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Design and Evaluation of a Visual Interface for an Approach Control Merging Task

Eline S. Bakker* and Ferdinand Dijkstra†
Air Traffic Control the Netherlands (LVNL), 1117 CV Amsterdam, The Netherlands
and
Clark Borst,‡ Marinus M. (René) van Paassen,§ and Max Mulder¶
Delft University of Technology, 2629 HS Delft, The Netherlands

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Air traffic growth leads to increasingly complex traffic situations near large airports. To support air traffic controllers in maintaining safety and improving efficiency, new support tools are needed. This paper presents the Inbound Traffic Support System (ITSS), a visual interface prototype developed in collaboration with the Netherlands' Air Navigation Service Provider, LVNL. The interface visualizes constraints associated with the merging task and was tested for the South Sector of Amsterdam Airport Schiphol. By portraying potential merging solutions, it helps area controllers anticipate the impact of their decisions and supports their role in managing inbound traffic. Professional controllers provided positive feedback during the development phase while also identifying concerns such as display clutter that should be addressed. An experiment with semiprofessional controllers assessed the impact of the interface on operator performance and workload. Participants were instructed to rely on the interface rather than operational experience to ensure consistent results. Findings showed that the interface improved aircraft adherence to altitude restrictions and reduced the number of clearances needed in more complex scenarios. By revealing the solution space, the ITSS encourages earlier planning and reduces the need for late-stage interventions. Future work will include professional controller evaluations, increased simulation fidelity, and extended training.

I. Introduction

CURRENT-DAY air traffic management (ATM) involves an area controller at the Area Control Center (ACC) who is responsible for the safe and efficient coordination of all flights within the control area (CTA). Maintaining adequate separation between aircraft to ensure safety is a primary requirement of the ACC Air Traffic Controller (ATCo). International Civil Aviation Organization (ICAO) regulations specify that all aircraft must either have vertical separation by more than 1000 ft or have a minimum horizontal separation of 5.0 NM [1]. Furthermore, an area controller must organize and expedite the traffic. This entails handling descending, climbing, and crossing aircraft around similar flight levels, organizing inbound and outbound traffic flows, and giving route clearances to aircraft entering the surrounding sectors.

Inbound traffic must be merged toward an initial approach fix (IAF). This position fix marks the transition from the en-route phase to the beginning of the initial approach phase, where an approach controller takes over from an area controller. Aircraft must pass the IAF at an instructed height (FL) and speed (IAS). Handling traffic at varying heights can be difficult. While speed clearances are given in indicated airspeed (IAS), the ground speed (GS) equivalent must consider aircraft altitude and wind conditions. Aircraft flying at a higher altitude are faster relative to the ground, and wind conditions affect possible solution strategies. The ATCo must estimate whether crossing and merging maneuvers are feasible, check if the situation will evolve as was initially anticipated, and ensure altitude adherence at IAF so that aircraft will cross the IAF within specified altitude bounds.

The demanding task of an area controller is expected to become more difficult in the future as air traffic increases [2]. Growth during the past 10 years has already led to increasingly complex situations involving more aircraft simultaneously requiring the same airspace. At Air Traffic Control the Netherlands (LVNL), ATCos report an increasing workload. Most recorded events of increased workload were a result of aircraft unable to reach the instructed height at the IAF in time [3]. Within the small and busy Amsterdam South sector, to mitigate the high frequency of inbound traffic, the control task is shared by two controllers: one to handle the inbound traffic and one to deal with all other traffic [3]. Even though no increase in serious incidents has been observed, the number of irregularities within the Electronic Guard Report has been increasing, especially within the South sector.

It is foreseen that new forms of automation and human–machine systems are needed to assist controllers in their current tasks and to facilitate further anticipated growth. In a distant future, this may take the form of area control support systems that make use of four-dimensional (4D) trajectories [4–6]. However, it will take considerable time before controllers can rely on such 4D systems. The same argument holds for fully automated solutions presented in various research projects [7–9]. Meanwhile, automation systems that match the *current* work domain practices are needed. These systems ideally support the present tasks of an area controller and bridge the gap between current-day and future 4D operations. Previous research to assist controllers in similar tasks investigated new concepts, such as point merge [10–12], and, at LVNL, the Speed and Route Advisor was built and tested [13]. Several ATCo interfaces were designed and tested that introduced novel tools such as the User Request Evaluation Tool [14], the Relative Position Indicator [15], ghosting tools [16,17], and others [18,19].

To gain operational acceptance of the designed automation, it is pivotal to include the controller's needs and work preferences. Research has shown that the level of acceptance of new support tools is driven by the extent to which the support system complies with the capabilities and strategies of the user [20–22]. Furthermore, ATCos (and humans in general) are more likely to accept automatic systems if they remain cognitively engaged in the task [21–25].

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*M.Sc., TU Delft; elinesbakker@gmail.com.
†ATC System Development; ferdinand.dijkstra@lvnl.nl.
‡Associate Professor; c.borst@tudelft.nl.
§Associate Professor; m.m.vanpaassen@tudelft.nl.
¶Professor; m.mulder@tudelft.nl. Associate Fellow AIAA.

With this in mind, an interface that supports parts of the decision-making process of an area controller was developed. The research focused on supporting the task of merging aircraft in a safe and efficient manner, aiming for higher altitude adherence. Although it is not the only task of an ATCo, merging coordination is essential and a major cause for workload. The small size of the Amsterdam South sector means that controllers must act quickly on aircraft entering the sector to achieve altitude adherence at the IAF. If this process can be better supported, another main cause for workload will be mitigated.

The purpose of this research is to obtain insight into the challenges of a merging task for an area controller within the congested, high-traffic Amsterdam South sector. These insights can then be used to design (and improve upon) automation and interfaces that support ground controllers in maintaining safety and improving performance. The leitmotif in the interface presented is to ensure that the impact of a controller's own decisions can be foreseen, allowing that controller to probe possible solutions without activating them and to quickly resolve multiple aircraft merging problems. These "solution space"-based interfaces for aircraft merging problems have been developed and tested previously in lower-fidelity setups [26–28]. Inspired by earlier designs for inbound traffic interfaces [29,30], the current interface tackles a real operational problem. It was developed in close collaboration with the LVNL to ensure that the novel tools match current air traffic control (ATC) operation and also to obtain feedback from professional area controllers.

This paper presents the proposed interface (and underlying algorithms) and the two ways in which it was evaluated. It is structured as follows. Section II provides some essential background information on the Amsterdam South sector. The interface concept is explained in detail in Sec. III, followed by a brief summary of expert evaluation from two professional area controllers in Sec. IV. The setup of the human-in-the-loop experiment, involving eight subject-matter experts, is given in Sec. V. Results are presented and discussed in Sec. VI. Section VII reflects on the research as a whole and contains recommendations for future work. The paper ends with conclusions in Sec. VIII.

II. Background

The Amsterdam South sector is one of the busiest CTAs in Europe. It spans the area between the border of Belgium and the Terminal Control Area (TMA) of Amsterdam Schiphol Airport and has an adjacent military airspace. Its size is approximately 90 NM (long) by 50 NM (lat). The area controller is responsible for all traffic within this area between FL 55 and FL 245. This section first explains why the sector is regarded as difficult by ATC experts and then describes how merging tasks are currently handled.

A. Complexities in the Amsterdam South Sector

The Amsterdam South sector is considered to be more difficult than other CTAs in the Netherlands. First and foremost, the sector is small: there is very limited space to efficiently sequence flights. Decisions must be made quickly, and there is limited space to correct for decisions that led the traffic flow to evolve differently than expected. When many inbound aircraft arrive at the same time, controllers must implement a holding pattern to accommodate the traffic.

Second, the South sector has considerable crossing traffic. In 2018, there were 67,638 aircraft in the sector that were not going to or coming from Schiphol. In comparison, in the (larger) East sector, only 34,173 aircraft were not inbound or outbound Schiphol flights [2]. The complexity of traffic handling in the South sector is greater. Most regional traffic in this sector goes to or comes from the surrounding airports (Rotterdam, Eindhoven, and Brussels). These aircraft constrain the solution space available for inbound traffic and require considerable controller attention. The standard arrival routes for surrounding airports cross the routes for Schiphol, and the traffic flows must cross whilst descending or climbing. Situations that involve aircraft changes in altitude are complicated and demanding for controllers.

Third, most inbound traffic going to Schiphol arrives from the South sector. In 2018, the Amsterdam South sector had 4241 inbound aircraft more than the Amsterdam East sector [2], which has the second-highest number of inbound aircraft. The volume of inbound traffic in the sector has increased considerably in the past few years, 15.8% since 2013 [2], causing traffic handling to become significantly more complex.

B. Merging Aircraft in the Amsterdam South Sector

In a merging task, the inbound traffic must be merged toward an IAF, which they pass with specific constraints on their altitude and speed. The inbound traffic comes from standard arrival routes, illustrated in Fig. 1. Traffic from the south comes via three arrival routes (DENUT, HELEN, and PUTTY). The majority of those aircraft come from DENUT and HELEN. The arrival routes converge at Haamstede (HSD), from where the arrival route continues toward the IAF RIVER. At RIVER the arrival routes are combined with the arrival route coming from PESER.

In practice, aircraft do not neatly follow these arrival routes. It is not unusual for an aircraft to fly a considerable offset from the standard arrival route. Figure 2 shows all inbound traffic paths going to Schiphol in the Amsterdam South sector, recorded for one typical 24-hour period. Clearly, aircraft do not fly directly over HELEN or DENUT.

Currently, the area controller sequences the incoming aircraft by vectoring (see Fig. 2). By adjusting path length, the controller determines which aircraft arrives at the IAF first. Some paths are shortened by commanding the aircraft to go directly toward RIVER, without first going to Haamstede. Other paths are elongated on the west side of the sector. Another method for extending the aircraft flight path is to place the aircraft in a holding pattern at RIVER. Although not optimal, this method is often used due to the small sector size. With support from the proposed display system, the controller will be able to decrease the use of the holding patterns.

III. Proposed New Concept

The proposed Inbound Traffic Support System (ITSS) is a new display that uses visual tools to assist the area controller in a merging task. Section III.A explains the design requirements. A version of the simulator environment without the visual tools

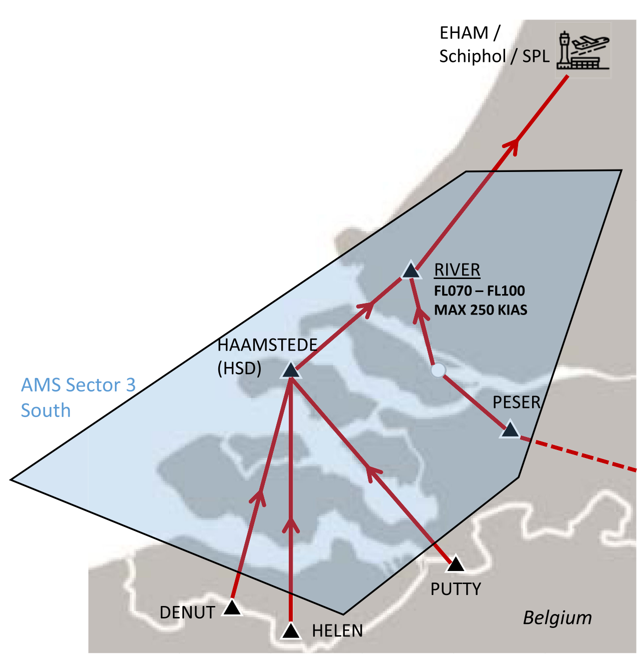


Fig. 1 Standard arrival routes for inbound traffic in the Amsterdam South sector.

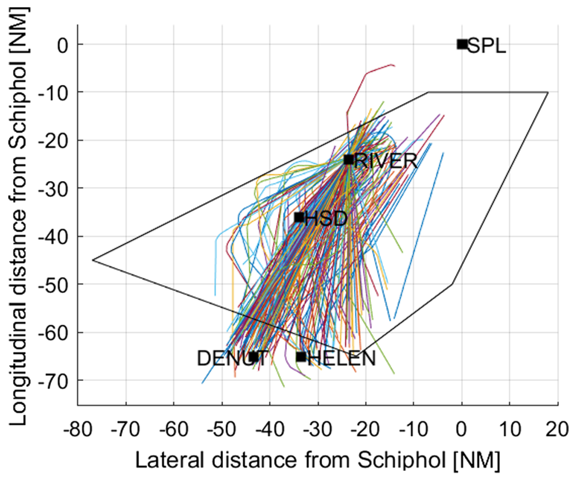


Fig. 2 All inbound traffic paths going to Schiphol in the Amsterdam South sector for one 24-hour period.

