Assessing the Air Traffic Control Safety Impact of Airline Pilot induced Latencies

Markus Vogel, Christoph Thiel, and Hartmut Fricke
Chair of Air Transport Technology and Logistics
Technische Universität Dresden
D-01092 Dresden, Germany
+49 351 463 3677
{vogel, thiel, fricke}@ifl.tu-dresden.de

ABSTRACT
Current arrival operations in the terminal airspace, designed according to ICAO guidelines to comply with a target level of safety of 10−7 per approach, rely on spatial protection zones and complementing procedures (ICAO Doc. 4444). The purpose of this paper is to quantitatively demonstrate inherent safety margins, which form the basic prerequisite for increasing flight efficiency both economically and ecologically. By means of expert interview, task analyses and experiments on a procedure trainer, human-machine interaction latencies on the flight deck are analyzed as a performance shaping factor and thus a potential driver for collision risk. The effects are studied by means of a sensitivity analysis, performed by coupling our actual-navigation-performance-enhanced collision risk model and agent-based fast-time simulation. The results show that temporal safety margins exist for implementation latencies of advised speed and heading changes alike. For heading changes, the margin is well-defined at 10 seconds. For speed changes, the safety level decreases gradually with human-machine interaction latencies, to become critical between 15 and 20 seconds. Trajectory-based concepts with fewer, but more time-consuming interactions between pilot and airborne IT systems may benefit from these findings.

Categories and Subject Descriptors
J.2 [Physical Sciences and Engineering]: Aerospace.

General Terms
Performance, Reliability, Experimentation.

Keywords

INTRODUCTION
Ever since the very beginning of commercial aviation, accident rates have been statistically tracked to demonstrate a superb safety record in comparison to competing traffic modes. To this day, the International Civil Aviation Organization (ICAO) has published several Target Levels of Safety (TLS) as a guide for engineers and operators alike. It is generally agreed that all TLS, which address diverse operational risks, are ultimately compatible with one ‘master TLS’ in the order of one catastrophic accident per ten million flight cycles (10−5) or one billion operating hours (10−6), respectively. Next to historic evidence (often dating as far back as the 1950s and -60s), we have found surprisingly straightforward analyses on life risks (e.g. one catastrophic accident per two human generations) to be the root of these figures [1]. The number of flight cycles has been growing significantly since commercial air transport began. To compensate the growth-induced operational risk, the air traffic system has been continuously improved, both technologically and operationally. To reflect this, a measurable improvement of the safety performance by a factor of ten is targeted for the near future, e.g. with Single European Sky [2].

Our research focuses on the operational safety performance of the air traffic management system (ATM), itself a complex result of the interactions of airborne human-machine systems, air traffic control (ATC), environmental influences, and infrastructural elements (communication, surveillance, navigation, guidance as well as flow and space management). The system as a whole is often described as a complex, distributed socio-technical system for this reason, as illustrated by Hawkins’ SHELL model [3] and others. ATM failures, leading to accidents and thus targeted by ICAO’s TLS concept, are consequently just as complex, distributed and socio-technical in nature. With 80% of all catastrophic accidents having in itself mostly insignificant human errors as a contributory factor, the organizational accident is the predominant explanatory model today. The image of an unfavorable event chain, which affects all stakeholders in control, is visibly transported by Reason’s well-known ‘Swiss cheese’ model [5]. Consequently, two major strategies can be followed to avoid human contributions to organizational failure (e.g. latencies, lapses, and errors) or reduce their impact: higher
levels of automation and/or more transparency in cause-effect chains inherent to operational procedures, thus guiding standardization of human activities (procedures, training). The research presented here follows the latter strategy.

RESEARCH QUESTION

Agent based modeling techniques allow for the simulative assessment of distributed failure events. Even under nominal conditions, i.e., all agents performing within operational limits (i.e., without explicit failure), it was learnt that the level of safety indicated by collision risk is very volatile. With the abundance of radar data containing the nominal operational state, we currently parameterize and refine the agent model by means of comparison of simulated scenarios with real trajectories based on the observed collision risk (obviously, well within the safe region), well aware that human errors are a relevant factor in procedure design (resilience criterion). Nevertheless, co-occurring unfavorable performance variations are one mode of ‘collaborative failure’ and thus an important hazard.

