INVESTIGATING THE SAFETY IMPACT OF TIME BUFFERS IN CURRENT TMA ARRIVAL OPERATIONS

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Abstract

This paper presents a study based on a novel safety evaluation concept designed to support definition phases of future air traffic management (ATM) operational concepts. Engineering and decision support tools may take advantage of the findings on time buffers in current terminal area (TMA) operations. The existence of such temporal windows for human activity is revealed analytically, establishing the hypothesis that time buffers moderate the safety impact of human performance variations. First, a surprisingly small time buffer for speed advisories was identified. With a refined experimental setup, it is then shown that the safety impact of delayed ATC interventions is acceptable up to ¼ min.

1 Introduction

ATM has been repeatedly defying attempts of predicting safety occurrences not previously identified by safety analysts and operational ATM experts by means of simulation. On the other hand, emergent behavior evolving from comparatively simple models without predefining potential hazards is a key feature of agent-based modeling and simulation (ABMS), which is why ATM safety research has favored this approach for the last 20 years, yet without significant standardization.

Air transportation is known to be a complex, distributed and highly dynamic socio-technical system. Human factors, especially human errors are a known weakness, being a contributing factor to 80% and more of all safety occurrences [1]. However, it has recently been acknowledged that also human performance variations can be safety critical if not appropriately accounted for. Accident causation models reflect this by framing the human component with a context of technology, environment, and organizational/social aspects [1, 2]. In consequence, simulative safety assessment of ATM concepts cannot significantly limit the scope, which has negative implications on abstraction and can contribute to ‘complexity explosion’ up to a point where models tend to become computationally infeasible or non-transparent.

2 ATM Modeling and Simulation

For classic human performance models, the modeling scope is very small and yet highly complex (including the human, its immanent environment, and limited factual/procedural knowledge). *AirMIDAS* [3] is an impressive example of continuing sophistication in that domain: It incorporates a goal-oriented production model (comparable to ACT-R, EPIC, or SOAR [4]), an anthropometric model and various custom models tailored to describe physiological and/or psychological effects of interest to crew station design, also in the ATM domain. Although there are promising achievements, the authors are critical about modeling effort, runtime performance, and interpretability of results, mostly because *MIDAS* may be too detailed for most of the candidate ATM applications.

Recent approaches for the ATM domain, most notably NLR’s *TOPAZ* [5], use far more aggregated models [6]. In *TOPAZ*, human operators are represented by state-models, which are specified by dynamically colored Petri-Nets (DCPN) and contain non-deterministic elements in form of probability distribution functions (PDF). The models are not simplistic, but complexity is carefully chosen upon necessity / relevance, e.g. with sensitivity analyses. Parameterized by expert contribution (interview, observation) and data analysis, *TOPAZ* produces varying outputs each simulation run. Monte-Carlo simulations allow for interpretable and yet detailed results as stochastic PDF. On the downside, the stochastic results obfuscate the failure modes that led to occurrences, thus requiring safety investigations. In this sense, identifying unforeseen occurrences is not a targeted feature in *TOPAZ.*

Research in autonomous piloting of Unmanned Aerial Systems (UAS) takes a different approach, mostly driven by the notion that control computers are deterministic in behavior. In line with kinematic ATM fast time simulations (e.g. *RAMS Plus*), the trajectory-based view on aircraft operations defines the modeling approach including functions such as conflict resolution/sense-and-avoid. As a result, the mechanisms that lead to a safety occurrence are documented in form of trajectories and trajectory-changing events. *A-Globe* & *AgentFly*, may become candidates for real-life applications [7].

