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Visual Interface for Time-Based Separation in Approach Air Traffic Control

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On final approach, an approach controller is responsible for separating aircraft lining up on the instrument landing system. In an attempt to increase traffic throughput, especially in strong headwind conditions, European regulation advises all European airports to move from distance-based to time-based separation. This effectively changes the controller's task from a distance-based to a time-based problem. Further complications arise because of the European recategorization of aircraft types initiative, and experts fear that the gains foreseen with time-based separation will not be realized. This paper presents a visual tool integrated into the radar screen to assist controllers in performing time-based separation, the ideal turn-in point (ITIP) display. To assist controllers in selecting optimal approach strategies, starting from the moment aircraft enter the terminal control area, the display shows the possibilities and restrictions in the system rather than giving (restricting) advisories. A proof-of-concept experiment was performed with people knowledgeable in air traffic control ($N = 8$) and compared the ITIP to a current industry state-of-the-art display designed by U.K.'s National Air Traffic Services in scenarios of varying difficulty. Results show that with the ITIP tool, efficiency improved with similar or higher levels of safety and similar or lower workload. These promising results justify testing the interface with professional air traffic controllers. Future work aims at reducing clutter, increasing simulation fidelity, and increasing the level of support in complex traffic situations.

I. Introduction

AT Amsterdam Airport Schiphol (AMS), in the final phase of flight of an aircraft, an approach (APP) air traffic controller (ATCo) is responsible for guiding aircraft to the runway threshold. This is accomplished by vectoring the aircraft toward the Instrument Landing System (ILS) localizer (LOC) and glideslope (G/S) for, respectively, lateral and vertical guidance. The controller must try to be as efficient as possible; a high landing rate means more capacity for the airport. At the same time, the ATCo must guarantee safety at all times through maintaining separation buffers between aircraft. Apart from the general separation buffer for aircraft flying close to each other, an extra separation buffer should be included when aircraft are *following* other aircraft, as on final approach. The size of this last separation margin between an aircraft pair varies from 3 to 8 NM, depending on the aircraft types involved.

The exact minimum per aircraft pair is defined by the International Civil Aviation Organisation (ICAO) [1]. The current industry standard is to provide these minima as predefined *distances* in nautical miles, distance-based separation (DBS). Aircraft are divided into classes based on, among other things, their maximum takeoff weight, with currently four categories yielding 16 possible combinations of these categories. The recent European wake vortex recategorization (RECAT-EU) initiative, however, will distinguish between as much as six categories, resulting in 36 possible combinations, significantly increasing complexity for the controller. While the implementation of RECAT is not mandatory, European airports are encouraged to do so [2].

Another factor increasing the complexity of APP Air Traffic Control (ATC) in the future is the implementation of time-based separation (TBS). TBS resolves one of the main disadvantages of DBS, which is that when large headwinds are present during final approach, the landing rate is significantly decreased. A strong headwind reduces the ground speed of all approaching aircraft. When using TBS, the APP controller keeps a specified *time* between each aircraft, instead of a distance. With TBS, when large headwinds are present, the distance between aircraft may be reduced, and the landing rate is maintained. European airports are advised to implement TBS [3].

In multiple analyses, the implementation of RECAT-EU and TBS has proven to increase landing rates in strong headwind conditions [4,5]. At Heathrow airport, in 2017, the National Air Traffic Services (NATS) reported a 62% reduction in wind-related delays with up to 44 movements a day recovered [6]. Experts fear, however, that the practical gains in runway throughput will be considerably less than the theoretical gain, since the implementation of TBS will change the APP controller's task from a geometrical, distance-based problem into a time-based one. Separating based on *time* is much less intuitive than separating based on distance. After all, whereas on the APP controller's radar screen used to monitor the whole process distance can be directly observed, time is not directly observable and must be inferred from position and speed.

At London Heathrow Airport, TBS has been operational since 2015. In cooperation with the U.K.'s NATS, a display tool was developed to assist APP controllers in separating the aircraft efficiently on the ILS [6]. While this tool provides a mark on the ILS where the ATCo can "aim at" to safely separate aircraft, the tool does not provide information or support on what strategies can be used earlier on in the approach phase to get the aircraft on that mark at the right time. Support is only available in the last, least flexible stage of the approach phase, where the ATCo has very limited control options available as aircraft are already lined up with the ILS. The same holds for the Landing with Optimised Runway Delivery (LORD) interface proposed by EUROCONTROL in 2021 [7].

To better support controllers in the new task and ensure as much gain as possible from when the implementation of TBS is realized, Air Traffic Control The Nederlands (LVNL) defined a project to develop a new interface and automation. The goal of this display and tools is to assist APP controllers in selecting a flight path for

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incoming aircraft *earlier on*, i.e., from the moment the APP controller obtains control of that aircraft, when these aircraft still need to be guided toward the ILS and possibly merged with other aircraft on the runway. The novel tool should support controllers to separate aircraft on the basis of time while maintaining separation at all times. In addition to increasing landing rates and capacity, the interface also aims at reducing controller workload, avoiding last-minute corrections close to the runway.

This paper presents the first concept of such a visual interface and accompanying automation. Since TBS was planned to be operational at AMS by 2024, a major requirement for the display was that it can be implemented in the current-day work environment with relatively few adaptations and matches current-day operations, which at AMS relies on the controller issuing vectoring, altitude, and speed commands, even close to the runway. A second requirement was that LVNL's APP controllers are involved in its design and evaluation, increasing the chance that they accept the novel interface. For these purposes, the interface was developed in close collaboration with the LVNL, which also led to receiving feedback during several design iterations from professional controllers.

In addition to involving the end-users in the earliest stages of interface support design, research also shows that the level of acceptance depends on the extent to which the support system complies with the capabilities and strategies of the user [8–12]. Human operators are more likely to accept automatic systems if they remain cognitively engaged in the task [10,12–15]. The interface presented in this paper aims to visualize the possible solutions of an approach controller's task of merging aircraft toward the runway, such that the impact of possible decisions made can be foreseen (i.e., support "what-if" probing), supporting decision-making while leaving the operator in full control. This approach is in contrast to most, if not all, earlier developments, such as the (distance-based) Final Approach Spacing Tool (FAST) developed in the United States [16–19] and the United Kingdom [20], which provide the controller with computer-generated *advisories*.

The interface presented here, the ideal turn-in point (ITIP) display, shows controllers a range of solutions on how to control aircraft to the ILS, possibly merging it with other aircraft, in a time-based concept of operations. With ITIP, the operators can directly see possible options for *when* to turn an aircraft (flying on a downwind leg) to fly to the ILS (the base leg), with what heading, in what sequence, and then when to turn it to the runway, such that separation is guaranteed. No advisories are given, and the full range of solutions is displayed, leaving the controller in full control.

This paper is structured as follows: In Sec. II, the APP controller task and the display created by NATS for Heathrow are discussed. Section III presents the ITIP interface. A sensitivity analysis of the procedure underlying ITIP, as well as results of a first evaluation with professional APP controllers, is presented in Sec. IV. The ITIP interface was compared to the NATS display in an experiment, described in Sec. V, with results shown in Sec. VI and discussed in Sec. VII. The paper ends with conclusions in Sec. VIII.

II. Background

This section provides some background to understand the current, distance-based, and future, time-based, APP task at AMS.

A. APP Controller Task

The APP controller's task is to guide aircraft to the runway threshold efficiently while maintaining separation. Efficiency is measured by the number of aircraft that can land in a certain amount of time. During an arrival peak, a typical runway capacity is approximately 30 arriving aircraft per hour, one aircraft every 2 minutes [21]. The APP controller should always keep 3 NM distance between aircraft when they are flying at the same altitude. If the aircraft have at least an altitude difference of 1000 ft, the lateral separation may be smaller than 3 NM [1]. A larger separation minimum is applied when aircraft fly close behind one another; this separation is treated in Sec. II.B.

The controller guides the aircraft to the runway by directing it toward the LOC and G/S of the ILS. These are predefined paths in the airspace preceding a runway, which the aircraft can intercept using radio receivers. The LOC plane aligns the aircraft with the runway centerline, and the G/S defines the perfect altitude path for an aircraft to follow (3 deg from the touchdown point). Figure 1 illustrates the APP's electronic radar display in a very schematic way to explain our novel interface in later sections. The ILS is visualized by a green line with dots placed at every 2 NM starting from the runway threshold, which is in this and the following figures located at the bottom. An aircraft is pictured west of the ILS; here, all aircraft will be visualized with their heading angle and speed vector.

The APP controller can control aircraft in his/her sector by vectoring, i.e., giving speed, heading, and altitude instructions to the pilot of the respective aircraft via radio communication. For vectoring of aircraft, the APP controller needs to adhere to some restrictions and guidelines. First of all, commands that *increase* speed and altitude should be avoided, since aircraft need to decrease their total energy in approach. Second, the ATCo must strive to have aircraft approach the G/S from below since a G/S capture from above is more complex and can result in a high workload for the pilot. At LVNL, it is considered improper to let aircraft catch the G/S from above.

Next to these restrictions, the controller has guidelines, defining what an "ideal" approach should be. LVNL teaches these guidelines to their student controllers. In Fig. 2, an "ideal" approach trajectory for an aircraft approaching from the south is illustrated. Four points of interest are indicated; for each of those points, certain ideal commands are defined. The points are not fixed but depend on the plan of the ATCo for the aircraft under control.

The first decision point for an APP controller is the point where an aircraft starts its turn toward the ILS localizer. This point is called the turn-to-base (TTB) point. The location of the TTB point and the heading angle the aircraft is given at that point greatly influence the approach path of the aircraft and thus its landing time. For an ideal approach path, this TTB point is located such that the aircraft will travel toward the ILS at approximately 10 NM from the runway threshold with a heading angle of 90° relative to the ILS (see Fig. 2).

The second decision point the controller encounters is the turn-to-ILS (TTI) point. At this point, the aircraft starts its turn into the ILS localizer with a maximum heading angle of 30° relative to the ILS. In the example of Fig. 2, the heading angle the aircraft would be given at the TTI point is 150°. It is at this point where the ATCo clears the aircraft to intercept the ILS localizer. The aircraft can now initiate its instrument landing procedure; ATCo heading and altitude vectoring is no longer needed. Ideally, the TTI point lies at a distance of 2 NM

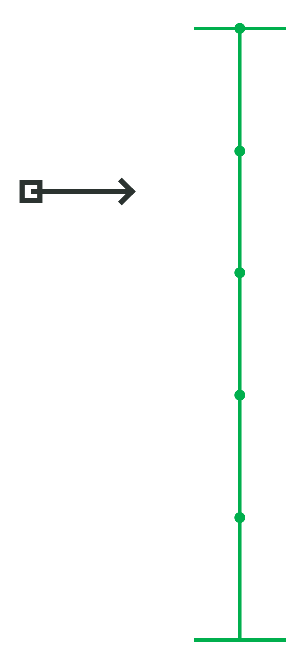


Fig. 1 Schematic representation of the APP electronic radar display, showing the ILS (green) and an aircraft (black square), its speed, and heading (black arrow).