The terminal airspace is of special interest in this context, because it brings many human stakeholders together. The traffic characteristics (e.g. density, diversity) are challenging, and the incentives to optimize and utilize potentially over-dimensional safety margins are high, as ground-based infrastructure is costly. The high rate of coordinating interactions needed to optimize the usage of the scarce ground-based resources effectively often limits the arrival throughput. For this reason, terminal ATC operations are known to be highly standardized.

Nevertheless, it was noted that aircraft following published area navigation (RNAV) transitions do not accurately track the defined paths but rather exhibit a rather loose compliance towards the published routes (see fig. 1). In the simulation, however, we assume precise tracking capabilities.

To explain: standard RNAV approach procedures require utilizing the aircraft’s flight management system (FMS) to automatically navigate the aircraft along routes defined by waypoints. The dual-S shaped approach infrastructure allows for flexible path stretching / shortening enabling the controller to build up an arrival queue with adequate capacity. An aircraft following the upwind approach segment (upper horizontal leg parallel to the runway centerline in fig. 1) would at some point be advised to turn onto the downwind leg (lower horizontal leg in fig. 1), thus stretching / shortening the approach. While path stretching itself is subject to the controller’s planning and thus highly variable, the observed tracking tolerances on the upwind / downwind legs parallel to the runway centerline are too significant and too frequent to be attributed to RNAV tolerances alone [6].

This question was raised at a model validation interview with a senior DFS\(^1\) approach sector controller, now in a management position, of Munich airport, Germany [7]. It was confirmed that at limited traffic demand, air traffic controllers indeed opt for shortening flight paths by means of ‘vector’ advisories to reach optimal economic efficiency whereas at busy periods, traffic is being guided along the full procedures gaining extra capacity and safety by means of path stretching.

Surprisingly though, the FMS-managed RNAV mode is not utilized to the expected extent. For path shortening, ATC have the option between two types of clearances - either a ‘direct’ to a subsequent waypoint on the pilot’s flight plan or – which is the typical ATC procedure today – a ‘vector’. In the latter, the pilot will switch the aircraft into ‘selected’ guidance mode: the flight management generated trajectory is not being transferred to the aircraft autopilot (AP) system. The AP instead follows the inputs set on the flight control unit (FCU) such as the selected heading, speed and vertical speed. In order to return to the pre-programmed flight path (as implemented in our simulation, the full procedure), the pilot will have to switch back into ‘managed’ mode. Quite often today though, aircraft remain in the ‘selected’ guidance mode after cutting short, as ATC issues more vector advisories for the pilot to implement in order to guide them along the defined routes. The resulting trajectories do vary remarkably, which explains the path deviations observed in radar data (compare fig. 1). Asked to refine, the controller noted that issuing a vector (‘turn [left/right] heading XYZ’) is ‘much faster’ than issuing a direct (‘go direct to waypoint XYZ’).

From ATC perspective, the timing to command an action is from voicing the advisory until recognizing conformance on the radar screen.

In summary, pilot induced latencies create a divergence between intended and actual use of the RNAV approach procedure. Whenever conditions allow, controllers optimize throughput with the flexibility of ‘vector’ advisories, thus sacrificing the guaranteed RNAV accuracy of the ‘managed’ mode. The implications for trajectory-based concepts targeting economically and environmentally improved flight efficiency by automatically ‘managing’ the flight path are somewhat problematic: when pilot induced latencies shift the optimum between safety, throughput and

\(^1\) Deutsche Flugsicherung, German ANSP
efficiency; and the controllers follow this new optimum, the aircraft’s trajectory processing unit will have to anticipate the controller intent, as it is ‘out of the loop’ as long as the aircraft remains in the ‘selected’ guidance mode. Future concepts must consider this.

Quantifying the criteria that lead to shifted optima can be achieved by our simulation-based assessment concept. With this paper, we present an analysis regarding the safety aspect, in order to answer the question if the latencies associated with implementing a ‘direct’ advisory are indeed problematic when performing RNAV approaches ‘by the book’.