3 Research Hypothesis

The authors combine the two approaches: (1) trajectory-based simulation of air traffic in the TMA using *A-Globe* & *AgentFly* and (2) incurporating human performance models of ALARP[1] complexity, focusing on the total system dynamics (individual human behavior being the driver). As a third component, we introduce a collision risk model (CRM) based on navigational uncertainty [8, 9], which allows for operational safety assessment and identification of marginal safety occurrences independent of standardized and fixed criteria along the ICAO Actual/Required Navigation Performance concept (ANP/RNP [10])

As such, our model consists of a deterministic, rule-based approach controller model that opportunistically applies control strategies 'learnt' from radar trajectory logs[2] (Munich Airport, Germany), fixed dead-time pilots that act as slaves to the controller, and exemplarily Airbus A320 flight performance and flight management models parameterized with trials at the department's flight simulator [11]. Integrated with *A-Globe*, a fully deterministic model that includes dynamic interactions and real-life traffic management strategies (traffic vectoring, sequencing, merging, etc.) is created. Non-deterministic delays in pilot responses were investigated in [12].

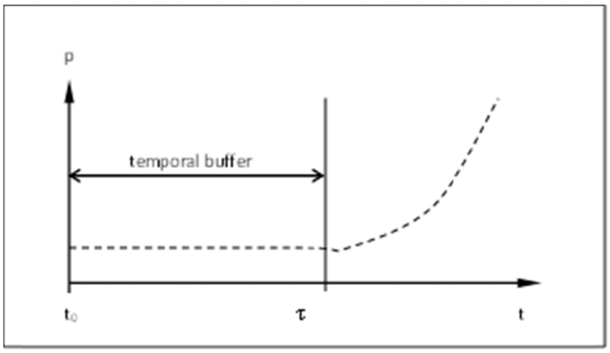

Fig. 1. Decision Time and Collision Risk - The Time Buffer

With the aim of introducing performance variations for R/T communication, verbalization, implicit social protocols, cognitive resources, workload-dependent time estimation, urgency-dependent strategy selection (e.g. [14, 15]), an important research question arises: where is the critical decision path that defines the complex socio-technical system's dynamics? NLR's *TOPAZ* group implemented relevant theories, e.g. Hollnagel's *CoCoM* [16] and expert judgment, e.g. on-task times for compliance monitoring after issuing advisories [6] and then evaluated the resulting performance variation. The authors have observed that, in their unconstrained model, there are pre-set time buffers in TMA operations designed for human intervention, built-in as a safety feature (see fig. 1), that allow to revert from distance based separation to time based separation. Though not new (time-based separation as a concept and arrival traffic man-

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[1] ALARP is a risk management principle: As Low As Reasonably Practicable.

[2] Radar trajectory logs kindly provided by *Deutsche Flugsicherung* (DFS, the German ANSP), for research purposes.

agement advisory tools like EUROCONTROL's arrival management decision support tool *A-MAN* [17] and NASA / FAA's traffic management advisor *TMA* [18] as an application take advantage of and improve this), explicit research on the quantity and stability of these time buffers helps identifying the critical path of safety-relevant decisions. In effect, this is also a sensitivity analysis of response delay/strategy selection to collision risk (compare fig. 1), because human performance variations will be non-critical as long as they remain within the constraints defined by the buffer.

4 Analytical Demonstration

Let an arrival flow fly at a target velocity v_0 within the aircraft speed envelope $[v_{min}|v_{max}]$ depending on aircraft type, economic constraints and throughput. To merge arrival queues, it is necessary for the controller to re-space and probably even re-sequence queues to cope with conflicting arrival times (fig. 2). The speed envelope along with the look-ahead time defines a lateral controllability envelope, principally fixing a time buffer for intervention depending on the situation (fig. 2, example A, time buffer τ_A).