(the Current Area Control System (CACS)) is used as a baseline. This system is inspired by the radar screen currently used at the LVNL and is explained in Sec. III.B.

The ITSS expands upon the CACS in numerous ways. The visual enhancements for a single aircraft are explained in Sec. III.C. Subsequent subsections describe additions in multiple aircraft situations. Some of the visual elements of the display are always shown; others appear only when interacting with an aircraft. The colors used in the explanatory figures resemble the colors used in the simulation as closely as possible, with changes in some cases to provide greater clarity.

A. Design Requirements

Air traffic controllers are responsible for managing a complex system. When merging aircraft, a controller cannot definitively account for all elements in the system. The exact dynamics of descent paths and effects of wind can be estimated with experience but never fully calculated. Here, a combination of clever automation and interface design can improve the way controllers operate.

Research has shown that a useful interface must help an operator to understand the link(s) between the data and the functional objectives [31–33]. Recent findings also suggest that human operators are not best suited for a supervisory control task where they are requested to accept or reject single, optimized, computer-generated advisories, as this can disturb their workflow and increase their workload when it comes to understanding the underlying reason for specific advice [34]. One effective approach to supporting human operators in decision-making is to portray the full state-action space—bounded by both causal and intentional constraints—and allow operators to select their preferred course of action. This aligns with the principles of Ecological Interface Design (EID) [35,36], which aims to assist professionals in complex systems by making the system's affordances—goal-relevant opportunities for action—more visible, while ensuring users retain full control. Prior research in flight decks, ATC, and other domains has demonstrated encouraging results using this approach [24,25,28,37–39].

Therefore, the goal of the interface is to portray *all* possible solutions of an area controller's task of merging aircraft toward a restricted waypoint in the current work domain, such that the impact of decisions made can be foreseen and safety is maintained. This translates into the following requirements:

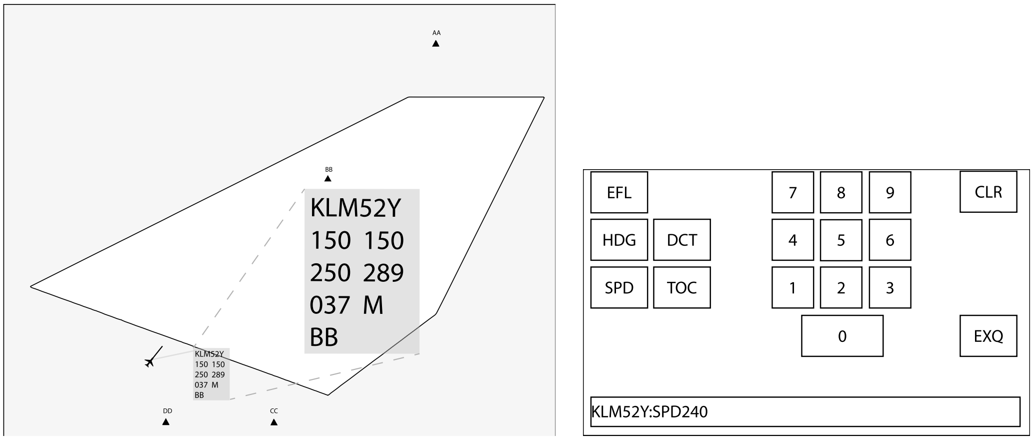
1) The display must keep the controller as the *active* decision maker.
2) The support system must support the controller's tasks in separating aircraft in the sector.
3) The support system must support the controller's tasks in merging aircraft before approach.
4) The support system must support the controller's tasks in achieving altitude adherence at the IAF.
5) The display must be implementable within current LVNL systems with minor modifications.
6) Display clutter must be minimized.

B. Current Area Control System (CACS)

Because the design should be comparable to current implementations, a simulation environment based on the radar screen and command interface currently used at the LVNL was developed. In the simulator, the Amsterdam South sector waypoints and the aircraft inside the sector are replicated (Fig. 3a). All aircraft information that is currently available to the area controllers is shown in the aircraft label, which is enlarged in the figure. For each aircraft, this label shows (left to right and then top to bottom): the callsign, the current flight level, the target flight level, the indicated airspeed, the ground speed, the heading, the aircraft type, and the destination waypoint.

Clearances to alter the course of an aircraft are given using the command window depicted in Fig. 3b. The user can change the target flight level (EFL), change the heading (HDG), proceed directly to the destination waypoint (DCT), change the aircraft target indicated airspeed (SPD), hand over the aircraft to the next sector (TOC), clear the commands given (CLR), and execute the given command (EXQ).

The simulator updates the radar screen every 5 s, which is in line with the radar update rate used at the LVNL. Because the simulator is able to take into account uniform wind conditions in all calculations, wind is assumed to be constant throughout time and without variance due to height or location.



a) Plan view display **b) Command interface**

Fig. 3 Replicas of the Amsterdam South sector radar screen (with enlarged aircraft label) (left) and the LVNL command interface (right).

When using the ITSS, additional information becomes available to the user. Specific visual elements can be requested to appear through interaction with the radar screen. When all optional elements are inactive, the ITSS shows approximately the same elements as current LVNL controllers are accustomed to seeing in the CACS. First, the interaction with a single aircraft will be discussed, followed by a more extensive description of how the controller can perform merging tasks for multiple aircraft.

C. ITSS: Single-Aircraft Visualization Elements

In the ITSS, each aircraft on the radar is circumscribed with a radius of 2.5 NM. The 5 NM separation requirement can then be evaluated at a glance, noting that the circles are not allowed to touch or overlap [30]. When the user selects an aircraft, Fig. 4a, its color changes and the radius of its circle is adjusted to the 5 NM separation minimum. The rationale behind this is that the perspective shifts from viewing the overall traffic situation to understanding the interaction of the selected aircraft within its environment [28]. In addition, a circular arc around the aircraft destination waypoint is generated. This arc represents the locations within the sector where the aircraft must start its descent maneuver *at the latest* for a direct-to path to the destination (here the IAF) while reaching the target flight level at that destination, given its current height and speed. A simplified aircraft performance database was used to model and predict descending trajectories.

In Fig. 4b, the aircraft has surpassed the arc and is no longer able to reach the target FL at the IAF when flying directly toward it. When this occurs, the arc color as well as the current and target flight levels in the aircraft label change to amber for alerting, as is standard in aviation guidelines. In case an aircraft is not selected whilst having surpassed the arc, the color in the aircraft label *still* changes to alert the user that action is required. The situation can be resolved by elongating the aircraft path toward the destination, e.g., through vectoring.

D. ITSS: Relative Track Line

When interacting with two (or more) aircraft, a second element can become active: the relative track line. The relative track line visualization informs the controller whether adequate separation is maintained in the subsequent projected flight path and gives an indication of the distance at which the aircraft will cross. This concept—based on adaptations of prototypes proposed by [40,41]—is explained using Fig. 5.

In this figure, two aircraft (the selected aircraft (own) and one other aircraft (intruder, int)) are shown at time t_0, along with their speed vectors V_{own} and V_{int}. Assuming that the aircraft states will remain unchanged in the subsequent projected path, a conflict prediction can be made. The speed vector V_{own} is subtracted from the V_{int} vector to obtain the relative speed vector V_{rel}. The line that extends from the relative velocity vector is the relative track line. This line indicates the path the intruder aircraft follows relative to the selected aircraft (own). At t_1, the aircraft have moved closer, and at t_2 the aircraft have crossed, but they have done so with insufficient distance between them. This could have been foreseen using the relative track line. As long as the line does not cross the 5 NM circle around the selected aircraft, the aircraft will retain separation, and the placement of the line will directly illustrate which aircraft will cross in front of the other. In Fig. 5, the intruder will cross in front of the selected aircraft.

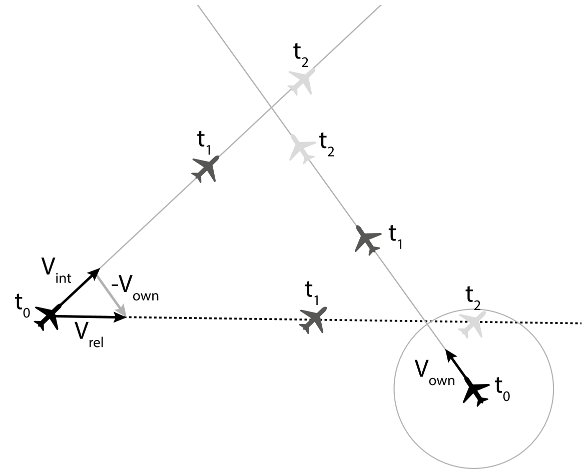
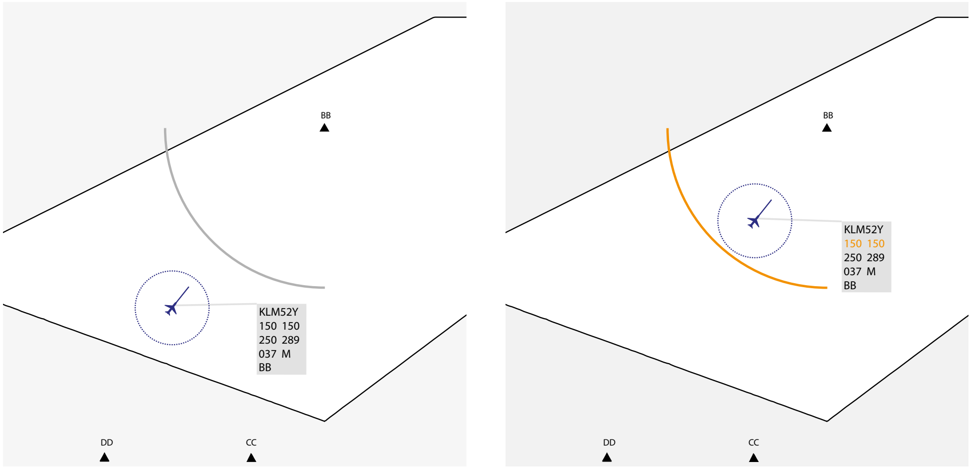


Fig. 5 Relative track line rationale.

The relative track line concept works well in separating aircraft at the same flight level because the aircraft are vectored. Within the ITSS display, the relative track line is automatically shown on the display for a selected aircraft when either the vertical separation is less than 1000 ft or the aircraft have an identical target flight level. When the aircraft have an identical target flight level, the current speed conditions are used in the calculations.

In Fig. 6a, a two-aircraft situation can be observed where both aircraft fly at the same altitude and with equal speed. The relative track line is tangent to the 5 NM boundary. Thus, the closest point of approach is predicted to be exactly 5 NM, as shown in Fig. 6b for the same scenario at a later time.

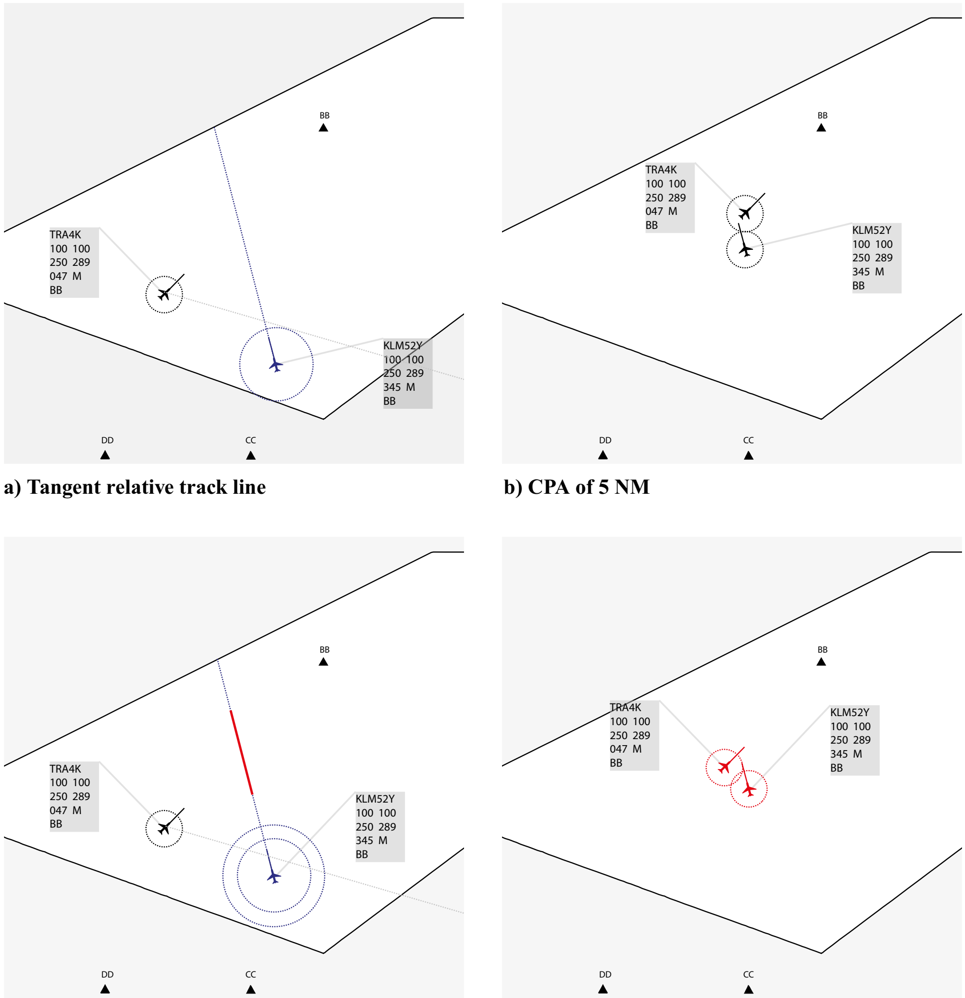
A loss of separation occurs for the situation depicted in Fig. 6c if the user does not intervene. Here, the location of the prospective safety violation is visualized along the trajectory using a red line segment. In Fig. 6d, it becomes apparent that the line segment indeed corresponds with a separation distance smaller than 5 NM.



a) 5 NM circle and the descent arc

b) Descent arc (and label) for a situation that needs to be addressed

Fig. 4 Single-aircraft visualization elements: descent arc and label changes.



a) Tangent relative track line

b) CPA of 5 NM

c) Relative track line crossing

d) Safety violation

Fig. 6 Relative track visualization for two two-aircraft situations (left column) and the consequences (right column).

