



## Executive summary

# Virtual Block Control and Separation Bubbles

## Evaluation in Cockpit Simulator Trials



Generic Cockpit Simulator (DLR – Braunschweig)

### Problem area

Low visibility at airports reduces the airport capacity considerably. The concepts of Virtual Blocks and Separation Bubbles are good Tower Control candidates to improve capacity in low visibility. The question was how pilots would react on both concepts.

### Management summary

This document is to be presented at the German Aerospace Congress, September 2009 in Aachen,, Germany. It is a result of the *Virtual Block Control and Separation Bubbles* study carried out by AT-One, for EUROCONTROL (TRS

T07/11070HG and part of the EUROCONTROL Airport Operations Programme (APR)).

This document describes the results of the airborne evaluation of Virtual Blocks and Separation Bubbles concepts. An evaluation of markings and signs to assist the pilots is also given.

### Description of work

Simulator trials in the DLR Generic Cockpit Simulator were performed to evaluate the pilot response to Virtual (non observable) Blocks, Virtual Stopbars and the Separation Bubbles as a safety net in low

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visibility conditions. Simulated Tower Control was provided by a portable NARSIM Tower facility. Three types of extra marking or holding and stopping lights in the taxway were evaluated

**Results and conclusions**

After earlier acceptance by Tower Controllers, the four test pilots partly accepted or rejected the concepts with preference for extra markings and signs.

**Applicability**

This study helps to understand the difficulties for pilots when taxiing in low visibility while separated and controlled by controllers using virtual Blocks and Separation Bubbles. It may lead to higher airport throughput in low visibility and to ICAO recommendations for better standardisation.



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### Evaluation in Cockpit Simulator Trials

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## Summary

Under contract of EUROCONTROL, the German Aerospace Center (DLR), together with its partner institute the National Aerospace Laboratory of the Netherlands (NLR), carried out research activities on the selection and evaluation of candidate concepts for advanced operations under low visibility conditions making use of the surveillance function of Advanced Surface Movement Guidance and Control Systems (A-SMGCS). These activities were carried out for the Airport Unit (AP) of the Centre of Expertise for Air Traffic Management (CoE/AT) of EUROCONTROL. As part of this research, two candidate concepts, Virtual Block Control and Separation Bubbles, have been evaluated in real-time cockpit simulator trials in the Generic Cockpit Simulator GECO of DLR in Braunschweig in May 2009. Virtual Blocks and Separation Bubbles are simple and low cost additions to the A-SMGCS surveillance function. They are aimed to increase airport throughput capacity in low visibility in a safe way. During the cockpit trials, pilots from major airlines taxied in the GECO within a simulated Rotterdam Airport environment. Aircraft were under control of a pseudo-controller applying Virtual Block Control with support of Separation Bubble Alerting. The main objective of the cockpit trials was to find out about the perception of the described procedures by pilots when taxiing under low visibility conditions. Different options for markings on the taxiways that are meant to support pilots in identifying the positions of virtual holding points were also investigated. The trials revealed that the concepts work down to the lowest visibility at which taxiing is possible at all. Pilots favoured Virtual Block Control supported by Intermediate Holding Lights as markings for holding positions and supported by Separation Bubbles as the best solution.



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## Abbreviations

|         |                                                       |
|---------|-------------------------------------------------------|
| A-SMGCS | Advanced Surface Movement Guidance and Control System |
| ATC     | Air Traffic Control                                   |
| GECO    | Generic Cockpit Simulator                             |
| ICAO    | International Civil Aviation Organisation             |
| M       | Mean                                                  |
| NASA    | National Aeronautics and Space Agency                 |
| PF      | Pilot Flying                                          |
| PNF     | Pilot Not Flying                                      |
| R/T     | Radio Telephony                                       |
| RVR     | Runway Visibility Rang                                |
| SB      | Separation Bubble                                     |
| VB      | Virtual Block                                         |
| SD      | Standard deviation                                    |
| VC      | Visibility Condition                                  |



## 1 Introduction

This paper presents the results of real-time cockpit simulator trials which have been conducted in the Generic Cockpit Simulator (GECO) of the Institute of Flight Guidance of the German Aerospace Center (DLR) in Braunschweig in May 2009. The cockpit simulator trials were part of the Virtual Block Control and Separation Bubbles project carried out by DLR and the National Aerospace Laboratory (NLR) of the Netherlands in their research alliance AT-One. The Virtual Block Control and Separation Bubbles project was conducted under contract of EUROCONTROL and was carried out for their Airports Unit (AP) of the Centre of Expertise for Air Traffic Management (CoE/AT). The aim of the project was to evaluate two promising concepts for increasing throughput on an airport movement area when pilots are not able see and avoid other traffic due to low visibility – the concept of Virtual Block Control and the concept of Separation Bubbles.

The following sections of this paper will give a short introduction to the background of the project and the recent activities, especially the trials in a tower simulator carried out by NLR in Amsterdam in December 2008. Chapter 2 describes the concepts of Virtual Block Control and Separation Bubbles as they are today and as they have been used in this prototype study. The objectives of the GECO trials can be found in Chapter 3, followed by a description of the experiment setup in Chapter 4. The last two chapters contain results, analysis, conclusions and recommendations.

### 1.1 Background of Project

Airport throughput and capacity drop considerably in low visibility conditions. While there are no problems in Visibility Condition 1 (VC1), in VC2 visibility is sufficient for pilots to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, but insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance [1]. A-SMGCS enhanced surveillance (Primary Radar plus Identification) allow for tower operations in Visibility Condition 2 as if in Visibility Condition 1. In Visibility Condition 3 (VC3) pilots are able to taxi but visibility is insufficient for the pilot to avoid collision with other traffic on taxiways and at intersections by visual reference, and insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance. For taxiing, this is normally taken as visibilities equivalent to a Runway Visual Range (RVR) of less than 400 m but more than 75 m. While in good visibility the airport serves about 30 to 35 aircraft per hour per runway, it will be difficult to control more than 6 aircraft in low visibility. If ICAO rules are strictly applied, only one aircraft is taxiing at a time in VC3. It was an open question whether A-SMGCS enhanced surveillance could also benefit tower operations in VC3. To study the potential of A-SMGCS in VC3, EUROCONTROL contracted



AT-One, the strategic alliance between DLR and NLR, to investigate how A-SMGCS enhanced surveillance could be further developed to have safe but increased airport operations in VC3. For reasons of overall standardisation and costs, no assumptions and requirements were made about the avionics to improve operations in low visibility. In other words, the aircraft were not required to be equipped with a moving map or a datalink.

Preliminary investigation of potential improvements traced five operational concepts to improve taxi operations in VC3. Three of them have been judged in the initial concept study as less preferable due to safety and efficiency considerations. The other two concepts, Virtual Blocks and Separation Bubbles, however, are simple and low cost A-SMGCS surveillance improvements with high expectations to benefit low visibility operations.

When in VC3 capacity drops, Procedural Control is applied on many airports. Pilots are cleared from reporting point to reporting point and have to inform the tower when reaching the next reporting point. The taxiway stretches between reporting points are called blocks. Controllers allow only one aircraft per block and mostly at least one empty block is kept between two aircraft. Procedural Control increases the capacity as more than one aircraft can taxi at a time but requires large investments if remote controlled stop bars are used at the block boundaries. The Virtual Block concept fits well with Procedural Control. Virtual Blocks do not require expensive infrastructure works. Virtual Blocks and virtual stop bars are equivalent in operation to real stop bars but only exist on the tower controller radar screens. To make clear to the pilots where to hold, virtual bars are chosen preferably at intersections and crossings.

The Separation Bubbles protect aircraft from coming too close to other traffic. The bubbles are a software safety net that warns and alarms the controller if separation is predicted to be violated. Separation Bubbles in combination with Virtual Blocks are high ranking candidates to improve airport capacity in VC3 in a safe way.