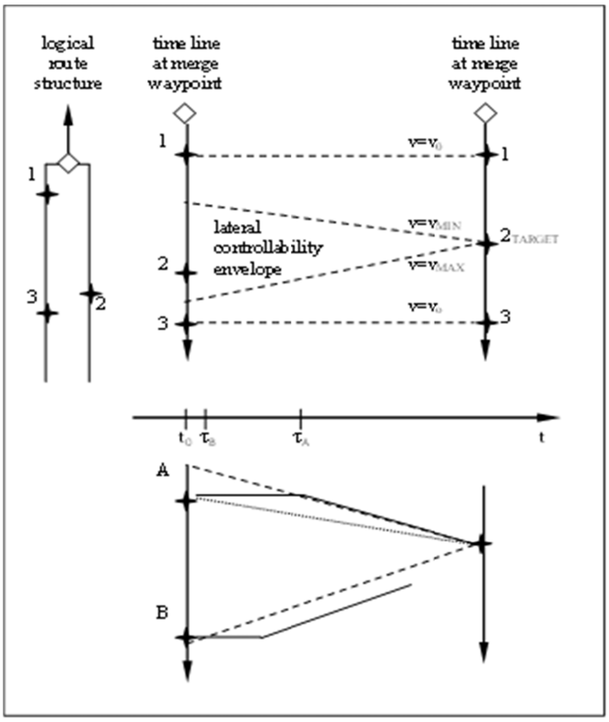


Fig. 2. Lateral Controllability Envelope and Time Buffer

Depending on workload and performance, the controller may find time to optimize for higher efficiency within the envelope (fig. 2, dotted alternative to A, not utilizing the entire time buffer). However, depending on the conditions, the buffer may be too short to implement the desired strategy, requiring another strategy (e.g. slowing another aircraft down to enlarge the gap, fig. 2, τ_B).

5 Timeline Construction

In order to identify the necessity of controller intervention, we have designed a method to construct timelines based on data typically provided by radar surveillance systems. This method is utilized to analytically 'learn' from radar data logs as well as in the approach controller human performance model (HPM), where it takes the role of the perception sub-module. Conceptually, the method seems quite similar to the ones driving the respective advisory tools, e.g. [17, 18].

Based on an idea developed in a workshop with Prof. Leon Urbas from TUD's institute of industrial process control, we designed a set of vector fields (circular, converging, parallel) that were placed in the defined route structure (fig. 3, defined routes in upper part, vector field overlay in lower part) in order to estimate remaining distances for all possible alternate paths along the arrival transitions. The defined RNAV arrival transitions at the investigation airport Munich, Germany, form a shape which is representative for central European hub airports ('cornerpost' layout, dual-S shaped arrival transitions which allow for flexible path stretching/shortening, thus called 'trombones'). The integration over the vector fields yields the remaining distance until touchdown as a potential field. Precisely put, we construct a set of distance-remaining potential fields. The selection of the currently applicable field is obtained by matching aircraft velocity vectors to the vector fields (the fitting criterion is the maximal scalar product between the field's vector and the aircraft's velocity vector).

