Agent-based safety risk analysis of Trajectory Based Operation in the Terminal Manoevring Area

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***Abstract* - In 2004 the European Commission initiated the Single European Sky ATM Research (SESAR) programme to meet significantly higher capacity and safety targets in the future. The current architecture of ATM services needs to be changed in order to realise these targets. This paper presents the results of an initial quantitative safety risk analysis of a Trajectory Based Operation (TBO) in the Terminal Manoeuvring Area (TMA) which allows pilots to make tactical decisions themselves rather than always having to await controller instructions. The safety risk analysis results obtained suggest that giving such a tactical role to pilots may have a remarkably positive effect on improving both capacity and safety under TBO in the TMA.**

Keywords - Airborne Separation Assistance System (ASAS); Terminal Manoeuvring Area (TMA); Agent-based modelling and simulation; Petri Nets; Safety; Minimum separation.

I. INTRODUCTION

As a step towards increasing future Air Traffic Management (ATM) capacity, [1] proposes a Trajectory Based Operation (TBO) using a four-dimensional (4D) trajectory planning, which is implemented through the exchange of Reference Business Trajectories (RBTs). According to [2] such RBT based approach is supported by aircraft equipment to better follow assigned trajectories with fewer controller tactical interventions, and automatic detection and timely resolution of any deviation that impacts loss of separation.

In order to increase the capacity of a high density TMA accommodating multi-airport traffic flows, e.g. [3], this could mean that that the lateral distance (spacing) between centrelines of traffic flows could be reduced from 8 Nautical Miles (NM) to 5 NM [4]. In such TMA, various closely spaced Standard Instrument Departure routes (SIDs) and Standard Terminal Arrival Routes (STARs) may be defined, which pass several en route lanes at lower flight levels. An earlier agent-based safety risk study [5],[6] focuses on whether such reduction of spacing between standard routes can safely be done in a future TMA under a ground-based TBO concept of operations, which is referred to as TMA-T1 ConOps [4].

In this TMA-T1 ConOps there are two layers of control: one is the TBO layer, which determines conflict-free 4D trajectory plans. The other layer is the tactical control loop, which consists of Air Traffic Control (ATC) providing tactical manoeuvre instructions to aircraft in case of an unexpectedly remaining conflict. The study [5] has shown that under this TMA-T1 ConOps a safe reduction between centrelines of route structures is feasible if demanding safety objectives are satisfied.

The aim of this paper is to evaluate the potential impact in terms of relaxing these demanding safety objectives by giving pilots tactical self-separation control support. To accomplish this, the paper evaluates the safety risk of a modified version of the TMA-T1 operation in which pilots actively make tactical conflict resolution decisions with support of an Airborne Separation Assistance System (ASAS). This modified TMA-T1 operation is referred to as TMA-T1-ASAS. Similarly as has been done in [5] for the TMA-T1 operation, the current paper conducts an initial safety risk analysis of the TMA-T1-ASAS operation with focus on the tactical conflict resolution phase, i.e. when remaining time is too short for resolving a conflict through a RBT update. Use is made of the quantitative part of the Traffic Organization and Perturbation Analyzer (TOPAZ) methodology, which combines human performance and agent-based modelling with rare event Monte Carlo (MC) simulation [7]-[9].

This paper is organised as follows. Section II describes the TMA-T1-ASAS operation. Section III presents the development of an agent-based model of the TMA-T1-ASAS operation. Section IV presents the rare event MC simulation results based on this model. Section V discusses the MC simulation results. Section VI draws conclusions.

II. TMA-T1-ASAS OPERATION

For the TMA-T1-ASAS operation, a high density TMA is considered which accommodates multi-airport traffic flows. In this TMA, there are various closely spaced SIDs and STARs which may pass several en route lanes at lower flight levels. Similar to the TMA-T1 ConOps [4], in order to increase capacity, the TMA-T1-ASAS ConOps aims to accommodate a safe reduction of spacing between these standard routes to 5 NM. There are no new constraints on the radar separation minimum, hence this can stay as today, i.e. at 3 NM. In the TMA-T1-ASAS operation, the responsibility for separation assurance is distributed between the controller and the pilots. This means that the controller is still responsible for the safe and orderly operation of flight in compliance with the ICAO

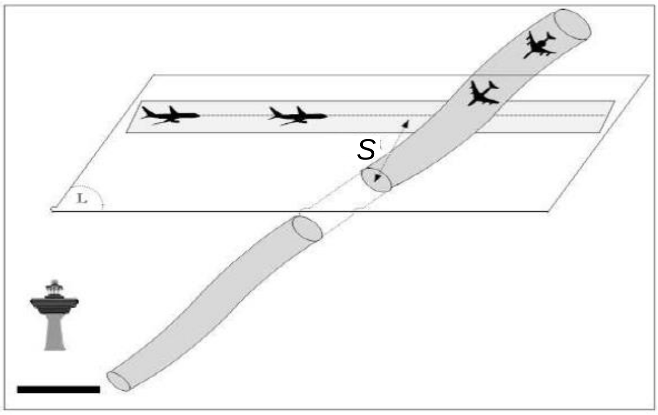

Figure 1. Encounter type considered with aircraft on a STAR and aircraft en-route [5], with spacing S between the centrelines of the STAR and the en-route lane going down to 5NM; currently this is 8 NM or more. The radar separation minimum remains at 3NM.

