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Controlled Time-of-Arrival Spacing Analysis

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Abstract*—Controlled Time of Arrival and Required Time of Arrival are two key concepts in the United States' NextGen and Europe's SESAR programs, supporting initial Trajectory Based Operations. One concern with using airborne Time of Arrival Control has been the potential spacing loss between aircraft when maneuvering to meet a time constraint. Within the scope of EUROCAE Working Group 85, EUROCONTROL and GE have performed simulations examining the likelihood of achieving a time constraint at a metering fix in descent, as well as the probability that a spacing infringement would occur while maneuvering to meet that time constraint. A large number of conditions were used, giving over 30,000 aircraft pairs in the comparison. For a target spacing at the metering fix of 90 seconds, approximately 82% of aircraft can meet their assigned RTA, and 5% of those cases would encounter some loss of separation if no active control were exerted to ensure separation. Heavy aircraft following Medium aircraft have the highest probability of a separation infringement, and increasing the target spacing at the metering fix to 120 seconds for those aircraft pairs decreases the probability of an infringement by over 50%. A trend-based alerting criterion using the rate of change of longitudinal and vertical separation over a 3 minute look-ahead was also simulated, to represent the more realistic case when the controller would undertake action well before separation is lost.

Keywords - Required Time-of-Arrival; Trajectory Based Operations; Controlled Time-of-Arrival; Flight Management System; 4D Trajectory

I. INTRODUCTION

In both North America and Europe air traffic is expected to grow significantly over the next twenty years, at the same time as concern over fuel consumption and environmental impact – both noise and greenhouse gas emissions – continues to increase. The International Civil Aviation Organization (ICAO) predicts that passenger traffic will grow at a rate of 4.8% per year through 2036, while fuel consumption will rise at the rate of 3.0% to 3.5% per year [1]. This issue is clearly recognized by both the USA's Next Generation Air Transport System (NextGen) and Europe's Single European Sky Air Traffic Management (ATM) Research (SESAR) programs, which aim to *reduce* the environmental impact of aviation while *increasing* capacity and safety. A key transformation to achieve these goals is the use of Trajectory Based Operations (TBO), including the use of Controlled Time of Arrival (CTA). The latter might be achieved using the airborne Required Time-of-Arrival (RTA) functionality.

The NextGen Avionics Roadmap has identified three mid-term (2015 – 2018) capabilities needed to improve traffic management with RTA:

- Route Clearance with RTA
- Route Clearance with RTA and Downlink of Expected Trajectory
- Trajectory Clearance with RTA and Downlink of Expected Trajectory [2]

The RTCA Task Force 5 provided specific recommendations on the use of RTA in the NextGen mid-term [3]. The Federal Aviation Administration (FAA) has concurred with these recommendations [4] and in its 2010 NextGen Implementation Plan describes plans for RTA capability to "ensure the safe and efficient transition of aircraft from en route to terminal airspace with appropriate sequencing and spacing" [5]. Moreover, in its mid-term Concept of Operations, the FAA identifies RTAs as a means to enable more efficient sequencing of aircraft, leading to increased use of Optimized Profile Descents (OPDs) [6]. In its Interim Report the RTCA Trajectory Operations Working Group has recommended the use of Time of Arrival Control (TOAC) in the mid-term time frame, while recognizing that there remain issues relative to incorporation of RTA and non-RTA aircraft in the same airspace [7]. To help address these issues FAA has initiated the 4 Dimensional Flight Management System Trajectory Based Operations (4D FMS TBO) project to evaluate benefits related to TBO and RTA operations in the mid-term [8].

Time-based navigation is being explored in Europe as well, and the use of Controlled Time of Arrival (CTA) being achieved by the airborne RTA functionality has been identified as a key component of SESAR [9]. The 2015 European Civil Aviation Conference (ECAC) Airspace Concept identifies the metering of traffic in time from en-route into Terminal Airspace along Air Traffic Service (ATS) routes as one of the key enablers to improved traffic management, with RTA being identified as one means to achieve this target [10]. Other means to achieve a CTA exist, as for example a ground based Trajectory Prediction tool possibly enhanced with Airborne Derived Data (ADD), linked to an Arrival

Manager (AMAN) and providing speed advisories to the controller. EUROCONTROL Projects like TMA2010+ and also the LVNL project SARA (Speed And Route Advisories) investigated this concept and demonstrated feasibility. However, issues were identified as controllers being sometimes reluctant to accept advisories from an automated tool that are not in line with their own working strategy, multi-sector and cross-border coordination and the integration of traffic flying RTA with ground controlled traffic (mixed mode) [11], [12]. It is also recognized that the use of CTA to meter aircraft into the terminal airspace will improve both flight efficiency and capacity, and the combination of CTA with Advanced-RNP capability is called a step towards the SESAR 4D Trajectory Management concept [13].