As a result of the feasibility study on concepts improving A-SMGCS surveillance operations in VC3, a more in depth study on the concepts of Virtual Blocks and Separation Bubbles with controllers and pilots in the loop was recommended. This paper presents results of real-time cockpit simulation trials with GECO at DLR Braunschweig. These trials were complementary to the real-time control tower simulations performed earlier at NLR. The cockpit simulations were aimed to get pilot feedback on taxi operations in low visibility applying Virtual Block Control with Separation Bubble Alerting. Results of the control tower simulations are summarised in the following chapter.

## **1.2 Tower Trials**

The tower trials were carried out in the NARSIM Tower validation platform of NLR Amsterdam in December 2008. Two controller teams consisting of two controllers each participated in the simulations. One of the teams was familiar with the Rotterdam working

environment used in the simulations. The other team came from a different European country. Prototypes with the functionality of virtual blocks and separation bubbles had been developed by NLR and implemented into NARSIM.

During interviews after first evaluation of the tools, a number of statements were made that were considered of importance:

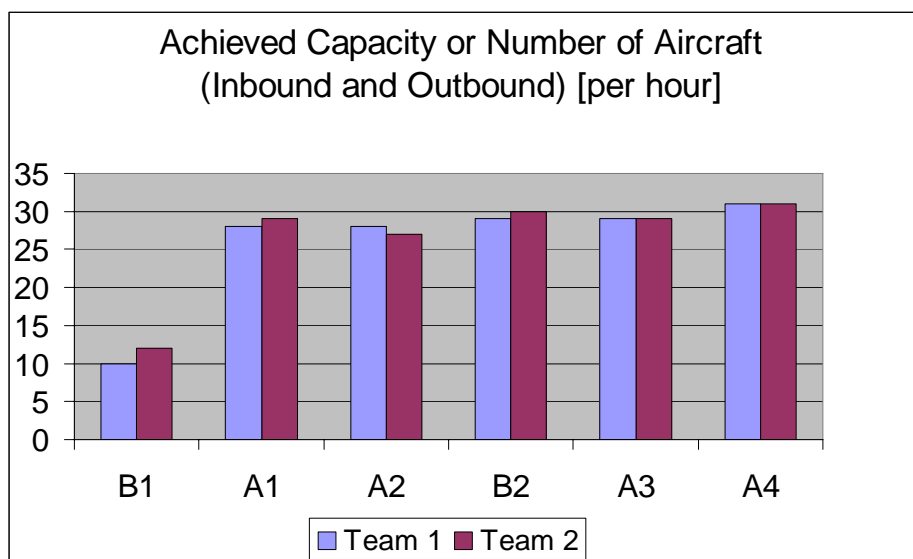
- Virtual blocks offer controllers a more structured and safe working approach under low visibility
- Separation bubbles should be used as extra safety net, especially when procedural control with virtual blocks is gradually lifted to allow for more throughput
- Making tools dependent of each other (no separation alerts across illuminated stop bars) could pose a safety risk

After the evaluation, an initial validation of the tools was carried out with the previously tested procedures. Results were analysed with a focus on human performance, usability, achieved capacity, R/T load, and general operational issues. Two baseline situations were looked at. The first baseline followed ICAO regulation, i.e. one aircraft moved at a time and Surface Movement Radar (SMR) screen were not used for control (separation of aircraft). In the second baseline exercise controllers followed their own intuition, i.e. they worked as efficient and safe as deemed necessary, and used the SMR screen for control (separation of aircraft).

When asked about operational improvements, 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 sceptical about the reduction in average stop time and an increase in throughput. This was reflected in interviews.

Regarding the alerting services, there was a clear preference for as few alerts as possible and the use of tools under low visibility conditions only. Further, there was general agreement on timeliness, presentation, and usefulness of the information provided. Nuisance was not considered a problem.

The most important result of the study was actually a system measurement made, namely the number of inbound and outbound within the simulation time, the so-called achieved capacity or runway throughput. With the exception of the first baseline (B1), which shows reduced capacity due to applied ICAO regulation, the rather high number of 30 aircraft movements per hour offered in the traffic scenarios (A1 to A4) could indeed be handled by the controllers (Figure 1). The same result was reflected in the number of R/T calls which were also multiplied by a factor of three.



*Figure 1 Achieved Capacity for Baseline and Advanced Validation Runs*

In conclusion, it can be said that 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 harmonise and standardise 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) that, according to controllers, reduced their perceived workload for monitoring traffic.

With baseline operations making use of SMR information for separation, both controller teams could manage the same amount of traffic as when using the Virtual Block Control and Separation Bubble tools.

Apart from the fact that Separation Bubbles need to be fine-tuned for each airport individually, the concepts were considered rather mature for operational use.

The NARSIM Tower trials did not include pilot awareness and opinions. Therefore, it was recommended to investigate the aspect of generation of clearance limits for pilots and their appreciation of Virtual Block and Separation Bubble control in cockpit simulations. For more details on the tower trials, the reader is referred to a conference paper on that topic [2].

## 2 Description of concepts

The following sections of this chapter describe the concepts of Virtual Block Control and Separation Bubbles. Both concepts have undergone multiple iterations and improvements in the course of the two studies carried out about the potential of A-SMGCS surveillance in VC3 since 2007. In this chapter, the two concepts are described as they are today and as they have been used in this prototype study. As innovative on-board technology is not foreseen in the studies, both concepts do only consist of new technology in the tower, while the cockpits do not receive innovative tools.

### 2.1 Virtual Block Control

To apply Virtual Block Control, the ground controller uses virtual bars on his A-SMGCS surveillance screen. These bars are only visible on his screen; they do not exist on the taxiways. They are operated like stop bars, i.e. they have a “green” status which means aircraft are allowed to cross these bars and a “red” status indicating aircraft are not allowed to cross. The controller can toggle the virtual bars between red and green on his surveillance screen. He can also deactivate a stop bar completely, which is then greyed out. In case an aircraft crosses a red virtual bar, an alert is given to the controller. This alert consists of the colour of the label of the aircraft which crossed the red bar turning red and an audio signal. The controller then has to advise the aircraft that crossed the bar to stop immediately, since the pilots are not aware of the virtual bar.

Figure 2 shows a part of the surveillance screen as it was used in the tower trials in Amsterdam and for the pseudo-controller in the cockpit trials in Braunschweig. The green and red virtual bars with handles next to them for toggling can clearly be seen.