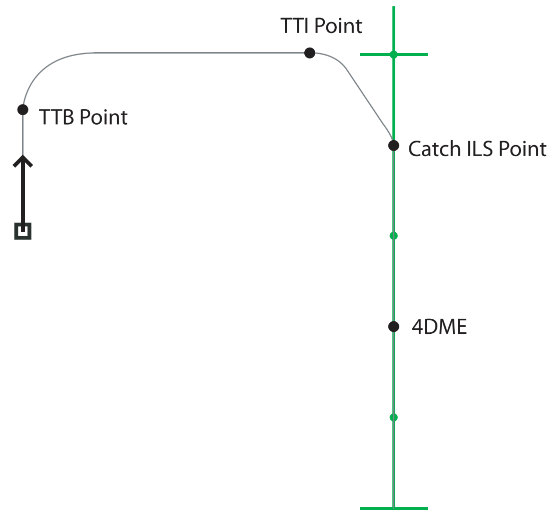


Fig. 2 An aircraft with its ideal approach trajectory, including the four points of interest.

from the ILS localizer, and a heading angle command of 30° relative to the ILS is given.

The third point of interest is the point at which the aircraft intercepts the ILS localizer, the "Catch ILS Point" in Fig. 2. Ideally, this point should lie about 8 NM from the runway threshold. From this point on, the aircraft heading and altitude is completely governed by the aircraft avionics flight control system, with the ILS signals as inputs.

The fourth and last point of interest lies at 4 NM Distance Measuring Equipment (4DME) from the runway threshold. From that moment, pilots are free to decelerate toward the landing speed as they see fit. Here, the APP controller does not direct the aircraft anymore and transfers the aircraft communication to the tower of the airport (TWR).

For each part in the approach path of an aircraft, certain speeds and altitudes are seen as ideal. An altitude of 2000 ft is considered to be ideal for the entire path up until the ILS interception, where the altitude is decreased automatically by the aircraft interacting with the ILS G/S. As such, the APP controller should strive to decrease the altitude of incoming aircraft toward 2000 ft as soon as possible. It is considered ideal for the aircraft to have an indicated airspeed (IAS) of approximately 220 kt at the TTB point, 180 kt at the TTI point, and 160 kt at the 4DME point.

B. Separation on Final Approach

When two aircraft fly closely behind one another, the follower aircraft should maintain sufficient separation with the leading aircraft to stay clear of wake vortices. The minimum separation is specified in regulations by the ICAO. The separation can be given in either a distance (leading to DBS) or a time (TBS). Whereas currently most airports use DBS, European airports are advised to implement TBS in this decade [3].

TBS has a major advantage over DBS when strong headwinds occur at the runway. At Heathrow Airport in the United Kingdom, TBS has been operational since 2015. The British NATS and EUROCONTROL have shown that the use of TBS does not increase the chance of follower aircraft encountering wake turbulence from leading aircraft [22]. While the use of TBS, in combination with RECAT-EU, can result in a permanent landing rate increase of 5–10% [5,23], it will also increase complexity for the APP task, since the time between aircraft, unlike distance, cannot be directly observed from the radar screen.

On final approach, separation between an aircraft pair will generally be at a minimum at the time the leading aircraft touches down. When assuming both aircraft to have the same final approach speeds, the separation between the lead and trailing aircraft decreases due to the leading aircraft starting its deceleration to landing speed earlier, the compression effect [24]. Hence, the APP controller must make sure that the distance between the follower and leader aircraft is always larger than or equal to the prescribed minimum *at* the moment the leading aircraft lands.

Table 1 Distance-based (in NM) and time-based (in seconds) separation minima for different wake category pairs [1,23]

	Follower							
Leader	Super		Heavy		Medium		Light	
Super	3	86	6	173	7	202	8	230
Heavy	3	86	4	115	5	144	6	173
Medium	3	86	3	86	3	86	5	144
Light	3	86	3	86	3	86	3	86

To obtain the minimum separation time in TBS, the DBS separation minimum distance is converted to a time. This is accomplished by taking the DBS minimum distance for the aircraft pair from Table 1 and calculating the time it would take the follower aircraft to traverse this distance, using the ground speed derived from an average approach IAS and an average headwind of 5 kt. In this table, the time-based criteria are computed for low headwind conditions (<5 kt) and 130 kt as average landing IAS. The average approach IAS can be obtained from data, and Table 1 also includes the separation *times* for an aircraft with an average approach IAS of 130 kt. This time is then converted to a distance again by taking the actual average ground speed of the follower aircraft, derived using the same average approach IAS but with the actual headwind at that time. This results in a smaller distance when the headwind present is larger than 5 kt.

C. State-of-the-Art: NATS Display

Since the spring of 2015, TBS has been operational at Heathrow Airport, for which NATS developed a final approach display tool to facilitate TBS operations. In this paper, this interface will be referred to as the NATS display. Unfortunately, there is little information on this tool in the scientific literature. But from a few information movies published by NATS and with the help of LVNL operational experts, a conceptual understanding of the display could be obtained.

Basically, the NATS display uses two markers: the TBS marker and the optimized runway delivery (ORD) marker. For an aircraft pair, the TBS marker can be placed by the controller at the minimum separation distance behind the leading aircraft, as computed from the minimum TBS. The follower aircraft should then never pass this marker, as this will lead to a TBS conflict. The ORD marker is a marker moving behind the TBS marker to visualize the compression effect mentioned above.

The idea behind the ORD marker is that if a follower aircraft is behind the ORD marker at any point on the ILS, no loss of separation will occur due to the compression effect. This gives ATCos a "target" to aim at when separating aircraft on the ILS. The ORD marker can be seen as a projection of the location of the TBS marker at the moment the leading aircraft lands, relative to the follower aircraft.

Figure 3 illustrates both markers, with the TBS marker as the red dot and the ORD marker as the blue dot. The markers are given for an aircraft pair where aircraft A and B are the leading and follower aircraft, respectively. Three situations are illustrated, from left to right: 1) both aircraft before the 4DME point, 2) the leading aircraft passed the 4DME point, and 3) the leading aircraft just before landing.

In situation (1), the aircraft travel behind one another with the same ground speed, as both fly at an IAS of 160 kt and at an altitude of 2000 ft. Since the ground speed of both aircraft is the same, the separation (in distance and time) will remain the same. The aircraft are safely separated; aircraft B is behind the red TBS marker, created behind aircraft A. The blue ORD marker lies behind the TBS marker; the distance between both markers equals the distance that the follower aircraft is predicted to gain on the leading aircraft.

In situation (2), aircraft A has passed the 4DME point and thus started its deceleration. The follower aircraft has not yet passed the 4DME point and still travels with an IAS of 160 kt. The follower aircraft is thus catching up to the leading aircraft, as depicted by the

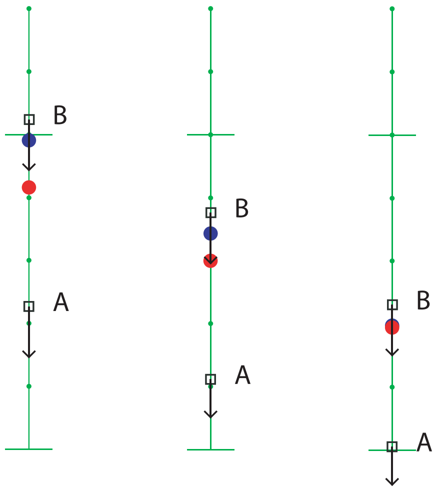


Fig. 3 The NATS display, schematically illustrated for an aircraft pair (A, B) in three situations.

decrease in distance between the TBS and ORD markers. Note that, while the distance between the TBS and ORD marker has decreased, the distance between the follower aircraft and the ORD marker has remained constant.

In situation (3), just before the leading aircraft lands, the ORD marker lies almost exactly on top of the TBS marker since the follower aircraft will not further catch up to the leading aircraft before it lands.

As mentioned earlier, the NATS display provides an aiming target to safely separate aircraft while being on the ILS. It does not provide support on when and how aircraft can be directed earlier on in the approach (e.g., when and how to best intercept the ILS) to get the aircraft on that target at the right time.

III. New Concept: The Ideal Turn-In Point (ITIP) Interface

A. Design Requirements

For the designed display, the main design drivers for LVNL were as follows:

1) The tool should help APP controllers in their task of separating aircraft based on time.

2) The tool should assist the controller in the early stages of approach control (from sector entry to ILS catch).

3) It should be possible to implement the tool in the current radar screen of the LVNL with minimum adaptations.

Since the tool was to be implemented in LVNL's current systems, it should be compatible with the current workflow of the APP controllers. The tool should be an (ideally, small) addition to the current electronic radar screen, rather than portraying it on a secondary screen. For APP controllers to accept and use the tool, it should avoid cluttering the existing radar screen with too much information, the most often heard concern of APP controllers at the start of the project. The chances of an operator accepting a new display tool increase when that tool leaves the operator in control; the display tool must show the operator the options in the system rather than giving advisories, as operators are shown to resist automation that takes control away from them [9].

From these goals, the main design requirements were defined:

1) The tool should be designed such that display clutter is avoided.

2) The tool should show all control options to the controller rather than advising the controller on, or limiting the controller to, a specific solution, leaving the controller in full command.

Because user acceptance is of major importance for this display and because the aim is to leave the APP controller in full control rather than taking control away from her or him, the design approach was inspired by ecological interface design (EID) [25,26]. EID is meant to support professionals working in complex systems and aims to reveal the "affordances" of the work domain while keeping users in full control. An affordance describes opportunities for action for the goal-relevant properties of a system [14,15,26,27].

Since this display is a first concept, it was chosen to include several functionalities in the design all at once. Although this will most likely result in some display clutter, it allows us to investigate what functionalities could be the most useful to an APP controller. The design can then be further iterated upon; e.g., the functionalities deemed the most useful could be included in the final design, in the least-cluttered way, and others eliminated.

B. Ideal Turn-In Point Display: ITIP

The path an aircraft takes is a significant variable in the time it takes for an aircraft to land. The major variables defining this path are the points where the aircraft turns toward the ILS (turn-to-base or TTB Point), the point where an aircraft turns into the ILS (turn-to-ILS or TTI point), and the heading commands given at these points (see Fig. 2). Of lesser importance for the arrival time of an aircraft are its speed and altitude since ideally these are already well-constrained (the responsibility of the previous ATCo dealing with that aircraft), and only deceleration and descend commands are given.

A concept display, the ideal turn-in point display, or ITIP display, was designed to assist approach controllers in their early decision-making, taking the future aircraft path as the variable of interest. It visualizes possible TTB and TTI points, along with possible turn headings, such that aircraft will be efficiently separated on the ILS, without compromising safety. The display first provides support to the APP controller for the possible TTB points and, further on the trajectory, support for choosing the TTI point. Support is displayed for an aircraft only when that aircraft is selected by the controller. The TBS marker as used by the NATS display is then also included.

All functions of the ITIP display will be discussed in this section. The computer algorithm underlying all calculations of display elements is briefly discussed in Sec. III.B.6. Note that, in all of the figures in this section, a strong wind to the northeast (top right) is assumed present to illustrate its effect on aircraft trajectory. Further note that the display aims at supporting the basic approach geometry applied at AMS airport and is therefore a simplification for other, more complicated airports.

1. ITIP Ideal Turn-In Points and Trajectory Prediction

In Fig. 4, the ITIP display is shown for a selected aircraft (B) that has not yet turned to base. The leading aircraft is aircraft A, for which the TBS marker is shown using the red dot, similar to the NATS display. The main new display feature is an array of small green and red dots. Each dot represents a future location of the aircraft if its heading angle were to remain unchanged. The display assumes that the controller will follow the ideal speed and altitude guidelines as described in Sec. II.C. A dot is visualized for every 5 s in the future, which is equal to the radar update rate in the simulator and in most real-life ATC applications. Each dot in the display represents a TTB possibility. The TTB dot is green when the algorithm predicts that the trajectory resulting from turning to base at this point is feasible. Here, feasible means that the aircraft catches the ILS from below and the aircraft will be separated on final approach from its leading and follower aircraft. A red TTB dot indicates a conflict; either the resulting trajectory will result in loss of separation on the ILS or the aircraft will capture the ILS from above.