Rules of Air and with other relevant regulatory provisions, within standard operating procedures. However, ASAS supported pilots are allowed to act themselves in case of a significant deviation from the conflict free intended 4D trajectory plans. Moreover it is assumed that all aircraft are ASAS equipped.

The conflict scenarios considered are the same as in [5]: an aircraft flying en route and aircraft flying on a STAR, on paths which are spaced laterally by 5 NM, see Figure 1. The aircraft on the STAR are flying a Continuous Descent Approach (CDA). In this scenario, the en-route flying aircraft suddenly makes a turn to the right, i.e. into the direction of the STAR, which is well known to be the key risk bearing non-nominal scenario in current ATM [10],[11].

III. AGENT-BASED MODEL OF TMA-T1-ASAS

A. *Agent-based modelling*

Agent-based modelling is a way to model the dynamics of complex adaptive systems. Agent-based models can integrate cognitive models of human performance, physical models of technology behaviour and descriptions of their operating environment [12]. Simulation of these individual models acting together can predict the result of completely new transformations in procedures and technologies. In combination with rare event MC simulation, this agent-based approach delivers a powerful safety risk analysis of advanced ATM concepts of operation, e.g. [13].

In the TMA-T1-ASAS initial model the following types of agents are taken into account:

- Air Traffic Control (ATC) system
- Air Traffic Controller (ATCo)
- Aircraft evolution
- Pilot Flying (PF)
- Airborne Separation Assistance System (ASAS)

Note that for each aircraft in the initial model there is one Aircraft evolution agent, one Pilot flying agent and one ASAS agent. There is only one Air Traffic Controller agent and one ATC system agent in the model. In comparison to the initial agent-based model of TMA-T1 in [5], [6] there is the new agent ASAS, the ATC system is extended with ADS-B Global, and agent Pilot flying is now extended to take advantage of ASAS. It should be noticed that this TMA-T1-ASAS initial model is focussed on the tactical conflict resolution phase, i.e. when remaining time is too short to resolve the conflict through RBT updating.

B. *Agent-level Petri Nets*

The agent-based model details are specified using the formalism of Stochastically and Dynamically Coloured Petri Net (SDCPN), [14]-[17]. SDCPN is a very powerful formalism to model air traffic operations, such as the future TMA-T1-ASAS operation, in which various non-deterministic dynamic scenarios may emerge.

For all agents one or more Local Petri Nets (LPNs) can be defined, where each LPN is a SDCPN-based submodel describing an agent-specific process. In the model for TMA-T1-ASAS there is one aircraft flying level (ac_0) and there are multiple aircraft flying on a STAR (ac_j is introduced *m* times, for $j = 1, .., m$). Each LPN consists of places, which represent the possible modes (discrete valued states), and transitions, which represent mode switches, connected by arcs (arrows).

Table I lists the LPNs for each agent in the TMA-T1-ASAS model. Below, a high level description of the LPNs is given, organised per agent. The complete SDCPN-based model for TMA-T1-ASAS, including all interconnections and other mathematical details is presented in [18]. Here we provide an overview of the LPNs for each agent.

ATC system as agent

The ATC system as agent contains two LPNs: LPN ATC system and LPN ADS-B Global. The former has one place which represents:

- *Info*: updates state information of all aircraft in the model, performs conflict detection and alerting as well as flight plan performance monitoring for all aircraft.

TABLE I. LOCAL PETRI NETS IN THE TMA-T1-ASAS MODEL; LPN'S WHICH DIFFER FROM TMA-T1 ARE MARKED BY *

Agent	Local Petri Net
1. ATC system	ATC system
	ADS-B global *
2. Air Traffic Controller	Air Traffic Controller (ATCo)
3. Aircraft evolution	Aircraft horizontal evolution
	Aircraft vertical evolution
4. Pilot flying	Pilot flying *
5. ASAS	ASAS processing *
	ASAS surveillance *
	ASAS system mode *
	ADS-B transmitter *
	ADS-B receiver *

The LPN ADS-B Global has the following two modes:

- *Not-Occupied*: ADS-B Global is not occupied.
- *Occupied*: ADS-B Global is occupied.

