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Automation Support in Low Visibility Conditions: Virtual Stop Bars in the Cockpit

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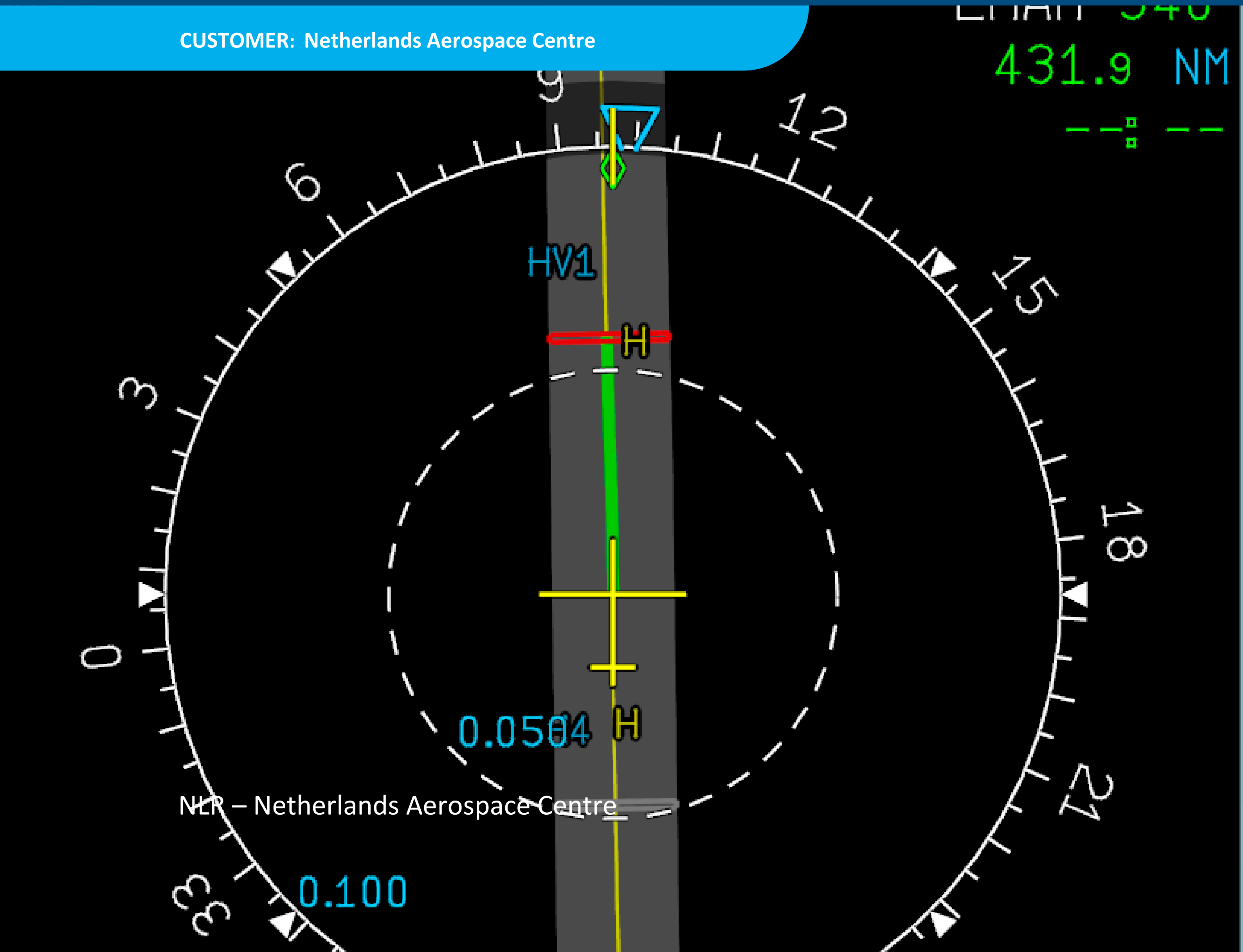

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EXECUTIVE SUMMARY

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Automation Support in Low Visibility Conditions: Virtual Stop Bars in the Cockpit

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Problem area

The Virtual Block Control (VBC) concept makes use of Virtual Stop Bar (VSB) positions on both controller and flight crew displays with the aim to reduce the size of control blocks used under low visibility conditions and, at the same time, ensure sufficient spacing between taxiing aircraft. In recent years, VBC was investigated within the European SESAR Programme (2008-2016) as an operational concept for improving weather resilience at airports. It has evolved in the SESAR timeframe towards the Dynamic VBC (D-VBC) concept allowing for smoother traffic flows. These validation activities predominantly focused on ground control aspects of the concept. In 2017 and 2018 investigations were followed up within the SESAR 2020 Programme, which is the successor to the SESAR Programme, with a clear focus on communication aspects between pilot crews and ground controllers.

Description of work

Simulation exercises were planned for an assessment of the D-VBC concept inside the cockpit as part of the project for Surface Management Operations (PJ03a) of

the SESAR 2020 Programme. In the exercise (with reference EXE.03a-01.050), the NARSIM-Tower validation platform of NLR with the existing realistic aerodrome tower simulation environment for Milan-Malpensa Airport was to be connected to a high-fidelity flight simulator environment (Leonardo GRA) with an industrial prototype of a moving map display (Thales AOF).
Since a one-shot solution to connecting all simulation units was considered challenging in terms of project risks, it was decided to carry out a preliminary exercise with a single ground controller for NARSIM-Tower in connection with NLR's own GRACE flight simulator. Both simulators were part of an integrated NLR validation platform and used existing protocols for relay of data link and simulation-related information for other aircraft traffic and the status of the airfield ground lighting. The exercise was carried out with pilot crews from NLR and two major European airlines.

Results and conclusions

The main results of this preliminary SESAR study with a focus on cockpit operations with D-VBC are reported. The most important comments and recommendations concerned the analogy between what pilots can or expect to see when looking out the cockpit windows and what is indicated on the displays inside the cockpit, as well as the identical mental picture that pilots and controllers need to maintain regarding the type and status of a VSB. Suggestions were also made regarding additional pilot support if there is no visual reference for a VSB on the outside. Specific recommendations were given on how to optimize the information content to be displayed to pilots and how future implementation strategies should deal with the parallel use of datalink and R/T communication.
Regarding implementation of the automation systems, recommendations for their improvement were given. They were based on pilot and controller interviews and concern the automation system logic, feasibility of the suggested operation, as well as safety, workload, and efficiency aspects.

Applicability

Exercise results will be an important input to other SESAR 2020 activities that are designed to bring the concept towards system specification and deployment phases. They will eventually pave the way for implementation of D-VBC as low visibility operational concept at European airports in the near future.

GENERAL NOTE

This report is based on a presentation held at the Integrated Communications Navigation and Surveillance Conference (ICNS) 2019, Herndon (VA), U.S.A., April 9, 2019.

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AUTOMATION SUPPORT IN LOW VISIBILITY CONDITIONS: VIRTUAL STOP BARS IN THE COCKPIT

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Abstract

The Virtual Block Control (VBC) concept makes use of Virtual Stop Bar (VSB) positions on both controller and flight crew displays with the aim to reduce the size of control blocks used under low visibility conditions and, at the same time, ensure sufficient spacing between taxiing aircraft. In recent years, VBC was investigated within the European SESAR Programme (2008-2016) as an operational concept for improving weather resilience at airports. It has evolved in the SESAR timeframe towards the Dynamic VBC (D-VBC) concept allowing for smoother traffic flows. The validation activities that were carried out on the NARSIM-Tower simulation platform at the Netherlands Aerospace Centre (NLR) in Amsterdam predominantly focused on ground control aspects of the concept.

In 2017 and 2018 investigations were followed up within the SESAR 2020 Programme, which is the successor to the SESAR Programme, with a clear focus on the cockpit side and on the communication aspects between aircraft and ground controllers. Due to this change of focus, the D-VBC concept on the ground was kept the same with on the NARSIM platform, while one of the flights was now performed in a high-fidelity simulation environment for aircraft, the NLR Generic Research Aircraft Cockpit Environment, GRACE (Figure 1).