In Fig. 6c a second 7 NM circle may be observed. This functionality can be activated by the user. Interviews with LVNL domain experts indicated that maintaining a slightly larger separation distance is often preferred, as it requires less monitoring effort. When using the 7 NM circle, the relative track line principle works identically to the 5 NM circle.

E. ITSS: Available Flight Paths to the IAF

Area controllers organize traffic flows such that each aircraft reaches the IAF at the correct flight level. To do this, more than conflict detection and resolution is needed. The available flight paths destined to reach the IAF are portrayed inside the sector to help the controller organize the traffic flows. Figure 7 illustrates this concept, which is a vector adaptation of the trajectory space visualization for 4D trajectory management [24,42].

At time t_0, two aircraft are visible. Aircraft 1 (bottom left) is already set on a direct-to path toward the IAF. The selected aircraft 2 (bottom right) still needs control commands to fly to the IAF. The controller must decide whether the selected aircraft 2 will end up *in front of* or *behind* aircraft 1, which is already on the direct-to path. To help with this decision, the time it takes the selected aircraft to fly directly to that point and from there to the IAF is calculated for multiple points in the sector. This is commonly known as a “dogleg” maneuver.

Point A and point B illustrate the locations where a direct-to command is given for two dogleg paths. The path going to point B and then to the IAF requires a heading change at time t_0 and is longer than the path going to point A and then to the IAF. For each dogleg path, the time it takes to reach the IAF is calculated. The

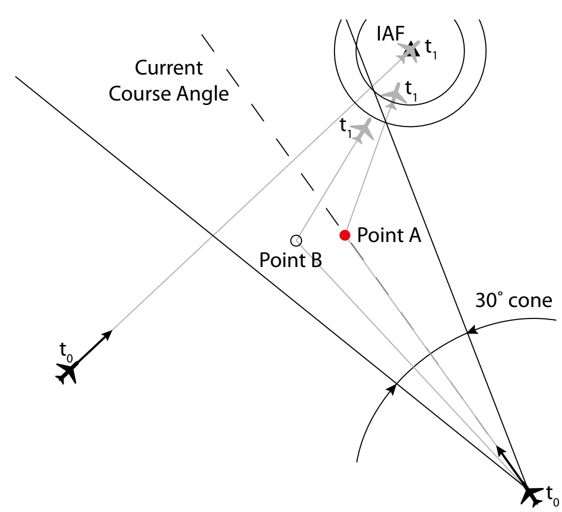


Fig. 7 “Dogleg” paths for selected aircraft (bottom right).

aircraft IAS is assumed to be constant, but the GS is adjusted according to the height in the predicted descent profile and the wind conditions. The same calculation is done for aircraft 1, and the time difference at the IAF is converted into a relative distance.

The difference in distance can then be shown within the sector using the colors in Table 1. The information for each possible

Table 1 Color given based on spatial difference at IAF (ITSS)

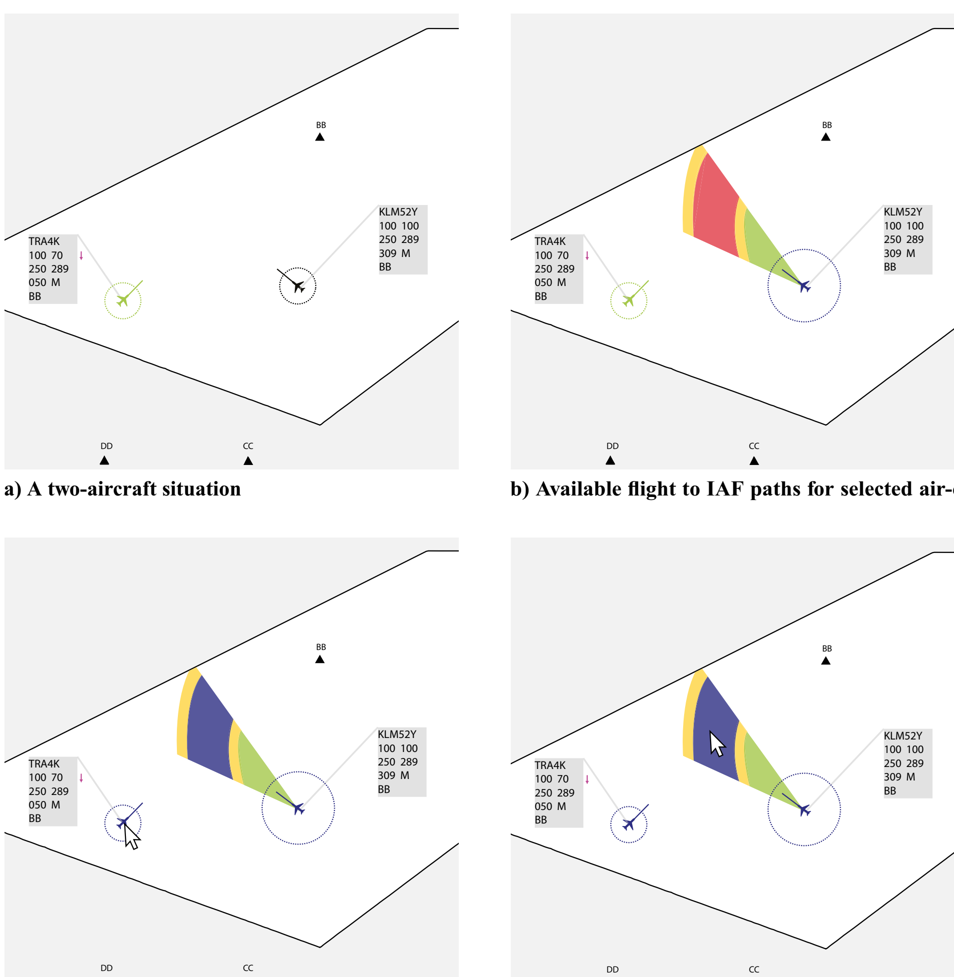
Distance at IAF, NM	Category	Color
0–5	Warning	Red
5–7	Caution	Amber
>7 (in front)	Safe	Green
>7 (behind)	Safe	No color

dogleg flight path is encapsulated in the pixel color at the location where a direct-to command is given. This means that for the potential flight path that first goes to point A and then to the IAF, the relative distance with aircraft 1 is displayed at the location of point A. In the figure the consequent separation distances at time t_1 are presented. The path through point A (red) results in a separation of less than 5 NM at the IAF, and the path through point B (transparent) has a separation distance of more than 7 NM at the IAF.

Because not all points within the sector provide realistic dogleg paths, the calculations are only performed within a flight "cone," which is created with its borders at ± 15 deg from the current course angle (see Fig. 7). This cone is estimated to cover *all* realistic flight paths and is based on analysis of professional controllers' strategies provided by the LVNL.

Since each decision taken by the controller affects the entire solution space, a starting point for the calculation is required. The (one or more) unselected aircraft included in the calculation (in the explanation above of aircraft 1, but more aircraft in the sector can fly toward the IAF) *must* be on their way (i.e., a direct-to) toward the IAF. Otherwise, too many degrees of freedom still affect these unselected aircraft arrival time(s) at the IAF, making it impossible to advise the controller about which path to take for the selected aircraft. Thus, once one aircraft has been commanded to fly directly toward the IAF, the display supports the controller to solve for the "next" aircraft to be guided toward the IAF, i.e., solving the merging problem *sequentially*, one aircraft at a time. This strategy works best when the aircraft enter the sector sequentially, as is indeed often the case, as this is stimulated by sector design (e.g., the DENUT, PUTTY, and HELEN trajectories in Fig. 1). The color of the aircraft inside the sector changes when on a direct-to path toward the IAF to inform the user which aircraft are included in the calculation. A distinction is made between aircraft on a descent path (green) and those not yet descending (gray).

Figure 8a shows a scenario for the ITSS display in which an aircraft (green) is on its way toward the destination waypoint. Upon selecting the other aircraft (black), the available flight paths become clear for this aircraft, Fig. 8b. The green color of the pixels in the vicinity of the aircraft indicates that if a direct-to command is given at one of those locations, the aircraft will arrive *in front* of the other by at least 7 NM. Evidently, when the path length is increased, the aircraft will take longer to reach its destination, which will affect the separation between the aircraft. If it continues along its current course and a direct-to command is given in the nearest orange area, the selected aircraft will still reach the position *ahead* of the other aircraft, but the margins will have become smaller. The red area indicates the locations for which a direct-to command would result in a safety violation at the IAF. The outermost orange area results in a separation distance between 5 and 7 NM, where the selected



a) A two-aircraft situation

b) Available flight to IAF paths for selected air-craft

c) Means-end connection (cursor on aircraft)

d) Means-end connection (cursor on critical area)

Fig. 8 Visualization of the available flight paths under current flight conditions (ITSS).

aircraft is vectored *behind* the other aircraft. If an aircraft ends up *behind* by more than 7 NM, no color is given. This is done to minimize screen clutter, since there are continuously aircraft (further) ahead in a continuing merging task.

In situations involving more aircraft, the "mental connection" between red zones and the aircraft causing them is made evident by highlighting the aircraft when hovering the mouse cursor over the red zone and highlighting the red zone when hovering over the aircraft. Figures 8c and 8d show this means–end connection [25] for a situation where the (enlarged) mouse cursor is hovered over an aircraft that causes a conflict (leading to the colors of the conflict zone *and* that aircraft to become blue) and a situation where the mouse is hovered over a conflict zone, respectively. This increases the interface's visual momentum [43].

