermes service that used the separation bubble tool to calculate and predict a possible conflict on the taxiways (see Figure 5 for bubble visualization at the experiment leader position and Figure 6 for the same situation on the SMR). Taxiway conflicts detected by the separation bubble algorithm (track enters a projected bubble) were indicated on the SMR with an orange label for the conflicting aircraft and an audio alert.

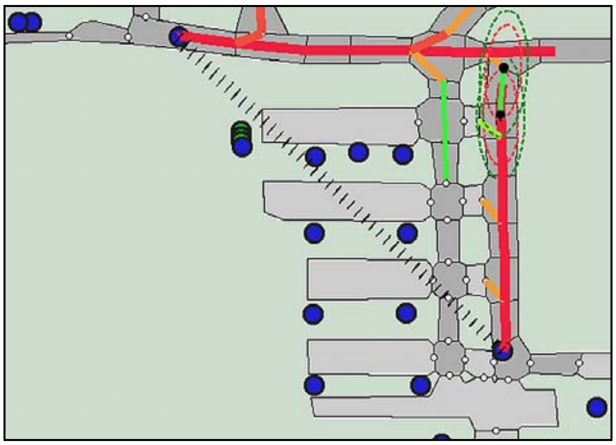

Figure 5. Separation Bubble Visualization

Figure 6. Separation Alert on SMR

The separation bubble tool had many settings regarding bubble size, location, and the look-ahead. Many rules could be configured, e.g. rules for probability thresholds and hysteresis (an idleness threshold that accounts for sensitivity) of alarms[9].

The main settings tested and confirmed by controllers during the training runs were a bubble length of 110 meters, a bubble width of 40 meters, and a bubble offset (from the center) of 25 meters. The look-ahead time was set to 35 seconds to prevent nuisance alerts in the virtual block on TWY V between V1 and Holding 24, and at line-up of Holding 24 (see indications on Figure 4). A look-ahead distance was not used (it had a value of 0 meters). The probability threshold was set at 0.5 (with the probability being a function of basic elements such as aircraft speed and taxiway segment geometry). Hysteresis values were set at 0.9 times the bubble size (alarm on) and 1.2 times the bubble size (alarm off) respectively.

At the runway controller position an additional Terminal Approach Radar (TAR) screen was available that could be used to keep an eye on departure separations and, more importantly, runway approach separations. As a general rule, aircraft were not cleared for line-up with an approaching aircraft flying within 6 NM of the runway threshold.

Traffic Samples

Different traffic samples were produced for training runs, evaluation runs, and the performance-related initial validation runs (baseline and advanced). While the training scenarios started with comparatively lower traffic volumes (20 aircraft movements per hour), both evaluation and performance related simulations had a rather high traffic load (28 to 34 aircraft movements per hour). There was a clear focus on outbound traffic (between 20 and 24 outbounds offered per hour).

Simulation Measurements

Subjective measurements from the participating controllers were obtained in the form of standard pre-experiment and post-experiment questionnaires.

Additionally, after each evaluation and each performance-related run with the tools, controllers had to fill in questionnaires concerning aspects of system usability (SUS scores). Furthermore, questionnaires on the assessment of expected operational improvements (OI and AL scores), such as safety (alerting), capacity, delay, throughput, situational awareness and human error, were filled in.

A set of standard questionnaires[1] from the Solutions for Human Automation Partnership in European ATM initiative (SHAPE) developed by EUROCONTROL and addressing human factors related issues were also part of the post-run assessment. The SASHA questionnaires assessed the level of controller situational awareness during the preceding simulation run. The SATI questionnaires assessed the controller level of trust in the system in the preceding simulation run. Trust is defined as the extent to which a user is willing to act on the basis of external information, recommendations, actions and decisions of another person, a computer-based tool or a decision aid. Finally, the AIM-s questionnaires assessed the impact of various ATC tasks in the preceding simulation run on controller workload.

General debriefing took place in the form of interviews in order to clarify questionnaire results and see whether there were any changes in the perception of controllers regarding the tools.

Regarding simulation system data, the NARSIM standard set of parameters was recorded. This set contained all the data necessary to make a replay of the scenarios, i.e. mainly aircraft positions (state), related frequency, and R/T times.

Concept Evaluation Results

The evaluation runs were carried out with each tool in isolation (virtual stop bars and Watch Dog functionality is considered a single tool) and in combined operation in order to investigate how the tools are used most effectively.