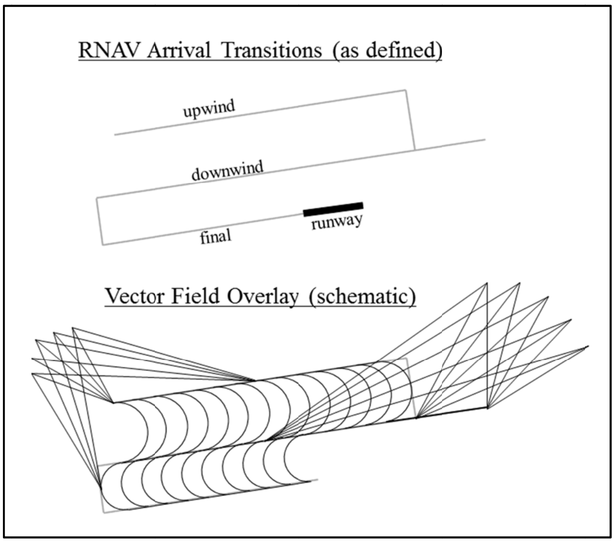
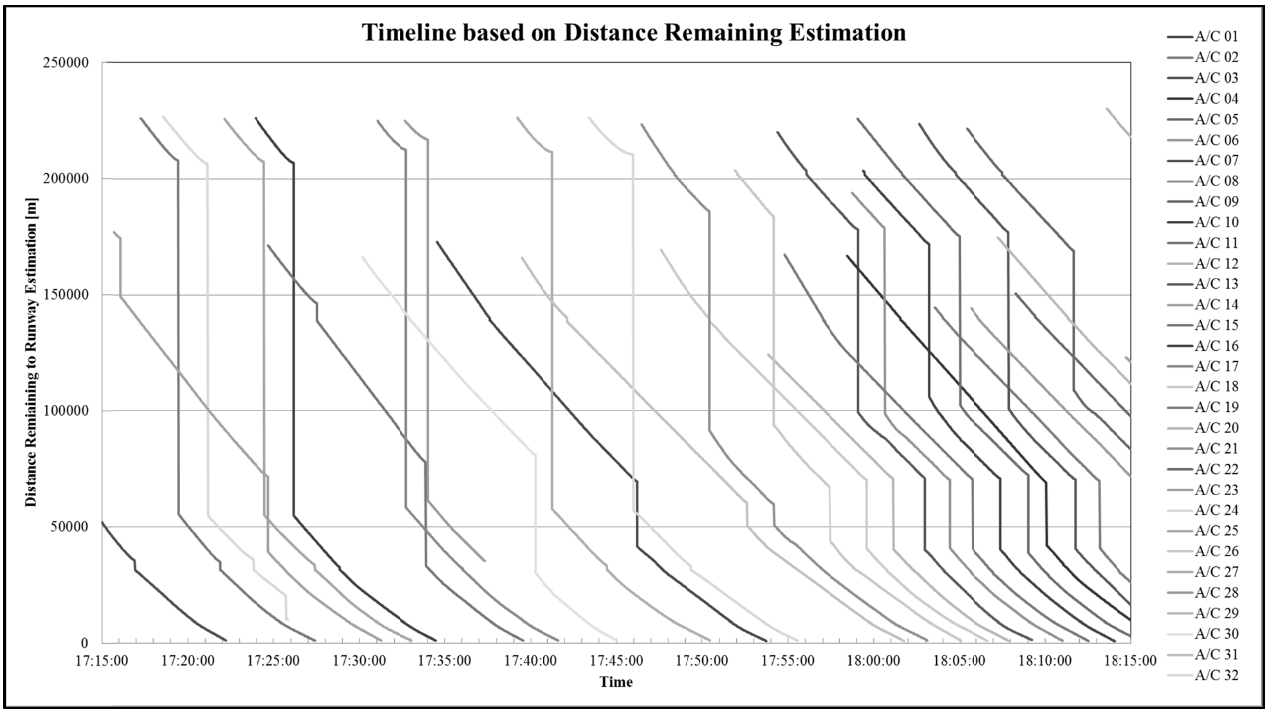


Fig. 3. Vector Fields for Remaining Distance Estimation

Fig. 4 shows an exemplary result of an analysis of recorded radar trajectories using this method. The progress in time is plotted on the x-axis, while the distance remaining estimation is plotted on the y-axis. Shortcuts through the trombone infrastructure are visible as vertical drops in the distance estimation: when an aircraft turns from upwind to downwind before the defined connection, the remaining distance estimation is lower, accordingly. In the example, we observe a transition in traffic patterns: In the first half, the controller makes regular use of the upwind-to-downwind shortcut for arrivals coming from the west (one large drop starting at 220 km estimated distance remaining) and merges traffic arriving from the west with downwind-to-final shortcuts. In the second half, clearly visible past timestamp 18:00:00, the controller uses both the upwind-to-downwind and the downwind-to-final shortcut for arrivals coming from the west. At this period, merging already occurs on the downwind leg.

This example is also given here to illustrate how significant events can be extracted automatically by means of this analytic method: Crossing curves indicate the re-sequencing of traffic (change in arrival positions). Converging curves indicate aircraft closing up on another. Since the analysis is fully two-dimensional, a check on separation in altitude must be made consulting the radar data, to decide if this indicates a conflict or a deliberate operation by air traffic control. A change in gradient indicates a speed change. Speed changes monotonously occur on the final approach leg where aircraft must achieve their respective approach speeds. We can see, that approach speeds and wake vortex separation values are quite homogeneous at this example, as typical for the investigation airport Munich, Germany (up to 90% medium jet).