Air Traffic Controller as agent

The Air Traffic Controller as agent contains one LPN Air Traffic Controller. The places in the LPN Air Traffic Controller represent the following modes [18]:

- *Monitoring*: The mode in which the air traffic controller collects, gathers and integrates information.
- *Decision-making and Execution*: Using information received, the air traffic controller makes up his mind about: whether co-ordination is required, and if so, with whom and what, and whether a particular action is required, and if so when and which specific action. Subsequently the air traffic controller gives an instruction to a pilot to resolve a conflict. The duration of this mode is assumed to be exponentially distributed.
- *Execution Monitoring:* The mode in which the air traffic controller overlooks the events and developments resulting from an action.

Aircraft evolution as agent

Similar as in [3], the aircraft evolution agent contains two LPNs. One is LPN Horizontal aircraft evolution, and the other is LPN Vertical Aircraft evolution. The former has modes:

- *On lane:* aircraft flies level.
- *Sharp turn left*: aircraft makes a sharp turn left.
- *Back to lane*: aircraft flies back to his lane.

The modes of the LPN vertical aircraft evolution are:

- *CDA*: aircraft flies Continuous Descent Approach.
- *Climb*: aircraft is climbing.
- *Level*: aircraft flies level.

Pilot flying as agent

The pilot flying as agent contains one LPN, which is more detailed than in [5]. The places in the LPN Pilot Flying represent similar modes as in the LPN Air Traffic Controller:

- *Monitoring*: The mode in which the pilot collects, gathers and integrates information.
- *Decision-making and Execution*: The mode in which the pilot is making up his mind and is activating a course change upon receiving a tactical advisory from ASAS or a tactical instruction from the controller. The duration of this mode is assumed to be exponentially distributed.
- *Execution Monitoring*: The mode in which the pilot monitors whether events and developments comply with the expected execution.

ASAS as agent

This agent contains five LPNs: LPN ASAS processing, LPN ASAS surveillance, LPN ASAS system mode, LPN ADS-B transmitter and LPN ADS-B receiver. LPN ASAS processing detects possible conflicts of own aircraft with other aircraft. LPN ASAS surveillance receives and updates the state information of all aircraft. LPN ASAS system has three places which represent the following modes:

- *Working:* ASAS is working correctly.
- *Failure:* ASAS fails.
- *Corrupted*: ASAS is corrupted.

LPN ADS-B transmitter denotes whether the ADS-B transmitter of the aircraft is working or not. The LPN has two places that represent the following modes:

- *Working:* ADS-B transmitter is working correctly/ No ADS-B transmission failure.
- *Not working*: ADS-B transmitter is not working / ADS-B transmission failure.

C. *Specification of agent interactions*

Figure 2 depicts the tactical interactions between the agents in the initial TMA-T1-ASAS model. One should remember that in this initial model of TMA-T1-ASAS aircraft send to each other state information only, i.e. no RBT information. Moreover, there is no ADS-B receiver in the ATC system model, which means that the ATC system estimates aircraft states on the basis of receiving multi-radar based information only.

For each aircraft in this model there are seven LPNs: LPN Aircraft evolution, LPN Pilot flying, LPN ASAS processing, LPN ASAS surveillance, LPN ASAS system mode, LPN ADS-B transmitter and LPN ADS-B receiver. Moreover there is one LPN Air Traffic Controller, one LPN ATC system and one LPN ADS-B global. Hence, when there are m aircraft on a STAR and one aircraft on level, there are $7(m+1)+3$ Local Petri Nets in the TMA-T1-ASAS model.

Now the tactical interactions between these LPNs are specified. Connections between LPNs are realised using the compositional specification principles of [15]. Two types of basic interconnections between nodes in different LPNs are used. The first is enabling arc (or inhibitor arc) from one place in one LPN to one transition in another LPN. These types of arcs have been used widely in Petri net literature. The second is Interaction Petri Net (IPN) from one (or more) transition(s) in one LPN to one (or more) transition(s) in another LPN.

The remainder of this subsection illustrates the SDCPN-based model developed for ASAS on-board each aircraft, including the interconnections between the LPNs. A distinction is made between $j=0$, referring to the aircraft en route, and $j=1,..,m$, referring to aircraft on a STAR. Figure 3 shows this SDCPN-based ASAS model for aircraft ac_j.

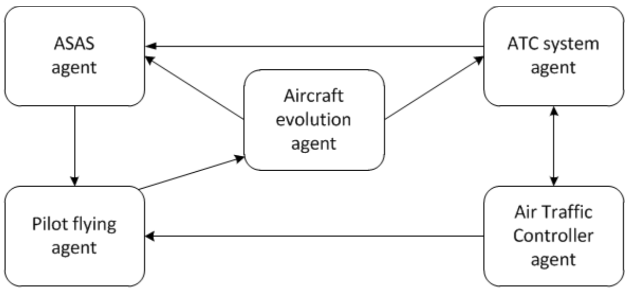

Figure 2. Agents in initial TMA-T1-ASAS model and their tactical interactions.