The main results of this preliminary SESAR study with a focus on cockpit operations with D-VBC are reported. The most important comments and recommendations concerned the analogy between what pilots can or expect to see when looking out the cockpit windows and what is indicated on the displays inside the cockpit, as well as the identical mental picture that pilots and controllers need to maintain regarding the type and status of a VSB. Suggestions were also made regarding additional pilot support if there is no visual reference for a VSB on the outside, as the cockpit display needs to allow the pilot to judge distances between the aircraft and the VSB positions to apply appropriate braking action.

While the D-VBC concept was appreciated and accepted in general, specific recommendations were given on how to optimize the information content to be displayed to pilots and how future implementation strategies should deal with the parallel use of datalink and R/T communication.

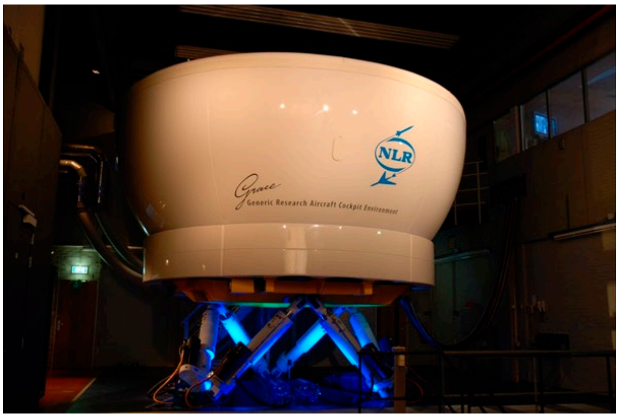

Figure 1. NLR GRACE Flight Simulator

Regarding implementation of the automation systems, recommendations for their improvement were given. They were based on pilot and controller interviews and concern the automation system logic, feasibility of the suggested operation, as well as safety, workload, and efficiency aspects. An outlook is given on related simulations with a full Milan-Malpensa tower crew and mainly pseudo-piloted aircraft in May 2018. Several performance-related results of these simulations will shortly be highlighted in the final sections of this paper.

Exercise results will be an important input to other SESAR 2020 activities that are designed to bring the concept towards system specification and deployment phases. They will eventually pave the way for implementation of D-VBC as low visibility operational concept at European airports in the near future.

Introduction and Background

The Virtual Block Control (VBC) concept describes airport ground control procedures for operations under low visibility conditions and must be seen as an enhancement of ordinary block control, which is also referred to as procedural control. When procedural control is applied, aircraft are cleared by ATC in the aerodrome tower to visually recognizable positions in the movement area of an airport, such as an Intermediate Holding Position (IHP). A sequence of several visually recognizable positions forms so-called control blocks in which one aircraft will be taxiing at a time to prevent collisions and increase operational safety in low visibility. Pilots report the aircraft position upon reaching the clearance limit of a control block. While such an operation can be considered safe, it reduces airport capacity in the movement area as well as taxiing throughput [10].

The VBC concept can be seen as an analogy to procedural control. So-called Virtual Stop Bar (VSB) positions are added to the Human-Machine Interface (HMI) of both ground and runway controllers and, if equipment is present, to the navigation display of pilots with the aim to increase efficiency and situational awareness of all actors. This further increases the safety of operations as earlier studies have shown [10]. Air traffic controllers sequentially guide aircraft from one VSB position to the next. Alerting functions for minimum spacing, unauthorized block boundary crossing and unauthorized runway entry can be combined with VBC for additional safety and to eliminate the need for an additional buffer block, which is recommended by ICAO for procedural control operations [5].

In 2012, the SESAR-Joint Undertaking (SJU) approved a validation activity (with reference EXE-06.08.07-VP-635) for a very detailed VBC concept with elaborate controller tools for a Milan-Malpensa Airport (LIMC) control tower working environment. NLR staff already gained experience with the LIMC environment in earlier European Commission projects [7], [8]. LIMC was therefore simulated on the high-fidelity NARSIM-Tower validation platform of NLR (Figure 2). The layout of the airport was considered appropriate for testing the concept due to several long taxi stretches that run parallel to the runway system and have numerous connection nodes to the apron areas, thus offering possibilities to reduce taxiway segment sizes. Furthermore, the airport already had hold lights installed at a large number of clearly defined IHPs [1]. This allowed the operational concept to be extended to non-data link equipped aircraft, in which pilots do not have a navigation display showing the location and status of a VSB and thus need to be able to detect a visual reference point for a VSB on the airport surface.

Figure 2. NARSIM Tower Facility at NLR

Results pointed out that (fuel) efficiency gains were still low meaning that further investigations would have to concentrate on improving procedures and providing advanced functionality for support of controller operations [11].

Development of the concept continued within the SJU project as part of a different work package addressing the guidance function (P06.07.03) which represents a specific service of the Advanced Surface Movement Guidance and Control System (A-SMGCS) as defined by EUROCONTROL in their latest specification document [4]. The VBC concept that emerged from the guidance function project was initially nick-named Dynamic VBC (D-VBC), as it allowed for more flexible block control operations. However, it actually represented a different working method and was seen as a major step from procedural control towards automation supported operations under low visibility conditions [12]. Elements of the previous concept were used to create more flexibility for the controller. The developed operation did not rely on the formation of control blocks anymore but rather on the assignment of individual clearance limits to aircraft with the help of a routing function. The focus of the defined exercises (with reference EXE-06.07.03-VP-092) was an evaluation of operations on the controller side, so that emphasis was put on the combination of VSB administration and route assignment. The SESAR exercise was again carried out on NARSIM-Tower in June 2015.

While the focus of this work on the air traffic controller side led to valuable feedback on both the D-VBC concept and the interface used, it did not clearly specify the part of the operation in the cockpit. Earlier studies used a flight simulator to investigate visibility of VSB reference positions (IHP) in low visibility [9]. However, the different elements of VBC with existing stop bars, VSBs at visually recognizable positions and VSBs without a visual reference in the movement area had not been investigated yet regarding their integration into a moving map display for pilots. Therefore, it was suggested to the SJU to carry out an exercise for assessment of the D-VBC concept inside the cockpit as part of the project for Surface Management Operations (PJ03a) of the SESAR 2020 Programme. In the exercise (with reference EXE.03a-01.050), the NARSIM-Tower validation platform of NLR with the existing realistic aerodrome tower simulation environment for Milan-Malpensa Airport was to be connected to a high-fidelity flight simulator environment with an industrial prototype of a moving map display. The flight simulator chosen for simulation with a full tower crew for Milan-Malpensa from Italian ANSP ENAV was the General Regional Aircraft (GRA) simulator of aerospace company Leonardo that included a Thales Avionics moving map display prototype (AOF).

Since a one-shot solution to connecting all simulation units was considered challenging in terms of project risks, NLR decided to carry out a preliminary exercise with a single ground controller for NARSIM-Tower in connection with NLR's own GRACE flight simulator. Both simulators were part of an integrated NLR validation platform and used existing protocols for relay of data link and simulation-related information for other aircraft traffic and the status of the airfield ground lighting (AGL). The exercise was carried out with pilot crews from NLR and two major European airlines.

D-VBC and FD-VBC Operational Concepts

As mentioned above, the D-VBC concept was developed in order to overcome the shortcomings of ordinary block control, as applied in the VBC concept, regarding efficiency of taxi operations. Details of the D-VBC concept were already discussed in [12]. In the following concept description, more emphasis is put on controller tasks and related pilot tasks. This should help to understand both the established operational procedures and the communication process between the cockpit side and the ground side.

As is shown in Figure 3, Block 1 needs to be clear before the follower aircraft can enter it. For the air traffic ground controller, this means that Aircraft A needs to be cleared towards T3 and the movement of Aircraft A towards Block 2 will then have to be monitored before Aircraft B is allowed to enter Block 1.