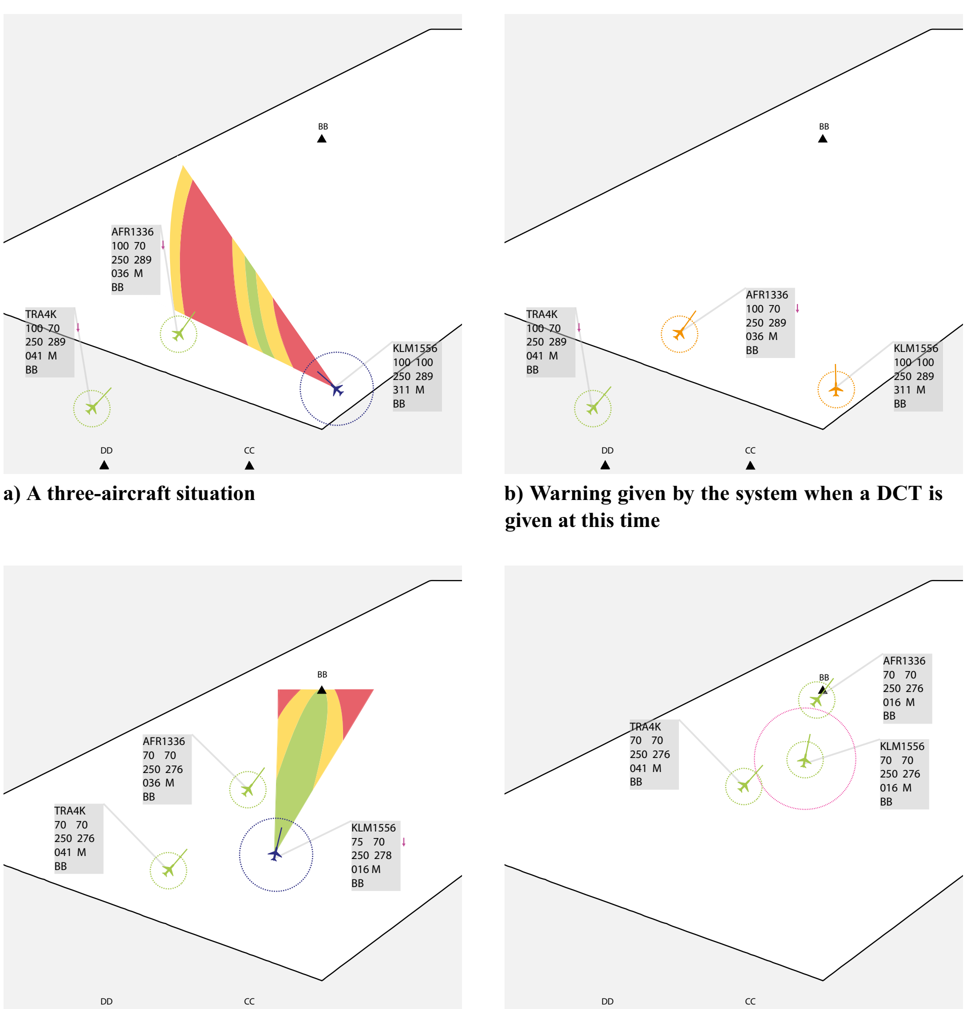
When the aircraft on a direct-to path are not yet descending, an additional uncertainty is introduced. It is known that the aircraft needs to descend, but not *where* that command will be given. The algorithm assumes that all aircraft on a direct-to path are already descending toward the restricted height. Therefore, the cone visualization is not entirely accurate. However, flying for a longer period of time at a higher altitude causes aircraft to fly faster due to the difference in true airspeed (TAS) with the increased height. A later descent command therefore causes an aircraft to arrive at the IAF faster, so when vectoring an aircraft behind, safety is not affected since the separation margins can *only* increase. When an aircraft is commanded to go in front of an aircraft that is not yet descending, it can lead to dangerous situations, so it is not a common procedure. The visualization is recalculated every 5 s and will therefore also change over time when the aircraft descends at a later stage.

For multiple aircraft situations, as for instance illustrated in Fig. 9, the visualizations are combined and the critical colors are given priority. Two critical areas are depicted in Fig. 9a. If a direct-to clearance is given at the moment illustrated, i.e., inside the first red zone directly emerging from the selected aircraft (bottom right), this will result in a loss of separation at the IAF. Should the choice be made to order the aircraft to go straight toward the destination waypoint anyhow, the consequences of that decision can also be seen when no aircraft is selected, as in Fig. 9b, where the orange color warns the user of a future conflict. A possible solution to this particular merging situation is to let the selected aircraft continue along its current trajectory until the green flight path region has been reached and to then give a direct-to command (see Fig. 9c). Figure 9d presents the separation result of that decision. A 7 NM distance is indeed kept with respect to both aircraft, as is illustrated by the 7 NM circle that is added for clarification.

The visualization only considers the separation when arriving at the IAF. This means that the information needs to be combined with the previously explained relative track information to ensure separation within the sector.

F. Available Flight Paths for Altered Speed (ITSS)

In addition to performing calculations for current speed conditions, the display portrays flight paths with *alternative* speed



a) A three-aircraft situation

b) Warning given by the system when a DCT is given at this time

c) DCT command moment when inside the green cone area

d) Continuation of situation (7 NM circle for reference)

Fig. 9 Possible solution strategy using the available flight paths under current flight conditions (ITSS).

selection. This is done in a distinct display layer that, initiated by the operator, can be superimposed on the present solution. By means of a mouse toggle function, the user can see the effects of adjusting the selected aircraft speed used in the calculation inside the new layer with steps of 10 kts, allowing for "what-if?" probing [25,33]. The areas inside the flight cone that do not cause a safety violation are given a transparent gray color. The selected aircraft's fictitious speed is shown within the label in a different color to notify what speed is used in the visualization.

Figure 10a illustrates this functionality for the available flight paths under the current conditions. The selected aircraft fits in between the two (green) aircraft already on descent. When toggling the speed, effects of changing speed become apparent as shown in Fig. 10b. For reduced speed, the aircraft must turn toward the destination waypoint earlier.

Alternatively, to increase throughput, the controller can examine whether the selected aircraft can reach the IAF first by speeding it up in the interface. Figure 10c shows the same situation but now for increased speed. Since a new highlighted area becomes apparent, it shows that the aircraft is indeed able to end up *in front* of both green aircraft with sufficient separation. The result of this solution is depicted in Fig. 10d. The selected aircraft will end up in front by at least 5 NM. If the user wants to extend this to 7 NM, additional measures can be taken.

G. Combining All Elements (ITSS)

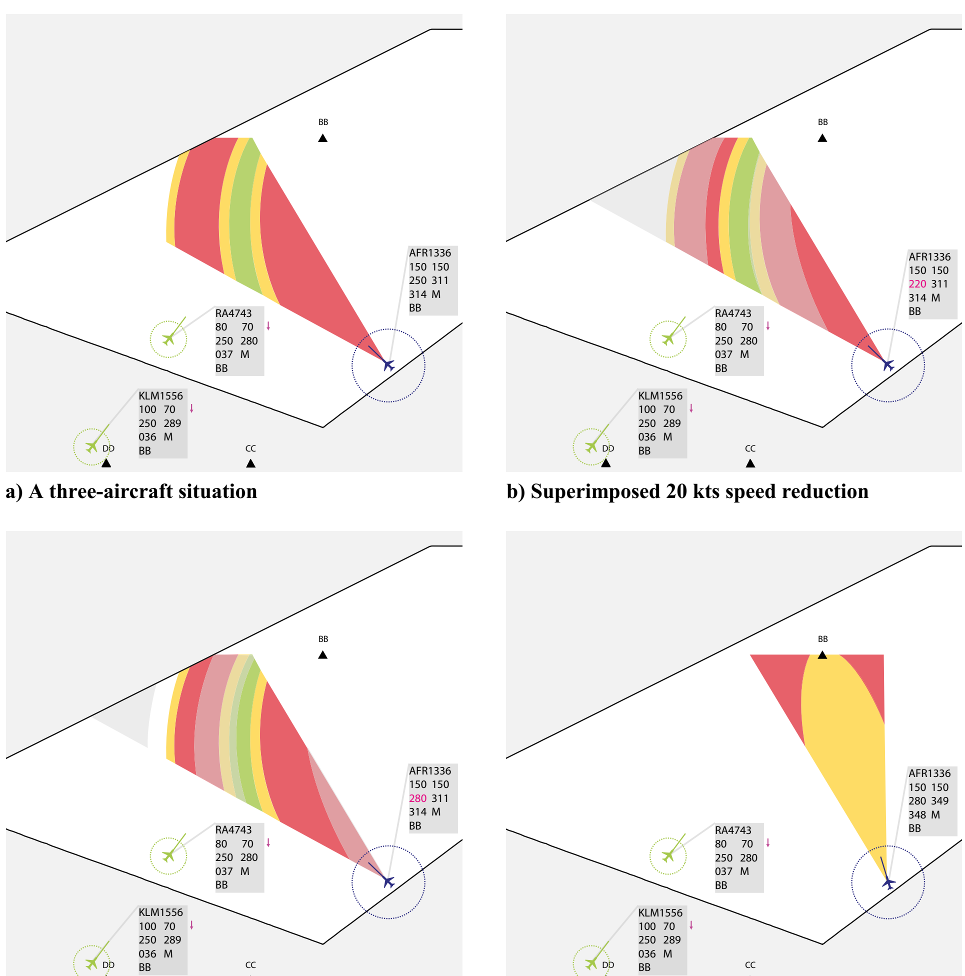
Combining all the elements yields the display shown in Fig. 11. In addition to presenting the system as a whole, the figure also illustrates how difficult it can be to establish the best solution strategy. For instance, a change in wind conditions completely changes the solution space. This underlines the usefulness of the support. By showing what the effects are, one can expect the controller to utilize the visualization elements to support and improve his or her internal mental model.

Figure 11a shows a situation for a 25-knot uniform wind coming from the west. According to the available flight path visualization for current flight conditions, the selected aircraft can end up in between the two other aircraft (green) even though the margins are small. However, the relative track line crosses the 5 NM circle, and a loss of separation will occur before reaching the direct-to location. A better solution for the current speed is to command the selected aircraft to go directly toward the IAF at this time. It will reach the IAF first, with a separation between 5 NM and 7 NM.

Figure 11b shows the same situation for a 25-knot wind coming from the east. Now the selected aircraft can no longer end up in front. The relative track line indicates that all aircraft will cross at more than 7 NM when continuing their trajectories. The margins in-between these aircraft have increased, showing that the more sensible solution is to let the selected aircraft continue its current trajectory and direct it to IAF when moving into the intermediate green zone.

IV. First Evaluation with Professional Controllers

The proposed ITSS display is a first attempt to develop a new interface for handling air traffic in the Amsterdam South sector. To investigate its effectiveness, two area controllers, ATCo A with 3 years of experience and ATCo B with 7 years of experience, were asked to subjectively assess the proposed solution. The purpose of



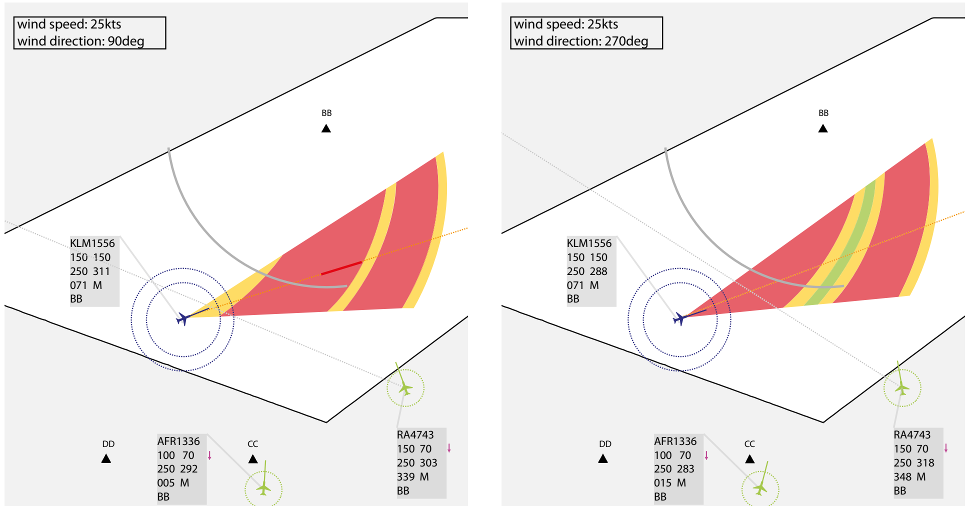
a) A three-aircraft situation

b) Superimposed 20 kts speed reduction

c) Superimposed 20 kts speed increment

d) Possible control strategy for 20 kts speed increment

Fig. 10 The available flight paths under current and altered speed conditions (ITSS).



a) 25 kts wind coming from the west **b) 25 kts wind coming from the east**

Fig. 11 The full ITSS display for two wind conditions.

this expert evaluation was to see whether controllers were interested in the proposed solution and whether they could see themselves using such tools in the future. All visual elements were first evaluated separately, and then as a whole, by means of a questionnaire.

Before working with the ITSS simulation, both controllers were asked whether they foresee a substantial change in their work in the upcoming years and if they consider humans to be a vital asset in the control task. This was done to assess the attitude they have toward automation within their work domain. ATCo A indicated that he expected that system support will assist in providing relevant information that can be used to verify planned solutions. They both agreed that in unexpected circumstances, human intervention remains essential. Furthermore, ATCo A noted that as long as an ATCo legally has the final responsibility, he or she should also be the one making the decisions.

After using the ITSS display, both area controllers agreed that the proposed visualization elements can make the ATC control task easier. ATCo A stated, “I see most benefit in spending less time checking and checking again if a situation will evolve the way I anticipated.” ATCo B found that the system gave a “clear input of when to give certain clearance.” When asked if, with further research, (part of) this solution should be implemented in the future, ATCo A strongly agreed and commented that specifically the merging and separation guidance would benefit the system currently in place. ATCo B agreed with the statement and noted that “The circles and IAF separation would make our core task a bit easier.” However, they also saw challenges. ATCo B wondered whether the benefits would outweigh the negative consequences of screen clutter. ATCo A also mentioned screen clutter as an issue and added that which information is useful in which case should be investigated. The relative track line was received less positively than the other elements. It was described as “too abstract” and “of no added value.”