6 Agent Model

6.1 Overview of Simulation System

For agent based modeling and simulation, we use CTU Prague's agent middleware platform *AglobeX* and the simulation environment *AgentFly*.

As of March 2012, the agent model consists of the following entities: (1) Airbus A320 flight performance model with FMC logic. The model runs synchronous with simulation time with an update rate of 100 ms. 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 ms per syllable, typical English syllable length of 3 characters, 100 ms between words) plus additions (300ms listening for a free channel, 150 ms 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 s. 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.

6.2 Perception Module for Radar Images

Our approach controller agent model uses the timeline construction method above but combines the remaining distance estimation with a linear prediction of future locations in order to perform planning of its actions with a time horizon of a few seconds up to 6 minutes.

6.3 Modeled Air Traffic Control Strategies

The approach controller's strategies and the resulting task model are described in detail in [11-13]. 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, constructed from estimated distance remaining and current ground speed) at join waypoint timeline, and finally (5) an observe radar task that identifies potential conflicts and triggers one of the tasks above, mostly based on the internal timeline constructed by the method described above.

We currently perform expert interviews to validate and refine this model. As a first result, we have learnt that the strategies employed in everyday operations differ significantly from the strategies defined in standard operating procedures [12].

6.4 Adaptions to investigate Time Buffers

In order to study time buffers by means of simulation, the approach controller model's internal timing was artificially constrained. Apart from voicing all advisories for transmission through the R/T channel, there had been no temporal constraints, resulting in an ideally 'fast' model. The model was adapted to run in cycles of 1 second, and instructions were added to constrain all tasks to respective multiples of this basic cycle. Two constraints variables were added based on the task's effects on the aircraft's 4D trajectory: (1) a cycle time for approach route assignation and path shortening/stretching tasks (horizontal component) and (2) a cycle time for speed and altitude management tasks (vertical / longitudinal component).

7 Simulation Results

7.1 Evaluation Scheme

The approach controller model's internal timing was artificially constrained by means of the two cycle values laid out above. The evaluation scheme is a deterministic sampling method similar to [12] and best explained graphically (fig. 5). Of all possible combinations, three pairs of interest were varied, simulated, and analyzed using our collision risk model (CRM), resulting in a collision risk estimate which is directly comparable to target levels of safety (TLS) published by ICAO. This sensitive and continuous figure provides an objective answer on the question of how safe simulated performance was. It is generally agreed that all TLS published to this day, 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^{-7}) or one billion operating hours (10^{-9}), respectively.

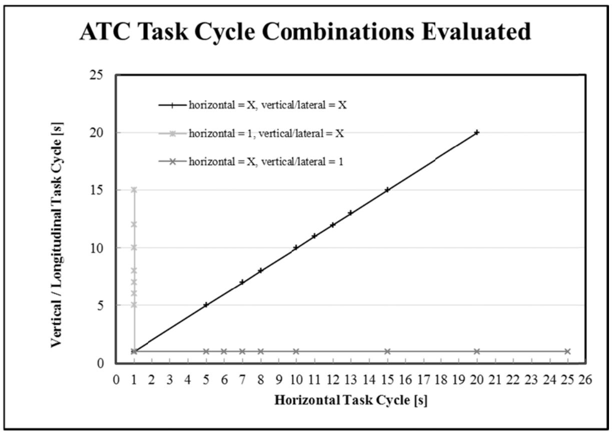


Fig. 5. Evaluation Scheme of three Task Tycle Combinations

The graphs in fig. 5 highlight the combinations of interest that were evaluated in this analysis: first, all tasks were constrained to the same cycle value regardless of their effect on the aircraft's trajectories (black); second, the vertical / longitudinal cycle was fixed to one second to observe the effects of varying cycle times affecting horizontal trajectory changes (medium gray); third, the vertical / longitudinal cycle was fixed to one second to observe the effects of varying cycle times affecting horizontal trajectory changes (light gray).

The simulation was loaded with ten hours of 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 throughput limit at the investigation airport.