In Fig. 4, the controller hovered the mouse over the first green dot, causing the interface to show a number (here 90), which is the default heading command to intercept the runway. The operator can change this heading by scrolling the mouse wheel, as will be explained later. The interface also shows the predicted trajectory of the aircraft when the heading command would be given, shown in magenta. The trajectory prediction uses a wind estimate (here the wind flows to the northeast), causing the ground trajectory to be slightly drifted (to the northeast). This is because the controller issues a heading command, not a ground track command.

The algorithm assumes that the controller will take the quickest feasible route; i.e., it assumes the controller to pick a TTB point such that the total time traveled will be minimized while making sure that

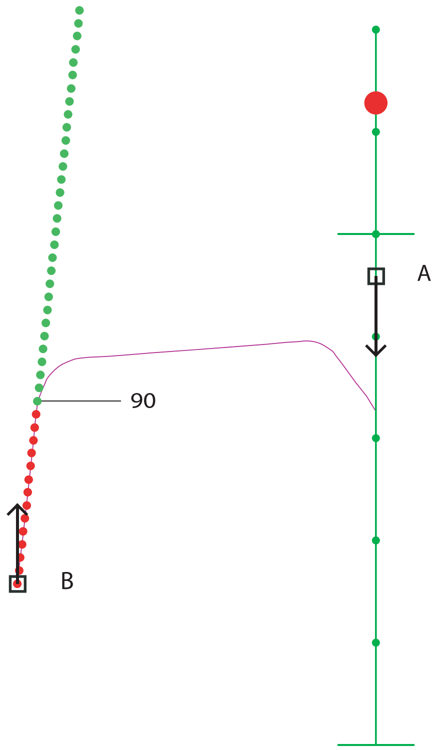


Fig. 4 The ITIP display for a selected aircraft (B) that has not yet received a TTB command.

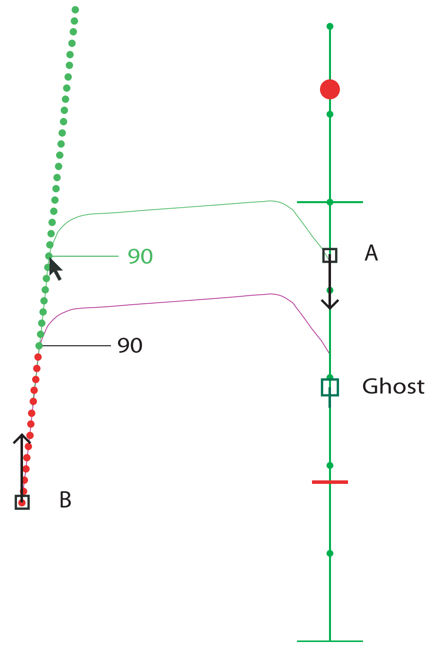


Fig. 5 The ITIP display for a selected aircraft (B) that has not yet received a TTB command when hovering the mouse over a green TTB point.

the trajectory is feasible. The controller can update this prediction by clicking on one of the dots, thereby indicating to the interface which strategy he/she is going to use. When clicking on a TTB point, the algorithm will update the prediction to a TTB at this point. Simultaneously, the data used for the plotting of the displays for all other aircraft will be updated with this new information. This way, controllers can *probe* their plan to the algorithm so that they can see if and how a certain path change will affect the solution space for other aircraft.

If the aircraft travels beyond the predicted turn-in point, the algorithm will assume that the aircraft will turn at the next turn-in point, effectively "pushing" the turn-in prediction forward.

2. *ITIP Trajectory Preview and Separation Ghost*

In the simulator, the controller can use the computer mouse to hover over all the dots of the TTB part of the display. Doing so will plot the predicted trajectory resulting from a TTB at this point, as can be seen in Fig. 5. The trajectory will be green if it is possible for the aircraft to take this trajectory; i.e., it does not cause a loss of separation on final approach or the aircraft catching the ILS from above. This is the case for the situation in Fig. 5. If the trajectory would result in loss of separation or the aircraft catching the ILS from above, the trajectory will be plotted in red.

In addition to plotting the predicted trajectory when hovering the mouse over a TTB point, the algorithm also shows a ghost aircraft on the ILS. The location of this ghost aircraft is equal to the location at which the selected aircraft is predicted to be at the time its leading aircraft lands. A small red horizontal line segment is shown on the ILS, representing the minimum separation the aircraft must have with respect to its leading aircraft. This way, the controller can assess the resulting separation at the moment the leading aircraft lands if the aircraft were to turn to base at the selected TTB point. To maximize throughput, aircraft must be as close to the TBS marker of a leading aircraft as possible at the moment the leading aircraft lands. Using the ghosting tool, one can quickly investigate which solution is optimal, when deciding which aircraft to send to the ILS and with what path.

3. *ITIP Heading Angle Preview and Manipulation*

In addition to the predicted route, the heading angle command that should be given at the TTB point is shown. This serves as a reminder to the controller. The controller can *vary* this heading angle by hovering over a turn-in point and using the mouse scroll wheel to adjust the heading angle, as can be seen in Fig. 6. Scrolling upward will increase the heading angle (clockwise), and scrolling down will decrease the heading angle (counterclockwise), up to some limits.

When adjusting the heading angle, the algorithm will directly assess separation at landing and path feasibility, changing the color of the drawn path accordingly. In case a TTB point is red, the controller can search for a heading that would result in that point

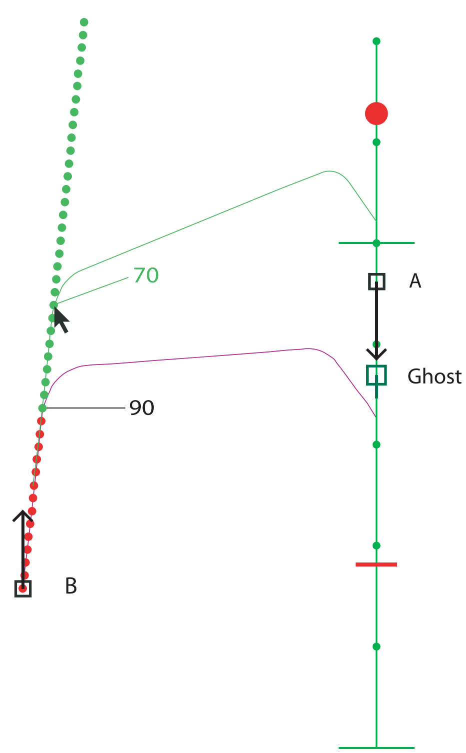


Fig. 6 The ITIP display for a selected aircraft (B) that has not yet received a TTB command while hovering the mouse over a TTB point and scrolling the mouse wheel to adjust the TTB angle.

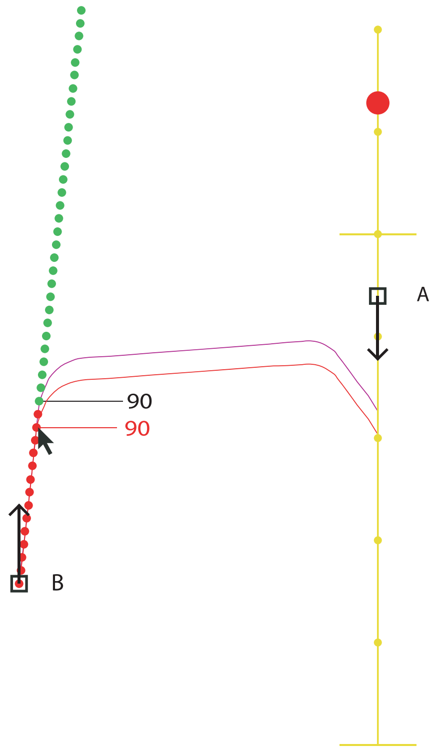


Fig. 7 The ITIP display for a selected aircraft (B) that has not yet received a TTB command while hovering over an infeasible TTB point due to the aircraft having to catch the ILS from above.

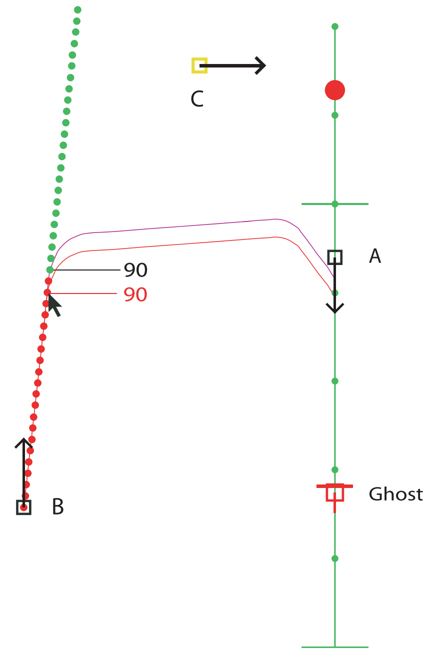


Fig. 8 The ITIP display for a selected aircraft (B) that has not yet received a TTB command while hovering the mouse over an infeasible TTB point due to a predicted loss of separation on the ILS with aircraft C.

being green and update the chosen angle by clicking the mouse. This will update the predicted heading angle for the TTB, the color of the dots in the display, and the updated angle is used as the heading angle for every TTB point. This allows controllers to assess how a change in TTB angle would impact the aircraft solution space.

4. *ITIP Highlighting of Cause of Trajectory Infeasibility*

If the plotted trajectory would result in a loss of separation on final approach, or if the trajectory is infeasible because of the aircraft having to catch the ILS from above, the trajectory will be drawn in red. This situation can be seen in Fig. 7. Here, the predicted trajectory resulting from a TTB at the selected point would result in the aircraft having to catch the ILS at less than 6.3 NM from the runway threshold, which would mean an ILS catch from above for an aircraft flying at an altitude of 2000 ft. In the simulator, if an infeasible trajectory is plotted when hovering over a point, the algorithm highlights the cause of the trajectory being infeasible. Here, the ILS is highlighted (yellow). As one can see, the ghost aircraft is not drawn for this case since separation is not the reason for the trajectory being drawn in red.

When separation is the reason for the trajectory being plotted in red, the display will highlight the aircraft with which a loss of separation is predicted to occur. This situation is illustrated in Fig. 8. In this figure, aircraft A and C have been previously dealt with and follow their predicted trajectories. When working with aircraft B, hovering the mouse over the red TTB dot automatically highlights the aircraft (yellow square) with which it would result in a loss of separation (here, aircraft C) when issuing this TTB command. On the ILS, the resulting separation can be previewed; the ghost location lies *before* the TBS marker, indicating a loss of separation will occur at the moment aircraft C lands.