Overall, the professional controllers were positive and expressed the desire to see part of the proposed solution implemented, despite a reserved initial attitude. They indicated that they wanted more time with the system to fully understand the meaning of all the elements. After this first evaluation by professional area controllers, the effects of the proposed interface on performance and workload were investigated experimentally and are discussed next.

V. Experiment: METHOD

The experiment aimed to investigate whether the new ITSS display elements affect safety, workload, and performance. The experiment was performed using ATC subject matter experts instead of operational controllers for two reasons. First, operational controllers are expected to rely less on the portrayed information due to their expertise and experiences, making it difficult to link results to the designed interface. Second, at the time of research, a large sample of controllers was not available.

A. Apparatus

The experiment was performed in a closed room at the TU Delft Faculty of Aerospace Engineering. Participants used one monitor for the radar screen (Fig. 3a) on their left-hand side and one for the command window (Fig. 3b) on their right (both 1920 by 1080 pixels resolution). All commands were given by a mouse by first selecting the aircraft on the left monitor and then clicking the buttons on the command window on the right monitor.

B. Participants, Instructions, and Procedure

The experiment was approved by the TU Delft Human Research Ethics Committee and involved eight participants. All can be considered ATC subject matter experts, as they had previously taken part in an extensive five-day Air Traffic Control course at the Netherlands Aerospace Centre (NLR).

All participants received identical instructions. First, an instruction manual was read, and 10 short training scenarios were performed to allow participants to familiarize themselves with the simulator and interfaces. Then, after the training phase, participants answered pre-experiment questions to make sure they understood the visualization elements.

Before starting the measurement phase, all participants were told to safely guide all incoming traffic toward the IAF and hand each aircraft over to a (fictitious) approach controller by giving a transfer of control (TOC) command. After the handover by a TOC was given, it was no longer possible to command the aircraft.

Participants were instructed to prevent conflicts and guide traffic as efficiently as possible: throughput should be maximized to the extent possible, while keeping the workload manageable. All aircraft had to arrive at the IAF at FL 70, not lower. A positive difference of less than 10 FL was tolerated and not registered as a “violation” of procedural compliance. The aircraft had to reach the IAF indicated airspeed of 250 kts; a two-sided speed difference of less than 10 knots was allowed.

C. Scenarios

Each participant conducted eight 12-minute scenarios in which only the inbound traffic was simulated to reduce operational complexity for nonprofessionals. The experiment scenarios were created using real flight data provided by the LVNL, such that they resembled reality as closely as possible for the merging inbound traffic task. As discussed in Sec. II, air traffic controllers have more

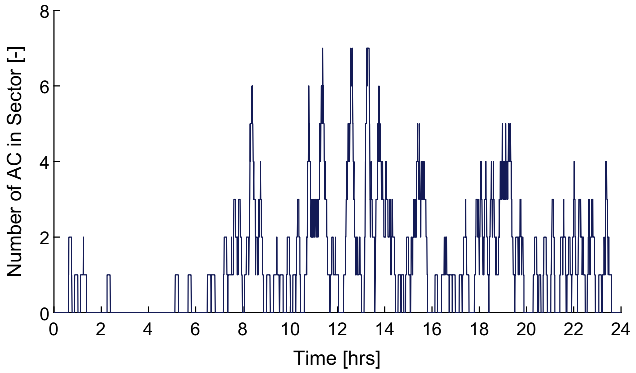


Fig. 12 Number of inbound aircraft in the Amsterdam South sector in a 24-hour period.

responsibilities than merging incoming traffic. Hence, an inevitable simplification of reality was introduced.

Using the LVNL data, the number of inbound aircraft within the Amsterdam South sector was recorded (see Fig. 12). For this particular day, there were at most 7 aircraft within the sector. The area controller's work consists of peak moments. The inbound flight data were further analyzed based on the flight paths, speed, and altitude of the traffic and then converted into traffic scenarios. Two complexity levels were distinguished: "Medium" and "Hard," which had, respectively, 4–5 aircraft or 5–6 aircraft flying in the sector simultaneously (see Sec. V.D).

From the provided LVNL data, the commands given by the previous controller could not be re-created. As a result, in the simulation, the incoming aircraft emerged on the radar screen before the South border of the sector *at* the moment they were transferred to the area controller.

Within the designed test scenarios, the aircraft entered the sector between FL 200 and FL 220, with some outliers coming in at a higher or lower flight level. There were two types of aircraft, Medium and Heavy. Most aircraft landing at Schiphol fall into the Medium category. This category contains short- to medium-range airliners such as the B737, the A320, and the E190. In the scenarios, Medium-type aircraft entered the sector at 260–280 kts IAS. Heavy aircraft, such as the B747 and the A380, generally flew faster when entering the sector, at a speed of 310–320 kts IAS.

D. Independent Variables

Two within-subject independent variables (IVs) were manipulated (see Table 2):

1) Display type, having two levels, i.e., the Current Area Control System (CACS) and the new Inbound Traffic Support System (ITSS)

2) Traffic scenario, having four levels categorized in two difficulty levels

The CACS resembles the current radar display professionals at the LVNL work with. The second condition is the newly designed ITSS. Here, participants can use the additional cues to solve conflicts and merge the inbound traffic.

Each participant completed two traffic scenarios per display type: A and B (Medium), and C and D (Hard). Thus, each participant solved all scenarios twice, once with the CACS display and once with the ITSS display. Because the scenarios with Medium traffic intensity (A and B) were assumed to be easier, all participants performed these experimental conditions first. Apart from this constraint, the measurement runs were further ordered as a Latin square.

Table 2 Independent variables: experiment conditions

Condition	Display	Traffic scenario	No. of aircraft	Difficulty level
1	CACS	A	7	Medium
2	ITSS			
3	CACS	B	7	
4	ITSS			
5	CACS	C	9 + 1x pop-up	Hard
6	ITSS			
7	CACS	D	10	
8	ITSS			

Finally, scenario C included one aircraft that would suddenly appear on the radar screen, close to the sector border screen, to simulate a "pop-up" aircraft that would disrupt a participant's initial plan. This would enable us to investigate the robustness of solutions and flexibility in strategy adaptation of the ITSS compared to CACS.

E. Control Variables

To avoid possible confounds, the following control variables (CVs) were kept constant: i) apparatus, ii) instructions, iii) sector layout, iv) aircraft performance, v) wind, and vi) simulator options. The aircraft descent rates and speed limits were based on aircraft type. The simulator traffic update rate was fixed at 5 s, wind conditions were uniform and constant, and the visualization colors used were unaltered.

F. Dependent Variables

The dependent variables (DVs) will presumably change in response to the conditions of the IVs. The DVs measured to determine safety are as follows:

1) Number of losses of separation (LOS)
2) Number of warning notifications
3) Duration of warning notifications

A warning notification was given for a potential LOS within 60 s; the duration of these notifications was recorded.

To determine operator performance, the following DVs were recorded:

1) Number of control instructions
2) Additional track miles
3) Average separation at the IAF
4) Number of aircraft arrived at and en route toward approach control
5) Number of violations of procedural compliance
6) Workload

The type, location, and time of all commands were recorded. Aircraft tracks were logged, and the number of additional track miles was computed, i.e., the difference between the number of flown track miles to reach the IAF and the minimum track miles required for each aircraft to reach the IAF on a direct-to path. For each aircraft that arrived at the IAF, the separation with the preceding aircraft was recorded.

Due to time limitations, not all aircraft in a scenario reached the IAF before the end of the scenario. The number of aircraft en route to approach control consists of the aircraft that have already passed the IAF and those that are on a direct-to path toward it. The number of aircraft handled after 12 min is an indication of how efficiently the participant operated. When a direct-to command resulted in a safety violation at the target waypoint, this was recorded. When an aircraft reached the IAF, it was checked whether it adhered to the altitude (FL 70) and speed constraints (IAS 250). All aircraft met the speed constraint; only the differences in altitude greater than 10 flight levels were registered as a violation of procedural compliance.

Participants were instructed to give instantaneous self-assessment (ISA) ratings of their workload [44] once every minute throughout the experiment.

The following DVs were used to investigate whether the ITSS visual functionalities were used:

1) Number of aircraft clicks
2) Number of hovers
3) Number of uses of the speed toggle
4) Number of uses of the 7 NM circle

Aircraft clicks are required to give commands, but when using the ITSS display, clicks also provide additional visual information for the selected aircraft. These options were only available for the ITSS condition.

G. Hypotheses

Regarding possible differences between the CACS and the ITSS, the following hypotheses are made:

1. Safety

1.1. No loss of separation occurs with both interfaces, irrespective of the traffic scenarios.

1.2. With the ITSS interface, the number of warning notifications decreases, especially for the most difficult traffic scenario, C.

2. Workload

2.1. With the ITSS interface, workload will be lower for the Hard scenarios, especially in traffic scenario C.

2.2. With the ITSS interface, workload is slightly increased for the Medium scenarios.

2.3. With the ITSS interface, workload shifts to an earlier moment in time.

3. Performance

3.1. With the ITSS interface, the number of control instructions will decrease for the Hard scenarios, especially in traffic scenario C.

3.2. With the ITSS interface, the number of violations of procedural compliance will reduce.

3.3. The interface does not affect the additional track miles metric.

4. Use of the Interface

4.1. Participants will use the visual assistance tools available in the ITSS display.

4.2. The number of aircraft clicks will increase due to the use of the ITSS display.

VI. Experiment: Results and Discussion

A. Statistical Analyses

Due to the relatively small sample size and clear violations of ANOVA assumptions (e.g., non-normal distributions and heterogeneity of variance), a factorial repeated-measures ANOVA was deemed inappropriate. Instead, conservative nonparametric Wilcoxon signed-rank tests were used to assess statistical significance between the two display conditions within each scenario. Since the two Medium and two Hard scenarios differed in content, comparing ”Medium” versus ”Hard” for main effects would be confounded. Bonferroni corrections were applied to account for multiple comparisons, adopting the same procedure as in [37].

B. Safety

1. Loss of Separation

Six losses of separation occurred, all for the high-density scenarios C (five) and D (one). Four safety violations were found when using the CACS display (three in C and one in D), and two violations for the ITSS (all in C). One of these two happened near the IAF; the participant noted that this separation loss was “not an issue,” since it happened near the IAF and the aircraft would come closer together during final approach anyway. All LOS were slight violations of the 5 NM constraint (minimum of 4.63 NM), except one (0.28 NM), which occurred using the CASC display in scenario C.

The hypothesis (H 1.1) that no losses of separation would occur is rejected. No significant statistical differences were found.

2. Number of Warning Notifications

When a warning notification was given for both the CACS and the ITSS display, participants were informed using red aircraft colors and an aural alert. When no action was taken, such a notification would result in a loss of separation within 60 s. Figure 13a shows the total number of warning notifications per scenario for each participant. An initial observation that stands out is the five warning notifications in the ITSS scenario A conditions. Possibly, the participants were still getting used to the display. Scenario A using the ITSS display was the first condition participants 2 and 4 tested; therefore, a learning effect could be the cause of the notifications.

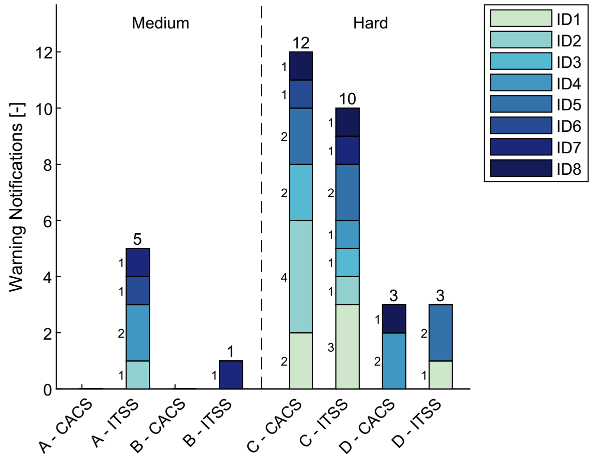
Scenario C contains many more warning notifications than scenario D, for both interfaces, which was not hypothesized. For some participants, the “sudden” appearance of an aircraft near to the sector boundary required them to (considerably) change their solution strategy. On the one hand, this could account for some of the notifications that could no longer be prevented. On the other hand, it is also possible that participants did not have the capacity to take full advantage of the ITSS functionality when performing under high pressure in such a small sector.