The three evaluation runs were performed in the following order:

- E1: Separation Bubbles
- E2: Virtual Block Control and Watch Dog
- E3: Combination of Tools

Critical situations were introduced in order to get an idea about the consequences for safety and the impact on ground handling efficiency.

[1] Available on the EUROCONTROL website (November 2008)

After experimenting with tools and operations in the evaluation session, controllers were asked questions concerning usability of the tools and the choice that should be made regarding the use of tools under advanced operational conditions during the performance-related simulations.

Furthermore, SHAPE questionnaires were filled in and scores were calculated. These scores provided insight into the controllers' perception of their own situational awareness, mental workload, and automation trust.

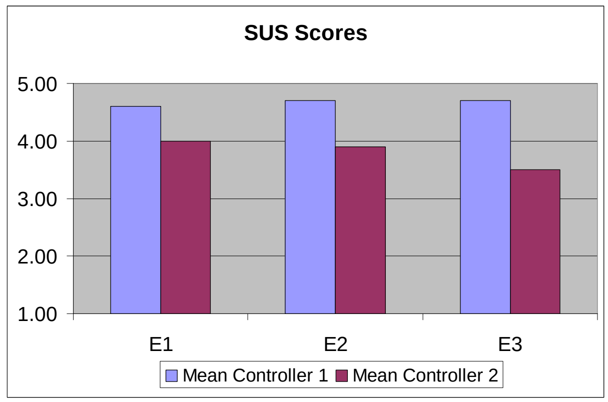

Figure 7. System Usability Scores (Evaluation)

The system usability scores were generally high but there was a noticeable difference in opinion between controllers regarding the use of the tools (see Figure 7).

Deeper analysis showed that the controller attributing higher scores was especially pointing out ease of use and quick learnability of the systems, while the other controller had doubts about whether he would like to use the system frequently and whether the tool combination was easy to use.

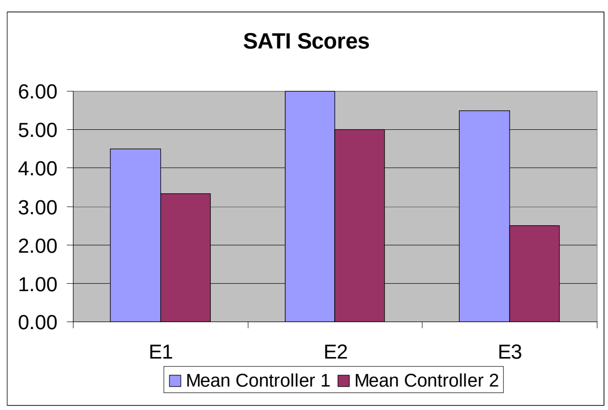

Figure 8. Automation Trust Scores (Evaluation)

Automation trust scores more clearly showed the difference in opinion (see Figure 8). While generally there seemed to be agreement that Virtual Block Control scored higher in automation trust than Separation Bubbles, the consequences for the tool combination were not as clear.

Analysis of the answers showed that none of the scores of the second controller was lower than a value of 2. Thus, the controller attitude could be described as indifferent rather than negative. Also, it had to be considered that the general score level for the second controller was lower throughout all SHAPE and SUS questionnaires.

Both scores for situational awareness and mental workload did not differ very much. As none of the values had any statistical relevance, it should suffice at this point to mention that the general level for situational awareness was high with an average rating of 4.9 out of 6, ranging from 4.6 (E3) to 5.2 (E2), and that the general level for mental workload was low with an average rating of 1.9 out of 6, ranging from 1.8 (E2) to 2.0 (E1).

Due to the fact that controller scores on automation trust differed, the evaluation debriefing and interviews with controllers had to elaborate why there was disagreement about the combined tool option.