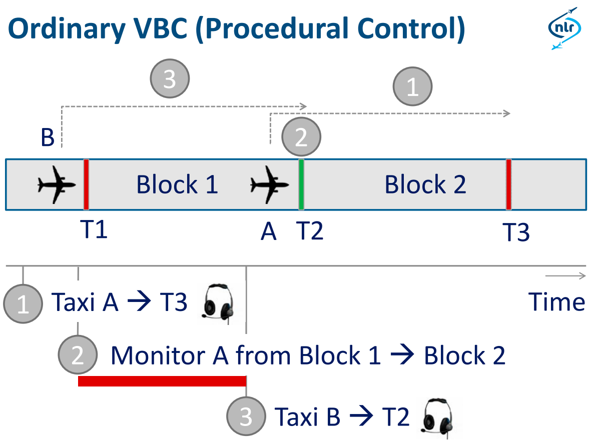

Figure 3. VBC Concept and Controller Tasks

The monitoring task would thus consume a considerable amount of time. While Aircraft A is taxiing from Block 1 towards Block 2, the controller could focus the attention on other tasks, but this would mean that the convoy operation is not continuing steadily. Aircraft B would still be waiting for clearance towards T2 and could not enter Block 1.

The deeper cause of this inefficiency is that the status of a (virtual) stop bar in the VBC concept is universal, i.e. the (virtual) stop bar status is the same for each aircraft. The actual power of a VSB, however, is the fact that its status can be different for different aircraft. This is accomplished with D-VBC. In this concept, a VSB status will be set to the switched-on status for Aircraft B when this aircraft is cleared to the VSB position. The VSB position then represents the clearance limit of Aircraft B. This does not mean that the clearance limit cannot be passed by Aircraft A, though. Aircraft A may have a different clearance limit and the pilots may not even be aware of the status of the VSB for Aircraft B.

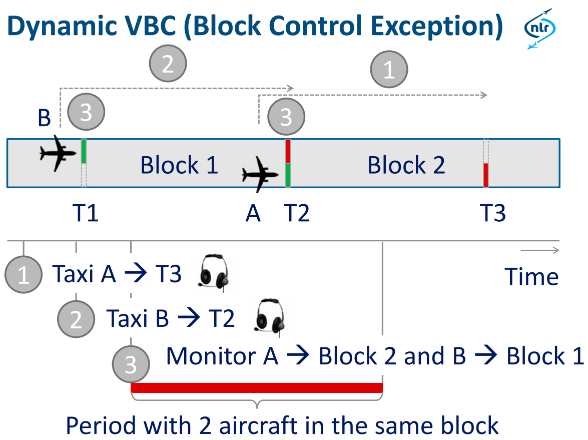

Figure 4. D-VBC Concept and Controller Tasks

In Figure 4 the individual character of a VSB status is shown by splitting the status of a VSB in half for Aircraft A and Aircraft B. For the procedure, this means that Aircraft A is cleared to T3 and Aircraft B is cleared to T2 in sequence. The ground controller will thus not have to wait for Aircraft A to leave Block 1 and, ideally, both aircraft A and B would move simultaneously from one block to the next. One of the consequences of this procedure would be that two aircraft would temporarily move together in one block. This again would reduce the safety aspect of the concept.

When the concept was first introduced to ENAV controllers, though, their expectation was that the temporary movement of two aircraft in one block would not lead to any problems in carrying out their tasks. Aircraft A would always get the clearance to move to the next block before Aircraft B, and although there might be some differences in reacting to the clearance, there would still be enough space between the two aircraft to compensate for these differences. Efficiency was valued more than safety in that case. The concept was successfully validated in a SESAR exercise in 2015 and was thus used again in the current exercise.

The only difference between D-VBC and the so-called Fully Dynamic VBC (FD-VBC) concept in SESAR 2020 was that all operationally relevant positions in the apron areas and on the taxiways were used as VSB positions. This meant that there were VSB positions at all IHP locations with yellow indicator lights in the field that could be used by all aircraft (equipped and unequipped), and there were ten additional VSB positions that were not located at IHP positions (the so-called $\mathrm{VSB}_{\mathrm{NIHP}}$) and that could only be used by adequately equipped aircraft (Figure 18). In that regard, adequately equipped meant being equipped with a data link for communication of the relevant VSB clearance limit and the route towards the clearance limit and a moving map display in the cockpit that would show route and VSB clearance limit on the map (including the status of real stop bars that was also communicated via data link).

Communication Aspects

In order to allow GRACE to be visible in a NARSIM simulation, it was necessary to set-up a Distributed Interactive Simulation (DIS) protocol on the TCP/IP connection between NARSIM and GRACE. Communication about VSB statuses, the cleared part of the route, and stop bar statuses in the outside view (visual) of GRACE was achieved via DIS. Figure 5 shows the different communication channels.

In more detail, the different elements or Protocol Data Units (PDU) being sent via the DIS link between NARSIM and GRACE were a Start/Stop PDU, an Entity/State PDU and a Free Data PDU. The latter was used to transfer a CPDLC message containing uplink message UM308 as part of the D-TAXI service defined in EUROCAE Document ED-228A, ATN Baseline 2 [2]. This message and an additionally defined free text message were used to transfer both taxi clearances and VSB statuses from NARSIM to GRACE. Non-CPDLC data was sent as part of the

Free Data PDU to communicate stop bar statuses on the GRACE visual.

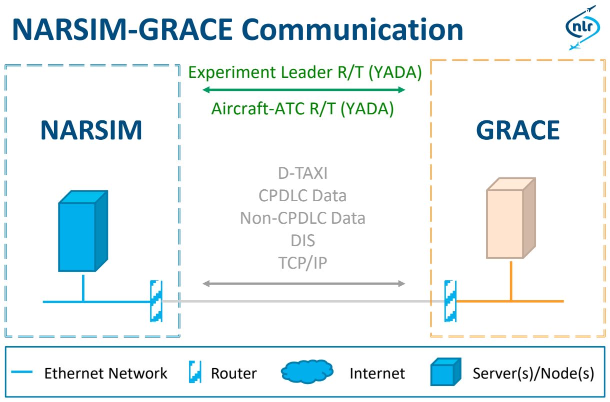

Figure 5. Simulated Communication Channels

The GRACE host computer then distributed information to the flight simulator outside view for presentation of other traffic and stop bar statuses and to the TMX traffic manager that distributes the relevant information to the FMS (taxi route) and the navigation display (other traffic and stop bar statuses). The own-ship position of GRACE was sent by the host computer to NARSIM via DIS and to the FMS internally. The FMS then relayed own-ship position and route information to the navigation display.

Pilot Interface Development

Figure 6 shows the GRACE visual and cockpit displays. GRACE has a number of avionics display suites available which can be further developed with the NLR HMI prototyping environment called VINCENT. Display suites available for GRACE include Boeing, Airbus and Fokker style displays.

For the purposes of this simulation, an Airbus A320 family cockpit environment was set up and adapted to display taxi routes and virtual stop bars on the navigation display. Additional development effort was put into the FMS display in GRACE that was used to receive D-TAXI (CPDLC) messages.

The operational concept of FD-VBC developed together with ENAV air traffic controllers described the use of R/T as the main mode of communication between ground controllers and pilots. Data link was supposed to be used as an addition and in parallel with voice communication. This meant that a full data link communication loop with planned and cleared routes and acknowledgement of the route instruction was not established.

Figure 6. GRACE Visual and Cockpit Displays

Instead, the ground controller would issue a clearance via R/T and, at the same time, choose a taxi route to a VSB clearance limit on the traffic situation display. The chosen route was then instantly sent to the FMS in the cockpit via data link. The pilot would perform a read-back of the clearance via R/T and acknowledge the received CPDLC message (WILCO button in Figure 7). The D-TAXI route instruction was then immediately converted into a displayed taxi route leading to the clearance limit, which could be an existing stop bar, a VSB at an IHP or a VSB without any visual reference outside in the field (VSB_{NIHP}).

Figure 7. GRACE FMS Interface

The example in Figure 7 shows an instruction to taxi towards stop bar position C5 via taxiways M and C on the North Apron of Milan Malpensa (see Figure 16 in the Appendix of this paper). The related taxi route and stop bar symbol (red bar) are shown on the navigation display in Figure 8.