For some participants, the notifications in the ITSS condition were a conscious choice. Because the exact location of a potential loss of separation was evident, these participants were willing to let the aircraft get closer to each other. Quoting Participant: “I can better estimate the moment I need to give commands, and that gives me more confidence to do it tighter.” Initially, this was not taken into consideration.

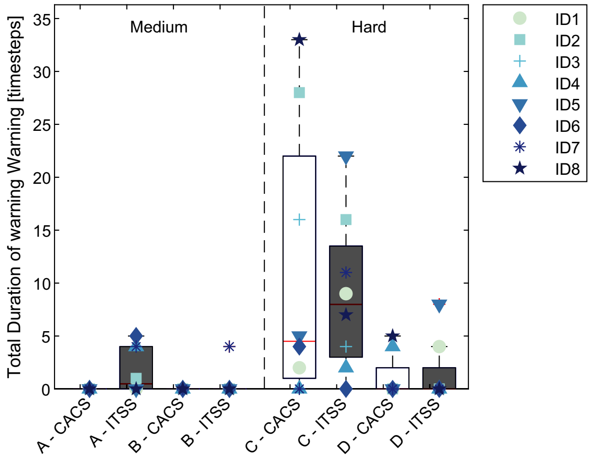
The hypothesis (H 1.2) that the number of warning notifications decreases when using the ITSS interface is rejected. There were no significant differences between interfaces: scenario A ($Z = -1.890$, $p = 0.059$), scenario B ($Z = -1.000$, $p = 0.317$), scenario C ($Z = -0.333$, $p = 0.739$), and scenario D ($Z = 0.000$, $p = 1.000$).

3. Duration of Warning Notifications

Figure 13b presents the total duration of the warning notifications, with a 5 s resolution, the simulated radar update rate. All notifications issued in scenario A in the ITSS condition were



a) Number



b) Total duration

Fig. 13 Number (left) and total duration (right) of warning notifications, per scenario and participant ID.

resolved quickly. The median duration is higher for the ITSS in scenario C. No statistical differences were found: scenario A ($Z = -1.841$, $p = 0.066$), scenario B ($Z = -1.000$, $p = 0.317$), scenario C ($Z = -0.421$, $p = 0.674$), and scenario D ($Z = -.184$, $p = 0.854$). As can be seen in Fig. 13b, scenario C (Hard) resulted in the most variability among controllers for both displays.

C. Workload

Figure 14 shows the normalized ISA workload ratings. In scenario A, the ITSS workload has a higher median and higher variability. For scenario B, the variability with the ITSS interface is also larger than with the CACS; the median is just slightly lower. In the Hard scenarios, the median is higher for scenario C and lower for scenario D in the ITSS display condition. When considering all scenarios, workload is higher for the Hard scenarios; there is no clear effect of interface. No statistical differences were found: scenario A ($Z = -1.960$, $p = 0.050$), scenario B ($Z = -0.140$, $p = 0.889$), scenario C ($Z = -1.260$, $p = 0.208$), and scenario D ($Z = -0.980$, $p = 0.327$).

It was hypothesized (H 2.2) that the ITSS display would slightly increase workload for the Medium scenarios, which is indeed found, but it is statistically nonsignificant. This could indicate that the additional information increased the workload, because participants had to monitor more information in the process of understanding and solving the merging problem. In these Medium scenarios, participants did not need additional information to solve the situations at hand. Here, the visualization elements require participants' attention without providing much benefit.

For the Hard scenarios, it was hypothesized that workload would decrease when using the ITSS (H 2.1), especially for scenario C. It was expected that by showing the possible solution strategies, participants could better anticipate the effects of their control decisions and thereby increase the flexibility to revise (initial) strategies when needed (scenario C). In a more demanding environment, this would potentially lead to fewer decisions to be adjusted throughout the scenario and a decrease in required monitoring time, leaving the participant with more time to think. This turned out not to be the case. For some participants, the visualization elements worked as expected, but others did not have sufficient time to make full use of the elements. In fact, scenario C that featured the "pop-up" aircraft resulted in a higher workload for the ITSS compared to CACS, which ran counter to what was hypothesized. Presumably, the increased visual complexity introduced by the ITSS raised the experienced workload levels of participants.

A large spread between participants is visible in the data. The data also varies per individual. Participant 3 gave the highest score of all participants in the ITSS scenario A condition and the lowest score in the ITSS scenario C and ITSS scenario D conditions. This could be due to a lack of experience. The complexity of a scenario is strongly related to the choices made. It can be hard to recover from problems that are created at the beginning of a scenario.

Another constraint that affected the workload ratings is that the scenarios were short and stopped after 12 min. The future workload *was* visible in the ITSS condition due to the visualization elements allowing participants to "look into the future," but was not visible in the CACS interface. The ISA workload ratings only indicate the perceived workload, and in some cases with the CACS interface, participants were convinced that everything was "under control," even though this was *not* the case. Their choices would have led to potential safety violations after 12 min, but they were not yet aware of this. Hence, these workload ratings were potentially lower than justified.

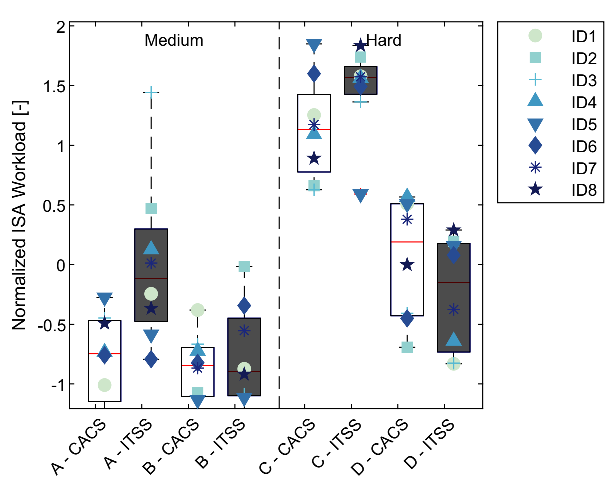


Fig. 14 Normalized ISA workload, per scenario and participant ID.

D. Control Performance

1. *Number of Commands*

Figure 15 shows the total number of commands given per scenario and participant, that is, all commands that alter the aircraft trajectory and the transfer of control commands. In the Medium scenarios, the values are approximately constant. A difference can be seen between participants; some used more commands than others. No significant differences were found: scenario A ($Z = -1.187$, $p = 0.235$) and scenario B ($Z = -1.1.03$, $p = 0.270$).

In the Hard scenarios, scenarios C and D appear differently. Fewer commands are issued with the ITSS, which is in line with the hypothesis (H 3.1). Tentatively, the ITSS participants "solve" the merging task for the first group of aircraft in the scenario and then only deal with each new aircraft appearing one by one. Many commands are given at the beginning, and fewer commands are needed to adjust the aircraft movements later, as *is* the case with the CACS.

This notion is supported in Fig. 16, which shows a cumulative plot of the commands over time for scenario D. In the first two minutes the values are approximately the same, then additional commands are given with the ITSS, then more with the CACS, and as the scenario

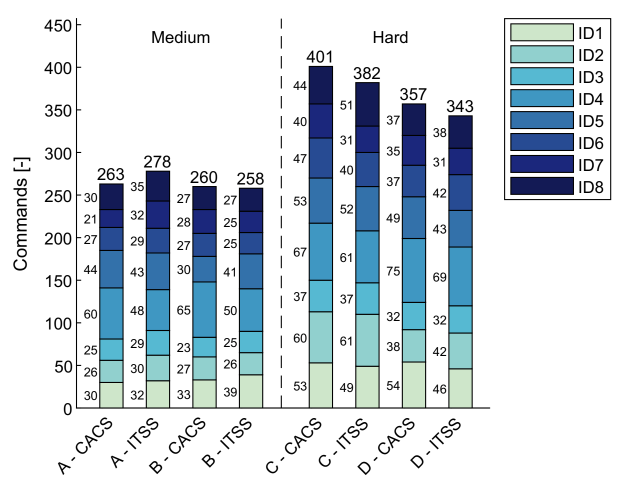


Fig. 15 Number of commands given, per scenario and participant ID.

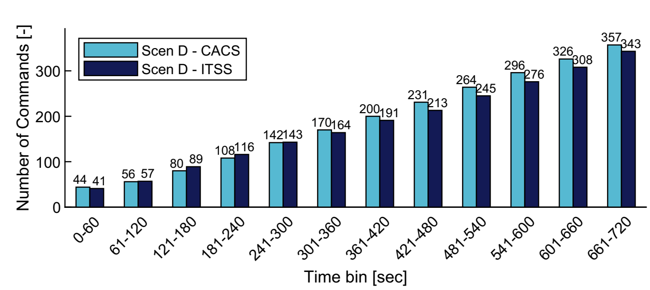


Fig. 16 Cumulative number of commands given over time (scenario D, CACS, and ITSS conditions).

progresses this difference becomes larger. Even though a trend is visible, it is statistically nonsignificant: scenario C ($Z = -1.187$, $p = 0.235$) and scenario D ($Z = -1.1.03$, $p = 0.270$).

2. *Violations of Procedural Compliance*

Figure 17a shows the number of times an aircraft reached the IAF at an altitude higher than FL 80. A clear distinction between the CACS (13 violations) and ITSS (1 violation) conditions is present. Here, the ITSS circular arc visualization helped participants to determine whether an aircraft was still able to descend before reaching the IAF. Participants indicated that it was easily understood, required no extra training, and provided clear insight into the main problem of the Amsterdam South sector: there is limited space in the sector, and descent commands must be issued early. When starting with the ITSS, participants knew that for the remaining scenarios, prompt actions were crucial.

For scenario A, the Wilcoxon signed-rank test proves significant after applying the Bonferroni correction ($Z = -2.646$, $p = 0.008$). For scenarios B ($Z = -1.342$, $p = 0.180$) and C ($Z = -1.414$, $p = 0.157$), the trend is apparent but not significant. The hypothesis (H 3.2) that the number of violations of procedural compliance in flight level will decrease for the ITSS condition therefore seems probable but could not be confirmed for all conditions.

3. *Additional Track Miles*

Figure 17b shows the additional track miles flown; values are similar for the CACS and ITSS conditions. In scenario C, which was considered more difficult, aircraft traveled a longer path. Data are widely dispersed between participants, revealing their varying skill levels and different solution strategies. For instance, participant 4 did not take any risks when under pressure and elongated the aircraft paths much more than others. The outlier in the CACS scenario A condition is due to an erroneously given TOC command. Participant 7 gave this command by accident, and because of this, the aircraft kept flying in the same direction at that time.

No statistical significance was found: scenario A ($Z = -1.120$, $p = 0.263$), scenario B ($Z = -0.700$, $p = 0.484$), scenario C ($Z = -0.840$, $p = 0.401$), and scenario D ($Z = -0.700$, $p = 0.484$). This is in line with the hypothesis (H 3.3).

4. *Separation at the IAF*

For each aircraft that passed the IAF, the distance with respect to the aircraft in front was logged. For those aircraft that had not yet reached the IAF (at the end of the 12-min scenario) *and* were on a direct-to path toward the IAF, the separation data were determined by extrapolating their trajectories.

Figure 18a shows the number of aircraft that have reached the IAF *or* are on a direct-to path toward it. Instead of showing the data per participant, the figure shows the "correct" and "incorrect" movements for all participants combined.

Incorrect movements are those that would result in a loss of separation at the IAF. The data indicate how many aircraft have been handled after 12 min and therefore illustrate how efficiently participants operated. Figure 18b illustrates that in some cases the aircraft will, under current conditions, experience a loss of separation at the IAF. This does not mean that a loss of separation will be the case, but it *does* imply that future action is required to prevent this from happening. This measurement is therefore related to the workload ratings: when no additional information is provided (the CACS), participants may have had the impression that everything is going all right, even when this is not the case.

For the Medium scenarios when using the ITSS, an increase in the number of handled aircraft is observed. Scenario D shows a similar number of aircraft sent toward the IAF for both the CACS and ITSS conditions. With the ITSS, however, no aircraft need to be adjusted. This indicates a calmer continuation of the scenario after 12 min.