In conclusion, the debriefing revealed that controllers felt that:

- Separation bubbles alone are less effective than virtual blocks as regards trust, situational awareness and mental workload
- Virtual blocks used in isolation are very effective as regards trust, situational awareness and mental workload when used procedural
- Combination of tools is deemed necessary when higher throughput is to be achieved (deviate from procedural control with virtual blocks and use separation bubbles as safety net when aircraft are taxiing somewhat closer within one virtual block)
- When used with current EHRD (good visibility) operations separation bubbles result in too many alerts (even though the alerts are considered valid)
- Use of Watch Dog as dynamic block on taxiways (Figure 9) is considered a safety risk (in case of R/T failure and/or with a missing clearance limit)

Figure 9. Use of Watch Dog on TWY V

Controllers had no doubts about the decision to continue working with the tool combination. During the evaluation interviews a number of statements were made that are considered of importance in this regard:

- Virtual blocks offer controllers a more structured and safe working approach under low visibility
- Separation bubbles should be used as extra safety net when procedural control with virtual blocks is gradually lifted to allow for more throughput
- Watch Dog should only be used on the apron or after a stop bar violation
- Current EHRD (good visibility) operations should change under low visibility (exit via V4 instead of V3, when using exit V3 do not hold aircraft at virtual stop bar N)
- Making tools dependent of each other (no separation alerts across illuminated stop bars) could pose a safety risk

Initial Concept Validation Results

After the evaluation session, an initial validation of the tool combination was carried out with the previously tested procedures. Results were analyzed with a focus on human performance, usability, achieved capacity, R/T load, and general operational issues.

The baseline scenarios were carried out without virtual block control and separation bubble tools but with the SMR screen in place (currently there is no SMR at Rotterdam). Two procedural options were simulated:

- B1: follow ICAO regulation, i.e. one aircraft moves at a time and SMR screen is not used for control (separation of aircraft)
- B2: do follow own intuition, i.e. work as efficient and safe as deemed necessary, and use the SMR screen for control (separation of aircraft)

The advanced scenarios were run with the tool combination several times to get a good indication of achievable capacity and efficiency:

- A1 to A4: different traffic scenarios with the same amount of traffic (about 30 aircraft per hour, inbound plus outbound)

In the baseline situation only situational awareness and mental workload questionnaires were filled in as all other questionnaires concerned the use of the tools in one way or another.

Each of the mentioned scenarios was carried out twice, i.e. once for each controller team.

Human Perception Results

The SHAPE scores provided insight into the controllers' perception of their own situational awareness, mental workload, and automation trust. Although not much could be deduced from the questionnaires from a statistical viewpoint (limited number of runs and participants), they at least indicated the generally perceived levels.

A trend in the automation trust score was a general learning curve from one advanced run to the next (see also Figure 10). Average values in overall SATI scores ranged from 4.8 (A1) to 5.6 (A3) with an overall mean of 5.3 on a scale from 0 to 6. In fact, most of the operational imprecision and mistakes (not adhering to approach spacing limits, not strictly performing block control) were observed during the first run (A1) for both controller teams.

Major differences between controller roles could not be found. It seemed though, that the ground controller was more skeptical in terms of trusting automation than the runway controller, especially in the A1 run.

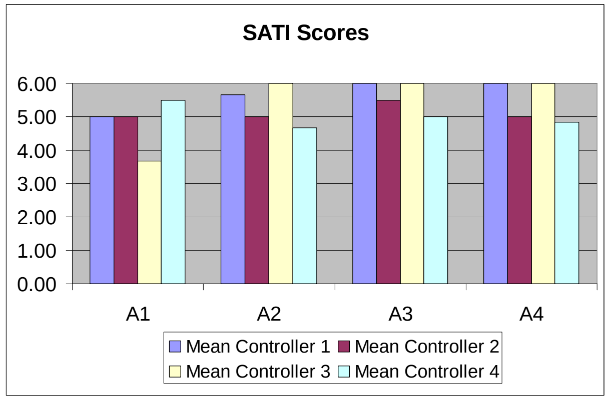

Figure 10. Automation Trust Scores for the Advanced Validation Runs

Also situational awareness scores and mental workload scores showed the same kind of stabilization or learning curve. However, due to the low number of runs and participants, this fact should not be overrated.

Average values in SASHA scores ranged from 4.9 (A1) to 5.6 (B1) with a mean value of 5.4 on a scale from 0 to 6. Average values in AIM-s scores ranged from 1.1 (A4) to 1.7 (A1) with a mean value of 1.5 on a scale from 0 to 6.

Surprisingly, there was no significant difference between the baseline and the advanced runs regarding the general level of situational awareness and mental workload perception, even though controllers noted in interviews and debriefings that especially virtual block control would lead to safer operations and less workload. This could mean that the controllers' perception of safety and the controllers' workload for conflict scanning on the monitor, which is part of the overall workload, is not captured accurately by the SHAPE questionnaires.