5. *ITIP TTI Support*

The TTI support of the display, shown in Fig. 9, operates similarly as for the TTB decision, the major difference being that it is only visualized when selecting an aircraft flying toward the ILS. The boundaries with which the controller can change the turn-in angle are such that the angle with respect to the ILS can only be 30° or less,

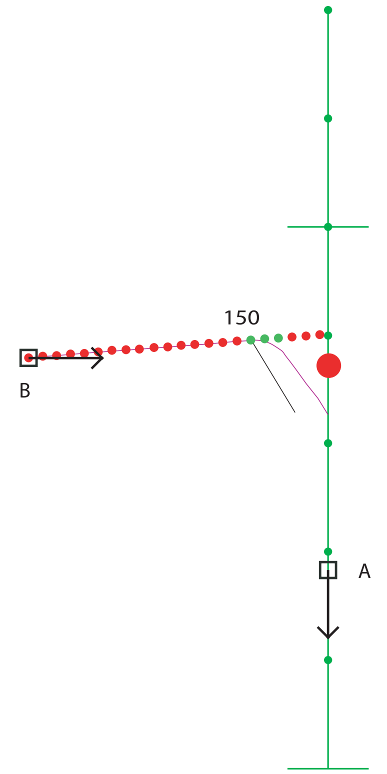


Fig. 9 The ITIP display for a selected aircraft (B) that is traveling toward the ILS.

up to 5°. All other functions work exactly the same as for the TTB support stage of the display; the cause of trajectory infeasibility will be highlighted when plotting a trajectory in red, the separation result will be visualized using ghost aircraft, and the controller can update the trajectory prediction by clicking TTI points and scrolling to adjust the turn-in angle.

Note that the TTI location impacts the final arrival time much less than the TTB location, as will be discussed in Sec. IV. As such, the TTI support can be used for smaller efficiency improvements and minor error corrections, whereas the more influential TTB support is used for selecting the main aircraft path.

6. *ITIP Display Algorithm*

To calculate whether a TTB point is feasible, the display algorithm integrates the predicted path and compares the predicted landing times of the selected aircraft with all aircraft that have received a TTB command. Aircraft that have not yet received a TTB command are considered "undecided"; taking these aircraft into account for the predictions would result in inaccurate visualizations since nothing is known about the controller's intentions with these aircraft. As soon as an aircraft receives a TTB command, the trajectory prediction is seen as more reliable.

When integrating the total path, the algorithm first decides which phase of approach the selected aircraft is in. Depending on the aircraft heading, location, and controller commands, the algorithm predicts if an aircraft still needs to turn to base or if it has already turned to base. Similarly, it predicts whether the aircraft has turned into the ILS or not. After the phase of approach is determined, the algorithm integrates the path that the aircraft has yet to take.

The path is integrated by first deriving the ground speed and flight path angle of the aircraft from its IAS, altitude, and wind speed and direction. A constant heading angle is assumed for all straight paths of flight, except when the aircraft has intercepted the ILS; here the heading angle is such that it counteracts drift caused by wind. For parts of the path where the aircraft is turning, the turn rate is derived assuming a constant bank angle and ground speed.

To predict the aircraft trajectory, the algorithm assumes that aircraft will follow the APP controller guidelines of Sec. II.C. First, it assumes that aircraft will slow down to an IAS of 220 when it has a higher IAS at that time and it has not yet received a TTB command. Second, the aircraft will slow down to 180 kt as soon as the TTB command is given and further slow down to an IAS of 160 kt when the aircraft is on the ILS. Third, the assumption for altitude is that aircraft will descend to 2000 ft as soon as possible. Deviation from these guidelines is possible and in some cases encouraged, but controllers should be aware of the implications when deviating from these reference guidelines.

IV. Concept Sensitivity Analysis and First Evaluation

This section will first discuss results of a sensitivity analysis performed to test the consequences of a 5 s delay in the controller's control actions on the approach landing time in several phases of the approach. The concept was further evaluated by two professional APP controllers at LVNL, and their comments are briefly summarized.

A. Trajectory Prediction Sensitivity Analysis

A possible weakness of the use of the ITIP display could be its dependence on trajectory predictions. Discrepancies in the landing time prediction can be caused by varying pilot response times or by the ATCo reacting later than anticipated. While the APP guidelines described in Sec. II.C are taught at the LVNL, individual ATCos will have their own strategies and common practices. Both situations are basically the same; the aircraft executes a control action later than expected. To assess how this affects landing time predictions, a sensitivity analysis has been performed.

To analyze this effect, the difference in landing time was plotted for certain control actions if these actions were to be delayed by 5 s (common traffic radar update frequency). The impact of delaying these actions was plotted for an array of wind headings, ranging from −45° to +45°, with 0° being a direction to the north, i.e., pure headwind at approach. Five wind velocities were used, ranging from 5 kt (standard headwind) to 25 kt (strong headwind).

The six controller actions for which the effects of issuing these actions 5 s later on the landing time of an aircraft were assessed are as follows:

1) Turning to base
2) Decelerating from 250 to 220 kt when flying parallel to the ILS
3) Descending from an altitude of 5000 ft to 2000 ft when flying parallel to the ILS
4) Turning into the ILS
5) Decelerating from 220 to 180 kt when flying toward the ILS
6) Decelerating from 180 to 160 kt when lined up with the ILS

These six actions represent the standard decision points in an aircraft approach (see Fig. 2) and are thus most likely to be delayed. The analysis was performed for one selected aircraft, "medium" type, flying at 2000 ft. For evaluating the first three actions, the aircraft was located at 8 NM to the west and 8 NM to the north of the runway threshold with a heading of 0°, and speed of 250 kt IAS. For the fourth action, the aircraft was located at 8 NM to the west and 10 NM to the north of the runway threshold with a heading of 90°. The fifth action had the aircraft located at 2 NM to the west and 10 NM to the north of the runway threshold with a heading of 90° and IAS of 180 kt. The sixth action was analyzed for the aircraft on the ILS, 8 NM to the north of the runway threshold.

Note that the data presented in this section are taken from simulator experiments. Due to simulation discretization effects, small ripples were present in the data. A second-order polynomial function was fit on the data to capture the main effect. In the following, the effects of delaying the six actions will be discussed one by one.

Figure 10a shows the landing time delay for a 5 s TTB delay. Clearly, the wind velocity has a large impact. The main parabolic effect of the time delay graph can be explained by the TTB delay lengthening the trajectory; a TTB delay increases the trajectory length by the aircraft traveling away from the runway but also by the aircraft drifting to the side by the wind. These effects cause a maximum value; i.e., there exists a certain wind angle (≈−20°) where the landing time delay due to 5 s TTB delay is at a maximum. Increasing wind velocities increase the landing time delay; for stronger winds a lengthened trajectory will result in more lost time. Up to 14.2 s of delay can be present, almost tripling that of the 5 s TTB delay.

Figure 10b shows the effect of delaying the deceleration from an IAS of 250 to 220 kt, while the aircraft is flying parallel to the ILS on the aircraft landing time can be found. The delay is always negative since a deceleration delay results in the aircraft flying at a higher ground speed for a longer period of time. The landing time deviation decreases for increased wind velocities and lightly varies with wind direction; at approximately −30°, the time deviation seems not to be influenced by the wind velocity.

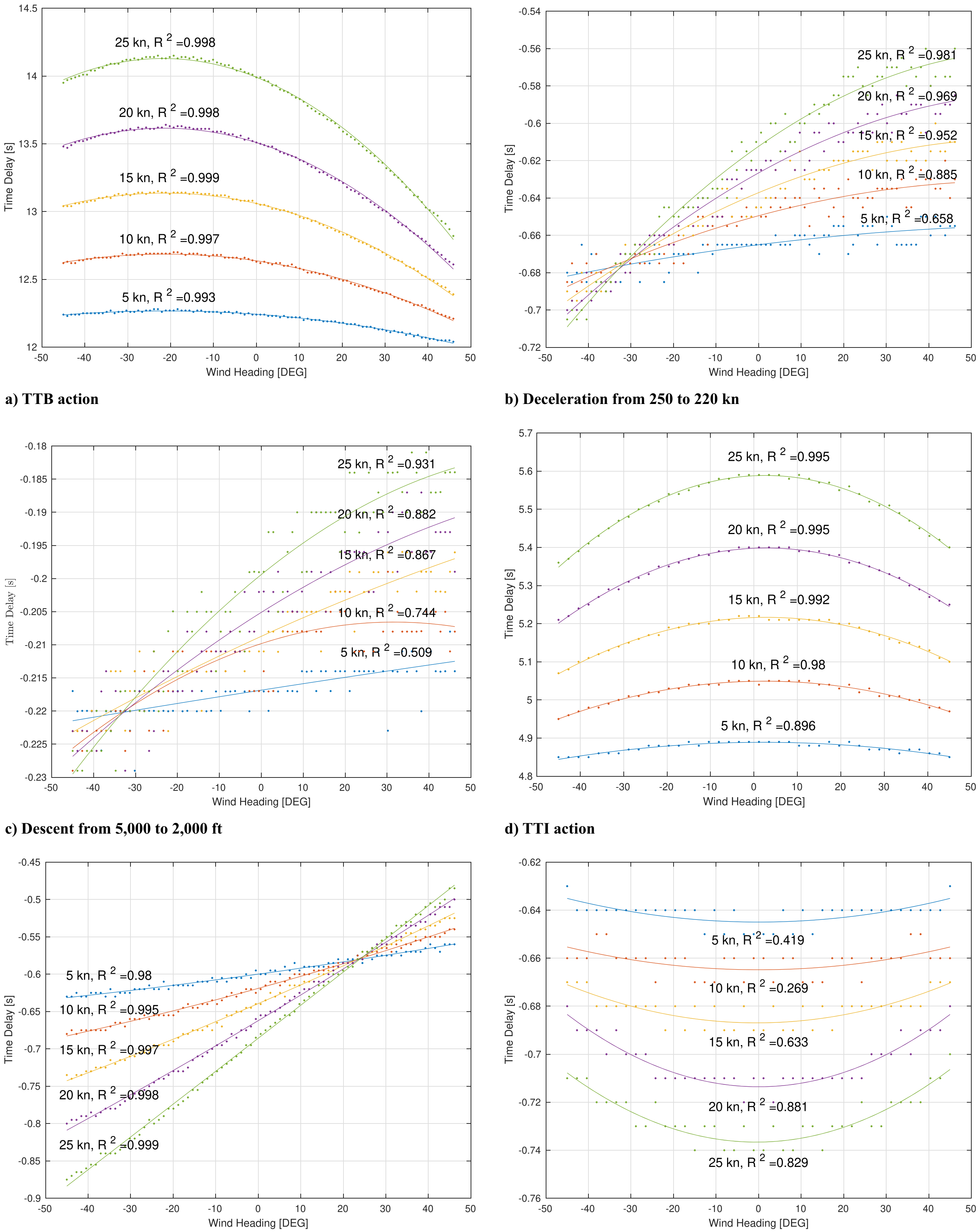
Figure 10c shows the landing time delay for a 5 s descent delay for an aircraft flying parallel to the ILS. The impact is minimal; the landing time prediction can only be shortened by 0.23–0.18 s. The shape of the time delay is approximately the same as for the deceleration delay, the difference being the magnitude of the effect, amplifying the signal-to-noise ratio for these data.

Figure 10d shows time deviations for a 5 s TTI delay, which largely follow the same pattern as the TTB delay but with a smaller magnitude. The main parabolic effect can be explained by the difference in path length the TTI delay causes; since the majority of the path after the TTI consists of the aircraft traveling in the opposite direction to the wind, a wind with a heading of 0° will result in the largest delay for an increased path length.

Figure 10e shows effects of a 5 s delay on decelerating from 220 to 180 kt. As could be expected, the effect bears resemblance to the deceleration delay for an aircraft flying parallel to the ILS. The time delay increases for increased wind heading, and the effect of wind heading angle is more pronounced for higher wind velocities.