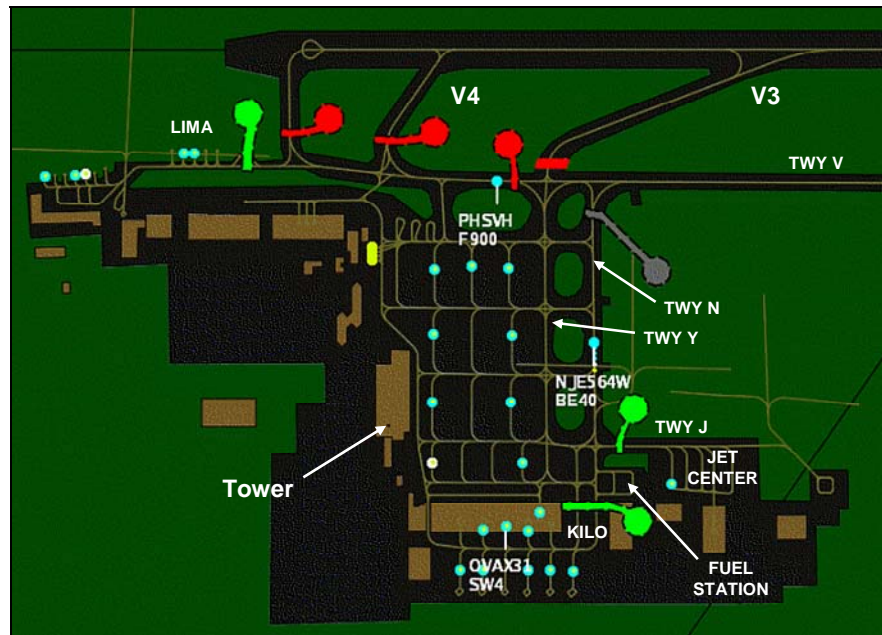


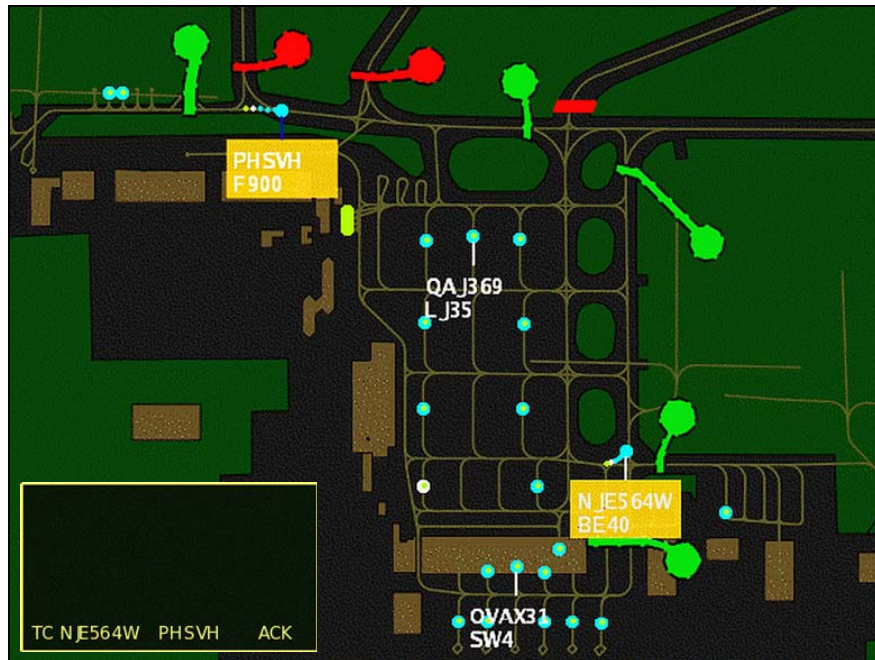
Figure 2 Virtual Bars on the Controller Screen

In order to tell pilots where to stop on the taxiways so that they do not cross a virtual bar, the virtual bars are positioned at places easily detectable for the pilots. These are in front of intersections and crossings, but also intermediate holding lines and lights have been used in the cockpit trials (see chapter 3).

## 2.2 Separation Bubbles

The basic idea of Separation Bubbles is to create an artificial bubble around each aircraft taxiing on the movement area. The size of a bubble depends primarily on the speed of the aircraft and the taxiway layout. If the bubbles of two aircraft touch each other, this indicates that they are not separated by a safe distance any more. In this case, an alert is given to the controller. The alert is given by the labels of the involved aircraft turning orange and an audio signal. Additionally, the callsigns of the involved aircraft are depicted in a box at the corner of the surveillance display. In case of a Separation Bubble alert the controller has to advise the involved aircraft to stop immediately. Thereafter, the conflict has to be solved by procedural control.

Figure 3 shows part of the surveillance screen that was used in the tower trials in Amsterdam and for the pseudo-controller in the cockpit trials in Braunschweig. A bubble alert is depicted between PH-SVH and NJE564W.



*Figure 3 Controller Screen with Separation Bubble Alert*

The bubbles sizes depend primarily on speed. Different settings can be applied for bubble length, offset, and look-ahead time. The tower trials showed that the settings for the bubbles need to be fine-tuned for each individual airport. As Rotterdam airport was simulated both for the tower as well as the cockpit trials, the settings found in the tower trials were also used in the cockpit trials. Figure 4 visualizes the separation bubble algorithm. The traffic situation and bubble alert are the same as depicted in Figure 3.



Figure 4 Separation Bubble Algorithm Visualisation

### 3 Objectives of GECO trials

The basic aim of the cockpit trials was to find out the perception of the concepts of Virtual Blocks and Separation Bubbles by pilots. After taxiing in GECO on an airport with these procedures applied, pilots were asked for their

- acceptance of the concepts
- situational awareness and
- workload due to the concepts

in dedicated questionnaires. It was also measured how fast they taxied while the control concepts were applied and what separation they maintained to the bars after detecting them and stopping at these positions.

The concepts of Virtual Blocks and Separation Bubbles were explicitly developed for use under Visibility Condition 3. Thus, simulations were carried out with the visual range set to VC3. The visibility condition is defined in the ICAO A-SMGCS manual [1], but clear numbers of visibility range are not given. In a study carried out by Airbus under contract of EUROCONTROL, the transition between conditions 2 and 3 had been evaluated, i.e. when pilots start to not being able to visually detect other traffic on the movement area [3]. But since the concepts of Virtual Blocks and Separation Bubbles are foreseen for VC3, they shall also work under the lowest visibility level at which pilots are able to taxi, i.e. the transition between



visibility conditions 3 and 4. In order to obtain this minimum visibility, simulation runs were carried out at different preset Runway Visual Ranges (RVR). Pilots taxied on the airport using procedural control, i.e. GECCO was the only aircraft moving on the airport surface. RVR was reduced in steps of 15 meters until pilots indicated the minimum RVR for operation was reached. Steps of 15m were used as this is the spacing of runway centreline lights according ICAO Annex 14 which are used for determination of RVR according ICAO Annex 3. The obtained RVR was then used in the evaluations of Virtual Blocks and Separation Bubbles, as these concepts shall be applicable down to VC4.

The third aim of the cockpit trials was to find out which kind of markings on the taxiways pilots deem necessary for detection of the positions of virtual bars. There were four different kinds of virtual bar visualisations investigated, all according to ICAO Annex 14:

1. Intersections with Information Signs next to it, which indicate the names of intersecting taxiways
2. Intermediate Holding Lines; these are yellow dashed lines on the taxiway perpendicular to the centreline
3. Intermediate Holding Lights; these are three yellow lights at a spacing of 1.5m oriented along the intermediate holding line in the centre of the taxiway
4. Stop Bars, as used in front of runways at the CATII/III holding points

Intermediate holding lines with or without lights and stop bars can also be located at a place apart from intersections, e.g. on a long taxiway stretch, which provides an additional block for separation. This was done in the simulation runs to see whether pilots accept such an additional intermediate holding point. The point was given the name "Spot1".

## **4 Experiment description**

This chapter describes the experimental setup of the real-time cockpit simulator trials. The experiments were carried out in the Generic Cockpit Simulator (GECCO) of DLR in Braunschweig. They were carried out in two campaigns which took place in two different weeks in May 2009, lasting two days each.

### **4.1 Simulation Environment**

The Generic Cockpit Simulator GECCO is a fixed based flight simulator with a 180° collimated visual system. The shape of the cockpit is that of an A320, also the cockpit height above ground while taxiing represents that of an A320 (ca. 4.2m). While many handling devices, e.g. the throttle levers and trim wheels as well as flap and slat handles, are that of an A320, the display layout and modern input devices like keyboard and trackball are derived from the new A350.



The flight model simulates the VFW614 ATTAS, the research aircraft of DLR. For this aircraft, DLR has a very sophisticated motion simulation, including ground movements, which have been validated by the ATTAS pilots of DLR. This combination has proven to be a very realistic though still generic cockpit and flight simulator in numerous preceding projects.

The visual range of GECO is freely scalable. Settings for 90, 75, 60, 45 and 30 meters of Runway Visual Range had been determined prior to the experiments. They were used to determine the minimum RVR at which pilots are still able to taxi.