But also for these scores deeper analysis showed that, especially in the case of workload, there was too much noise in the data, caused by learning curve, controller task, or traffic sample.

System usability values showed no clear difference in any of the advanced runs. The score was generally high. Average values ranged from 4.4 (A2) to 4.7 (A3) with a mean value of 4.5 on a scale from 1 to 5.

Operational Assessment Results

The first simulation run (A1) was an outlier regarding operational performance for both controller teams. This result was also reflected in the more complex questionnaires concerning operational improvements and an assessment of the alerting tools. Overall scores showed the same results as in all other questionnaires (see Figure 11 and Figure 12).

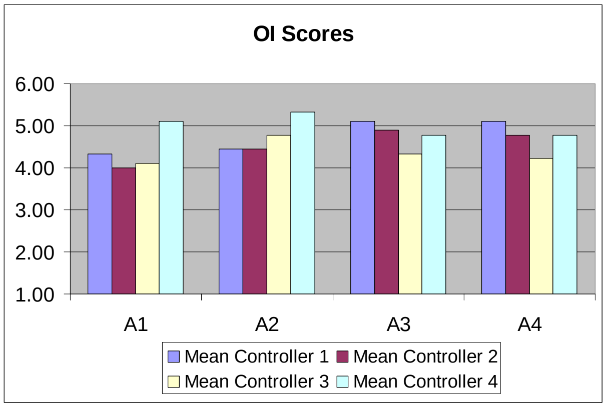

Figure 11. Operational Improvement Scores for Advanced Validation Runs

Average values in Operational Improvement scores ranged from 4.4 (A1) to 4.8 (A3) with a mean value of 4.7 on a scale from 1 to 6.

Average values in Alerting Tool Assessment scores ranged from 3.8 (A1) to 4.3 (A3) with a mean value of 4.1 on a scale from 1 to 6.

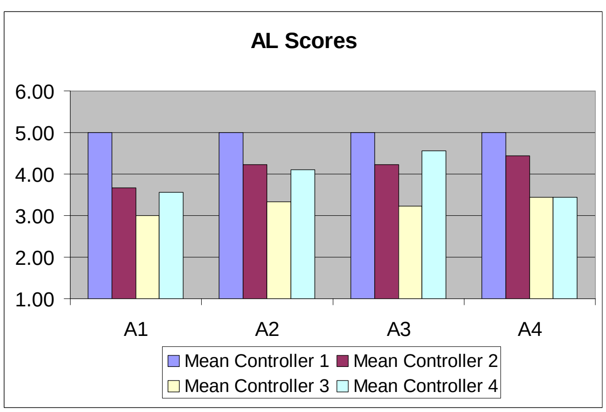

Figure 12. Alerting Tool Assessment Scores for Advanced Validation Runs

Operational improvement and alerting tool questionnaires were additionally analyzed deeper by segregating the questions into different categories, each addressing a specific aspect. Questions were answered on a scale of 1 to 6 (from no agreement to complete agreement). Average values per category are reported.

Operational Improvements	Score
Tools do not impair safety:	5.2
Tools allow handling more traffic:	4.9
Tools do not increase average stop time:	3.9
Tools increase traffic throughput:	4.2
Tools reduce human error:	5.1

This means that while controllers were very positive about the tools being able to reduce human error, handle more traffic, and not contributing negatively to safety, they were more skeptical about the reduction in average stop time and an increase in throughput. This was reflected in the interviews.

Alerting Tool Assessment	Score
Tools identify conflicts in time:	4.3
Presentation of conflict unambiguous:	4.8
False alert number sufficiently low:	4.2
Alerts only on taxiways are useful:	4.9
Use alerting under better visibility:	3.4
Two stages of alerts are useful:	2.3

Thus, there was a clear preference for as few alerts as possible (with only one kind of alert) and the use of tools under low visibility conditions only. Further, there was general agreement and values for alerting tool performance were high.

R/T Assessment Results

One of the system measurements made during the simulation runs was the number and duration of R/T calls.

Again A1 was an outlier with one of the controller teams having operational difficulties (procedure familiarization) in the beginning, which caused a higher R/T load (see Figure 13). As could be expected, the number of R/T calls did not differ too much between the second baseline and the advanced runs, especially when considering that perceived workload was the same.