Figure 10f illustrates effects when the aircraft decelerates from 180 to 160 kt 5 s later. The delay is symmetrical around 0°, as can be expected with the aircraft on the ILS. For larger headwinds, aircraft arrive slightly *earlier* when decelerating 5 s later.

Clearly, the timing of the TTB action and, to a lesser extent, the TTI action are crucial. This is exactly where the ITIP display supports the ATCo in the control actions well before the aircraft is aligned with the ILS. Furthermore, in larger headwind conditions, deviations from the "ideal" action times will have a bigger impact for those actions that are the most influential, i.e., the TTB, TTI, and deceleration to



a) TTB action

b) Deceleration from 250 to 220 kn

c) Descent from 5,000 to 2,000 ft

d) TTI action

e) Deceleration from 220 to 180 kn

f) Deceleration from 180 to 160 kn (on ILS)

Fig. 10 Landing time delay caused by a 5 s delay in six control actions (multiple wind settings).

160 on the ILS actions. This result is important since the ITIP interface is developed for TBS, a concept where the most efficiency gains are accomplished in strong headwind conditions. The interface is thus more susceptible to ATCo (or pilot) response time deviations when strong headwinds are present. Next to this being a possible weakness of the display algorithm, this finding also underscores the importance of precise action timing and support thereof, especially in strong headwind conditions.

B. Evaluation of the Concept with Professional Controllers

The concept has been proposed to two professional APP controllers at LVNL. In these test sessions, the controllers used the ITIP display and the NATS display in a simulated environment and provided feedback on their experience.

The opinions of the controllers were diverse; one controller was very positive; he found the ITIP display to be a "great experimental tool that could be a great benefit in real life to support or help controllers optimize the final approach." He noted that he strongly believed that, with further iterations, the ITIP display should be (partly) implemented in future APP control. He found that the ITIP display was more useful than the NATS display, and he experienced no increased display clutter when using it. This controller used the interface primarily to confirm his own flight path strategy. He noted that speed advisories might be added for a future display iteration.

The second APP controller stated his interest in the TTI support of the display. However, he noted that "at the moment [he does not] need additional support, just the TBS indicator." He found that "more support leads to a more passive controller and might delay corrective actions if needed."

These comments are in line with expectations and previous evaluations of ATC support interfaces [28,29]. Some ATCos are positive toward new display tools and welcome more, newer forms of support. Other, more conservative controllers tend to rely on their current tools and are suspicious of large adaptations to their trusted work environment.

After this first evaluation by professional area controllers, the effects of the proposed ITIP interface on performance and workload were investigated experimentally, discussed next.

V. Experiment

To investigate operator performance with the ITIP interface, a proof-of-concept experiment was conducted. Professional controllers were not available; our participants were eight persons with extensive ATC knowledge. These participants played out APP scenarios in real time, both with the NATS display and with the ITIP display.

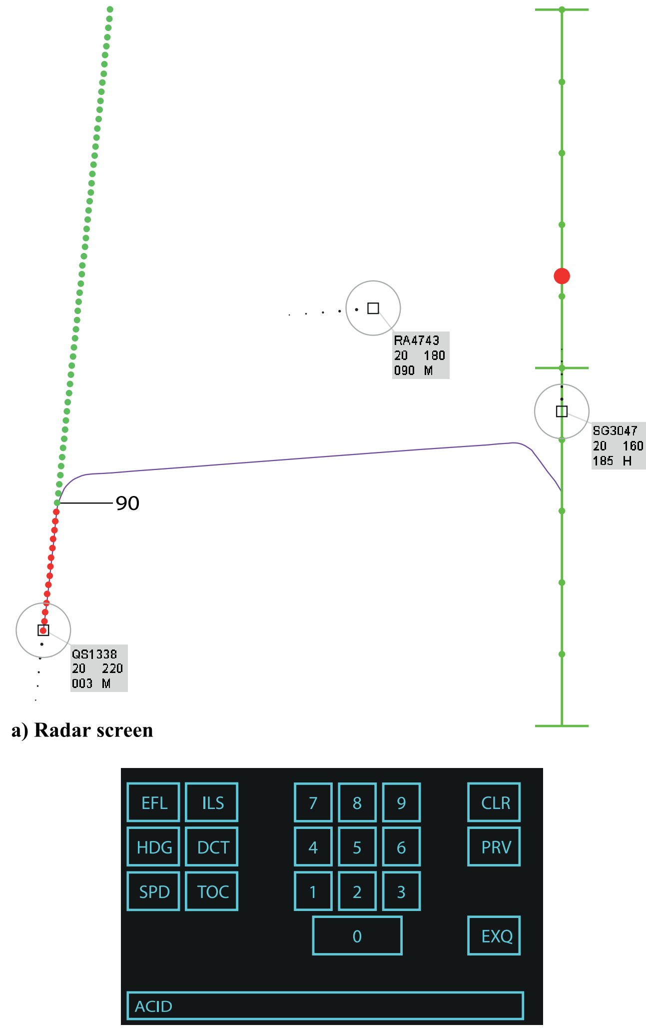
A. Apparatus

The experiment was performed in a closed room at the TU Delft Aerospace Engineering faculty. Participants used one monitor for the radar screen (Fig. 11a) on their left-hand side and one for the LVNL command interface (Fig. 11b) on their right (both 1920 by 1080 pixels resolution). All commands were given by a mouse, through first selecting the aircraft on the left monitor and, subsequently, clicking the buttons on the command window on the right monitor.

Figure 11a illustrates the radar screen, with colors changed for this paper. The radar screen background was black; all other colors were as indicated. Participants used the mouse to select aircraft, manipulate their labels, and work with the ITIP interface integrated into the radar screen as explained in Sec. III. The aircraft labels showed, starting from the top left, the aircraft call sign, flight level, speed in IAS, heading, and weight class. At AMS, the IAS is known through Mode-S Enhanced Surveillance radar data.

In real-life operation by LVNL at AMS, APP controllers use radio communication to issue instructions to aircraft and then simultaneously input these commands (using a touch screen) to a command interface (Fig. 11b). In the simulator, radio communication was *not* used. Participants could give all the basic commands to an aircraft that an APP controller would give in a real-life situation: heading, altitude, and speed commands, as well as clearing the aircraft to catch the ILS using the "ILS" button (see Fig. 11b).

In the simulation, a number of modeling assumptions were made. All aircraft respond *immediately* to the given commands: pilot reaction delay times were set to zero. The aircraft turned with a maximum bank angle of 30°, and accelerated and decelerated with 2 kt/s. Their rate of climb varied from 470 ft/min for a medium aircraft to 3160 ft/min for a heavy aircraft; the rate of descent varied from 1345 ft/min for a heavy aircraft to 2580 ft/min for a medium aircraft.



a) Radar screen

b) Command interface

Fig. 11 Radar screen (top) and LVNL command interface as implemented in the simulator.

The International Standard Atmosphere model was used to calculate ground speed from IAS and altitude.

In the simulator, only aircraft of type "medium" and "heavy" were present, and the current separation minima of Table 1 were used. For future research, the six RECAT-EU categories [2] can be implemented with relative ease. It was considered outside the current scope as first the effects of the ITIP display should be sufficiently tested.

B. Participants, Instructions, and Procedure

The experiment was approved by the TU Delft Human Research Ethics Committee and involved eight subjects. All were knowledgeable in ATC operations as they had previously taken part in an extensive 5-day ATC course at the Netherlands Aerospace Centre (NLR). They were instructed to optimize efficiency in the scenarios: maximize throughput by landing as many aircraft as possible while keeping separation at all times.

A within-subjects design was chosen where all participants performed all conditions. Two "easy" and two "hard" scenarios were designed. All participants played through these scenarios, both with the NATS and with the ITIP display, totalling four measurement runs per participant.

Before the measurement, each participant received 75 min of training. The first 15 min without a support interface, with just a few aircraft to be controlled to the runway, mainly for the participants to get accustomed to the experimental setup, the task, and the command interface. Then the participants practiced using the support interfaces: 30 min with the NATS display and 30 min with the ITIP display. The measurement runs were balanced such that each possible order of measurement runs was given to one participant; they took about 15 min each.

C. Independent Variables

Two independent variables (IVs) were defined:

1) The display type (two levels): the NATS display or the ITIP interface

2) Scenario difficulty (two levels): easy and hard

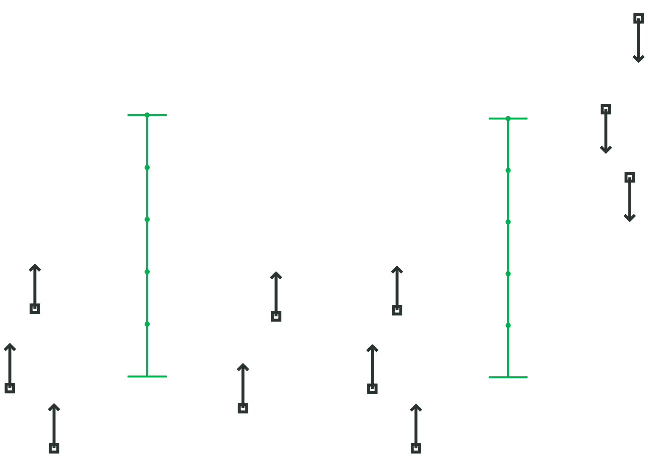
A factorial design led to four experimental conditions.

The motivation for testing two scenario difficulties was the possibility that participants would conduct the easy scenarios perfectly, not showing any performance deviation between the NATS and ITIP displays. For the more difficult scenarios, the deviations were expected to be more pronounced.

In the easy and hard scenarios, the number of aircraft arriving in the TMA was the same, but the direction in which the aircraft arrived differed. The easy scenarios featured traffic arriving from the south, at both the east and west sides of the ILS, as can be seen in Fig. 12a. For the hard scenarios, traffic arrived from the south on one side of the ILS and from the north on the other side of the ILS (see Fig. 12b). While merging all aircraft on the single runway, participants were instructed to apply reasonably staggered (3 NM or more) intercepts.

All aircraft arrived with speeds ranging from 220 to 250 kt, at an altitude of 2000 ft. The reason for changing the direction of arriving traffic to vary scenario difficulty, as opposed to increasing the number of aircraft, was to avoid measuring the obvious increase in efficiency when more aircraft were present in a scenario.

For both the easy and the hard scenarios, two versions were made (V1 and V2), with small deviations (e.g., aircraft callsigns, headings, arrival intervals) to prevent scenario recognition by the participants [30]. The order in which participants received these different versions and the combination with displays with which they received them was balanced. The balanced within-subjects design matrix can be found in Table 2.



a) Easy scenario b) Hard scenario

Fig. 12 Examples of an easy and hard scenario.

Table 2 Within-subject design experiment matrix (E = easy, H = hard)

Participant	Run 1	Run 2	Run 3	Run 4
1	NATS, E, V1	NATS, H, V1	ITIP, E, V2	ITIP, H, V2
2	ITIP, E, V2	ITIP, H, V2	NATS, E, V1	NATS, H, V1
3	NATS, H, V1	NATS, E, V1	ITIP, H, V2	ITIP, E, V2
4	ITIP, H, V2	ITIP, E, V2	NATS, H, V1	NATS, E, V1
5	NATS, E, V2	NATS, H, V2	ITIP, E, V1	ITIP, H, V1
6	ITIP, E, V1	ITIP, H, V1	NATS, E, V2	NATS, H, V2
7	NATS, H, V2	NATS, E, V2	ITIP, H, V1	ITIP, E, V1
8	ITIP, H, V1	ITIP, E, V1	NATS, H, V2	NATS, E, V2

In the scenarios, a wind of 25 kt was present, coming from the south. For the easy scenarios, this wind had a heading angle of $\pm 10°$; for the hard scenarios, a heading angle of $\pm 15°$ was used. The wind direction was varied to further distinguish between the scenarios, not to increase or decrease scenario difficulty.