The NLR ATC Research Simulator, NARSIM was available at DLR and provided the following simulation facilities:

- Tower Controller Working Positions
- Pseudo-pilot positions
- Traffic Generator
- Flight Data Processing System
- Surface Movement Radar and Terminal Approach Radar display
- A-SMGCS tools (Virtual Block and Separation Bubble Human Machine Interfaces)
- Interface with GECO

#### **4.2 Simulated Airport**

The airport used in the simulations was Rotterdam. This airport had also been used in the tower trials. Therefore, using Rotterdam did not require any tuning of the blocks and bubbles prototypes, as the fine-tuned settings of the tower trials could be used for the cockpit experiments as well.

Furthermore, Rotterdam has a rather basic airport layout with a single runway and one long parallel taxiway ideally suited for first evaluations of Virtual Blocks and Separation Bubbles. One long stretch on the parallel taxiway V between the apron and taxiway V2 is also ideally suited for the additional intermediate holding position.

#### **4.3 Participants**

Four pilots were invited to take part in the simulations. Two pilots attended the first campaign, the other two pilots the second campaign two weeks later. All pilots had been Pilot Flying (PF) and Pilot Non Flying (PNF) for the same number of simulation runs; the roles were changed between the different runs.

Of the four pilots, three were active captains at a major German airline and one was a First Officer at a German commuter airline. The pilots were on average 41.5 years old, their ages ranged from 29 to 48 years. They had an average total of 9,300 flight hours with total flight hours ranging from 2,500 to 13,000 hours. They possessed their Air Transport Pilot Licenses (ATPL) for 17 years on average, the oldest ATPL was from 1988, the youngest from 2001. The

aircraft types the four pilots are currently working on are: A340/A330, B737, MD11, and ATR42/ATR72. On their current aircraft types, the pilots had, on average, accumulated 4700 hours each.

The simulated traffic surrounding GECO on the movement area was controlled by pseudo-pilots. A pseudo-controller applied the concepts of Virtual Blocks and Separation Bubbles to these aircraft as well as to GECO. Both pseudo-pilots and pseudo-controller had received training in air traffic control and radio telephony prior to the experiments.

#### **4.4 Scenarios**

After familiarisation with GECO and Rotterdam airport, pilots started with the runs for determination of the minimum RVR at which they could still taxi. Thereafter, the simulation runs for evaluation of the concepts of Virtual Blocks and Separation Bubbles were carried out.

##### **4.4.1 Determination of Minimum RVR**

For these runs, RVR was initially set to 90 meters. It was reduced by steps of 15 meters during the runs until pilots indicated the minimum RVR they felt able to taxi at was reached. This reduction was done on agreement between the experiment leader and the pilots.

The markings on the movement area were as they are today in Rotterdam, i.e. there were no intermediate holding lines, lights or stop bars. The holding point “Spot1” was also not there. There were a total of four runs, two runs for each pilot. The first run began with GECO positioned on the apron. GECO was cleared on the usual route to line-up on runway 24. After line-up, GECO was repositioned on runway 24 shortly before exit V4. From there, GECO was cleared on the usual route back to the apron. The second run started at the General Aviation Terminal. From there, GECO was cleared on the usual route to line up runway 24 again; after line-up, GECO was repositioned on runway 24 shortly before exit V4 and from there cleared on the usual route to the apron again. The routes in the third and fourth run were similar to those in the first two runs, with the starting position and destination gate on the apron differing.

##### **4.4.2 Evaluation of Blocks & Bubbles**

For all evaluation runs, the runway visual range was set to the value that had been determined as the lowest value at which pilots could still taxi during the RVR runs just before. In the first campaign, an RVR of 30m was thus used (see also 5.6). While the pilots of the second campaign also proved to be able to taxi at an RVR of 30m, 75m was used for the evaluation runs. This is the commonly accepted RVR at the transition from Visibility 3 to Visibility 4. The route the pilots had to follow was the same for all runs. All runs were supposed to start with GECO positioned approx. 16 NM east of Rotterdam airport at an altitude of 3,000 ft and a heading of 270 in level flight left of the localizer. The pilots were cleared for the ILS-approach.

After initial contact with the tower, they received the clearance to land on runway 24 and to exit via V4. After switching to the ground frequency, they were cleared on the standard route to a free gate on the apron. After a short stop at the gate of about one minute (during which the run continued), they were cleared to runway 24. There, the pilots switched to the tower frequency and received the take-off clearance. After take-off the simulation run was ended. After the eighth run of the first campaign, it was agreed among all relevant participants that the landing and take-off did not add a lot to the immersion of the pilots and thus realism of the experiments. Hence the following runs were conducted without landing and take-off, i.e. the runs started with GECO positioned on runway 24 just in front of exit V4 and ended after line-up on runway 24. The baseline runs were carried out with landing and take-off again for better comparability. During the second campaign, landings and take-offs were completely omitted. One aim of the evaluation runs was to find out the kind of supporting markings pilots prefer in order to be able to detect the positions at which they are supposed to stop, i.e. the positions of the virtual bars. Therefore, each run took place with one of the four different kinds of virtual bar visualisation. In those cases with no bars, the additional intermediate holding position on the long taxiway stretch named Spot1 was not depicted in the scenery and not used. In those cases with stop bars, the stop bars were linked to the virtual bars on the screen of the pseudo-controller, so pilots were aware whether a virtual bar is activated or not. As the concept of Virtual Blocks implies, all aircraft, including GECO, were cleared consecutively from one holding position, i.e. virtual bar, to the next. Nevertheless, pilots were also confronted with holding positions they were supposed to cross. This meant they were already cleared to the following virtual bar and had to cross the previous holding position on their way although it was clearly visible to them. For evaluation of the Separation Bubbles concept, bubble alerts had to be created, though not in every scenario. Bubble alerts do only occur when two aircraft are coming too close to each other, which can only happen after a violation of virtual bars (except nuisance alerts). In the trials, bubble alerts could therefore only occur after an intentional mistake by the pseudo-controller. For each scenario containing a bubble alert, it was clearly stated in a scenario description where and how they were supposed to occur. The last two evaluation runs were the baseline runs with current Rotterdam procedures applied. Here, the pilots encountered the same weather and flew on the same route as in the other evaluation runs, but procedural control was applied. For Rotterdam, this meant GECO was the only aircraft moving in the control zone, thus there was no surrounding traffic and Virtual Blocks as well as Separation Bubbles were not active.

#### **4.5 Measurements**

Both objective and subjective measurements were used in the cockpit trials. The position of GECO was recorded during all simulation runs. Relevant objective measures can be derived from this information. One item investigated was the speed the pilots taxied at. It was investigated whether they taxied at different speeds when different kinds of markings were used, which might have an effect on throughput. It was also evaluated at which distance to the virtual bars GECO came to a stop. This gives a clue to when pilots detect the different markings and if they are able to react in time.

A set of different questionnaires was used during the experiments. There were standard as well as tailored questionnaires. The standard questionnaires were used for obtaining situational awareness and workload results after each simulation run. The tailored questionnaires were used before the trials to obtain biographical data as well as after the trials to find out about the pilots' opinion and acceptance of the concepts of Virtual Blocks and Separation Bubbles. The different questionnaires are briefly introduced in the following.

**NASA-TLX:** The NASA-Task Load Index was used to assess the workload of pilots after each evaluation run. It has been developed by Hart et al. in 1988 [4]. The NASA-TLX determines a score for the level of workload perceived that is used for comparison of different markings and the concepts of Virtual Blocks and Separation Bubbles against the baseline scenario.

**SART:** The Situational Awareness Rating Technique was used to obtain the situational awareness of the pilots after each evaluation run. It has been developed by Taylor in 1990 [5][5]. The SART determines a score for the level of situational awareness perceived which is used for comparison of different markings and the concepts of Virtual Blocks and Separation Bubbles against the baseline scenario.