7.2 Simulation Results

In the first analysis, all tasks were constrained with the same cycle time: altitude, speed management, and routing tasks. The resulting collision risk indicates a well-defined temporal buffer of about 10 seconds: if the controller model always reacts within those 10 seconds, the level of safety remains almost stable as formulated in the research hypothesis. If the value is exceeded, the level of safety exhibits a steep gradient, forming a sharp transition into the unsafe region (fig. 6). All reasonable TLS are well breached at 12 seconds.

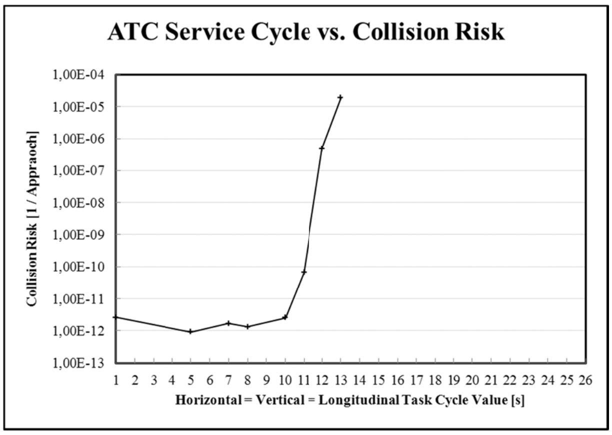


Fig. 6. Well-defined safety margin for all tasks in combination

In an exploratory study performed beforehand, its was observed that for mean time-separation between aircraft in the arrival flow of 105 s (90 s minimum plus safety margin), delays below app. 20 s did not significantly impact onto safety, seemingly contradicting the results of this first analysis. The exploratory study however, varied the temporal implementation of path stretching / shortening tasks alone. By varying all task cycles together, the speed and altitude management task are now included as well, which motivates the evaluation scheme laid out above. Furthermore, it can be shown by detailed analysis of the simulations' trajectory output, that the individual approach control task are highly interdependent, meaning that actions and their consequences form a tight-knit network. For example, delays in the speed control task do not impact in separation infringements right away, but re-shape the trajectories as other control options are taken and in turn hampered by conflict situations that arise. Figs. 7 and 8 illustrate this by a visual comparison between superimposed trajectories for a 1 s and a 10 s service cycle.