The average value for B1 was at 117 calls per hour and the average value for B2 was at 275 calls per hour. The latter did not differ much from the average value for the advanced runs, which was at 301 calls per hour (291 without run A1).

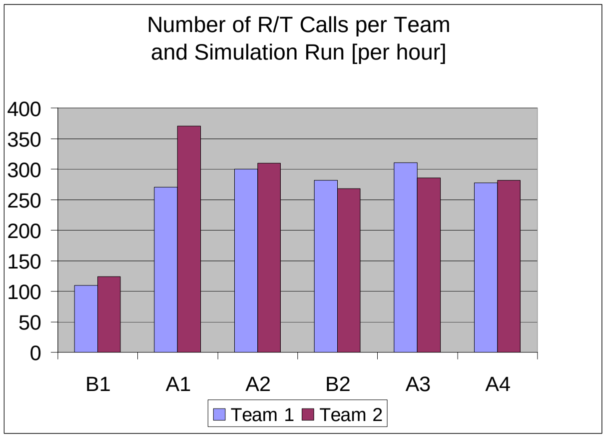

Figure 13. R/T Calls in Baseline and Advanced Validation Runs

Capacity Assessment

Another system measurement made was the number of inbounds and outbounds within the simulation time, the so-called achieved capacity or runway throughput. Again values did not differ too much between B2 and the advanced runs (see Figure 14). A1 did not seem to be an outlier this time, which means that the operational difficulties controllers experienced in the first run did not prevent them from achieving the average capacity level.

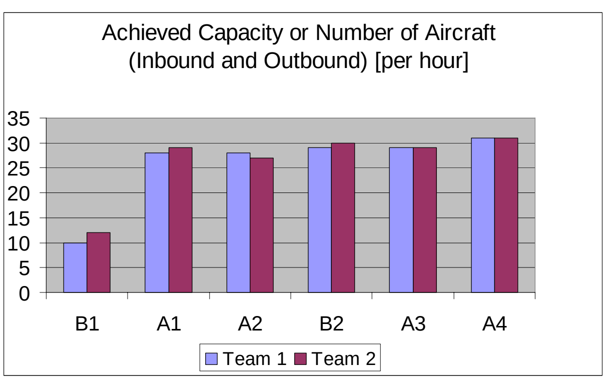

Figure 14. Achieved Capacity for Baseline and Advanced Validation Runs

The average value for B1 was at 11 aircraft per hour and the average value for B2 was at 29.5 aircraft per hour. The latter did not differ much from the average value for the advanced runs, which was at 29 aircraft per hour.

Considering a number of observed operational mistakes these numbers might be corrected by 1 to 2 aircraft, which would more or less level results at 10 aircraft per hour for B1 and 30 aircraft per hour for all other runs.

In other words, with the exception of B1, the number of aircraft offered in the traffic scenarios could indeed be handled by the controllers.

Conclusions and Recommendations

The study for evaluation and initial validation of the VB and SB concepts found that low visibility procedures differ per airport. It was highly recommended to harmonize and standardize VC3 operations across airports, and to promote application of Virtual Block and Separation Bubble Control as a means to increase airport capacity in VC3 in a safe way. ICAO should be advised.

Virtual Blocks with Virtual Stop Bars and Separation Bubbles provided an operational concept with additional safety nets (for illegal stop bar crossings and separation alerts as well as a Watch Dog for specific monitoring purposes) that, according to controllers, reduced their perceived workload for monitoring traffic.

With baseline operations making use of SMR information for separation, both controller groups could manage the same amount of traffic as when using the Virtual Block Control and Separation Bubble tools (about 30 aircraft per hour). As compared to the current procedure at Rotterdam Airport, having no SMR and following ICAO recommendations, capacity was increased by a factor of three[2].

In-depth Safety Assessment

The next recommended step in the Virtual Block Control and Separation Bubble concept development is to perform an in-depth operational safety assessment making use of the results reported here, including an additional safety analysis of cockpit operations in VC3.

[2] N.B.: the difference in capacity is mainly due to current safety measures at Rotterdam Airport

Virtual Block Control

Virtual Block Control procedures are identical to procedural control with position reporting. Virtual blocks offered controllers a more structured and safe working approach under low visibility. Virtual blocks and virtual stop bars were considered a solid operational and procedural framework that improves controller situational awareness and reduces workload. Overall the Virtual Block Control concept was appreciated and well-received.