In recognition that RTA is a key component of 4D TBO, the European Organization for Civil Aviation Equipment (EUROCAE) initiated Working Group 85, stating that “in order to provide the required capacity and the required performances, enhanced solutions must be selected, standardized and deployed to answer the mid-term implementation of Initial 4D Trajectory Management” [14]. These standards will include updated Minimum Aviation System Performance Standards (MASPS) for airborne Time of Arrival Control.

It is clear that the use of airborne TOAC functionality is a key enabler to Trajectory Based Operations as proposed by NextGen and SESAR. There have also been numerous flight trials evaluating how FMS RTA functionality can be used in both Europe and the U.S. There are varying degrees of RTA functionality implemented in modern commercial aircraft FMSs, and some of these are described in [15]. Although airborne TOAC was originally designed for use in the en route portion of a flight, it is now recognized that this functionality can also be very beneficial in the descent and arrival flight area by providing increased predictability to the Air Navigation Service Provider (ANSP), allowing an orderly, metered flow of traffic from en-route to terminal airspace, thereby possibly reducing the amount of vectoring needed to ensure the appropriate spacing between aircraft.

Although a certain level of TOAC functionality has been available in most modern commercial jet transport FMSs for many years, the use of the functionality to improve traffic management and efficiency has been investigated only recently. Simulation analysis has been used to demonstrate the potential ATM improvements using airborne time control functionality [16], [17], [18]. Flight trials have also demonstrated this potential. In 2001, a series of flight trials with Scandinavian Airlines System (SAS) evaluating the use of their Boeing 737 FMS and its RTA function for a future ATM environment was performed, indicating that aircraft equipped with the current generation avionics can reliably ‘predict’ and maintain a 4D trajectory over an entire flight in real-world fleet operations [19], [20]. Subsequent flight trials in 2006 [21] and 2007 [22] evaluated improvements to the RTA algorithm, showing increased time control accuracy. A larger set of trials took place in 2008 through 2009 investigating additional types of equipment and the impact of placing a time constraint at different waypoints [23], [24]. More recently, flight trials with Alaska Airlines and FAA were conducted demonstrating how a Scheduled Time of Arrival (STA) computed by ground automation can be assigned as a time constraint to appropriately equipped aircraft [25]. These flight trials showed the accuracy of modern FMS RTA functionality in descent in the presence of wind modeling error. The accuracy and stability of the FMS-generated 4DT as well as the trajectory file size and dynamics were evaluated, demonstrating the role TBO may have in contributing to the SESAR and NextGen goals of increased capacity and safety with a reduction in environmental impact.

II. DISTANCE REDUCTION

One of the primary Air Traffic Control (ATC) concerns with the use of airborne TOAC functionality, however, is the potential distance reduction between two in-trail aircraft which are each controlling to a specified Time of Arrival at a fix. This distance reduction could occur primarily for the following reasons:

- Different speed strategies (combination of Cruise and Descent CAS/Mach) to meet the specified time
- Different forecast winds and temperatures (this could also be a contributing factor to the first reason)
- Different TOAC algorithms to provide closed loop control to correct for time errors

If the airborne trajectory prediction and forecast wind profiles are quite accurate, the different speed strategies will be the primary contribution to the potential distance reduction, although the other two items will always exist to some extent.

The impact on intermediate spacing when flying to a time constraint has been examined already in both simulations and flight trials. In one simulation, the use of two different FMS RTA algorithms was examined, finding that when very different cruise and descent target speeds were used to meet the respective time constraints, a loss of minimum spacing was possible during the descent even if both aircraft exactly met their assigned metering times [26]. However, this simulation involved a single pair of aircraft, and demonstrated an extreme example of different speed strategies. Later simulation analysis showed that although separation losses were possible in cases of extreme wind modeling errors, the results were the same or better than when a ground issued speed target was used for the operation [16], [17].