METHODOLOGY

Outline of Analysis

First, a task analysis of the steps associated with implementing the ‘direct’ and ‘vector’ advisories is performed, down to basic manual interactions with the flight deck human machine interface (pressing keys, turning dials). We refrain from quantifying time-consumption or failure rates of part-tasks (e.g. with Fitt’s Law, Human Reliability Assessment), and we also do not characterize cognitive processes in detail. The overall time-consumption of the tasks is rather quantified by means of informal experiments on TU Dresden’s A320 procedure trainer. To create an understanding of how the latencies destabilize the controller’s planning; an interpretation of the operational effects on ATC is presented. Next, a scheme for the simulation-based sensitivity analysis is derived to make the relation between interaction latencies (input, cause) and resulting collision risk (output, effect) more transparent.

Simulation-based Sensitivity Analysis

Within the approach controller agent model, which is described in the next chapter, all internal timing effects were disabled, effectively allowing ideal situation assessment opportunities with a full service cycle time of just one second (i.e. de-facto instant de-confliction and organization of all traffic situations). Then, HMI latencies were configured for the pilot model.

Since the approach controller model makes use of layered strategies (e.g. may compensate late reactions of pilots with a subsequent advisory to increase speed, see next chapter), we taxed all pilot actions with one of two possible latency values, as determined via task analysis: (1) using the dial knobs at the FCU (select speed, altitude, or heading) and (2) programming approach routes (waypoint lists) and directs (single waypoints) at the MCDU. In a worst-case assumption, these latency values apply to all pilots and do not vary (neither individually nor over time).

With respect to other non-deterministic elements included in the model and also introduced by the traffic scenario, a significant scenario length is needed for a stable collision probability estimate. So far, this is determined empirically before the simulation is run systematically. An objective criterion or a formal method would be preferable to objectively find a good compromise between computational effort and quality of results. The manually determined scenario consists of ten hours continuous arrival operations at a rate of 70 arrivals per hour, evenly distributed over the north and south sector and east and west reporting fixes, but temporally distributed by a Poisson process. The arrival rate is close to the current capacity limit at the investigation airport. It is important to note that the traffic scenarios for all simulation runs were exactly the same.

Agent-Based Simulation Model

Put in a nutshell, our agent model comprises organization (function allocation, standard operating procedures) and operational performance (aircraft dynamics, human performance) relevant to today’s operations in the terminal airspace. It is characterized by asynchronous, time-discrete interaction events between intelligent agents and physical entities. A time-synchronous simulation of the physical entities (aircraft flying) drives the interaction process. Details on our efforts in modeling and simulation as well as case studies can be found in [8-11].

As of April 2012, the agent model consists of the following agents and entities: (1) Airbus A320 flight performance model with FMC logic. The model runs synchronous with simulation time with an update rate of 100 milliseconds. It processes flight plans (waypoint list) and speed inputs by the pilot. The aircraft control by the FMC is based on pitch, roll and power (thrust). (2) Pilot agent without explicit intent except for ‘landing on designated runway’. Pilots communicate with ATC and their Aircraft. Aircraft communication is through the cockpit HMI. ATC communication is ‘verbal’ through a radio channel. (3) Radio channel agent that implements a blocking resource for all participants. This agent also determines the time needed to verbalize a given message with an estimator derived from the jACT-R implementation (50 milliseconds per syllable, typical English syllable length of 3 characters, 100 milliseconds between words) plus additions (300 milliseconds listening for a free channel, 150 milliseconds to formulate a sentence, spelling of callsigns and numbers, etc.). (4) Approach controller agent, that contains the complex planning algorithms, as described below. (5) Airport radar agent that detects all aircrafts’ positions and reports updated ‘images’ to the ATC agent with representative a cycle time of 4 seconds. All Agents except the Aircraft entity agent and the radar agent run asynchronous with simulation time, which means that they trigger each other dependent of their current activities and intents.