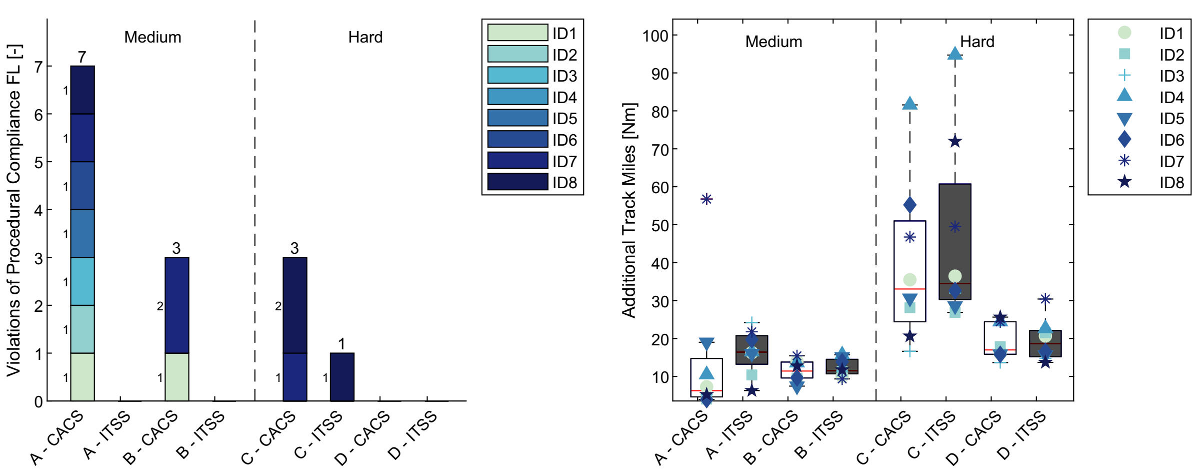
When considering scenario C, this was not the case. With the ITSS, a *lower* number of aircraft was sent toward the IAF, and additional commands are still required. Again, this might mean that under high-pressure conditions, participants were not able to fully benefit from the additional information to quickly change their strategy when faced with a pop-up aircraft.

Figure 18b shows the mean separation at the IAF, a combination of actual and extrapolated data. It is seen that the mean separation is higher for the Medium scenarios. This makes sense; a controller only wants to decrease the separation between aircraft when it results in increased throughput. Performing the Wilcoxon signed-rank test gave the following nonsignificant results: scenario A ($Z = -0.840$, $p = 0.401$), scenario B ($Z = -0.840$, $p = 0.401$), scenario C ($Z = -1.680$, $p = 0.093$), and scenario D ($Z = 0.000$, $p = 1.000$). For scenario D, the sum of negative ranks equaled the sum of positive ranks. Results for the CACS display were found to be not statistically different from those obtained with the ITSS.

5. *Performance per Scenario*

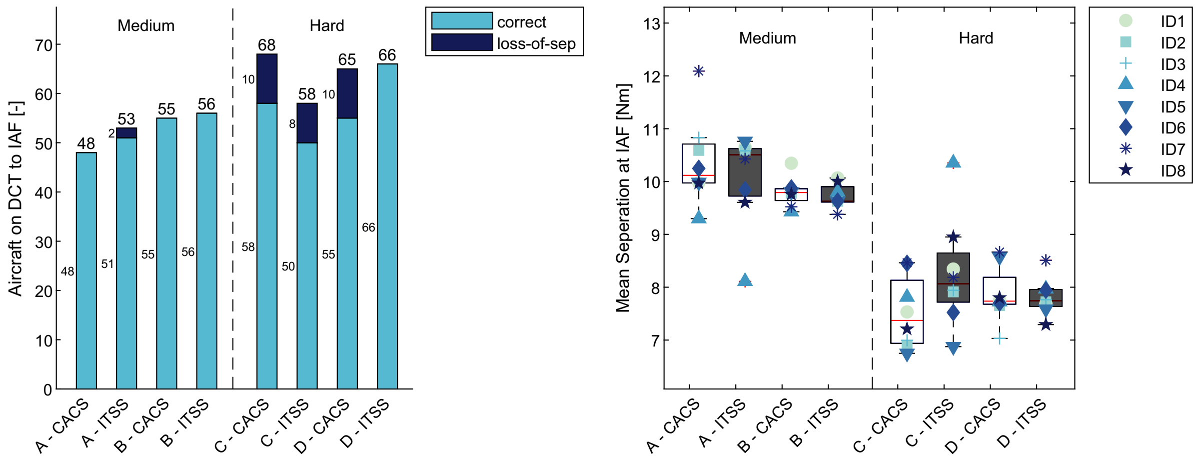
The positions of all aircraft after 12 minutes were inspected, their locations visualized, and problematic cases indicated in red. This allows for a straightforward analysis of the consequences of participants' control actions and strategies. Figure 19 shows an example where the ITSS proved to be of added value: participant 2 in scenario D.

Figures 19a and 19b show the aircraft positions as they were when the scenario ended. With the CACS, five aircraft are headed toward IAF. However, future problems are expected if the situation is continued "as is": the aircraft will come too close together, and



a) Violations **b) Additional track miles**

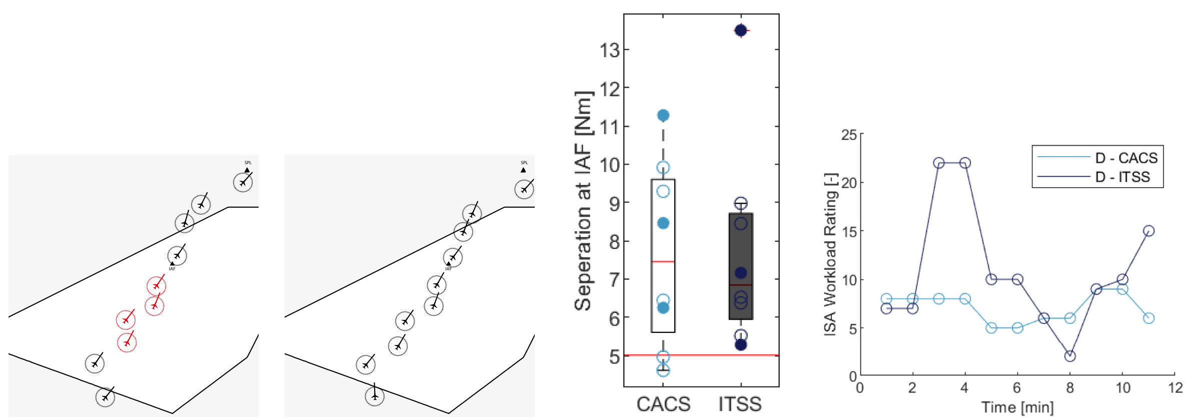
Fig. 17 Number of violations of procedural compliance for FL (left) and number of additional track miles traveled (right), per scenario and participant ID.



a) Number of aircraft

b) Average separation at IAF

Fig. 18 Number of aircraft on a direct-to path toward the IAF (left), and average separation at the IAF in NM for extrapolated data (right), per scenario and participant ID.



a) CACS

b) ITSS

c) Separation at IAF

d) ISA workload over time

Fig. 19 Final situations (left), separation at IAF, and workload ratings over time (scenario D, participant 2).

additional control actions will be required. With the ITSS display, the situation looks similar, but here aircraft have been merged successfully, and no further control actions are needed.

Figure 19c shows the separation at IAF for both conditions. The filled circles represent aircraft that have not reached the IAF, and the transparent circles stand for the predicted separation. With the CACS, two losses of separation are *predicted* to occur, i.e., requiring future control actions.

Figure 19d shows the workload ratings given as a function of time (every 30 s one rating, for the 12-min scenario). With the ITSS, workload fluctuates and is initially higher, as was hypothesized (H 2.3). With the CACS, workload ratings are more stable. The increased initial workload with the ITSS display was expected, because its portrayed elements (when selecting aircraft) immediately reveal all constraints, leading participants to “start solving” the situation at the very beginning. Note that even though workload is currently stable in the CACS display, an increased workload can be expected at a later stage because of the potential safety violations identified above.

This illustrates that the full effect of the decisions made is not always present in the data after 12 min. The ITSS stimulates participants to “solve the problem” when any new aircraft enters the sector, almost on a “one-by-one” or even (depending on the geometry) “first-come, first-served” basis, which is believed to eventually lead to a lower workload. These transient effects are expected to disappear for longer simulations, which are recommended for future work.

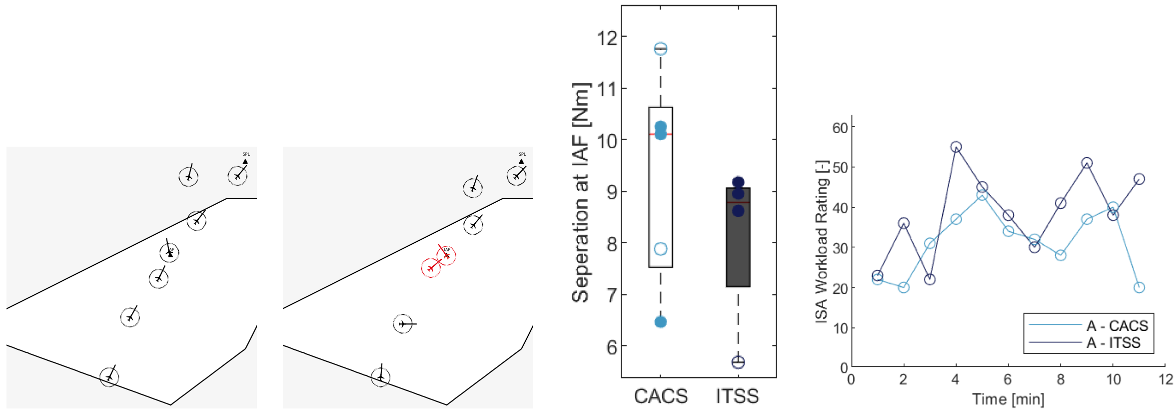
Figure 20 shows a situation where the ITSS display was *not* used as was intended by participant 4 in scenario A. Here, the participant noticed he was too late to give several descend commands and tried to solve the problem by elongating the aircraft paths, but without properly taking the other aircraft into account. Although this did not result in a loss of separation within the 12 min of the simulation, the predicted loss of separation could only have been prevented using an altitude command. Figure 20c shows a predicted separation of 5.5 NM, because it only considers the separation when the aircraft reaches the IAF. Higher workload ratings for the ITSS are clear from Fig. 20d.

More training is likely to help participants to understand the elements better and remain calm when confronted with the limited space available in the sector. Potentially, this will make the performance data more consistent.

E. Use of the Interfaces

1. *Aircraft Clicks (CACS and ITSS)*

Figure 21 shows the number of times an aircraft was selected. To make use of the visual extensions in the ITSS display, participants had to interact with the display by selecting an aircraft. It was hypothesized (H 4.2) that the number of aircraft clicks would increase with the ITSS, as this indicates that participants were gathering additional information to solve the situation. The difference was significant for scenarios A ($Z = -2.380$, $p = 0.017$), B ($Z = -2.366$, $p = 0.018$), and C ($Z = -2.384$, $p = 0.017$), but not for scenario D ($Z = -2.103$, $p = 0.035$).



a) CACS b) ITSS c) Separation at IAF d) ISA workload over time

Fig. 20 Final situations (left), separation at IAF, and workload ratings over time (scenario A, participant 4).

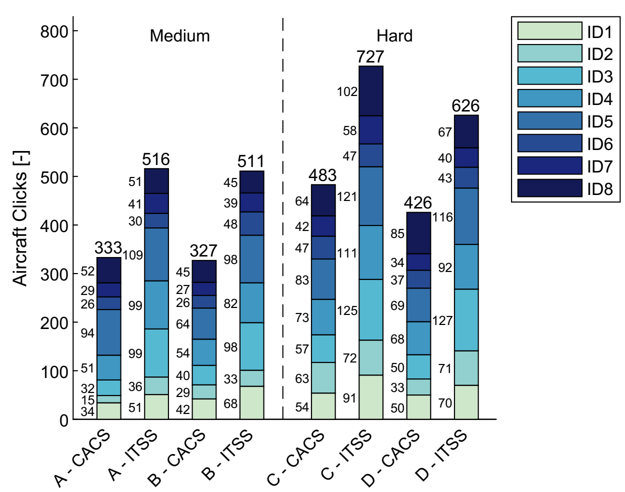


Fig. 21 Number of times an aircraft was selected, per scenario and participant ID.

2. *Use of Means–End Relationship of a Safety Violation (ITSS)*

The number of times participants explored the means–end relationship of a potential safety violation was recorded. How often they hovered the mouse cursor over a conflict region, or the aircraft causing the conflict, is shown by Figs. 22a and 22b, respectively. Both functionalities were used most in scenario C, perceived to be the most difficult scenario, where safety notifications more frequently occurred. In the case of more conflicts, participants used the functionality more to help them work out a solution to the situation. Differences between participants are visible; e.g., participant 3 made use of the conflict region detector more often than others throughout all scenarios.