Figure 8. GRACE Navigation Display with Taxi Route towards a Stop Bar Position

While stop bars on taxiways are not very common, in Milan-Malpensa they are predominantly used on the West Apron to separate traffic streams that will be merged towards TWY H (see Figure 18 in the Appendix of this paper). On the North Apron such a stop bar position does not exist at this moment. For the sake of the concept and to be able to compare operations on both aprons, C5 was chosen as an extra stop bar position, thereby separating inbound and outbound traffic streams. Further along TWY C, which leads directly towards the departure RWY 35R, each IHP had a VSB position attached on the controller display. Additionally, three VSB_{NIHP} were defined to be able to create more control blocks for equipped aircraft. The display of each of these VSB positions on the navigation display in the cockpit will be shown in the following.

In Figure 9, the ground controller of the North Apron cleared the GRACE aircraft from the stop bar position C5 to the VSB position at IHP C4. It should be noted that the preceding aircraft (BCS820) was moving in the same control block for a short while, i.e. until C4 was passed by the aircraft which was already cleared to a position beyond C4. As the VSB status will be different for the GRACE aircraft (switched-on status) and the preceding aircraft (switched-off status), there will be no violation alert on the controller position when the preceding aircraft passes C4.

Figure 9. GRACE FMS and Navigation Display with Taxi Route towards a VSB Position

Yellow indicator lights at the C4 holding position and yellow markings on TWY C showed the GRACE pilot where to stop the aircraft. Usually, controller instructions with FD-VBC will be given such that the aircraft will already be cleared to the next position before the pilot will have to stop, though. It should be noted that the VSB at C4 is displayed as a dashed line with two gaps, indicating to the pilot that it is located at an IHP and yellow indicator lights and markings in the field can be looked for as visual reference points.

In Figure 10, the ground controller of the North Apron, who is also responsible for the largest part of TWY C, cleared the GRACE aircraft to VSB_{NIHP} position CV2. At a VSB_{NIHP} position, there are no indicator lights for reference outside in the field (i.e. on the GRACE visual) and the pilots would need to rely on the navigation display for stopping the aircraft at the indicated position. It should be noted that the VSB at CV2 is displayed as a dashed line with four gaps, indicating to the pilot that this is a VSB_{NIHP} without visual reference outside.

Figure 10. GRACE Navigation Display with Taxi Route towards a VSB_{NIHP} Position

In the very first prototype navigation display all VSB positions were indicated with a red bar. Feedback from pilots quickly showed that expectations on what to look for when stopping the aircraft needed to be managed to maintain Situational Awareness of the cockpit crew. Thus, the two different VSB symbols were introduced.

Air Traffic Controller Interface

With respect to earlier SESAR validation exercises that focused on the D-VBC concept, the interface for the ground controller did not change much [12]. The biggest difference was the fact that a larger touch screen monitor was used to display the traffic situation display (TSD) with SMR/MLAT information together with an integrated terminal area radar (TAR) picture, as is shown in Figure 11. Recommendations of the previous validation exercise pointed at difficulties for the Apron West ground controller in handling larger amounts of traffic (40 movements per hour). This was mainly due to overlapping labels between aircraft and an overlap between labels and the switches used for selecting a VSB position as clearance limit. Accordingly, strategies to improve the interface were tested. The most promising strategy was to put labels on a standard position when entering specific apron areas. The change was only implemented later in May 2018, when a Milan-Malpensa tower crew was available.

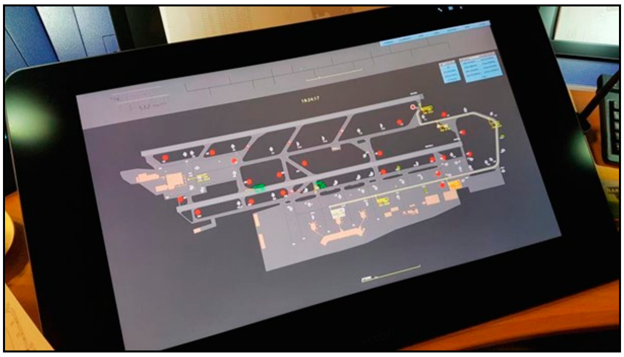

Figure 11. NARSIM Ground Controller Traffic Situation Display with Touch Input

Figure 12 shows a number of typical HMI elements on the ground controller TSD. No Entry Stop Bars were represented by a red bar (e.g. D) and could not be switched. All other stop bars were represented by a full circle (e.g. DE) and were always switched on. They could be switched off and were automatically switched on again after a time-out of 45 seconds or when an aircraft had passed the stop bar position. That was true for both the stop bars related with the runway operation and the stop bars on taxiways and in apron areas.

VSBs located at IHPs were shown with a so-called light bulb symbol (e.g. C3 and C4), i.e. two semicircles with different sizes, where the smaller circle indicated the direction in which the VSB was to be used operationally (aircraft were meant to taxi towards the smaller circle). As was the case in all previous simulation exercises, a VSB at an IHP could be assigned as holding position to all aircraft, equipped or unequipped.

VSBs not located at IHPs (VSB_{NIHP}) were represented by a single semicircle (e.g. CV2, CV3) which corresponded to the light bulb symbol without the smaller semicircle. It should be noted, that this representation was different from the one used in the previous SESAR exercise where there was no difference in the symbol [12]. The VSB_{NIHP} could only be used as clearance limit for equipped aircraft. Equipage was indicated in the label of an aircraft by a yellow frame around the callsign (as shown in Figure 12). The system did not allow the use of these positions with unequipped aircraft.

Track symbols in the TSD indicated the control state of an aircraft and labels could be selected for more information. Clearance limits were specifically indicated by a white outline around the respective symbol and were highlighted in the label.

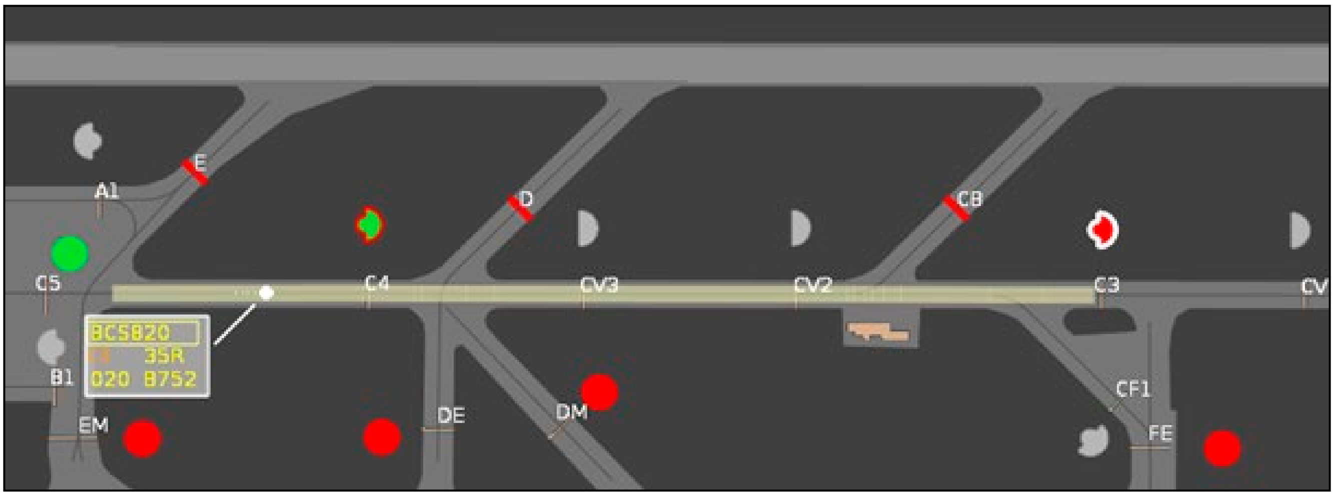

Figure 12. Ground Controller HMI with Typical Elements

When clearing an aircraft to a stop bar or VSB, the previous clearance limit in the label disappeared and was replaced by the new clearance limit. The previously switched-on (red) VSB was switched off automatically and the VSB at the new clearance limit was switched on and highlighted. This was denoted as clearance automation [13].