D. Control Variables

A number of control variables (CVs) were identified:

1) The sector geometry with the runway and ILS location

2) The number of aircraft in each scenario

3) The update rate of the traffic (each 5 s)

4) Aircraft performance

5) Aircraft altitude at TMA entry

6) Type of aircraft mix

The sector used was a square of 72 by 72 NM, corresponding to the radar screen used at the LVNL, which is a circle with a radius of 36 NM. The runway was located in the middle, and the ILS was directed due north. In each scenario, 11 aircraft would enter the sector. Traffic was updated every 5 s, the standard radar update frequency at LVNL. In the scenarios, only medium and heavy aircraft types were used. The traffic mix corresponded to that at AMS; 10% of the aircraft was of the type heavy and 90% of type medium.

E. Dependent Measures

The main variables of interest were safety, efficiency, and workload. For determining *safety*, the following dependent measures (DMs) were measured during the runs:

1) Number of TBS conflicts

2) Average intrusion

3) Average conflict duration

4) Average distance from the runway at conflict initiation

Here, one TBS conflict is counted when a follower aircraft intrudes on the minimum separation behind a leading aircraft on the ILS, irrespective of the conflict duration. For every conflict, the maximum distance that the follower aircraft intrudes on its minimum separation is also stored and divided by the number of total TBS conflicts to get the average intrusion. The duration of the conflict in seconds is also logged, as well as the distance from the runway at the time the conflict is initiated. An increase in the amount of conflicts, average intrusion, average conflict duration, and average distance from the runway at conflict initiation could indicate decreased safety.

For determining *efficiency*, the following DMs were measured:

1) Average time separation buffer per landed aircraft

2) Landing rate

3) Distance from runway to ILS catch point

4) Number of nontreated aircraft at the end of the scenario

The separation buffer is the spare amount of separation in seconds between an aircraft and its leader at the moment the leading aircraft lands. A lower separation buffer would indicate a more efficient solution. The landing rate is equal to the number of aircraft landed per hour, starting from the time at which the first aircraft lands. A higher landing rate would indicate higher efficiency. The point at which the aircraft catches the ILS is also logged. When aircraft catch the ILS at a larger distance from the runway, capacity is considered *decreased* since there is less room on the ILS. The number of nontreated aircraft is the number of aircraft that have not yet received a TTB command at the end of the scenario and are thus considered "untreated" by the participant. More nontreated aircraft would indicate lower controller capacity and thus a lower efficiency. Nontreated aircraft continued flying along their downwind trajectory.

Controller *workload* is the workload as experienced by the participants. A subjective rating scale (on paper) was given after each run in which participants could mark the perceived workload on a Rating Scale Mental Effort (RSME [31]) for that specific run. The RSME consists of a vertical line ranging from 0 to 150 (usually in mm), marked with nine anchor points describing the degree of mental effort. The first anchor point is described as "absolutely no effort" (level at 2 mm) and the ninth anchor point as "extreme effort" (level at 113 mm).

A distinction was made between three kinds of workload: overall workload, physical workload, and mental workload. Hence, the RSME ratings were given three times. Physical workload reflects the effort in interacting (clicks and scrolls) with the proposed system using the computer mouse.

Next to these numerical data, at the end of the experiment, participants were asked to complete a postexperiment questionnaire, a survey with questions about both displays, allowing them to submit their opinion and comment on the simulation and interfaces.

F. Hypotheses

The first hypothesis (H.1) is that the use of the ITIP display will at least maintain safety with respect to the NATS display. That is, the use of the ITIP display will result in 1) the same amount of TBS conflicts (or less), 2) the same (or less) average intrusion, 3) the same (or less) conflict duration, and 4) the same (or less) average distance from the runway at conflict initiation.

The second hypothesis (H.2) is that the use of the ITIP display will increase efficiency with respect to the NATS display. That is, it will result in 1) a smaller separation buffer, 2) a higher landing rate, 3) fewer nontreated aircraft at the end of the scenario, and 4) an average ILS catch point closer to the runway.

The third hypothesis (H.3) is that the use of the ITIP display will result in a lower workload compared to the workload when using the NATS display.

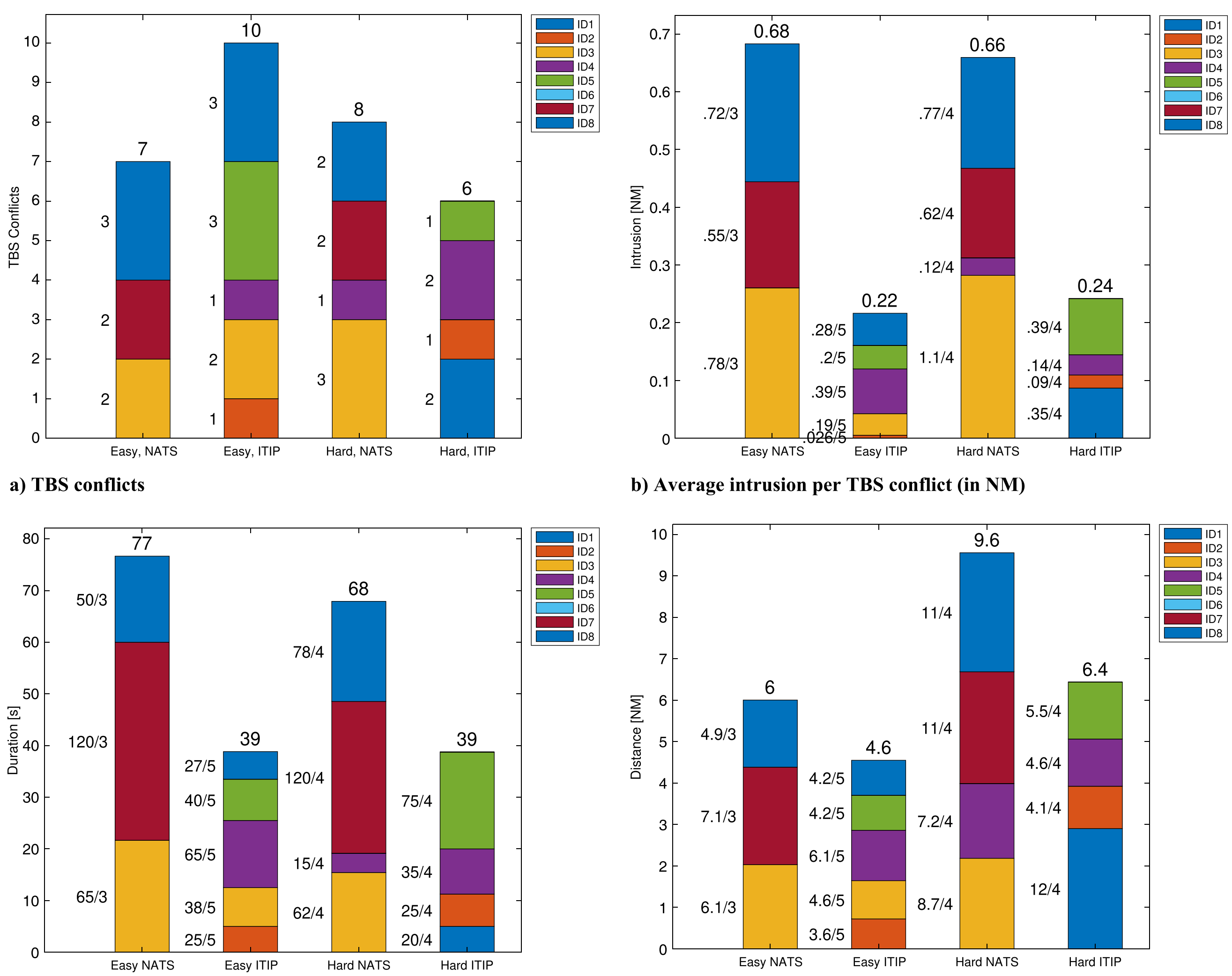
VI. Results

In this section, the results obtained from the experiment are presented. An initial evaluation of all dependent measures showed that their distribution did not differ significantly from a normal distribution. However, because of the small sample size ($N = 8$), the statistical significance of any trends was assessed using the non-parametric, relatively conservative Wilcoxon signed-rank test. In these tests, statistical significance was assessed only for the two display types (NATS display, ITIP interface) per scenario difficulty. Possible differences because of scenario difficulty were not further investigated. To reduce the chance of type I error, we applied a Bonferroni correction (significance level $0.05/2 = 0.025$).

A. Safety

Figure 13 shows bar charts of the number of TBS conflicts, the average intrusion, the conflict duration, and the average distance from the runway at conflict initiation. The bar charts include individual contributions by subject ID, where the IDs are ordered from bottom to top in the bars (i.e., ID8 is the top blue bar). For average data about TBS conflicts, only participants who caused conflicts in that scenario are considered. For bar charts listing averages, the fraction of the total average contributed by that participant is given. Because not all participants had TBS conflicts, the data set was too small and unbalanced for performing statistical tests.

As an example, consider the ITIP, an easy condition, which had 10 TBS conflicts (Fig. 13a) caused by five participants (subjects 8 and 5–2). Subject ID8 had three had three conflicts, with an average



a) TBS conflicts

b) Average intrusion per TBS conflict (in NM)

c) Average duration of TBS conflict (in s)

d) Average distance from runway at TBS conflict initiation (in NM)

Fig. 13 Safety-related measures (all scenarios, all subjects).

intrusion of 0.28 NM, an average intrusion duration 27 s, and occurring at an average distance from the runway of 4.2 NM. Subject ID2 had one had one conflict, with an intrusion of 0.26 NM, an intrusion duration of 25 s, and occurring at 3.6 NM from the runway. Now, the bar showing the average intrusion (Fig. 13b) shows the *summed* average intrusion of the five participants, averaged over the five participants. Similarly, the bar showing the average intrusion duration (Fig. 13c) shows the *summed* average intrusion duration of the five participants, averaged over the five participants. In this way, the safety achieved by the participants for the four conditions can be visualized.

A trend can be seen where the number of conflicts increases when using the ITIP display in the easy scenarios (+3) and decreases in the hard scenarios (−2). The average intrusion and average conflict duration considerably decrease with the ITIP interface in all scenarios. For the average distance to the runway at conflict initiation, the trend is also a decrease in distance when using the ITIP display, indicating that conflicts occurred *later* in the approach phase.

Two observations can be made. First, the finding that the use of the ITIP display increases the number of conflicts for the easy scenarios while decreasing the number of conflicts for the hard scenarios is in line with observations made during the experiment. When using the ITIP display, participants were more likely to select more higher-risk strategies since they were more confident that these strategies were safe. During the easy scenarios, participants also had more time and were more likely to explore better solutions, including higher-risk ones. These strategies often resulted in (very) small conflicts close to the runway, as participants gave the 160 kt command a little too late on the ILS, resulting in a small intrusion caused by the compression effect. Participants were then not able to solve these conflicts any more as they occurred close to the runway (see Fig. 13d). Often, the leading aircraft had already passed the 4DME point, reducing the control options to mitigate an impending conflict. Reducing the follower aircraft speed would either not impact the separation enough or cause new conflicts behind that aircraft. That these conflicts were small and less severe than the conflicts for the NATS scenarios is reflected in both the average intrusion (Fig. 13b) and the average conflict duration (Fig. 13c).