**Blocks & Bubbles Questionnaire:** This questionnaire has been tailored to obtain the perception of the concepts of Virtual Blocks and Separation Bubbles by the pilots. The pilots were asked to fill out this questionnaire after all evaluation runs. It contains questions about the acceptance of both Virtual Blocks and Separation Bubbles, as well as questions about the situational awareness under Virtual Block Control with different kinds of supporting bar visualisation and with use of Separation Bubbles.

## 5 Results and analysis

This chapter presents the results of the simulation runs and the analysis of the data obtained during the runs. It must be noted that all data discussed was obtained from a rather small sample of just four subjects.

### 5.1 Taxi Speed

Figure 5 shows the average taxi speeds on the taxiway parallel to the runway during taxi-out. The values of the first campaign are given in blue colour, those of the second campaign in red colour. The order of the values is that of the trials as they had been conducted. On the ninth trial of the first campaign, position storage did not work and thus data is unfortunately not available.

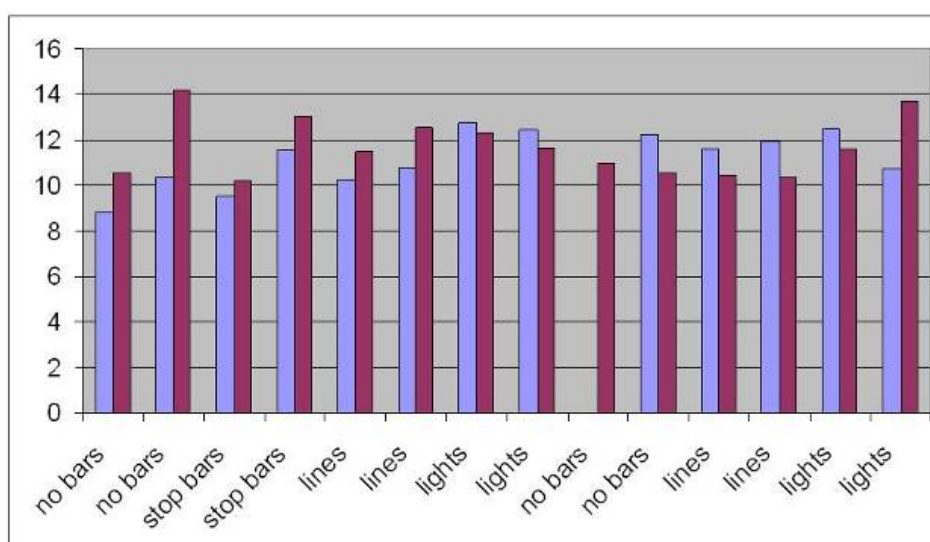


Figure 5 Average Taxi Speed of each trial [kts]

Taxi speeds are on average 11.45 kts, with the lowest taxi speed 8.82 kts and the highest 14.18 kts. For the first campaign, an increase in taxi speed can be noted during the first runs, which shows pilots adapted to the low visibility conditions during the first runs. For the second campaign, an alteration of taxi speed between 10 kts and 13 to 14 kts can be noted for the first four runs, where pilots changed roles between each run. The first pilot of the second campaign stated that for his airplane and at his airline, 10 kts is the maximum allowed taxi speed under low visibility. He therefore kept the GECO at 10 kts with the help of the ground speed indication on the Multi Function Display (MFD) during his first runs, as was noted also by the observers, but in later runs accelerated to more than 12 kts.

Figure 6 shows the averages of the average taxi speeds of trials with identical virtual bar visualisation. Standard deviation is also given. Condition with no bars, i.e. only intersections with information signs, is given in black colour, those with intermediate holding lines in blue

colour, with intermediate holding lights in yellow, and the condition with stop bars is shown in red.

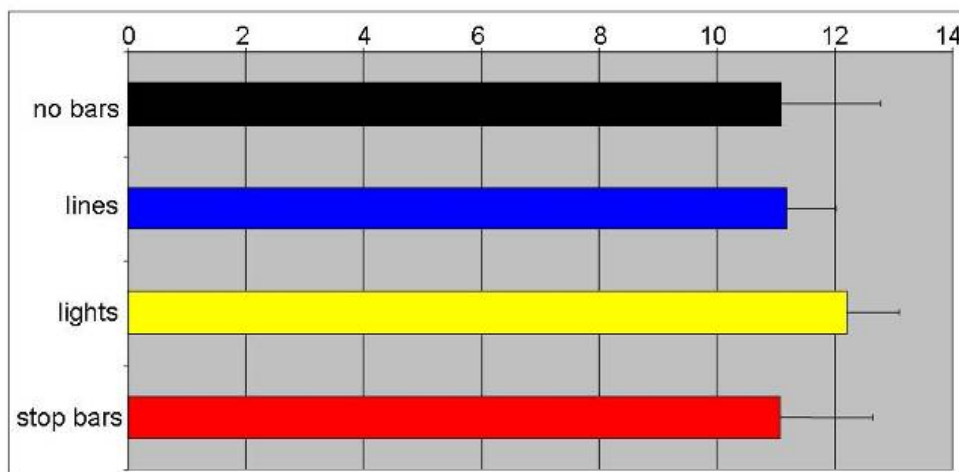


Figure 6 Average Taxi Speeds for different kinds of bar visualisations [kts]

There is a slight increase of one knot in average taxi speeds for trials with lights, i.e. intermediate holding lights according ICAO Annex 14. This corresponds to the pilots stating that with intermediate holding lights virtual bar positions were easier to detect for them compared to runs with no visualisation or only intermediate holding lines (see also 5.3.2). Thus, pilots were confident to taxi slightly faster with intermediate holding lights. The average taxi speeds of all other trials do not differ notably.

## 5.2 Stopped Distances to Bars

Figure 7 shows for each run the average distance of GECO to the virtual bar positions on the parallel taxiway when stopped in front of them. Distance is given in meters and represents the distance between the pilot's eye point projected onto the surface and a virtual bar, i.e. not slant distance from the pilot's eye above the taxiway. The values of the first campaign are again given in blue, those of the second campaign in red. The order of the values is that of the trials as they had been conducted. On the ninth trial of the first campaign, position storage did not work. Thus, taxi speed data is not available.

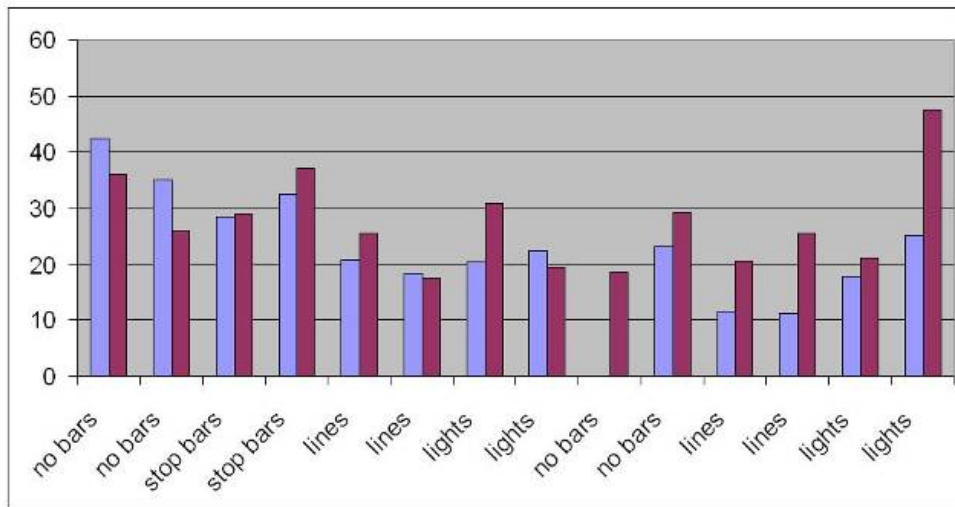


Figure 7 Average Stopped Distances to Bars [m]

The smallest stopped distance to a virtual bar measured was -0.5m, so pilots had already crossed the virtual bar position, but an alert for bar violation was not yet given on the controller display. This occurred during a run with intermediate holding lines. The largest stopped distance measured was 47.6m in a run with intermediate holding lights. As this was the only position to stop at during this particular run, the average for this run is also 47.6m, the last run of the second campaign. This was also the run with the second highest average taxi speed. It seemed that the pilot was very confident to taxi with intermediate holding lights so he both taxied fast and was prepared to brake timely during this run. As can also be seen, stopped distances decrease during the first runs, which corresponds to the average taxi speed increasing during the first runs. When taxiing faster, pilots had less time to detect virtual bar positions and thus stopped at smaller distances. During the runs, it was observed that no pilot crossed a virtual bar without clearance. Also pilots never got lost on the movement area.