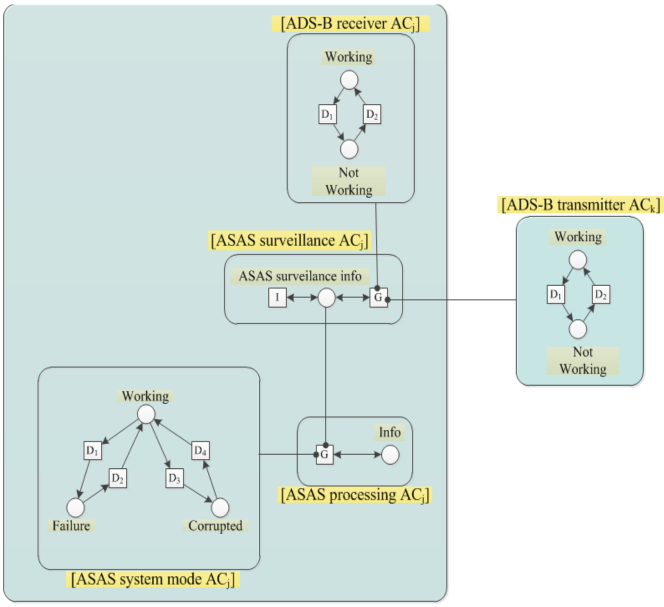

Figure 3. The ASAS agent in the TMA-T1-ASAS operation is modelled by five LPNs and a number of ordinary and enabling arcs, and receives info from ADS-B transmitter of other aircraft $k \neq j$.

In this SDCPN-based model of ASAS, the LPN ASAS surveillance of ac_j receives ADS-B information from other aircraft ac_k ($k \neq j$) if:

- LPN ADS-B receiver of ac_j is working,
- LPN ADS-B transmitter of aircraft ac_k is working,
- LPN ADS-B global is not occupied.

Under these three conditions, LPN ASAS processing of ac_j receives the state information from the other aircraft. Furthermore, if LPN ASAS system mode is working, then ASAS will alert Pilot flying of a potential conflict. Hence the ASAS agent is also connected to the Aircraft evolution agent, the ATC system and the Pilot flying agent, though this is not drawn in Figure 3.

D. Implementation, parametrization and verification

The SDCPN model specification has been implemented in an object oriented programming language; in this study Delphi XE3 was used. The SDCPN specification was implemented in four steps: The first step is the translation of the formal SDCPN structure into software code per LPN component. The second step is the development of the software code at the agent level. The third step is the software implementation at agent interactions level. And the fourth and final step is the implementation of the software code that supports running Monte Carlo simulations of the implemented SDCPN.

During the implementation of the SDCPN model specification in object oriented Delphi XE3 code, the software was thoroughly tested. This was done through conducting the following sequence of tests: common functions, each Local Petri Net implementation, each agent implementation, interactions between agents, full Monte Carlo simulation. Also the graphical user interface was tested. This was to verify that the input and output of data works well.

TABLE II. PARAMETER VALUES IN TMA-T1-ASAS MODEL [17]

Parameter	**Value**	**Source**
RNP value	1 NM	[5]
Radar separation minimum	3 NM	[5]
Vertical spacing minimum	1000 ft	[5]
Aircraft speed	325 knots	[5]
Angle of sudden turn	60 degrees	[5]
Aircraft bank angle	25 degrees	[5]
Vertical acceleration/deceleration	2 m/s^2	[5]
Time distance between aircraft on STAR/level lane	2 minutes	[5]
Mean controller execution response time of a FPCM or STCA triggered clearance/instruction	7.0 + 0.6 = 7.6 seconds	[5],[19], [20]
Mean pilot execution response time to a proximity resolution instruction by controller or by ASAS	5.7 seconds	[5],[10], [19]
Number of aircraft on STAR	6	[5]
Probability ADS-B global being occupied	1/1000	*)
Mean duration ADS-B global being occupied	1 hour	[13]
Probability ASAS system mode fails	1/20000	[13]
Probability ASAS system mode is corrupted	1/20000	[13]
Mean duration ASAS system mode fails or is corrupted	1 hour	[13]
Probability ADS-B transmitter is not working	1/20000	[13]
Mean duration ADS-B transmitter is not working	½ hour	[13]
Probability ADS-B receiver is not working	1/20000	[13]
Mean duration ADS-B receiver is not working	½ hour	[13]

*) Conservative value; in [13] a thousand times better value was assumed.

This was followed by parameterization, through using the same values used in [5],[6] and the ASAS specific values used in [13]. The main baseline parameter values adopted are given in Table II.

Finally, full model verification tests have been performed by running Monte Carlo simulations of the TMA-T1-ASAS model. One test was to run TMA-T1-ASAS under the same conditions as TMA-T1 in [5], i.e. by disabling the ASAS component; this yielded similar results as in [5]. Other verification tests were to run Monte Carlo simulations with specific parameter settings for which the outcome could be predicted, e.g. the effect of a very high reaction time of pilot flying should give a predictable increase of the conditional collision risk per STAR passing.