Second, some participants who chose a safe strategy in the NATS display scenarios were tempted to pick more high-risk strategies when using the ITIP display, whereas participants who were more risk-taking in the NATS display scenarios tended to select *safer* solutions when using the ITIP display. This can be seen by looking at participants 3, 7, and 8, who have a large number of lengthy TBS conflicts with significant intrusions for the NATS scenarios that are reduced in amount and severity when using the ITIP display, whereas participants 2, 4, and 5 seem to cause more, prolonged conflicts with larger intrusions when using the ITIP display. This corresponds to the verbal responses of the participants given after finishing the experiment. Some indicated that the ITIP display encouraged them to take more risky decisions, while others noted that the display showed them their preferred strategy was unsafe.

While any conflict should be avoided in real-life ATC, the number of conflicts and their intrusions must be seen *relative* to the other scenarios, as nonprofessional participants were used. These less-experienced participants are likely to cause more conflicts in this relatively difficult ATC task, with small margins for error. It is expected that professional controllers will not cause *any* separation conflicts, as they are known to always implement some safety buffer; they will most likely not choose risky boundary solutions [32]. The conflicts that were encountered for the ITIP display scenarios could also be mitigated by design, i.e., using a small buffer in the algorithm. To conclude that the use of the ITIP display increases safety at this point would be premature; however, in the current setup, the use of the ITIP display certainly did not decrease safety. This is in support of Hypothesis H.1, which stated that safety would be (at least) maintained with the ITIP interface.

B. Efficiency

All efficiency-related metrics are shown in Fig. 14. The average separation buffer for each scenario is shown in Fig. 14a, revealing a trend where the ITIP display results in a reduction of the average separation buffer. Wilcoxon signed-rank tests showed that this effect was indeed significant in the easy scenarios ($Z(1) = 1.0$, $p = .017$), but not for the hard scenarios ($Z(1) = 26.0$, $p = 0.263$). Figure 14b shows the average landing rate for each scenario, indicating a trend where the ITIP display yields a higher landing rate. For both the easy and hard scenarios, this effect was not significant (easy: $Z(1) = 27.0$, $p = .208$; hard: $Z(1) = 28.0$, $p = 0.161$).

Figure 14c shows the average point at which aircraft catch the ILS, as measured from the runway threshold. The red line indicates the minimum distance at which an aircraft flying at a standard approach altitude of 2000 ft can intercept the ILS: 6.3 NM. A trend where the ITIP display results in ILS catch closer to the runway can be observed. Wilcoxon signed-rank tests showed this trend to be not significant for the easy scenarios ($Z(1) = 6.0$, $p = .093$) but significant for the hard scenarios ($Z(1) = 1.0$, $p = 0.017$).

Figure 14d shows bar charts of the number of nontreated aircraft at the end of the scenario. A clear trend where the ITIP display results in fewer nontreated aircraft is visible (no statistical test applied to the small dataset).

Summarizing, the overall trends clearly indicate that the use of the ITIP display indeed increases efficiency, supporting Hypothesis H.2. Most of the trends were not significant, however, which is likely because of the relatively small group of participants.

C. Workload

Figure 15 shows the (normalized, Z-scores) perceived overall, physical, and mental workload for all subjects and all scenarios. The overall workload showed no significant effects of the display conditions (easy: $Z(1) = 14.0$, $p = .547$; hard: $Z(1) = 11.0$, $p = .383$). A small trend seems to be visible where the use of the ITIP display yields a lower physical workload, but tests showed no significant effect of the display (easy: $Z(1) = 13.0$, $p = .484$; hard: $Z(1) = 16.0$, $p = .779$); the same result was found for the perceived mental workload (easy: $Z(1) = 23.0$, $p = .484$; hard: $Z(1) = 9.0$, $p = .208$). Summarizing, although the trends are in line with Hypothesis H.3, it can neither be accepted nor rejected with the current data set.

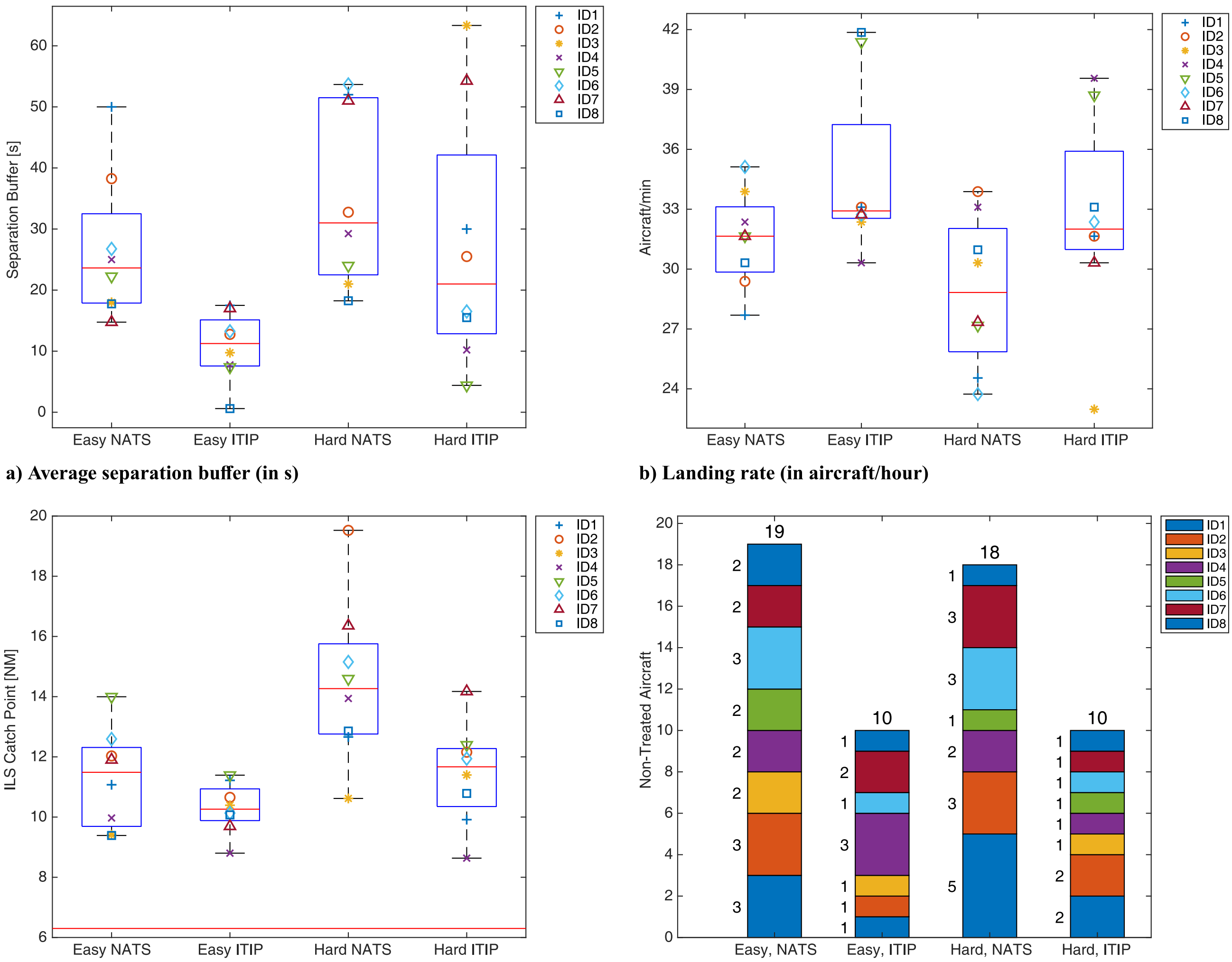
D. Subjective Comments from Postexperiment Questionnaire

In the postexperiment questionnaire, some participants noted *reduced* situation awareness, trusting the tool "to do all the thinking for them." These participants noted that they were not paying much attention to, among other things, aircraft types and aircraft that were considered "already dealt with," i.e., those aligned on the ILS with a speed of 160 kt. If the display tool were to malfunction for some reason, the controller must be able to take over without losing control of the situation. The impact of the display on situation awareness must thus be assessed thoroughly before implementation.

Concluding the Results section, the trends of decreased separation buffer, increased landing rate, decreased ILS catch point distance, reduced number of nontreated aircraft, and reduced physical and mental workload all lead to the belief that the use of the ITIP display increases the overall efficiency in this specific setup. For both the separation buffer and the ILS catch point, the spread of the results seems smaller for the ITIP display in the easy scenarios. This could indicate more consistent performance of our participants when using the ITIP in these scenarios. It is important to investigate this effect for professional ATCos, as increasing performance consistency would increase overall system predictability.

VII. Discussion

In this section, the main results will be summarized, together with a discussion of the implications and real-life relevance of the results, as well as the experiment design; recommendations for future research are given.



a) Average separation buffer (in s)

b) Landing rate (in aircraft/hour)

c) ILS catch point distance (in NM)

d) Number of non-treated aircraft

Fig. 14 Efficiency-related measures (all subjects, all conditions).

A. Summary of Experimental Results

Table 3 summarizes the effects of the ITIP display on the safety, efficiency, and workload-dependent measures for the easy and hard scenarios. In this table, the entries "y" or "no" indicate whether the trend found in the data is in line with the hypotheses or not, respectively; when the effect is significant, a bold "yes" or "no" is used. From this table and the discussion of the results in the previous section, it can be concluded that the general trends in the data are in line with the three hypotheses. Apart from two occurrences in the easy scenarios, the trends in the dependent measures show that the ITIP displays maintains (in fact, improves) safety, increases efficiency while maintaining (in fact, reduces) workload compared to the NATS TBS display. The low number of experimental participants ($N = 8$) led to only two significant effects, however. Further testing should be done with more and better-trained test participants, ideally professional controllers. Although this first evaluation was a proof-of-concept test and its findings cannot directly be extrapolated to real-life APP ATC, the results are promising and justify more testing.

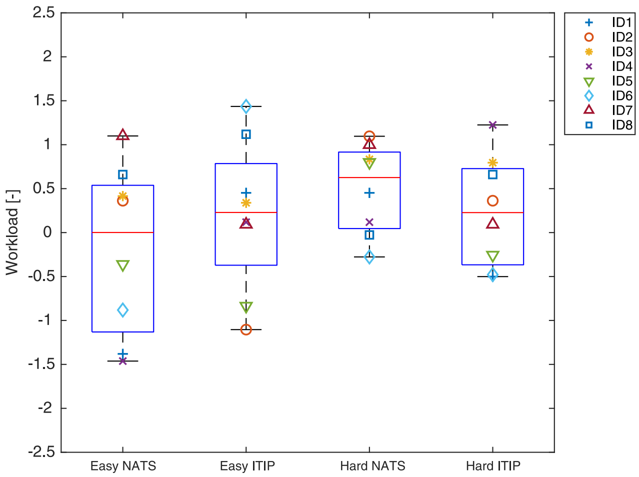
B. Learning Effects

The observed effect where the use of the ITIP display decreased the number of TBS conflicts for some participants while increasing it for others might have been due to the *order* in which the participants tested the respective displays, in combination with the participants still improving their skills during the four test runs. To assess this potential learning effect, the number of TBS conflicts was evaluated per run in the order the test participants received them. Results are shown in Fig. 16a; clearly, there is no learning effect present in this dependent measure.