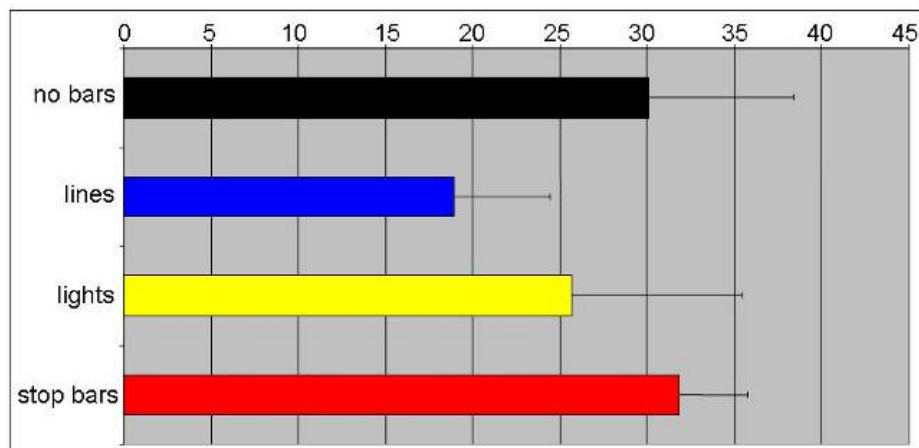


Figure 8 Average Stopped Distance for different kinds of bar visualisations [m]



Figure 8 shows the averages of the average stopped distances of trials with identical virtual bar visualisations. Standard deviation is also given. Stopped distances are notably lower for trials with intermediate holding lines than for trials with other kinds of virtual bar visualisation. This corresponds to pilots stating that lines were the least detectable for them, especially at Spot1, so they braked comparatively late in trials with lines. The second smallest average stopped distance is that of trials with intermediate holding lines; but this also has the highest standard deviation (9.75). As pilots were taxiing notably faster during runs with intermediate holding lights, they also had less time to brake after detection of the virtual bars, which might explain the smaller average stopped distance compared to trials with no bars or stop bars. The average stopped distance does not differ notably between trials without virtual bar visualisation and those with stop bars. A larger stopped distance might be safer as more separation distance is eventually kept to other traffic.

### 5.3 Acceptance

#### 5.3.1 Results from Blocks & Bubbles Questionnaire

All answers on the Blocks & Bubbles Questionnaire were answered on a scale ranging from 1 to 10, with 1 representing complete rejection and 10 representing full acceptance.

The first four columns of Figure 9 show pilots' acceptance of the different experimental conditions. The highest acceptance is reported for the condition "separation with stop bars" ( $M=9$ ;  $SD=0.8$ ). The second highest acceptance is reported for the condition "separation by intermediate holding lights" ( $M=5.5$ ;  $SD=4.7$ ), reflected by medium acceptance. The next two conditions (separation by intermediate holding lines and without bar visualisation) were rejected by pilots ( $M=2.8$ ;  $SD=2.9$  /  $M=2.8$ ;  $SD=2.1$ ). Acceptance of procedures is influenced by pilots' awareness of where to stop in trials with different experimental conditions. Columns 5 to 8 of Figure 9 show a comparable pattern with the highest awareness of where to stop given for the condition with stop bars ( $M=8.3$ ;  $SD=2.4$ ). Also the condition with lights is accepted ( $M=7.8$ ;  $SD=2.2$ ). The lowest average awareness is reported for the conditions with intermediate holding lines respectively without lines.

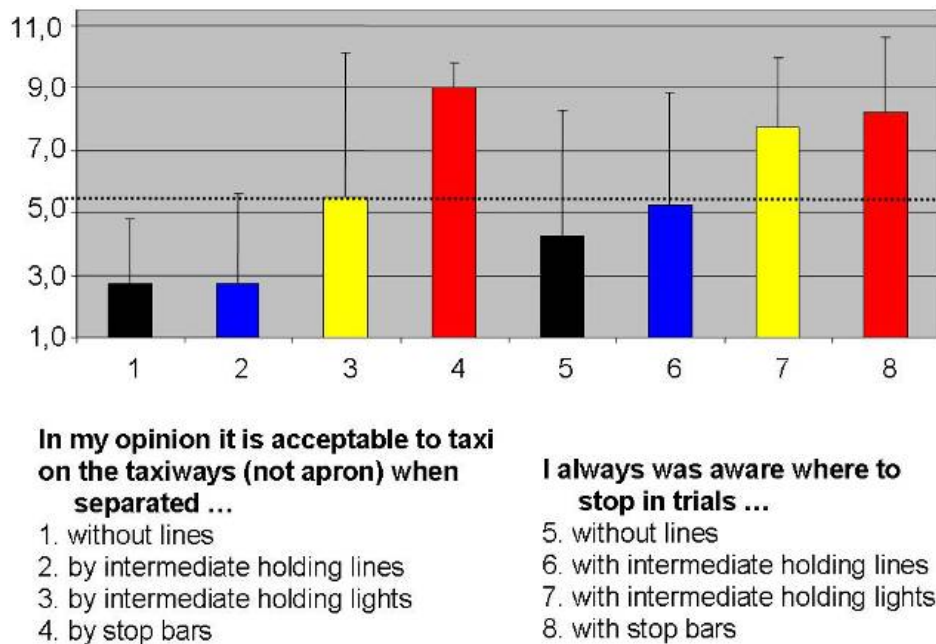
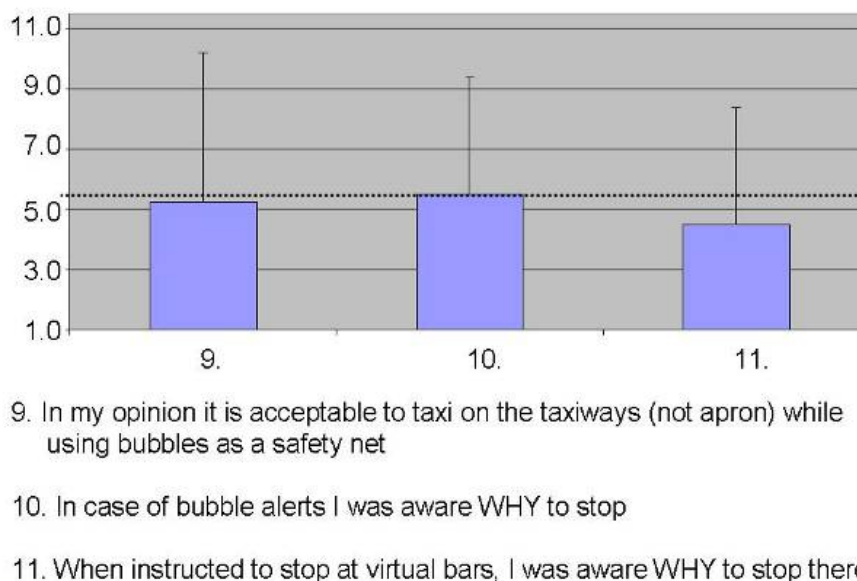


Figure 9 Blocks & Bubbles Questionnaire Item 1-8

On average, pilots were less convinced to accept to taxi on the taxiway while using bubbles as a safety net (item 9 in Figure 10) ( $M=5.3;SD=4.9$ ). The high standard deviation indicates the different levels of acceptance between the two crews of the first and second campaign. While crew 1 rejected bubbles as a safety net, crew 2 was in favour of the concept. This seems to be influenced by the awareness of why to stop in case of bubble alerts. Column 10 shows a similar result with average agreement and high standard deviation. Again the high standard deviation is explained by the negative feedback of crew 1. Column 11 shows a similar result with average agreement and high standard deviation. Again the high standard deviation is explained by the negative feedback of crew 1. In case of column 11 the topic was not Separation Bubbles but Virtual Bars. Nevertheless, crew 1 rejected Virtual Bars as well.