IV. MONTE CARLO SIMULATION

The next step is to perform Monte Carlo simulations for the same non-nominal scenarios that have been used in [5],[6] to evaluate the TMA-T1 operation. In these non-nominal scenarios the en-route aircraft makes a sudden turn to the right under three specific conditions that are referred to as “No ATC”, “Short Term Conflict Alert (STCA) only” and “Flight Plan Conformance Monitoring (FPCM) and/or STCA”. In order to analyse the effect of allowing pilots to make tactical decisions themselves, the MC simulation results will be compared with those obtained in [5] for TMA-T1.

A. Non-nominal scenario sudden turn under "No ATC"

This non-nominal scenario considers a situation in which the aircraft en route makes a sudden turn away from its lane; the aircraft on the STAR maintains a straight line, all under the rare condition of "No ATC". The latter rare condition means that the controller does not, or is not able to give a conflict recovery instruction to an aircraft in conflict. Such rare condition may occur, e.g. due to failing communication or failing ground surveillance equipment.

In this non-nominal scenario each pilot flying is monitoring the positions and velocities of all aircraft that are available to him through the Cockpit Display of Traffic Information (CDTI). About two minutes before a conflict is due to occur (i.e. two minutes before separation is less than 3 NM), the ASAS alerting system warns the pilot for a conflict. If a conflict occurs the pilot should make a resolution manoeuvre. ASAS gets as input only position information, from which it derives velocity information.

The conditional collision risk results for this non-nominal scenario are given in Figure 4. The (upper) blue line shows the results of the TMA-T1 operation and the (lower) red line shows the results of the TMA-T1-ASAS operation in which pilots are making tactical decisions themselves rather than having to await controller instructions. The horizontal axes in the figures show various values for the spacing between the en route lane and the STAR in NM. The vertical axis provides the conditional collision risk, i.e. the probability for an aircraft on the en route lane to collide with an aircraft on the STAR, for the situation described. Between 100 thousand and 170 million Monte Carlo simulations were run for each point estimate on the graph, depending on the number of collisions counted per run. Lower collision risk requires more runs to obtain more accurate results.

Figure 4 shows that for all spacing values the conditional collision risk results for the TMA-T1 operation are at a constant probability level of about 3.3E-3 per STAR passing.

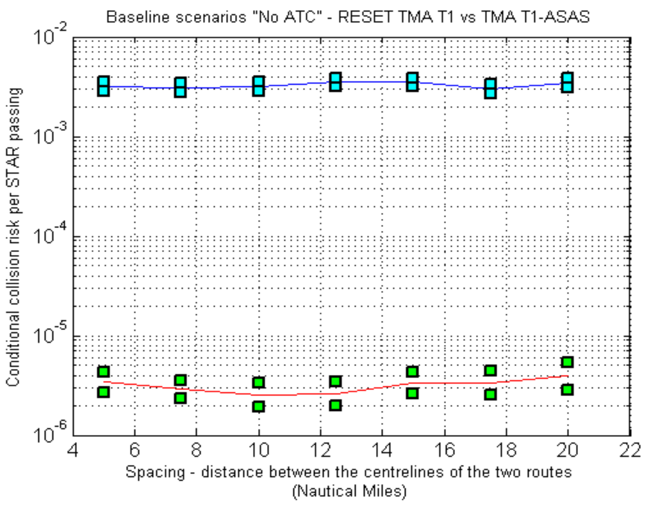

Figure 4. Monte Carlo simulation results for non-nominal encounter scenario "No ATC" for TMA-T1 (upper, blue line) and TMA-T1-ASAS (lower, red line). The small blue and green blocks indicate the upper bound and the lower bound of a 95% confidence interval.

Hence for ten million Monte Carlo simulation runs of the non-nominal scenario, about 33000 collisions have been counted because the controller could not give an avoidance instruction. This happens when the rare condition of a loss of R/T or surveillance continues for many minutes, as a result of which the controller is not able to resolve the conflict, not even when the spacing value S is enlarged. The small blue and green blocks in the figure indicate the upper bound and the lower bound of a 95% confidence interval for each conditional risk point.

In the TMA-T1-ASAS operation pilots are allowed to make tactical decisions themselves. In this case pilots are able to reduce the risk of collision to 34 collisions per ten million MC simulation runs of the non-nominal scenario, which is a factor 971 reduction over TMA-T1. For the TMA-T1-ASAS operation the mean conditional collision probability is at a level of about 3.4E-6 per STAR passing, with bounds 2.7E-6 and 4.3E-6 for the 95% confidence interval. This means that due to allowing pilots to resolve tactical conflicts themselves, according to the TMA-T1-ASAS initial model the collision risk reduces by a factor 971 (= 3.3E-3 / 3.4E-6). Further analysis of the collision events revealed that about 97% of the remaining collisions happen when ADS-B global is occupied, which makes it impossible for pilots to see other aircraft. It should be noticed that due to basic pilot errors [21] in reality this factor may be lower, although it still will be a large improvement.