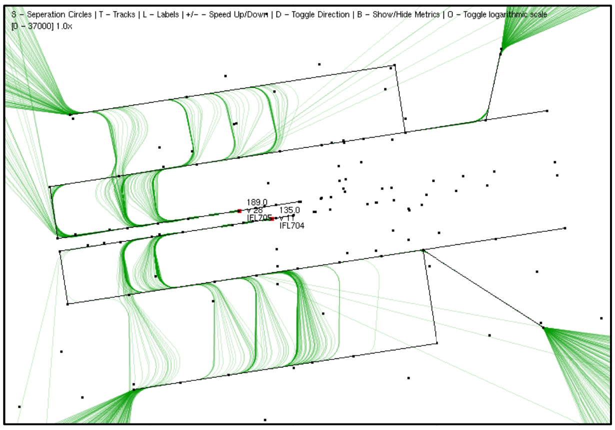


Fig. 7. Simulated Trajectories for 1 s Full ATC Service Cycle

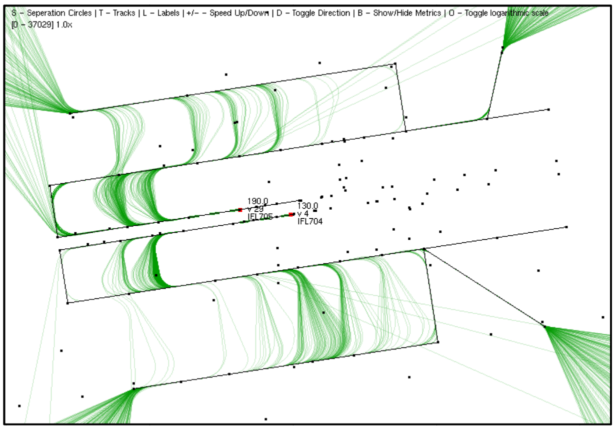


Fig. 8. Simulated Trajectories for 10 s Full ATC Service Cycle

The combined curve shown in fig. 6 was then dissected by explicitly quantifying the effects of the two contributing task cycles (horizontal and vertical / longitudinal component, fig. 9). The aggregated results clearly show that the combined (black) system response is not the sum of the two contributor curves (light and medium gray), but is 'worse' from a safety point of view because of the task interdependencies. This confirms our long-term hypothesis that adverse coincidence of human performance variations can indeed pose a major hazard on ATM.

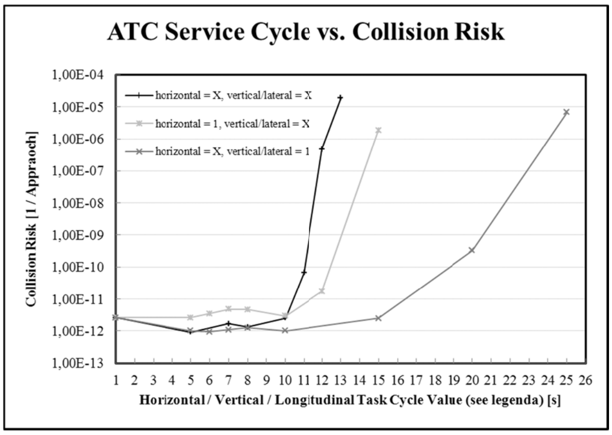


Fig. 9. Aggregated Results: Sensitivity

The light gray curve shows the results of varying the altitude and speed management cycle while keeping the horizontal cycle at its minimum (one second). It is clearly visible that the safety margin is in the same order as in the combined curve, making this the major contributor. The dark curve representing the horizontal component, in contrast, seems to be a lesser contributor with a larger temporal buffer (about 15 seconds) and a smoother transition into the unsafe region (reasonable TLS are not breached at 20 seconds, as observed in the exploratory study performed beforehand).

This high sensitivity of the speed and altitude management task can be explained by looking at the simulated incidents. Safety occurrences were extracted automatically from the simulation output und then analyzed manually by replaying the incidents. Situations where aircraft approach fast on their slow predecessors, distance remaining prediction errors and large speed differences were identified as the major cause of critical situations. As a minor contributor, delayed climb/sink advisories were identified: if aircraft are not well spaced, delays in this respect are highly safety-critical because controllers' conflict resolution techniques are hampered. Nevertheless, the most safety-relevant case to be addressed by controllers lies in large speed differences. At not untypical 30 knots difference in speed, separation decreases at a rate of ½ NM per minute. Human factors studies are needed to verify if these simulation-based results holds true in the everyday application of the tasks modeled here.

8 Summary and Outlook

With this paper, time windows defining safety-neutral buffers for potentially delayed reactions of human players were motivated and explained by discussing the problem analytically. Timelines were introduced as an important helper to analyze traffic situations and derive the need for controller interventions. Consequently, a method for efficient construction of timelines by means of vector fields was presented. This approach is utilized in our approach controller agent model as the logical sub-module for the perception of radar images. After the current development stage of our agent based simulation system was briefly presented, we introduced the experimental setup for investigating time buffers in current TMA operations.

The results show that there are different time buffers for various tasks/rules whose quantity differ significantly depending on the type of task (and its look-ahead time). These findings allow us to introduce time-constraining limitations and variations of performance in a precise and purpose-driven manner, in order to reproduce flexible and variable human behavior into the agent based model. As next steps, the sampling technique must be elaborated and automated in order to evaluate all possible value pairs. Stochastic modeling and Monte-Carlo simulation will be our next big step in order to evaluate unfavorable combinations of varying human performance as a safety hazard.

A novel validation technique for artificial controller models evolves out of the analyses presented here: The time buffer remaining when advisories are issued is comparable to real-life human performance.

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