Both routing and alerting worked in very much the same way as in the previous SESAR exercise [12]. A set of route options to reach the clearance limit was provided by the system. These route options were obtained from a set of operational rules taking standard routing and efficiency into account. The route options were presented in a pop-up menu when right-clicking a VSB (for a selected aircraft under control). The route options were presented in a textual string which was very similar to the R/T instruction given by the controller.

When a controller had entered a clearance that was accompanied by a route option, the system monitored for route deviations (label background turned semi-transparent red and a triple chime audio signal was played). Other safety nets included in the prototype were stop bar and VSB violation detection, which gave the same kind of alerts as the route deviation, and the so-called Watch Dog functionality. The Watch Dog was a tool that alerted the controller in case an aircraft that was supposed to hold its position started to move again unexpectedly. Thus, the tool performed a monitoring activity that was usually performed by the controller, e.g. when a stop bar violation occurred. The Watch Dog was activated with a left-click on the track symbol.

Simulation Conduct

Different types of scenarios were developed for Milan-Malpensa Airport (LIMC). The baseline or reference scenario, from a ground controller view, considered the following assumptions:

- Current-day operations at LIMC for low visibility conditions were simulated
- The FD-VBC concept was not in use, so there were no Virtual Stop Bars (VSB)
- Tower Controllers used paper strips
- Only R/T was used for communication

Additionally, from a flight crew perspective, the baseline also considered that:

- All aircraft were unequipped, i.e. the advanced functionality was not used

This meant that the reference scenario had the same conditions for both controllers and flight crew. For the solution scenarios the situation was a bit different. A mixed equipage environment (aiming at a 2025 situation, i.e. 70% equipped) was considered. Thus, there were two kinds of solution scenarios for the flight crew: one in which the aircraft was unequipped and could only use VSB positions related to IHPs, and one in which the aircraft was equipped with data link and the possibility to present routes and VSBs on the navigation display.

In summary, the advanced solution scenarios considered the following assumptions:

- Use of the FD-VBC concept
- Taxi route information and stop bar and VSB statuses were transmitted via data link
- Advanced labelling was used to avoid label cluttering in the busy West Apron area
- Equipped and non-equipped aircraft

In all scenarios the weather conditions were set to visibility condition 3 (VIS-3) with a selected RVR of 300m approximately [6]. Furthermore, in all scenarios R/T was used as the main communication means between ATC and the flight crew. Data link usage in the solution scenarios was considered to be a means of additional support on top of the basic R/T.

The following independent experiment variables were defined:

- Aircraft equipment level (equipped vs. non-equipped)
- Traffic direction (taxi-in vs. taxi-out)
- Apron involved (North vs. West)

The last two characteristics were varied and led to the following four scenario variants:

- Taxi Out North Apron to RWY35R
- Taxi Out West Apron to RWY 35R
- Taxi In RWY 35L to North Apron
- Taxi In RWY 35L to West Apron

The detailed scenarios describing the taxi-in and taxi-out routes taken by the GRACE flight simulator can be found in Appendix II. Each flight crew performed 7 scenarios, consisting of one baseline scenario, two (advanced) scenarios with a non-equipped aircraft and four (advanced) scenarios with an equipped aircraft.

The following dependent experiment variables were measured or assessed to obtain feedback relevant for the development process of concept and technology in preparation of a larger exercise with an ENAV tower crew:

- Flight crew mental workload
- Flight crew operational acceptability
- Flight crew Situational Awareness
- Flight crew Cockpit Resource Management
- Cockpit Human Factors aspects
- Taxi times (NARSIM and GRACE)
- Ground controller questionnaires gathering qualitative feedback for improvement of concept and HMI (SHAPE, SUS)

Generally, there were thus three different means to obtain the data: questionnaires, including debriefings and interviews, simulator-generated data and video recordings in the cockpit. Results for the ground controller were mainly used to receive feedback on the concept from a controller who was not involved in the concept and HMI development processes.

Figure 13. GRACE Video Data Capturing

Validation Results and Conclusions

As the focus of the validation activity was an assessment of cockpit HMI and procedures, the results will describe the feedback obtained from the two flight crews. The results for the ground controller position were of a qualitative nature, since only one ground controller managed low traffic scenarios. This ground controller was a very experienced controller, but had never worked at Milan-Malpensa tower before.

After each run, the flight crew participants filled in a questionnaire in which ratings were requested for Situational Awareness (SA), Safety, Workload and Traffic Awareness. The results are shown in Table 1.

The difference in ratings between the Baseline and the Advanced Equipped situations was significant with respect to SA, Workload and Traffic Awareness. The difference between Baseline and Advanced Non-Equipped situations was relatively small, as in both situations no taxi display was available in the cockpit.

The main questionnaire comments can be summarized as follows:

Situational Awareness

- A taxi map display improves the SA in low visibility conditions, especially if the flight crew is not familiar with airport.
- Distance units on the taxi display should be in meters (or feet) instead of NM.

Safety

- Generally, when own-ship position is known, taxi speed is low, and ATC instructions are clear, the operation is considered safe.

- If multiple CPDLC clearances are given (either by the controller making a mistake or revising the clearance) the flight crew might be distracted too much. There is a risk of too much head-down time by the Pilot Not Flying (PNF), while an important part of the PNF role is to monitor the Pilot Flying (PF).

Workload

- In general, low visibility conditions are always more demanding.
- Cross-checking the current position with outside cues is easier on the taxi display than on a paper airport map.
- Additional processing of CPDLC clearance messages on the FMS (along with processing of R/T clearance and monitoring PF) increases workload for the PNF.

Traffic Awareness

- Other traffic was visible on the taxi display. This significantly improved the traffic awareness of the flight crew.
- The callsign label that was attached to other traffic was very helpful.
- Improved traffic awareness helps the flight crew understand ATC clearances.

General comments

- Pilots expected that the clearance limit symbology on the taxi map display would match the visual cues outside.
- Collocation of a VSB (red symbol on display) with an IHP (yellow lighting outside) was confusing.
- A VSB was considered a clearance limit, not a stop bar.
- Stopping at locations without visual cue felt very strange.
- Pilots expected to only see one clearance limit at a time on the taxi map display (N.B.: this was caused by the statuses of existing stop bars (e.g. C5 on the North Apron) which were always visible on the taxi map display).
- Further comments regarding HMI improvements were given and summarized.

Ratings	Baseline	Advanced Non-Equipped	Advanced Equipped
Situational Awareness	Rather low	Rather low	High
Safety	Rather high	Rather high	High
Workload	High	Rather high	Rather low
Traffic Awareness	Low	Rather low	High

Table 1. Flight Crew Questionnaire Results

System Usability

Average values for System Usability that were assessed in the equipped situation were always rated rather high. The values were obtained from the so-called System Usability Scale (SUS or Brooke's Scale) that is widely known as a reliable tool for giving a first impression of the usability of a system. In this case, the system was considered to be the combination of the FMS CPDLC message display and the taxi map on the navigation display. The scale of an SUS ranges from 1 (strongly disagree) to 5 (strongly agree) per question item. The scores for individual items, however, are not meaningful on their own. SUS yields a single number representing a composite measure of the overall usability of the system being studied. This number ranges between 0 (not usable) and 100 (very usable).

The overall average SUS score that was obtained from the evaluation of the equipped runs with two flight crews was 80. While this result is certainly positive and valuable, the strength of an SUS usually lies in comparing different systems, which is not possible when the baseline is carried out without a comparable system. This means that operational considerations should corroborate the SUS result to make it more meaningful. This is achieved when looking at the result in Table 1

Automation Trust

Results of the SHAPE Automation Trust Index (SATI) also show a very positive result. The average value obtained was 4.7 on a scale that ranges from 0 to 6 and combines a few general questions concerning usefulness, reliability, accuracy, understandability, robustness and confidence when working with the automated system.

Simulation Data

The data obtained from the simulation regarding the number of stops, the taxi time and related fuel burn can be found in Appendix III.