The approach controller’s strategies and the resulting task model are described in detail in [8, 9]. In summary, there are (1) a task to pick-up new aircraft, plan an initial route (including the possibility for a direct-to-final-approach) and send them to their route, (2) a path stretching task that flexibly issues turn-onto-downwind and turn-onto-final advisories to make use of the RNAV trombone infrastructure, (3) a speed monitor task that adapts aircraft’s speeds depending on the location on route as well as traffic ahead and traffic following, (4) a queue merge task that adapts speeds of aircraft on joining routes based on an estimated time of arrival (ETA) at join waypoint timeline, and finally
Decomposed, the task of implementing a heading using the FCU (assumed: aircraft already in selected mode) comprises the following steps:

1. move hand to FCU heading dial knob,
2. in parallel: determine direction of turn
   a. already anticipated (approach procedures)
   b. visual comparison (navigation display)
   c. numerical comparison (3-digit display)
   d. explicitly advised by ATC
3. then, turn knob in desired direction
4. <aircraft starts turning>
5. in parallel, adjust target heading accurately

If the aircraft is not yet in selected mode, the dial knob needs first to be pulled to switch into selected mode before performing the above 1 to 5.

For the task of programming a waypoint to approach directly using the MCDU, the following steps are to be performed:

1. move hand to MCDU keypad
2. then, push the DIR(ECT) button
3. then, select the target waypoint
   a. locate it on screen (flight plan page) and select it by using the appropriate Line Selector Key (LSK)
   b. if not visible, scroll through the flight plan using arrows keys, then a.
   c. type in the waypoint name manually using the scratch pad
4. then, select intercept maneuver using LSK (unless mandatory)
5. check the setup on navigation display (optional)
6. then, commit programming using LSK
7. <aircraft starts turning>

INFORMAL EXPERIMENT ON PROCEDURE TRAINER

The interactions analyzed above were then tested and timed by a team of two engineers (both no flying experience, stopwatch for timing). The instructor took the role of ATC and also measured the latency (from read-back to increase of bank angle, indicating that the aircraft is beginning to turn). Target headings/waypoints were chosen randomly, which made the task more challenging than in reality (pilot anticipation and MCDU’s pre-selection of typical target waypoints are both hampered, this way).

The results show that the task of implementing a ‘vector’ advisory can stably be performed within five seconds, and significantly earlier if the aircraft is already in selected mode (the aircraft starts turning as soon as the knob is rotated). The task of implementing a ‘direct’ advisory can usually be performed well within ten seconds, but mistyping keys or the failure to correctly navigate through on-screen pages may extend this period up to 20s. This is due to error recognition appearing quite late in the activity chain, sometimes as late as step 5 (consulting the NAV display).
It was positively verified that the tasks for implementing speed and altitude changes are identical to implementing a ‘vector’ advisory (i.e. heading change). The speed selector panel of the FCU is visible on the very left of fig. 2

**INTERPRETING OPERATIONAL EFFECTS FOR ATC**

The operational effects of the flight deck latencies are best discussed on exemplary traffic situations. We concentrate on the times needed for implementing ‘vector’ and ‘direct’ advisories in the aircraft’s control computers. Since readily available, we later include latencies for speed and altitude settings as well.

**Exemplary Traffic Situation from Simulation**

Fig. 3 shows a traffic situation from simulation where the approach control agent has just opted for issuing a direct-to-downwind in order to build up an arrival queue (the affected aircraft are highlighted with red circles). Prior to issuing the advisory, the approach controller (software agent and human alike) has performed spatial planning in order to determine the right time to advise the change of heading and speed. The main focus of our expert interview was to determine how controllers assess situations and derive a plan. The model currently performs a linear prediction of aircrafts’ future locations based on current speed (local timelines). It was learnt that human controllers use rules of thumb plus years of expertise and thus act in a very standardized way.

Fig. 4 depicts the same situation 50 seconds later and about halfway into solving. The target waypoint of the intercepting aircraft is highlighted with a red dot. In our model, the controller fine-tunes the speeds to obtain an even separation. In consequence, the aircraft behind the third aircraft needs to slow down as well. In general, the vicinity of the highlighted traffic situation shows how interdependent TMA operations are. With respect to unforeseeable timing deviations, we can conclude that a magnitude of about 10 seconds will lead to a significantly altered situation (after 50 seconds as shown here). Fig. 5 shows the situation after it has been solved. We can clearly see that the middle aircraft was already late (this situation: unplanned latency of 5 seconds).