3. *Use of Speed Toggle (ITSS)*

Figure 22c shows that the speed toggle function was used more often in the Hard scenarios. It could be that with fewer aircraft in the sector (A and B), it is simpler to resolve the situation without issuing speed changes. It could also be argued that as all our participants started with the Medium scenarios, the additional "practice" may have helped them to increase their understanding of this relatively complicated scenario. Only three participants used the speed toggle function in scenario C and used it extensively. Others either did not have time to probe to see the consequences of speed commands, or did not think a speed change helped to resolve the situation, or did not consider it altogether.

4. *Use of 7 NM Circle (ITSS)*

Figure 22d shows the number of times the 7 NM circle toggle was used. Not all participants used this functionality. In scenario C, this functionality was only used once by participant 3. Apparently, in this most difficult scenario, our participants had less time to focus on things that were not critical for safety.

Overall, Hypothesis 4.1 is only partially confirmed, as some ITSS display items were not used as extensively as expected. More training of participants with the interface and longer scenarios might paint a different picture.

VII. Discussion and Recommendations

The main objective of this research was to investigate whether the radar display of an area controller within the Amsterdam South sector could be enhanced for the purpose of improving procedural compliance while supporting the task of merging and separating aircraft. The research set out to keep the controller as the active decision maker, to prevent a potential decrease in situation awareness, and to decrease the risk of nonacceptance of the automated tools.

The proposed ITSS display succeeds in mapping the complexity of the Amsterdam South sector, while the user retains full control. The display (and its use) indicates that there is indeed very little room for manipulating the aircraft descent maneuvers due to the small size of the sector. With the ITSS tools, users are made aware that, for incoming aircraft, the correct control actions must be made quickly and a control strategy is needed to deal with high-density situations.

This section reflects on the hypotheses, discusses the experiment limitations, and provides recommendations.

A. Reflecting on the Hypotheses and Experiment

It was hypothesized that the number of violations of procedural compliance in flight level would decrease when using the ITSS display, when compared to the baseline. Results show that this indeed seems probable, with only 1 violation with the ITSS versus 13 violations with the baseline display. This trend could not be statistically confirmed. The increased altitude adherence is achieved without additional track miles, reflecting more effective and efficient control.

Whereas it was hypothesized that loss of separation would not happen, six losses occurred, of which five were minor. This can be attributed to a lack of experience and insufficient training with both interfaces, combined with the difficulty of the task. It is expected that no such violations would occur with professional controllers. Related to this, the hypothesized reduction in the number of separation warning notifications when using the ITSS interface also did not happen. Perhaps our participants did not have the capacity to take full advantage of all functionalities offered when performing under high pressure. In fact, some let aircraft get closer to each other when they *had* the additional information at their disposal. They felt more confident to do so because the exact location and time of the loss of separation were clearer. This boundary-seeking behavior has

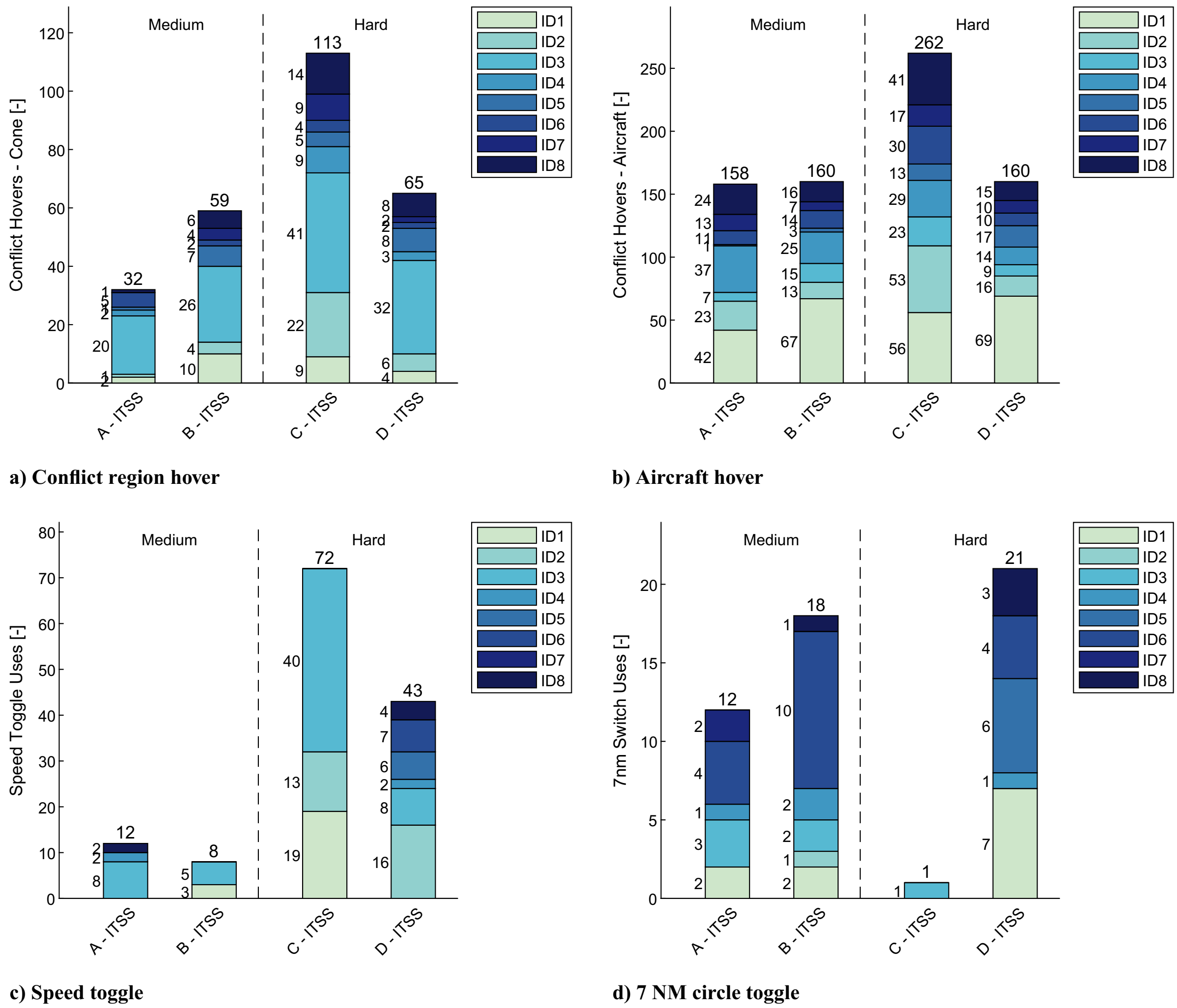


Fig. 22 Number of hovering events over a conflict region or aircraft (top row). Number of speed and 7-NM-circle toggles (bottom row), per scenario and participant ID.

been reported in earlier applications of EID-inspired interfaces in aviation [42,45]. Presumably, this type of behavior also decreased the flexibility to let participants cope successfully with unexpected events such as the "pop-up" aircraft in scenario C. More professional controllers generally tend to avoid operating close to the boundary, as they are experienced with operational uncertainties that often require them to revise earlier decisions [42].

Results further show that the additional information did not always lead to a better control strategy. Because of the predictions shown by the ITSS, participants are made aware of upcoming safety violations at a much earlier stage and are thereby stimulated to think about (and effectuate) solutions sooner. The hypothesis that workload would shift to an earlier moment in time was confirmed for some participants, but not all. It was hypothesized that working with the ITSS interface would slightly *increase* workload for the Medium scenarios, as much information had to be processed. This trend was indeed visible, but not significant. For the Hard scenarios, it was hypothesized that workload would *decrease* with the ITSS: by showing the possible solution strategies, participants could better anticipate the effects of control decisions. It became clear, however, that the additional ITSS features did not always have the desired effect. At times, some participants created hazardous situations, possibly because they were overwhelmed by the amount of information and the speed at which the difficult scenarios emerged. This is supported by user comments: participant 1 stated to be "overtaken by events," and participant 4 stated that he had "no time to use the tools." On the one hand, this confirms earlier findings that, for a complex work domain, EID-inspired interfaces can have a workload-increasing effect [24]. But on the other hand, our participants may have benefited from more extensive training, and the "pop-up" aircraft in scenario C did not help.

The difference between participants is also visible when analyzing the control commands. It was hypothesized that fewer commands would be used when using the ITSS display in the Hard scenarios. Here, the consequences of the commands are visible *at* the moment they are given, with the expectation that previous control commands no longer have to be adjusted later on in the scenario. Although a decreasing trend is found as expected, it does not occur for all participants. The decreasing trend is supported by the analysis of commands over time: as the scenario progressed, the difference between the CACS and ITSS interfaces grew.

Differences are also visible in the analysis of the use of the interface. The number of aircraft clicks indeed increases with the ITSS, since users must interact with it to obtain the additional information. A related hypothesis, that participants would use the visual assistance tools available in the ITSS interface, was partially confirmed by some participants using the functionalities much more than others. In the Hard scenarios, some participants made little use of the ITSS features. This may all change with more training.

B. Recommendations for Future Work

Earlier research shows that EID-inspired interfaces are not simple: they reflect the complexity of the work domain and will not eliminate the need for extensive learning and training [24]. Hence, a first recommendation is that more training time be scheduled, such that participants can fully understand and get used to the functionality provided by the system. More extensive training sessions will lead operators to become more proficient in using the ITSS functionalities, even under demanding circumstances.

Limited resources impacted the scope of the experiment, resulting in mostly nonsignificant data trends. Establishing data trends proved difficult due to variability in control behavior and a low sample size of eight participants. It is recommended that in addition to more extensive training, the pool of participants be increased to establish significant data trends. Time constraints restricted scenarios to just 12 min, potentially masking effects of control decisions and leading to a strong transient at the beginning of the scenarios. Hence, it is recommended that scenarios last for a much longer duration: 60 min is proposed.

In the current evaluation, wind is constant, and only arriving aircraft are included in the simulation. Future experiments should include more realistic wind and traffic conditions. Although in the current experiment the emphasis is on evaluating the usefulness of the ITSS tools and visualizations to manage arriving aircraft, it is important to include departures and crossing flights in the next evaluation. Furthermore, there is a discrepancy between the instantaneous execution of a command in the simulator and the natural delay in real operation, where the controller depends on how quickly pilots execute the commands. A sensitivity analysis to study actual and potential impacts of this discrepancy is needed.

Given the nature of the observations, it is strongly recommended to evaluate the ITSS interface with professional area controllers who are experienced with the sector's complexity and uncertainties. It is expected that while performance differences will lessen, the effects of the display will become clearer, especially in more difficult scenarios like traffic peaks.

A possible caveat here is that having accumulated years of daily experience, professional controllers may be biased toward the strategies enabled by existing interfaces. These controllers are highly proficient with the current area control system tools; however, as was discovered in the current study, their availability is extremely limited. The availability constraint of professional controllers reiterates the importance of developing and implementing the interface to facilitate safe and efficient merging tasks while taking into consideration the experience, training, and workload of operators.

Finally, in a preliminary evaluation, two professional controllers positively evaluated the ITSS while providing valuable insight for practical application and ease of interpreting the visual interface. Acknowledging the high volume and density within the display, their consideration for reducing display clutter is valuable. There is potential to reduce clutter, while maintaining the range of options, by selecting the features that are most useful in specific situations. Future research should investigate whether the benefits of additional information outweigh the impact of display clutter for professionals.

VIII. Conclusions

In this paper, novel automated design and evaluation utilizing a visual interface for approach control merging tasks are presented, using the Amsterdam South sector of Schiphol Airport, to support area controllers in the merging task. The specific dynamics of this sector—area size and traffic volume, which result in consistent high congestion challenges for area controllers—provide an excellent environment to test the results of the proposed visual interface. The interface portrays possible merging task solutions, such that the impact of decisions can be seen in advance, taking into consideration the constraints of the sector. Expert assessment from professional area controllers supports this concept and contributes to its mitigation of clutter in the display. In the experiment, the difference between the novel concept and the current system was investigated using semiprofessional participants. Results show that aircraft more often adhered to the required flight level at IAF when using the proposed interface while requiring fewer commands in more difficult scenarios. Time analysis of control commands supports expectations that fewer control adjustments are required. The new interface led participants to think about their solution strategies earlier on in the scenarios, reducing the need for multiple course alterations. Aircraft trajectories and separation at the IAF are maintained. Future research should test the interface with professional area controllers, with more extensive training on the system. Scenarios should have higher fidelity and a longer observation period to study controller performance and workload within a more steady-state workflow so that clear trends may be identified. Considering the constraints imposed by the Amsterdam South sector of Schiphol Airport, these and future research findings will be universally transferable, particularly for high-volume and high-density air traffic environments.

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J. Clarke
Associate Editor