While it is hard to make any comparison between the different movements due to the different taxiing conditions, what is still interesting is a comparison between the baseline and the equipped movement from the West Apron. In both cases, flights started from stand 405 but had very different taxi-out times that were apart by about five minutes for the first crew and about three minutes for the second crew. Although this result could have been achieved by chance, mostly the conditions for taxiing out from Apron West were the same, as the controller tried to build up a convoy operation towards the departure runway. Furthermore, the traffic samples used were the same. This result was thus taken as an indicator of a possibly significant improvement for movements from the West Apron, which, due to the complex structure of that part of the movement area was also expected.

Only when simulations were eventually carried out with a larger amount of traffic and a Milan-Malpensa tower crew from ENAV on the NARSIM-Tower platform in Amsterdam in May 2018, such a comparison could be made on the basis of longer simulation runs (1 hour) and an increased number of flights (40 movements/hour).

In these simulations, taxi-out predictability clearly increased when the FD-VBC concept was used as the variance of the taxi-out times in all apron and taxiway areas was reduced. The result, as expected, was more obvious for the West Apron and TWY H that benefited from a more structured guidance approach and that provided room for additional equipped flights being cleared to VSB_{NIHP} (Figure 14). There was also a reduction of taxi-out times on TWY C. For the North Apron, no such result could be found due to its small size, low complexity and only a few additional VSBs available. But even on the North Apron the variance slightly decreased.

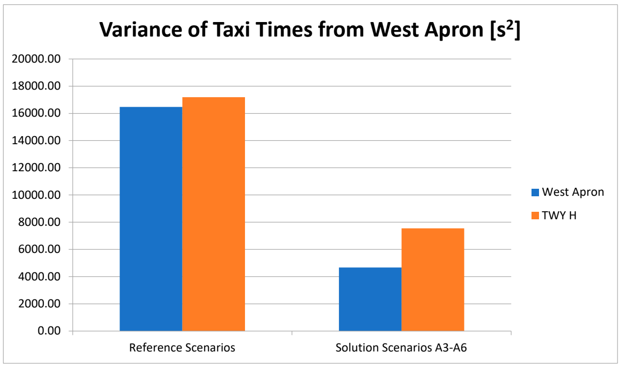

Figure 14: Predictability Result of Full-scale Simulation in May 2018

Taxi-out times were also looked at in the full-scale simulations in May 2018 for the analysis of fuel burn and CO_2 emissions.

It could be shown that the scenarios with use of FD-VBC led to much better results in terms of taxi-out efficiency and fuel burn on the very complex West Apron. On the North Apron the advantage was small to non-existent, as could be expected given the previously mentioned considerations of size and simplicity of that area. Further, traffic on TWY C showed an improvement in taxi times between 6% and 14%. Benefits in the reduction of burnt fuel led to the same percentage as all aircraft departing on the North Apron were of the same type. On the West Apron, taxi-out times were reduced significantly, and values ranged between 9% and 25%. On TWY H they ranged between 20% and 27%. Burnt fuel benefits were higher as larger aircraft contributed more to the reduced taxi-times. Fuel burn per aircraft on the West Apron was reduced by more than 28kg (39%) and on TWY H by more than 66kg (47%). On the North Apron no reduction was achieved.

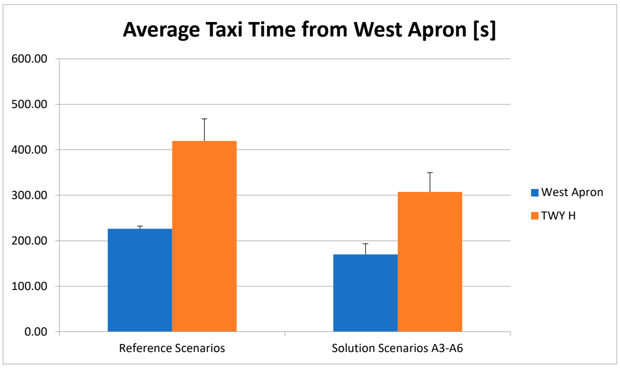

Figure 15: Taxi-out Time Result of Full-scale Simulation in May 2018

Capacity, or rather ground movement throughput was also assessed during the simulations in 2018 and led to a better value for FD-VBC. Up to two aircraft more (per 3000s of simulation) could be handled with FD-VBC (21 movements on average), while inbound traffic was kept at the same level (15 movements).

Conclusions

The following conclusions are drawn based on the feedback and simulator-generated data of the preliminary validation exercise with GRACE and NARSIM carried out in December 2017. A few performance results of a follow-up exercise in May 2018 are added to quantify additionally expected benefits:

- Taxi operations with the FD-VBC concept under low visibility conditions were considered feasible and safe to perform from a flight crew point of view.
- A flight deck equipped with a taxi map display improves flight crew Situational Awareness and Workload.
- Traffic Awareness is increased if other traffic is displayed on the taxi map display (achieved via ADS-B IN/ATSA-SURF)
- System Usability and Automation Trust received high ratings, with the SUS reaching a value of 80 out of 100 and the SATI score reaching a value of 4.7 out of 6.
- Simulation data indicated reduced taxi times and fuel burn for FD-VBC when taxiing out from the West Apron towards RWY 35R.
- A related full-scale simulation activity with a Milan-Malpensa tower crew from ENAV and mainly pseudo-piloted aircraft confirmed the expected results in terms of reduced taxi times, fuel burn and CO_2 emissions. These simulations also showed improvements in taxi-out time predictability (reduced variance) and increased ground movement throughput.
- Ground controller feedback was of a qualitative nature and addressed improvements in procedures and HMI. Furthermore, questionnaire strategies for the full-scale simulation with ENAV controllers could be determined.

Recommendations and Future Activities

In summary, the following recommendations were a result of this preliminary part-task activity. They led to improvements when carrying out the full-scale simulations with an ENAV controller team and a larger number of pseudo-piloted aircraft.

- Taxi clearance limit symbology for the pilots should match the visual reference on the airfield. Furthermore, different symbology should be used for the different types of stop positions to prepare pilots for what to look for outside the cockpit window.
- In case the aircraft is required to stop at a specific location without visual cues on the airfield, guidance in the cockpit HMI should be provided on where exactly the aircraft must stop. In this context it should be noted that a taxi map display should be used for navigation purposes only. It should not be used for guidance purposes. In general, guidance related information is

provided on the Primary Flight Display (PFD).

- Only one (red) taxi clearance limit/stop bar status should be presented at a time. Concurrent presentation of a taxi clearance limit (red) and the status of a (physical) stop bar (red) may be confusing for the flight crew, and is not advised.
- Required head-down time to accept a taxi clearance via a data link should be kept to a minimum. Accepting (or rejecting) a clearance should only require one HMI interaction (key stroke). It was further suggested to present an incoming taxi route clearance via data link directly on the taxi map as a dashed line without requiring HMI interaction by the flight crew. The route should become a solid line on the taxi display after acceptance by the flight crew.
- According to the pilots, providing a taxi clearance via R/T and data link could be confusing, and may generate additional workload for cross-checking. It was suggested to use data link for taxi clearances and R/T as a back-up. However, it was realized that this could lead to a decrease in SA as data link messages only reach the concerned aircraft and not everyone on the frequency. This was confirmed by the controller. He warned that data link should only be used to complement R/T, not replace it. Even if all the aircraft were equipped, the SA of where other aircraft were cleared to would be lost.
- Regarding the performance questionnaires, it was suggested to use the full set of SHAPE questionnaires for the controller. Regarding system usability, the SUS questionnaire was considered appropriate.
- In order to better assess performance-related indicators, more detailed operational questionnaires for controllers needed to be made. Specific aspects of the HMI and the consequences for human performance had to be considered.
- It had to be ensured that controllers were trained well enough regarding both the FD-VBC concept as well as the use of the HMI.
- Several recommendations regarding the controller interface were made. Labels that overlap each other or the stop bar and VSB switches should be prevented at all times. Also the final clearance to the gate should be made possible for all stands and gates. Concerning the routing interface it was suggested to have a possibility to preview the route when still hovering over the selection button. Finally, selecting labels should be made easier.