B. Non-nominal scenario sudden turn under "STCA only"

This non-nominal scenario considers a situation in which the aircraft en route makes a sudden turn away from its lane; the aircraft on the STAR maintains a straight line, all under the rare condition of "STCA only". The latter rare condition means that the controller does not notice the conflict until a STCA alert is given by the ATC system. In the simulation model, STCA gets as input only position information, from which it derives velocity information. In this scenario, about two minutes before separation is less than 3NM, the Short Term Conflict Alert (STCA) system warns the controller of a conflict. Upon this, after a reaction time, the controller takes action: he uses R/T to give the flight crew of one of the aircraft an avoidance instruction. R/T is assumed to be working properly. One option is for the controller to give the aircraft on the STAR an instruction to level off, thus ensuring vertical separation. Another option is to send the aircraft en route back to the en route lane. After a reaction time, the pilot flying of the aircraft that has been given the instruction, reacts and follows the instruction.

Moreover, in this non-nominal scenario the pilot flying is monitoring positions and velocities of all aircraft that are available to him through the CDTI. About two minutes before a conflict is due to occur (i.e. two minutes before separation is less than 3 NM), the ASAS alerting system warns the pilot for a conflict. ASAS gets as input only position information, from which it derives velocity information. If a conflict occurs the pilot should make a resolution manoeuvre.

The conditional collision risk results for non-nominal encounter scenario "STCA only" are given in Figure 5. The (upper) blue line shows the results of the TMA-T1 operation and the (lower) red line shows the results of the TMA-T1-

ASAS operation in which pilots are making tactical decisions themselves rather than having to await controller instructions. The conditional collision risk in the TMA-T1 operation at a spacing of 5 NM is 6.0E-5 collisions per level aircraft passing a STAR and decreases to a level of about 2.5E-7 collisions per level aircraft passing a STAR at larger spacings. The conditional collision risk in the TMA-T1-ASAS operation at a spacing of 5 NM is 8.6E-8 collisions per level aircraft passing a STAR with bounds 4.9E-8 and 1.5E-7 of the 95% confidence interval. It appears that for spacing larger than 5 NM no collisions have been counted in 140 million Monte Carlo simulations. Hence, the conditional collision risk for spacings larger than 5 NM is less than 1 in 140 million (i.e. less than 7.1E-9 collisions per level aircraft passing a STAR).

When comparing the conditional collision risk results of the TMA-T1 operation with those of the TMA-T1-ASAS operation (see Figure 5), one may notice that for a spacing of 5 NM, the results of the TMA-T1-ASAS operation are a factor 698 better than those of the TMA-T1 operation.

C. Non-nominal scenario sudden turn under "FPCM and/or STCA"

This non-nominal scenario considers a situation in which the aircraft en route makes a sudden turn away from its lane; the aircraft on the STAR maintains a straight line, all under the rare condition of "FPCM and/or STCA". The latter means that the controller does not notice the conflict until a FPCM or a STCA alert is given by the ATC system.

In this scenario, at some point, FPCM detects that the aircraft is making a turn away from its RBT. The controller is alerted to this deviation, and after a reaction time, the controller takes action: he uses R/T to give the flight crew of one of the aircraft a recovering instruction. R/T is assumed to be working properly. One option is to give the aircraft on the STAR an instruction to level off, thus ensuring vertical separation. Another option is to send the aircraft en route back to the en route lane. It is assumed that FPCM gets as input precise state information (position, velocity) of aircraft, e.g. through ADS-B or Mode S.

In addition, about two minutes before a conflict is due to occur STCA warns the controller of a conflict. Upon this, after a reaction time, the controller takes action, by using R/T to give the flight crew of the aircraft on the STAR an instruction to level off, or to send the aircraft en route back to the en route lane. After a reaction time, the pilot flying of the aircraft that has been given the instruction, reacts and follows the instruction. Moreover, in this non-nominal encounter scenario the pilot flying is monitoring the positions and velocities of all aircraft that are available to him through ASAS. About two minutes before a conflict is due to occur (i.e. two minutes before separation is less than 3 NM), the ASAS system warns the pilot for a conflict. If a conflict occurs the pilot should make a resolution manoeuvre. ASAS gets as input only position information, from which it derives velocity information.

The conditional collision risk results for non-nominal encounter scenario "FPCM and/or STCA" are given in Figure 6. The (upper) blue line shows the results of the TMA-T1 operation and the (lower) red line shows the results of the TMA-T1-ASAS operation in which pilots are making tactical decisions themselves rather than having to await controller instructions. The small blue and green blocks in the figure indicate the upper bound and the lower bound of a 95% confidence interval for each conditional risk point.

The conditional collision risk in the TMA-T1 operation at a spacing of 5 NM is 1.1E-5 collisions per level aircraft passing a STAR and at a spacing of 7.5 NM it is 3.3E-7 collisions per level aircraft passing a STAR.