**Discussion of HMI Latency Effects**

The key consequence from the traffic situation described above is that unexpected latencies will be problematic from the perspective of air traffic control since expected latencies should be part of the controller’s planning (e.g. safety margins). We will now discuss the effects of this unexpected delay in implementing an advisory for both directs and vectors by comparing the expected trajectory with its unexpected equivalent (black and red respectively, see fig. 6).

At 250 knots, ten seconds of unexpected latency in a turn advisory mean that an aircraft will travel straight-on almost 1300 meters before initiating the turn maneuver. Every procedure turn will be executed with 3° per second (direct or heading) according to ICAO [4]. In selected mode, the aircraft will complete the turn at the advised heading (upper figure), while in managed mode, the aircraft will turn until the heading lines up with the target waypoint (lower figure). Consequently, an aircraft turning late on a vector...
will intersect the target segment both later and further outwards while an aircraft turning late on a direct will intersect at the desired location but be later than expected. Seen as an undesired path elongation, the temporal offset is twice the latency for vectors but only the single latency for direct (plus the negligible overhead for flying the diagonal, 0.4% in the visually exaggerated example in fig. 6). The typical temporal spacing in the TMA is about 90 seconds. Unexpected latencies in the order of ten seconds should thus fall into the safety margin of the controller’s planning. Nevertheless, the error will be clearly visible, allowing for compensatory actions by the controller (e.g. increasing speed, advising a heading ‘further in’).

SIMULATION RESULTS
In a first step, we varied both flight deck latency values uniformly (FCU turn knob and FMS keypad interaction) and observed the resulting collision probability estimate with our TMA arrival simulation that uses the ‘direct’ variant of path stretching / shortening and thus yields RNP-exact navigation performance on the route legs. Figs. 7 and 8 show flight trace examples for 0 and 15 second unexpected latency. The fan-like spread of trajectories is not due to the latencies but results from varying traffic situations (compare description of exemplary traffic situation above). The latency manifests in slanted shortcut paths (see lower part of fig. 6 and note the difference in slant between figs. 7 and 8).

Figure 7: superimposed trajectories (no latency)

Figure 8: superimposed trajectories (15 s latency)

It is clearly visible that the system behaved differently because of the latencies. The shortcut locations moved further outwards (east in the upwind to downwind transition, west in the downwind to final transition), and exhibit a larger spread (‘fans’). This is due to subsequent speed reductions that are necessary to accommodate non-optimally shortcutting aircraft. As traffic slows, more space is needed to queue traffic in a well-separated way. In numbers: the average approach time rises from 1144 to 1334 seconds (i.e. longer, slower approaches) and the controller’s time on radio rises from about 17 to 22 seconds per minute (more advisories, more workload).

Fig. 9 summarizes the main result of this first sensitivity analysis: the resulting collision probability estimate on a logarithmic scale depending on uniform latencies for cockpit interaction. It is clearly visible that there is a jump from well below $10^{-10}$ per approach to well above defined TLS (e.g. $10^{-7}$ per approach) between 10 and 15 second latency. The interpretation from observing the simulation output in detail is that the failure to adapt speeds within 10 seconds leads to unsafe states regardless of the traffic situation (e.g. aircraft shortcutting, aircraft following).

Figure 9: sensitivity of collision risk on HMI latency

In a second step, the latency for FCU dial knob interactions was set to a constant value of five seconds as determined through the task analysis and the informal experiment. The density of data points was increased in the transition between ‘well safe’ and unacceptable. The latency of implementing speeds seems to be relatively negligible, as the curves in fig. 10 exhibits a shape very similar to fig. 9 (apart from the lower density of data points in the transition region in fig. 9). Remarkably, the transition itself has a large positive gradient, indicating a very crisp boundary for the safety margin which applies to the latency of FMS inputs. Between 10 and 10.5 seconds of latency, the average collision risk per approach transitions from ‘well safe’ to ‘not acceptable’.