In conclusion, all recommendations from the preliminary simulation exercise with GRACE and NARSIM were considered in the preparation of the already addressed full-scale simulations with a Milan-Malpensa tower crew and more pseudo-piloted traffic. The simulations that were eventually carried out on the NARSIM-Tower platform in Amsterdam in May 2018 also allowed for connection of a flight simulator from Italian aerospace company Leonardo (GRA) with a taxi map display prototype of Thales Avionics. The experience that was gained by connecting GRACE with NARSIM was of indispensable value for the connection that had to be established between the ATC simulator in Amsterdam and the flight simulator in Turin.

Recommendations from both exercises which were carried out as EXE-050 of PJ03A of the SESAR 2020 Programme will give input to a high maturity exercise of Virtual Block Control (Validation Phase V3, as described in the E-OCVM [3]) that will be carried out in the upcoming second phase of the programme. This activity must be designed in such a way that the concept will be transferred towards system specification and deployment phases. Therefore, it will be of importance that recommendations regarding the detailed pilot and controller procedures as well as relevant HMI improvements are considered.

It is expected that the follow-up activity will eventually pave the way for implementation of FD-VBC as an operational concept for low visibility conditions at European airports in the not too distant future.

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Appendix I

Low Visibility Procedures Chart for Milan-Malpensa Airport (LIMC)

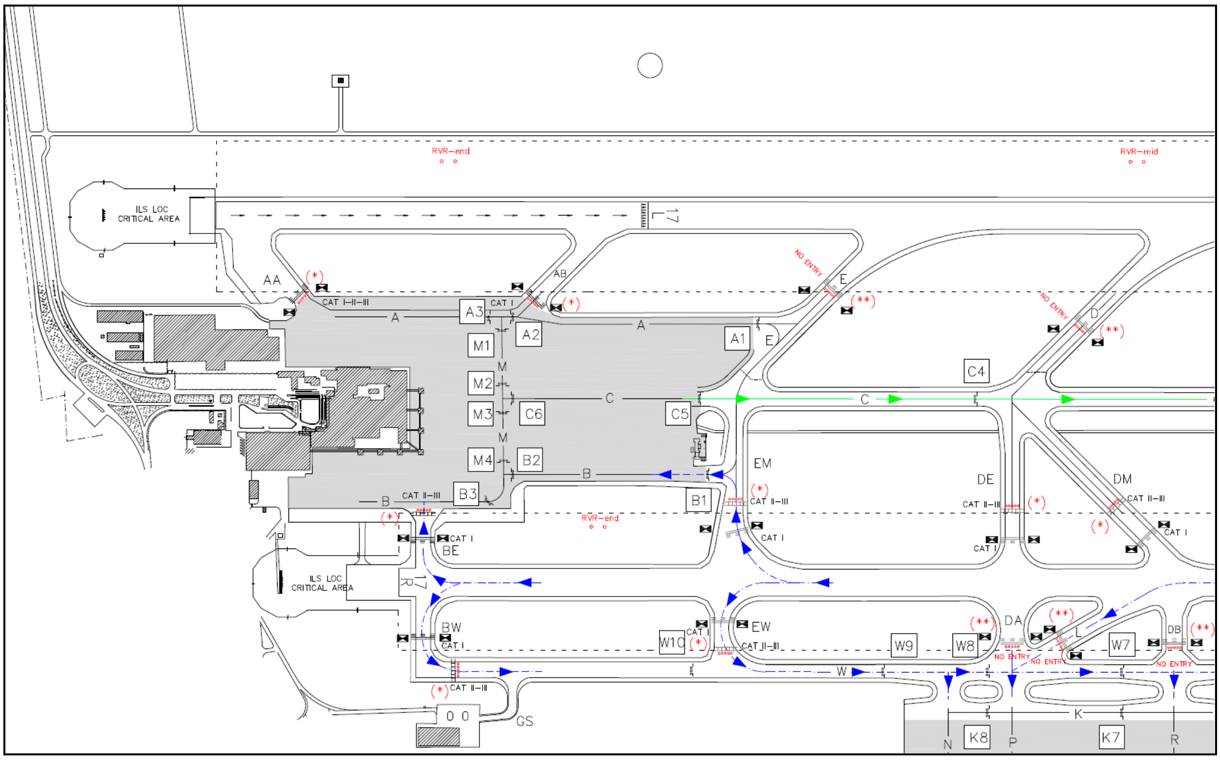

Figure 16. AIP Detail with Apron North - September 2016 (Source: AIP Italy [1])

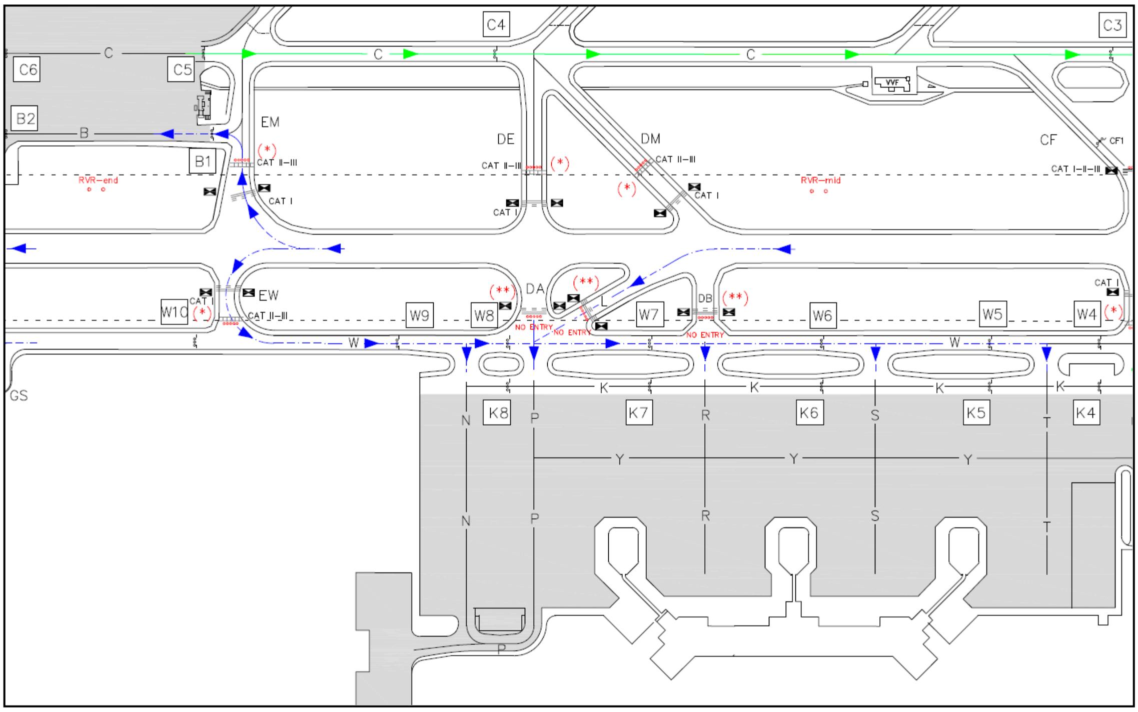

Figure 17. AIP Detail with Apron West - September 2016 (Source: AIP Italy [1])