The positioning of virtual stop bars is a matter of careful design. Already in an early stage of the evaluation, it was decided to prefer virtual stop bars close to crossings and intersections. This improves pilot situational awareness because pilots will still be able to visually identify the holding position. The situational awareness aspect for pilots will be further investigated in cockpit simulations as part of the described study.

If there are too many virtual stop bars, there will be administrative delay, i.e. workload to implement stop-and-go instructions will increase. Fast-time simulations should be executed to reveal how virtual block size and the number of virtual stop bars will affect flow and capacity.

When operating virtual blocks, there must always be a clearance limit for aircraft. When clearance limits are clearly defined, traffic will remain well-separated, even when communication is no longer possible. For capacity reasons, however, it is sometimes preferred to have two aircraft in the same block. In discussions it was concluded that procedures should only allow one aircraft per block at a time.

Separation Bubbles

Separation Bubbles alert controllers when separations between aircraft are violated. They act as an additional safety net underneath present day taxi operations and should be used when procedural control with virtual blocks is gradually lifted to allow for more airport throughput.

Separation Bubbles alone are less effective than Virtual Block Control as regards trust, situational awareness and mental workload, though.

The bubbles worked well on taxiways and crossings, but on aprons they caused too many nuisance alarms. Separation Bubbles could be tuned for that purpose, but this would require setting local separation standards for different parts of the aerodrome.

Separation Bubbles caused nuisance alerts when the distance between reporting points was too small. Thus, procedures should be tested on their compatibility with separation standards carefully, before the system is brought into operation.

The bubbles provided additional safety at any time, even across illuminated virtual stop bars or when two aircraft are controlled within one large block. If virtual block sizes are too small, Separation Bubbles might cause alerts that are perceived as nuisance by the controller. It was considered unsafe to include knowledge about illuminated virtual stop bars in the Separation Bubble tool as a stop bar violation alert might be too late for controller action. Thus, it is recommended to carefully choose block sizes in accordance with the agreed local separation standards.

Combination of VB and SB

Although the combination of Virtual Block Control and Separation Bubble tools scored somewhat lower on the system usability scale, their combination was deemed necessary. Separation Bubbles will serve as an additional safety net that warns controllers of separation violations between aircraft. This warning may come earlier than a stop bar violation alert. Thus, the use of the tool combination is recommended.

Small virtual blocks may trigger unwanted alerts by Separation Bubbles. While separation violations between aircraft in different blocks should not go unnoticed, it will be necessary to create blocks that are large enough to separate aircraft with the agreed separation limits. Reducing the nuisance by limiting look-ahead time was considered dangerous.

Watch Dog Tool

The concept of a Watch Dog tool was developed to be able to dynamically place a Virtual Stop Bar in the movement area of the airfield. The procedure was to drop a Virtual Stop Bar in front of an aircraft after it stopped at a location without a

Virtual Stop Bar. Early evaluation concluded that this procedure required too much interaction and that it was better to surround an aircraft with a circle that watches whether the aircraft stops within a certain time and continues to monitor the aircraft to hold its position. This circle was called Watch Dog and was evaluated together with Virtual Block Control in the simulation sessions. Operationally, it was used to split a long taxi stretch, thereby effectively dividing it into two separate virtual blocks. That, however, was considered a safety risk. When communication failed controllers could not prevent collision because of a missing clearance limit and reference point for the pilot. Thus, the only operational use of a Watch Dog had to be a situation in which a violation had already occurred and aircraft had to be monitored more closely.

Therefore, the Watch Dog should be used after illegal virtual stop bar crossings only. When aircraft cross a virtual stop bar without a clearance, they would receive an extra hold instruction and the Watch Dog would be placed around them to monitor the situation. This operation was considered by controllers to have a safety benefit.

The Watch Dog monitor could also be used to simply hold any aircraft in the movement area, e.g. on the apron. But it was not used much in this way. It was primarily used as a second line of defense, i.e. after an illegal virtual stop bar crossing.

Concept Improvement

Apart from the local tuning issue for the Separation Bubbles, the concepts were considered rather mature for operational use. Virtual stop bars should be positioned with care, if possible, on the basis of fast-time simulation results (for flow and capacity issues, i.e. workload), and on the basis of dynamic risk modeling or further real-time simulations (for tuning of separation violation tools, i.e. safety issues). These aspects were reported above.