Figure 10: sensitivity of collision risk on FMS latency
As the last step, the latency for implementing FMS screen / keypad interactions was fixed to ten seconds as determined by the initial analyses and the considerations about the safety margin above, and FCU interactions were varied.

![HMI latency vs. Collision Risk per Approach](image)

Figure 11: sensitivity of collision risk on FCU latency

The curve of FCU dial knob interaction latencies vs. safety shows a much smaller gradient, also starting the transition between ‘well safe’ and ‘not acceptable’ at about ten seconds of latency. Because of the smooth transition with small gradient, the unacceptable region above $10^{-7}$ is reached between ten and 20 seconds.

**DISCUSSION OF RESULTS**

The simple truth to be concluded from fig. 9, which is the superimposition of figs. 10 and 11, is that operations are to be considered safe if all pilot-to-flight-guidance-system interactions on the flight deck are completed within ten seconds regardless of the human-machine interface used. The sensitivity analyses reveal that the task latency of programming a new trajectory into the flight management system (FMS) via the Multi-purpose Control and Display unit’s (MCDU) screen and keypad is most defining for this fact. Setting speeds and altitudes via the Flight Control Unit’s (FCU) dial knobs is not only much quicker, as stated by a controller in the validation interview; it is also less time-critical.

With respect to the research question formulated, this is an interesting observation: the current practice of guiding RNAV arrivals along the routes by means of consecutive ‘vector’ advisories may indeed be safety-motivated. The mental effort and the required number of radio transmissions per arrival may be higher, but controllers opt to accept this higher workload because they can control traffic directly, more flexibly and more safely. Performing RNAV arrivals ‘by the book’, i.e. having pilots and their aircraft follow the defined waypoints with full support of navigational aids, is only safe if the controller can rely on the pilots to program trajectories within ten seconds sharp, which contradicting the experimental results obtained at our procedure trainer. Hence, if controllers need an immediate reaction that reliably occurs within ten seconds, they will rightfully issue a ‘vector’ instead of a ‘direct’.

Nevertheless, the reader is reminded that the analyses presented consider the worst case of all pilots being either slow or fast. Further simulation-based analyses with stochastically mixed latencies are needed to show if there is an option for longer trajectory programming latencies that still yield safe operations because of compensatory effects. Vice-versa, this also applies to the hazard of unfavorably coinciding performance variations presented in the introduction and targeted by our (further) research.

**CONCLUSION AND OUTLOOK**

To validate our agent simulation based safety assessment concept for air traffic management operational safety under nominal conditions, we did initiate interview series with experienced air traffic controllers. In multiple interview sessions it was learnt that air traffic control is always strictly complying to operating procedures as set out in ICAO Doc. 4444 [4], but that every ATC controller applies an individual scheme to make best use of the scarce TMA airspace capacity and ground infrastructure: This is perfectly visible when analyzing radar data showing a significant portion of radar vector advisories and less ‘direct’ vector advisories because conformance is instant and vectors are obviously better representing the mental strategy components of today’s controllers, having typically little flight deck systems experience. With this paper, we presented sensitivity analyses aimed at quantifying the correlation between flight deck human machine interaction latencies and the behavior of the air traffic management system, and most notably its safety performance. It was explained and illustrated in the results that complex interactions between all entities define the system response to a traffic scenario. The analyses are so far constrained to the direct advisory variant, so a comparison between both options is not possible. The results obtained indicate that the system remains well within limits as long as pilots always implement advisories within ten seconds of reading back to the air traffic controller while the margin of safe operations is clearly limited for trajectory-changing advisories while it smoothly ‘fades out’ for speed and altitude advisories.

As next steps, an analysis of stochastically varying latencies shall be performed, as we regard unfavorably coinciding performance variations as a significant hazard to the air traffic management system. The results presented in this paper provide the upper bounds for acceptable latency values to be used in further simulations. A validation of these bounds with experienced pilots should be undertaken, before further research is built up on these values.

**REFERENCES**