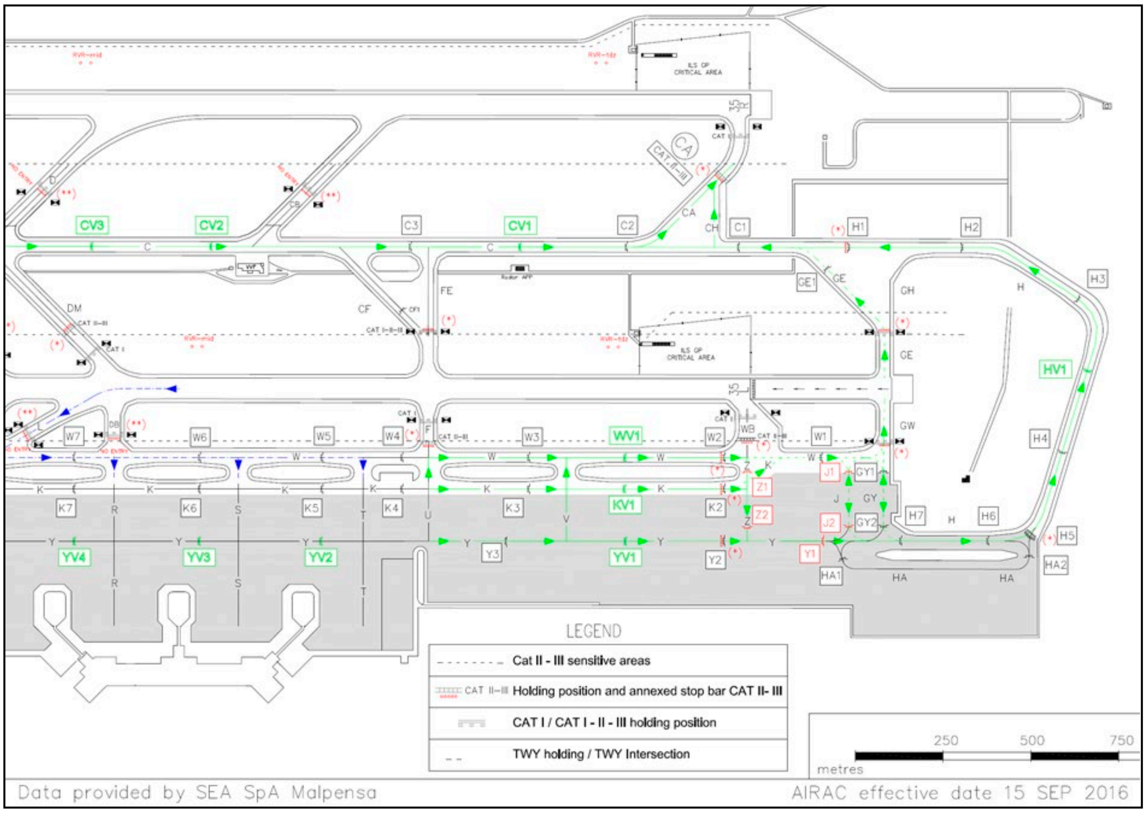

Figure 18. AIP Detail with all VSB_{NIHP} Positions in Green - September 2016 (Source: AIP Italy [1])

Appendix II

Detailed Scenarios for GRACE Taxi-In and Taxi-Out Movements

Taxi Out North Apron TONA35R		**Positions**	**Type**
Taxi route origin	T2 North Apron stand 113		
Taxi route	B	B3	VSB-IHP
	M	M3	VSB-IHP
	C	C5	STOPBAR
		C4	VSB-IHP
		CV3	VSB-NIHP
		CV2	VSB-NIHP
		C3	VSB-IHP
		CV1	VSB-NIHP
		C2	STOPBAR
	CA	CA	STOPBAR
Taxi destination	RWY 35R		

Taxi Out West Apron TOWA35R		**Positions**	**Type**
Taxi route origin	T1 West Apron stand 405		
Taxi route	Y	YV4	VSB-NIHP
		YV3	VBS-NIHP
		YV2	VSB-NIHP
	via R, S, T, of U to		
	W	W6	VSB-IHP
		W5	VSB-IHP
		W4	VSB-IHP
		W3	VSB-IHP
		WV1	VSB-NIHP
		W2	STOPBAR
	Z	Z1	VSB-IHP

Taxi Out West Apron TOWA35R		Positions	Type
		Z2	VSB-IHP
	Y	Y1	VSB-IHP
	H	H7	VSB-IHP
		H6	VSB-IHP
		H5	STOPBAR
		H4	VSB-IHP
		HV1	VSB-NIHP
		H3	VSB-IHP
		H2	VSB-IHP
		H1	STOPBAR
	C	C1	VSB-IHP
	CH	CA	STOPBAR
Taxi destination	RWY 35R		

Taxi In North Apron TINA35L		Positions	Type
Taxi route origin	RWY 35L		
Taxi route	EM		
	B	B1	VSB-IHP
		B2	VSB-IHP
	M	M3	VSB-IHP
		M1	VSB-IHP
	A	A3	VSB-IHP
Taxi destination	T2 North Apron stand 104		

Taxi In West Apron TIWA35L		Positions	Type
Taxi route origin	RWY 35L		
Taxi route	EW		
	W	W9	VSB-IHP

Taxi In West Apron TIWA35L		Positions	Type
		W8	STOPBAR
		W7	VSB-IHP
		W6	VSB-IHP
		W5	VSB-IHP
	T		
	Y	Y3	VSB-IHP
Taxi destination	T1 West Apron stand 712		

Appendix III

Aircraft Simulation Data

Run	Type	Apron	Stops									Taxi Time [mm:ss]	Fuel Burn [kg]
			#1	#2	#3	#4	#5	#6	#7	#8	#9		
Day 1													
102	B	W	Y3	Y2	H7	H5	H4	H2	H1	C1	CA	22:00	279
109	AE	N	M3	C5	CV3	C3	CV1	C2	CA			16:32	188
110	AE	W	YV2	YV1	Y2	H7	H5	H2	H1	CA		17:09	199
111	AE	N	A1	A2	Stand							8:41	111
112	AE	W	EW	W9	W8	W6	W5	Y3	Stand			11:19	134
107	AN	N	A2	Stand								6:43	89
108	AN	W	W8	W5	W3	Stand						7:19	90
Day 2													
102	B	W	H7	H1	CA							13:01	146
109	AE	N	C2	CA								9:17	103
110	AE	W	Y2	HV1	H2	H1	CA					9:59	112
111	AE	N	B2	Stand								5:32	60
112	AE	W	W3	Stand								8:53	106
107	AN	N	EM	B2	Stand							6:32	70
108	AN	W	EW	W9	W3	Stand						7:54	91

Blue: Outbound
Yellow: Inbound

Abbreviation List

ADS-B	Automatic Dependent Surveillance Broadcast
AGL	Airfield Ground Lighting
AIP	Aeronautical Information Publication
AOF	Airport Operation Function (Thales Avionics)
A-SMGCS	Advanced Surface Movement Guidance and Control System
ATC	Air Traffic Control
ATM	Air Traffic Management
ATN	Aeronautical Telecommunications Network
ATSA-SURF	Air Traffic Situational Awareness on Airport Surface
CPDLC	Controller-Pilot Data Link Communications
DIS	Distributed Interactive Simulation
D-TAXI	Data Link Taxi Clearance Service
D-VBC	Dynamic Virtual Block Control
EMMA	European Airport Movement Management by A-SMGCS
ENAV	The Italian Company for Air Navigation Services
E-OCVM	European Operational Concept Validation Methodology
EUROCAE	European Organisation for Civil Aviation Equipment
FD-VBC	Fully Dynamic Virtual Block Control
FMS	Flight Management System
GRA	General Regional Aircraft (Leonardo)
GRACE	Generic Research Aircraft Cockpit Environment (NLR)
HMI	Human-Machine Interface
ICAO	International Civil Aviation Organization
IHP	Intermediate Holding Position
LIMC	Milan-Malpensa Airport (ICAO Code)
MLAT	Multilateration
NARSIM	NLR ATC Research Simulator
NIHP	No Intermediate Holding Position
NLR	Netherlands Aerospace Centre
NM	Nautical Miles
PDU	Protocol Data Unit
PF	Pilot Flying
PFD	Primary Flight Display
PNF	Pilot Not Flying
R/T	Radio Telephony
RVR	Runway Visual Range
RWY	Runway
SA	Situational Awareness
SATI	SHAPE Automation Trust Index
SESAR	Single European Sky ATM Research
SHAPE	Solutions for Human Automation Partnership in European ATM
SJU	SESAR Joint Undertaking
SMR	Surface Movement Radar
SUS	System Usability Scale
TAR	Terminal Area Radar
TCP/IP	Transmission Control Protocol/ Internet Protocol
TMX	Traffic Manager (NLR/NASA)
TSD	Traffic Situation Display
TWY	Taxiway
VBC	Virtual Block Control
VSB	Virtual Stop Bar

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