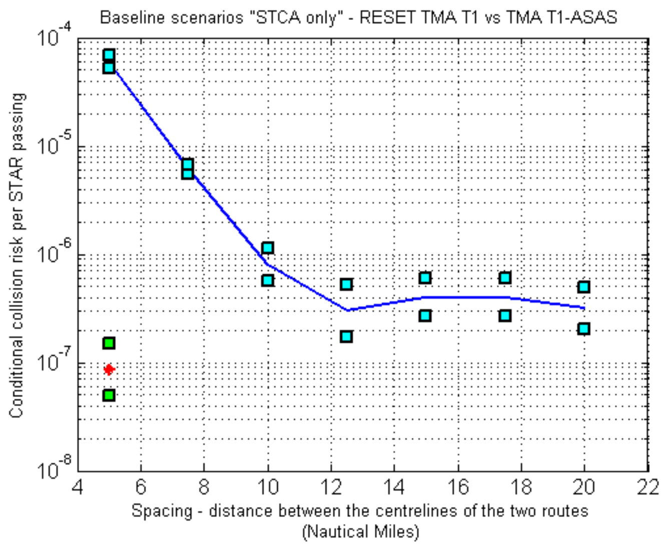

Figure 5. Monte Carlo simulation results for non-nominal encounter scenario "STCA only" for TMA-T1 (upper, blue line) and TMA-T1-ASAS (lower, red dot). The small blue and green blocks indicate the upper bound and the lower bound of a 95% confidence interval.

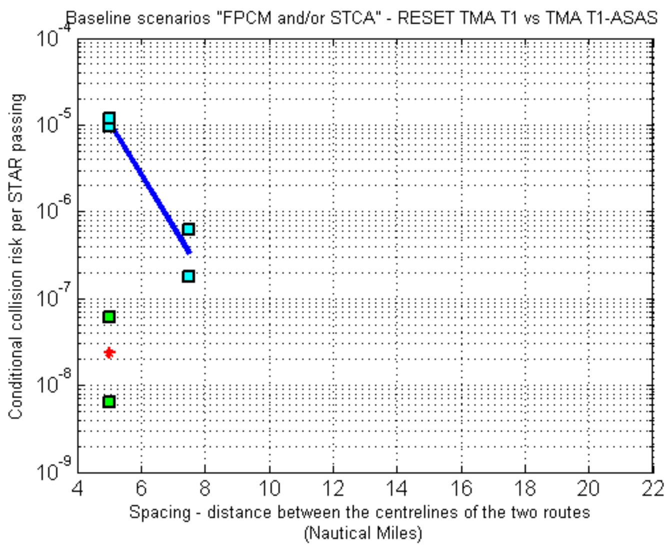

Figure 6. Monte Carlo simulation results for non-nominal encounter scenario "FPCM and/or STCA" for TMA-T1 (upper, blue line) and TMA-T1-ASAS (lower, red dot). The small blue and green blocks indicate the upper bound and the lower bound of a 95% confidence interval.

The conditional collision risk in the TMA-T1-ASAS operation at a spacing of 5 NM is 2.4E-8 collisions per level aircraft passing a STAR with bounds 6.4E-9 and 6.0E-8 of the 95% confidence interval. It appears that for spacing larger than 5 NM no collisions have been counted in 170 million Monte Carlo simulations. Hence the conditional collision risk for spacings larger than 5 NM is less than 1 in 170 million (i.e. which is less than 5.9E-9 collisions per level aircraft passing a STAR).

When comparing the conditional collision risk results of the TMA-T1 operation with the TMA-T1-ASAS operation (see Figure 6), one may notice that for a spacing of 5 NM, the results of operation of the TMA-T1-ASAS operation are a factor 458 better than those of the TMA-T1 operation. This shows that according to the model of the three non-nominal conditions, the pilots (who are allowed to make tactical decisions themselves), supported by ASAS, have a major contribution to solving conflicts.

V. Interpretation of Simulation Results

A. Safety Objectives

Section IV explained that for TMA-T1-ASAS, factors of conditional collision risk improvement (relative to TMA-T1) have been measured for sudden turn of an en-route aircraft under the conditions "No ATC", "STCA only" and "FPCM and/or STCA" respectively. These factors straightforwardly reduce the Safety Objectives derived in [5],[6] for the TMA-T1 ConOps. The resulting Safety Objectives for TMA-T1-ASAS reflect that non-nominal encounter scenario "No ATC" in the TMA-T1-ASAS operation is allowed to occur about a factor 971 more often than in the TMA-T1 operation. The non-nominal encounter scenario "STCA only" in the TMA-T1-ASAS operation is allowed to occur about a factor 698 more often than in the TMA-T1 operation. Furthermore the non-nominal encounter scenario "FPCM and/or STCA" in the TMA-T1-ASAS operation is allowed to occur about a factor 458 more often than in the TMA-T1 operation.