*Figure 10 Blocks & Bubbles Questionnaire Item 9-11*

### 5.3.2 Results from Debriefing

Crew 1 taxied with an RVR of 30m during the evaluation runs, while crew 2 chose 75m RVR for the evaluation runs. This did affect the results of the debriefing in terms of rejection of the new procedures by crew 1. The only acceptable means of separation on the movement area for crew 1 were stop bars. Crew 1 stated that stop bars are the only safety net for the pilots. Only stop bars provide the possibility to cross-check clearances given via radio. Crew 2 agreed to stop bars being the best solution, but also favoured intermediate holding lights as virtual bar presentation. In conjunction with intermediate holding lights, they generally found the concepts of Virtual Blocks and Separation Bubbles to have feasible procedures. A pilot of the second crew stated his home-base airport already had intermediate holding lights installed. He also reported instructions to stop immediately did occur occasionally at his home-base. He therefore reported that from his perspective, the introduction of Virtual Blocks and Separation Bubbles would make no difference at all. Separation Bubbles would just be an additional safety net for the controller. When asked whether they feel confident when relying completely on the ground controller, crew 2 answered that this is already usual operation in many fields, e.g. runway clearance under low visibility or en-route separation without TCAS.

The second crew also reported that with intermediate holding lights they felt more confident while taxiing on the taxiways and looking for the places where to stop. This is reflected by the average taxi speeds being the highest and stopped distances being the largest for trials with lights. In case of no bars they used the diverting taxiway centreline lights at intersections for first detection of virtual bar positions. Nevertheless, as intermediate holding lights are of different colour than centreline lights, they are still easier to detect than intersections. In case of

intermediate holding lines the additional holding position “Spot1” was difficult to detect for the pilots. Therefore, the pilots favoured intermediate holding lights for virtual bar visualisation. One pilot remarked that taxi speeds would be lower in real life than they were in the experiments. In real life, passenger and cabin crew comfort have to be taken into consideration in case the aircraft has to be stopped immediately.

#### 5.4 Situation Awareness

While acceptance was different between the four experimental conditions (with “stop bars” and “lights” as favourite procedures), pilots reported that situation awareness was almost comparable between the four test conditions as can be seen in Figure 11 ( $M=8;SD=2.7$  /  $M=8;SD=3.4$  /  $M=9.3;SD=1$  /  $M=8.8;SD=1.5$ ). In addition, situation awareness was subjectively reported as high enough in case of bubble alerts ( $M=9.5;SD=1$ ). Here, the standard deviation was rather low which shows that both crews agreed on their perceived high situational awareness.

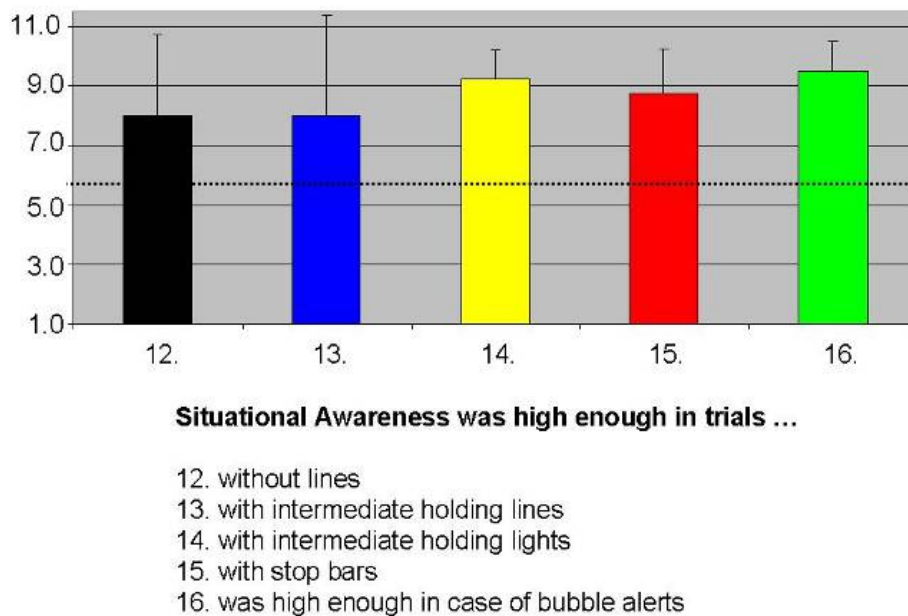


Figure 11 Blocks & Bubbles Questionnaire Item 12-16

Results from SART, shown in Figure 12, are comparable to the results obtained from the Blocks & Bubbles Questionnaire. Situational Awareness is above the average value (4) in all cases.

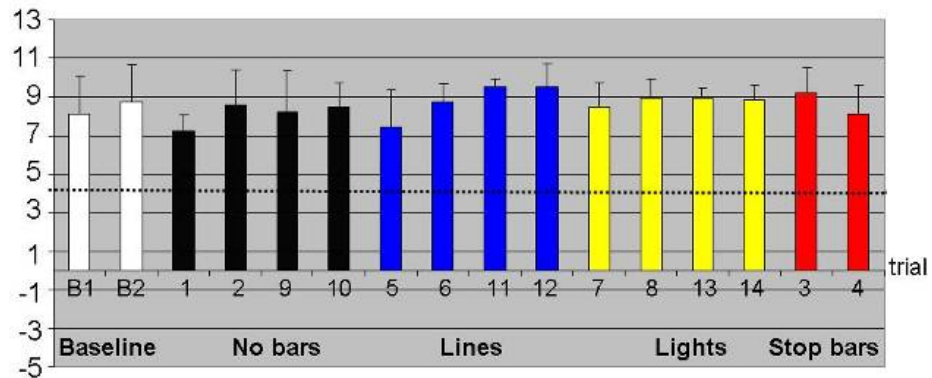


Figure 12 Results from SART

### 5.5 Workload

NASA-TLX rates the task-load of the pilots on six subscales. In general, means for all six subscales of the NASA-TLX had been below average (under 10). Thus, neither experimental condition was perceived to cause a high workload by the pilots. Especially on the subscales for Frustration, Performance, and Physical Demand, average values had been comparatively low. No effect could be derived from these subscales. The results from the subscales Mental Demand, Temporal Demand, and Effort are given in Figure 13 to Figure 15.