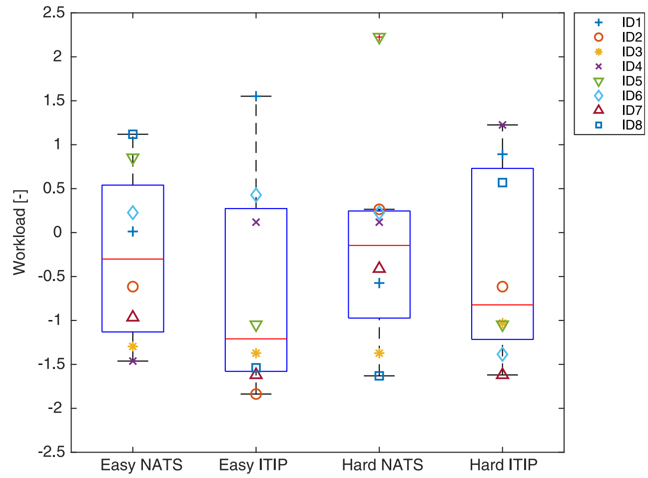
To further investigate a learning effect, the separation buffer was evaluated per run (see Fig. 16b). Again, no discernible learning effect is found. To conclude that no learning effect was present at all would be premature, however. In the survey, some participants commented that they felt that more training would have improved their performance.

C. Display Use by Participants

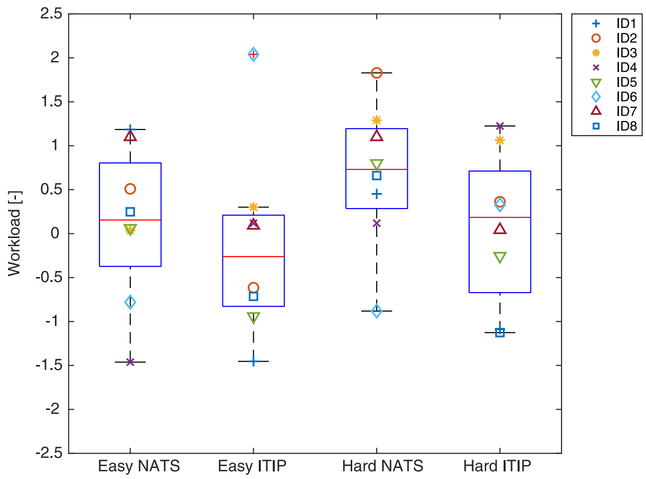
During the experiment, it was noted that some participants used the trajectory prediction line (see, e.g., Fig. 4) as an advisory path, limiting their incentive to explore; participants followed the trajectory prediction as if it were the goal of the simulation. This is in line with what some participants commented about the display, with one of them noting that he "used the display in a rule-based fashion [. . .] very rarely looking at the ghost or trying an optimal trajectory." Others were more active in looking for an optimal solution using the ghost, noting that "the ITIP helped me validate (and optimize) the control strategies that [he] had planned." Almost none of the participants made frequent use of the ability to change turn-in heading angles (Fig. 6). Some participants experienced restrictions from using the ITIP display, while others were able to use it to its full advantage, probing for the most optimal solution in the scenario.



a) Overall workload



b) Physical workload

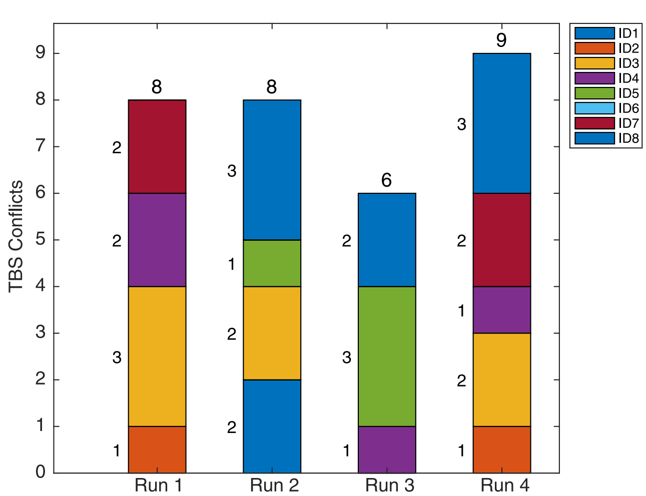


c) Mental workload

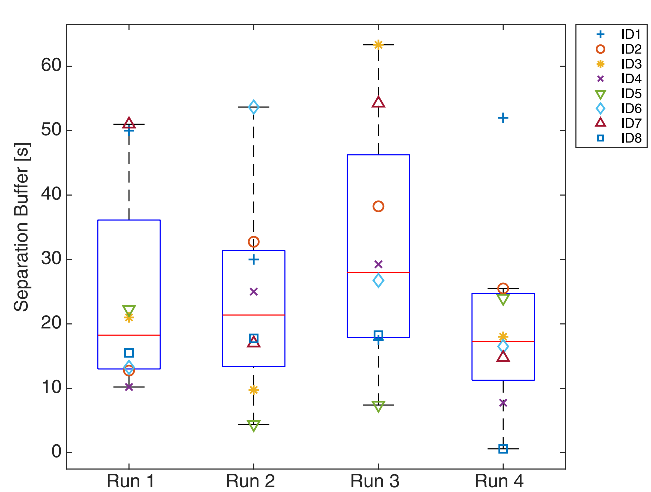
Fig. 15 Normalized subjective workload scores (all subjects, all scenarios).

Table 3 Summary of all trends in dependent measures (see text)

	Safety (H.1)				Efficiency (H.2)				Workload (H.3)		
	No. of conflicts	Avg. intrusion	Avg. duration	Distance RWY	Sep. buffer	Landing rate	Capture ILS	Nontreated a/c	Overall	Physical	Mental
Easy	no	y	y	y	**yes**	y	y	y	no	y	y
Hard	y	y	y	y	y	y	**yes**	y	y	y	y



a) Number of TBS conflicts, per run



b) Average separation buffer in seconds, per run

Fig. 16 Analysis of possible learning effects (all subjects, all conditions).

Participants who experienced restrictions noted that, if they would have had more training, they would most likely have had more incentive to explore optimal solutions.

The restrictive nature of the display comes forth from the requirement of minimizing display clutter; if the display is to be designed to be as minimalistic as possible, some assumptions have to be made and some restrictions applied. For instance, the ITIP display only shows the TTB points for the aircraft without a heading change. As a result, one trajectory was emphasized, and although users were *able* to explore multiple other options, this exploration was not actively encouraged by the visualization itself. Plotting the TTB points in an area around the selected aircraft is possible and would show more possibilities but would also result in significant clutter.

Future research should investigate whether professional ATCos also experience restrictions while using the ITIP display, as it could very well be that professionals will “ignore” the solution proposed by the display and use it in a more investigative manner. This is underscored by the fact that, in the first evaluation of the ITIP display with professional APP controllers, one controller noted that he did make frequent use of the ability to change the turn-in heading angle. Tentatively, professional APP controllers might experience more incentive to explore based on their experience and their desire to create optimal, yet robust, solutions. However, as underlined by the sensitivity analysis, too much exploration and decision-making freedom might become counterproductive in meeting more stringent TBS objectives in this restrictive approach phase.

D. Concept Maturity

One of the design requirements for the ITIP display was that it could be implemented in the APP controller radar display at the LVNL without drastic alterations. A few considerations on implementation should be taken into account.

First of all, in this study, pilot response times were instantaneous; i.e., there was no time delay between the execution of the command by the controller and the execution by the aircraft. In reality, the delay between the command being received by the aircraft and the aircraft executing that command depends on multiple factors: the pilots, the airline company, the aircraft, etc. The sensitivity study of Sec. IV provided a first analysis of the effects of delays, yet the impact of these stochastic aircraft response times on the functioning of the ITIP display should be further investigated.

Second, an extra separation buffer should be considered to eliminate TBS conflicts. Although it can be expected that professional ATCos will not cause any TBS conflicts no matter what display they use, any alteration to their trusted work environment should be made with extreme caution. In the ITIP algorithm, a small safety buffer could be implemented, extending the current minimum separation with a few seconds. The separation is, after all, an *intentional* rather than physical constraint and could be manipulated to improve safety [33,34]. The separation performance should then be assessed with the ITIP display operational in a real or in a simulated environment. The safety buffer should be tuned such that the probability of a TBS conflict occurring is at an acceptable (low) level while not sacrificing efficiency.

In the simulator model, wind was modeled to be uniform. With minimal adaptions, detailed wind prediction models from, e.g., the Royal Dutch Meteorological Institute (KNMI), can be used for the trajectory prediction. After implementation, the display should further be tested for robustness. It is expected that the implementation of nonuniform wind models will not drastically impact display functionality since it only affects the integration done by the display algorithm. But *uncertainties* in the wind models can be of greater impact: inaccurate landing time predictions will most likely result in a need for larger buffers, which will yield less efficient solutions. The sensitivity study showed that especially regarding the TTB and TTI decisions, the effects of wind can play a major role.

E. Future Work

The experiment performed was meant as a proof-of-concept evaluation, conducted with limited resources. The sample size was small ($N = 8$), and the training time of the participants was limited. This was noted by the participants as well, many of whom commented on a need for more training with both displays. Hence, to further test the hypotheses, more and better-trained participants and ideally professional APP controllers need to be involved, which is a major challenge given their limited availability.

Due to the APP controller task being relatively difficult for the participants, some simplifications were made in the scenarios. Altitude was not used as a variable (all aircraft entered the simulation at 2000 ft) and aircraft only arrived parallel to the ILS. More real-life scenarios, with aircraft arriving from all directions, should be tested.

The participants that were chosen were nonprofessional ATCos. It should be noted that it is expected that these ATCos would profit more from the use of the ITIP display than professionals [35]. The effect of the ITIP display on the performance of professional ATCos will be less pronounced, and professionals will most likely perform satisfactorily in the baseline NATS scenario. The testing of professionals should thus focus more on if and how the ITIP display affects controller strategy and workload, as the impact on performance may be less evident.

The impact of real-life factors such as controller/pilot communications, pilot response times, and imperfect approach speed models on the display’s robustness and operator workload should be further investigated, as well as the impact of the interface on controller situation awareness and acceptance. Safety buffers should be implemented and tuned to the desired performance levels to optimize separation while maintaining safety at all times.

Finally, in a following design iteration, preferably together with professional controllers, it should be investigated whether a more “minimal,” i.e., less-cluttered, design is feasible to increase the chances of controller acceptance and actual implementation in the AMS controller environment. Before further testing, the interface should be adapted to replicate the current use of the radar screen and LVNL command interface.

VIII. Conclusions

A display tool to support APP controllers in attaining efficient TBS on final approach was designed and evaluated in an initial proof-of-concept experiment. In contrast to the current industry standard that provides separation support for aircraft close to the ILS, the interface aimed to aid controllers in the early stage of approach; support was provided from the moment the aircraft entered the TMA. The display was tested against the current industry standard designed by the National Air Traffic Services in the United Kingdom, currently operational at Heathrow Airport. Results are promising, showing trends of maintained safety, increased efficiency, and reduced physical and mental workload. This suggests that early-stage strategy support for separation could potentially mitigate the feared performance gap between theory and practice when implementing TBS. Before implementation, more extensive testing should be done with professional controllers.

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