The overall HMI was well accepted by controllers. A valuable suggestion made by controllers was that they would prefer to be able to enter clearance limits into labels, establishing a direct correlation between aircraft and their clearance limits (virtual stop bar positions). This would require, for example, an Electronic Flight Strip (EFS) system and has the advantage that the automation system is aware of the clearance limits. This information could be used for safety purposes.

Thus, it was also recommended to investigate options for integration of Virtual Block Control and Separation Bubble concepts with an EFS system and to analyze the benefits for workload, safety and capacity.

The experiments reported here did not include pilot awareness and opinions. The aspect of generation of clearance limits for pilots and their appreciation of Virtual Block and Separation Bubble control should thus be covered by cockpit simulations.

Outlook

Virtual Block Control and Separation Bubbles are simple and inexpensive improvements for tower ATC when proper A-SMGCS surveillance (MLAT and SMR) is present. They can be implemented rather easily and their use does not differ much from procedural control operations with real stop bars. Compared to the installation of real stop bars, virtual bars cost less and do not need to be installed on the airport surface. Virtual Blocks and Separation Bubbles are good candidates to mitigate effects of low visibility conditions on airport throughput and capacity in a safe and effective manner.

Further evaluation of the VB and SB concepts will take place in the DLR Generic Cockpit Simulator (GECO) in Braunschweig in May 2009. GECO is a fixed-base flight simulator with a 180 degrees collimated visual system. Four active airline pilots will take part in the simulations. They will taxi along with other simulated traffic in a Rotterdam Airport environment under VC3, while VB and SB procedures will be applied by a pseudo controller. The aim of these simulations is to find out whether pilots appreciate the concepts, how they perceive safety while operating under the given conditions, and how workload and situational awareness for the pilots change due to the new procedures. It will also be investigated whether intersections are sufficiently visible clearance limits for the pilots when taxiing in low visibility or whether additional lines need to be painted or lights need to be installed on the taxiways for intermediate holding positions.

The authors expect that further investigations of the tools will concentrate on operational safety aspects and the applicability of the tools at airports with a more complex taxiway structure. To this end, the already implemented Schiphol environment on the NARSIM Tower validation platform would offer an excellent testing ground and could lead to quick results. The authors further express the hope that research efforts in that direction are also incorporated into the SESAR programme to continue the promising efforts in studying low visibility tools and procedures.

Credits

The authors of this paper wish to thank Bengt Collin from EUROCONTROL and Frans van Schaik from NLR for their role in defining and managing the studies and for organizing all stakeholder events.

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Disclaimer

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Email Addresses

The authors of this paper can be contacted under the following e-mail addresses:

Jürgen Teutsch: teutsch@nlr.nl

Vilmar Mollwitz: vilmar.mollwitz@dlr.de

Appendix I

Abbreviation List

AIM-s	Assessing the Impact of Automation on Mental Workload (Short Version)
ANSP	Air Navigation Service Provider
APR	Airport Operations Programme
A-SMGCS	Advanced Surface Movement Guidance and Control Systems
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
ATM	Air Traffic Management
ATS	Air Traffic Service
CCIS	Closed Circuit Information System
CO	Convoy Operations
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EDD	Electronic Data Display
EMMA	European Movement Management by A-SMGCS
GECO	Generic Cockpit Simulator
HMI	Human-Machine Interface
ICAO	International Civil Aviation Organization
LFV	Luftfartsverket
LVNL	Luchtverkeersleiding Nederland
ML	Multiple Line-up
MLAT	Multilateration
NARSIM	NLR ATC Research Simulator
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium
NM	Nautical Miles
PP	Parallel Push-backs
R/T	Radio Telephony
RVR	Runway Visual Range
RWY	Runway
SB	Separation Bubbles
SASHA	Situational Awareness Rating Scale for SHAPE

SATI	SHAPE Automation Trust Index
SHAPE	Solutions for Human Automation Partnership in European ATM
SMGCS	Surface Movement Guidance and Control Systems
SMR	Surface Movement Radar
STCA	Short-term Conflict Alert
SUS	System Usability Scale
TAR	Terminal Approach Radar
TCM	Taxiway Conflict Monitoring
TMA	Terminal Maneuvering Area
TSD	Traffic Situation Display
TWY	Taxiway
UK	United Kingdom
VB	Virtual Block Control
VC	Visibility Condition

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