B. Contribution of Air Traffic Controller

It is important to notice that under TMA-T1-ASAS, the tactical role of the controller still is very significant under the conditions "STCA only" and "STCA and/or FPCM". By using the simulation results obtained we quantify what factor in safety is due to these tactical controller roles.

In comparing the results obtained for the three encounter scenarios of the TMA-T1-ASAS model in which pilots are allowed to make tactical decisions themselves, one may notice that for a spacing of 5 NM, the result of encounter scenario "STCA only" is about a factor 40 better than the result of encounter scenario "No ATC". This shows that according to the model, the controller still has a major contribution to reducing the collision risk, even if the controller only reacts upon a STCA alert.

Moreover when comparing the results of encounter scenario "FPCM and/or STCA" and "STCA only", one may notice that for a spacing of 5 NM, "FPCM and/or STCA" is about a factor 3.6 better than "STCA only". This shows that according to the model, the FPCM-supported controller still has a significant contribution in reducing collision risk, relative to the STCA only-supported controller.

C. Sensitivity results

Finally, a sensitivity analysis was conducted to analyse the sensitivity to risk of changes in values for a selection of key parameters in the Monte Carlo simulation model. The main conclusion that can be drawn from the sensitivity results is that according to the model, under the conditions "STCA only" and "FPCM and/or STCA" the conditional collision risk is highly sensitive to changes in any parameter that influences the time available to resolve a conflict between two aircraft. These parameter values are the average pilot reaction time, the average controller reaction time, the radar separation minimum, the angle of turn and the speed. For example, if the average reaction time of the pilot increases there is less time available to resolve a conflict. If the separation minimum used by ASAS decreases, ASAS will react later, leaving less time for the pilot to resolve a conflict.

Under the condition "No ATC", the main sensitivity comes from the probability of ADS-B global being occupied. This can be explained by the fact that when ADS-B global is occupied the aircraft does not receive state information of other aircraft. In that case ASAS cannot detect possible conflicts and therefore the pilots are not able to avoid the collision. If the probability of ADS-B global being occupied decreases the pilots are expected to be able to further reduce the collision risk under the "No ATC" condition.

VI. Concluding Remarks

The purpose of this study was to evaluate safety risk of a modified TMA-T1 operation in which pilots are making tactical decisions themselves rather than having to await controller instructions. This operation is called the TMA-T1-ASAS operation. The encounter scenario considered in this operation is the same as in [5]: a stream of aircraft that are flying on a Standard Terminal Arrival Route (STAR) and an aircraft flying level in the TMA, with a spacing of 5 NM between these routes.

In order to evaluate safety risk the Traffic Organization and Perturbation Analyzer (TOPAZ) methodology was used. The quantitative safety risk results were obtained through conducting rare event Monte Carlo simulations of a multi-agent stochastic dynamic risk model of the tactical interactions of the TMA-T1-ASAS operation in the encounter scenario considered. All mathematical details of the model were described in [18] using the formalism of Stochastically and Dynamically Coloured Petri Nets (SDCPN).

Comparison of the Monte Carlo results for an initial model of the TMA-T1-ASAS operation with those for an initial model of the TMA-T1 operation shows that pilots may have a major contribution in tactical resolution of a sudden turn of an en-route aircraft into the direction of aircraft on the STAR, under each of the three rare conditions considered, i.e. "No ATC", "STCA only" and "FPCM and/or STCA". On top of this, the air traffic controller has a significant complementary role conflict resolution under the two rare event conditions "STCA only" and "FPCM and/or STCA". Most importantly, their combined tactical conflict resolution power is much better than it was found for the ATCo alone in the ATM-T1 model.

The paper has also derived Safety Objectives, under the adopted agent-based model and the baseline values for its parameter values, regarding the allowable rate of occurrence of three selected conflict and resolution conditions. Due to allowing pilots to start tactical resolutions, for TMA-T1-ASAS the Safety Objectives are orders of magnitude more relaxed than they are for TMA-T1.

These remarkably positive findings clearly stimulate follow-up research regarding the further development of the TMA-T1-ASAS Concept of Operations, preferably by a team of ATM ConOps designers that work independently from the TOPAZ safety risk analysts. This would allow for the safety analysts to focus on the further improvement of the Monte Carlo simulation models, e.g. to account for controller and pilot errors in tactical decision-making and for non-exponential delays, and to run rare event MC simulations for these improved models.

Complementary follow-up research is to use the agent-based models for conducting a systematic bias and uncertainty analysis. Both for TMA-T1 and for TMA-T1-ASAS, there will remain various types of differences between the improved models and the true operations. Through a systematic bias and uncertainty analysis the effect of these differences on the assessed safety risk values can be analysed [22]; the types of differences that can be taken into account are parameter value differences, model structural differences, identified hazards not modelled, and numerical approximations.

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