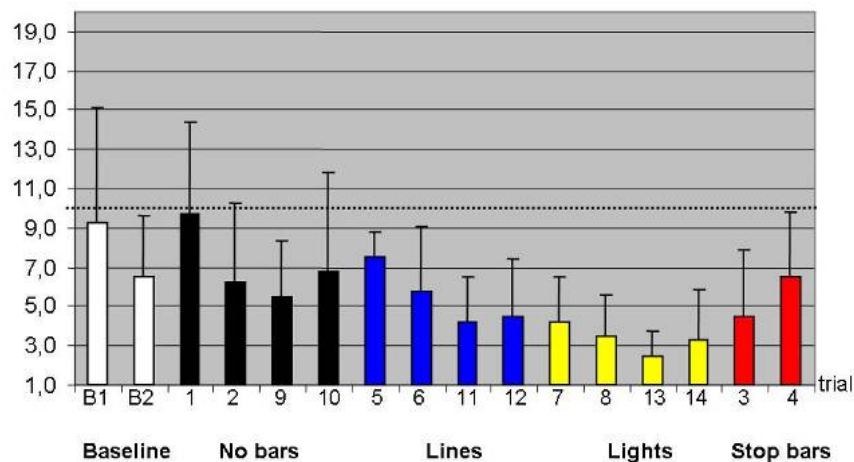


Figure 13 NASA-TLX Mental Demand

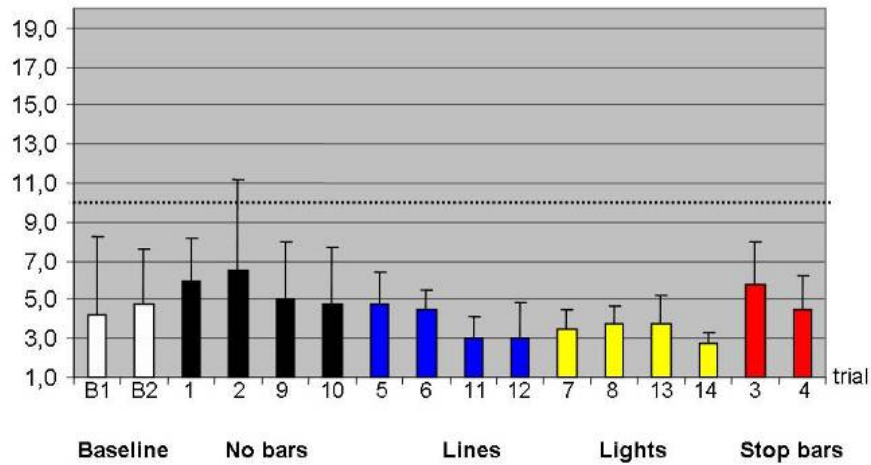


Figure 14 NASA-TLX Temporal Demand

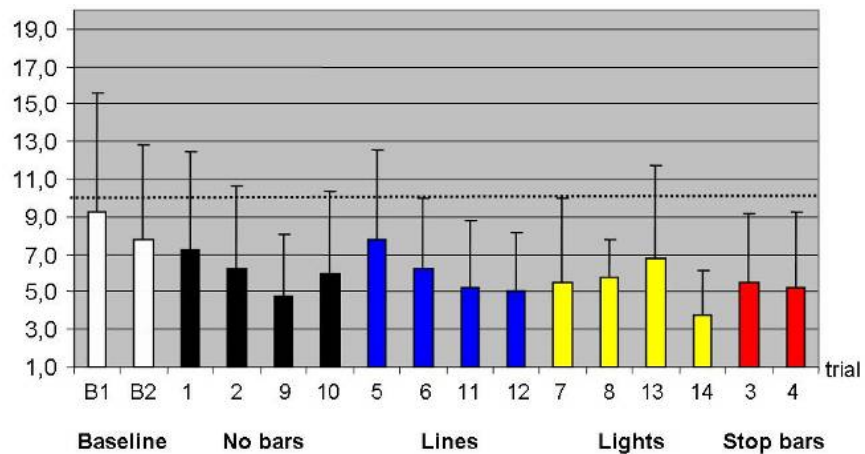


Figure 15 NASA-TLX Effort

Both Effort and Temporal Demand have the trend to be lowest for experiments with intermediate holding lights. Further testing is required to verify this trend. Mental Demand is comparatively the highest for experimental setups with no bars, as for baseline and lines, whereas the lowest Mental Demand was measured in the test condition with lights. Especially for the subscale Effort a typical learning effect can be seen (e.g. in the no bar condition) as values systematically decrease from trial 1 to 2 and 9.

### 5.6 Additional Results

Before the evaluation runs, Runway Visual Range runs were performed by each flight crew. These runs were meant to determine the minimum RVR at which pilots were still able to taxi and thus to determine the transition between Visibility Conditions 3 and 4. In these trials, GECO was the only aircraft taxiing on the movement area, so pilots did not have to bother about conflicting traffic. Both crews succeeded in taxiing at a minimum RVR of 30m. Both



crews defined this RVR value as the absolute minimum for safe taxi operations. The crews emphasised that they would refuse to taxi at an RVR of 30m on the apron in real life, but the apron was not part of the evaluation area of these trials. The first crew performed the following evaluation runs with an RVR of 30m. In the second campaign, 75m was used as this is the commonly accepted RVR transition between VC3 and 4. In the first campaign, pilots were still able to taxi at the RVR of 30m even with surrounding traffic and when Virtual Blocks and Separation Bubbles were applied. They found all holding positions and never violated a virtual bar. Thus, the concepts have proven to work even down to Visibility Condition 4. The second crew performed an additional run after the trials. This run was meant to investigate whether pilots were able to taxi under low visibility conditions without the aid of taxiway centreline lights. Centreline lights were thus switched off for these trials; only taxiway edge lights and standard painted yellow lines were provided. RVR was again set to 75m. Crew 2 proved to be able to taxi without the centreline lights. But when interviewed, the pilots stated that the omitted centreline lights caused an extreme workload to them and they do not consider it a safe procedure. Hence taxiway centreline lights are deemed necessary for safe low visibility operations.

## **6 Conclusions**

In May 2009, cockpit evaluation trials were carried out in Braunschweig in the course of the Virtual Block Control and Separation Bubbles project. Four pilots from major German airlines taxied in two consecutive campaigns in DLR's GECCO in a simulated Rotterdam Airport environment while Virtual Blocks and Separation Bubbles concepts were applied. Virtual Blocks and Separation Bubbles are simple and low cost additions to enhanced Surveillance and Identification components of Advanced Surface Movement Guidance and Control Systems. They are aimed to increase airport throughput capacity in Visibility Condition 3. The major aim of the trials was to investigate pilots' acceptance of these innovative concepts. Runs for determination of the transition between Visibility Conditions 3 and 4 revealed that an RVR of 30m was the absolute minimum at which pilots found they could still taxi. The concepts of Virtual Blocks and Separation Bubbles proved to work also at this RVR. The evaluation runs proved that Virtual Blocks work with all provided kinds of virtual bar visualisation. Pilots never violated a virtual bar and never got lost. Situation Awareness was high for all trials; workload was measured with values below average for all trials. Nevertheless, pilots had different opinions about the acceptability of Virtual Blocks. The crew of the first campaign stated that only remote controlled stop bars are an acceptable means of separation on the movement area, as only they provide a safety net for the pilots by giving a reference for

cross-check of radio clearances. The second crew stated that also intermediate holding lights are acceptable for virtual bar visualisation, though. Both crews agreed in not accepting intermediate holding lines or just intersections for virtual bar visualisation. They both found these hard to detect.

Virtual Bars are meant as a low cost solution to increase airport throughput capacity under Visibility Condition 3. While the installation of stop bars is a large investment, intermediate holding lights are expected to cause notably lower costs. It has been proven in an extra trial run that pilots need taxiway centreline lights under Visibility Condition 3 for safe guidance. Hence, intermediate holding lights are expected to merely cause a few additional lights to the necessary centreline lights. Virtual Blocks in conjunction with intermediate holding lights are thus considered a simple and low cost concept to increase throughput under Visibility Condition 3. Separation Bubbles proved to be a feasible concept in the evaluation runs. When instructed to stop immediately, all pilots did so instantly. In terms of acceptability, the crews had different opinions again. Just like in the case of Virtual Blocks, the first crew stated that Separation Bubbles did not provide a safety net for pilots and thus rejected the concept. The second crew favoured Separation Bubbles as a simple additional safety net for the ground controller. One of the pilots of the second crew stated that at his home-base airport instructions to stop immediately did occur occasionally under low visibility. Hence the introduction of Separation Bubbles would mean no difference for him. Separation Bubbles, used in conjunction with Virtual Blocks, are thus considered a feasible simple and low cost concept to increase throughput in Visibility Condition 3 in a safe way.



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