As part of the CTA-ATM System Integration Studies (CASSIS) project, a set of flight trials were performed to investigate the use of airborne TOAC [27]. Analysis performed on these flights indicated that given a 90 second spacing target at the runway threshold, 13.6% of flights would come within 3 nautical miles and 1000 feet prior to meeting that time target. Given a 120 second spacing target none of the flights in the analysis would have incurred a similar spacing violation [28]. This result, while interesting, was obtained using only Boeing 737 aircraft with a General Electric (GE) FMS, and the analysis was performed on only 66 aircraft pairs.

Thus, while some analysis has been performed on the impact of airborne TOAC operations on intermediate spacing, previous work has been limited in terms of the types of aircraft involved in the study and the number of aircraft pairs and conditions.

III. SCOPE OF THE ANALYSIS

Recognizing the need for larger scale analysis related to spacing between aircraft meeting a time constraint, a subgroup has been formed in the scope of EUROCAE Working Group 85 to analyze the potential loss of spacing, or distance reduction, between aircraft pairs flying in-trail to a time constraint in the en-route and initial descent phase of flight. Simulations were performed by GE and EUROCONTROL within this "Distance Reduction" subgroup, evaluating aspects of FMS RTA behavior that may need to be harmonized amongst different systems. One such aspect relates to the speed profile generated by the aircraft to meet an RTA, and the impact of the different speeds on intermediate spacing after the RTA has been assigned but prior to arriving at the RTA fix. These differences in speed profile may result from several different factors, such as:

- different speed strategies, such as modification of cruise vs. descent speeds;
- different speed envelopes for different aircraft types or due to operator defined speed bounds;
- Different thrust and drag characteristics resulting in different idle descent profiles between aircraft.

One of the primary benefits of using RTA is more efficient sequencing and spacing at a metering fix, reducing the variance of aircraft arrival times over that fix. If the metering time is chosen appropriately, the reduced variance of aircraft arriving over the metering fix may result in reduced controller workload and possibly, a reduction in radar vectoring in the terminal area. However, if there is a loss of spacing between aircraft after assignment of the RTA but prior to crossing the metering fix, ATC will be forced to manually separate the aircraft which could increase controller workload and decrease efficiency – the opposite of the desired result. To evaluate the potential for this to occur, GE and EUROCONTROL designed a set of experiments to analyze the potential distance reduction between aircraft flying to an RTA. This section describes the setup of the experiment and the desired objectives.

A. *Objectives*

To evaluate the potential loss of spacing (both longitudinal and vertical) between two aircraft flying the same lateral profile to meet an RTA constraint, GE and EUROCONTROL have collaborated on an experiment to quantify its likelihood of occurrence. In this experiment, it was important that a variety of aircraft types were evaluated to capture the of different performance characteristics, both in terms of speed envelope as well as idle descent path. In addition, to make the results as widely applicable as possible it was desired to simulate a range of conditions, such as initial speeds, initial spacing, initial distances to the RTA waypoint and atmospheric conditions. Finally, to ensure that results are statistically relevant, the experiment should include a large number of scenarios.

The primary goals of these experiments were relevant to a diverse audience, including avionics manufacturers, ATM automation suppliers, and airspace designers. These goals included addressing the following questions:

1. What is an acceptable rate of spacing infringement?
2. Is standardized speed behavior needed for RTA operations?
3. Is there any relationship between initial conditions and rate of spacing infringement?
4. Is a Decision Support Tool (DST) needed for controllers to assist them in assigning RTAs to suitable aircraft pairs and to monitor the spacing between those aircraft during RTA operation?
5. Are there any airspace design implications for RTA operations?

The following section describes how the experiment was constructed to answer these questions in a way that is widely applicable and to provide results that are statistically relevant.

B. *Experiment Design*

The experiment evaluating the loss of spacing between in-trail aircraft flying to an RTA used a simulation environment capable of generating an aircraft trajectory, as well as computing a speed profile to meet a given time of arrival. EUROCONTROL and GE coordinated the design of the experiment and the conditions to be tested, but executed the simulations independently. The Trajectory Predictor (TP) used by EUROCONTROL used the Base of Aircraft Data (BADA) Aircraft Performance Model (APM) to generate the trajectory. A pseudo Cost Index (CI) between 0 and 100 was used, where a CI of 0 represents the minimum speed schedule, a CI of 100 represents the maximum speed schedule, and the speed profile is linearly interpolated between the minimum and maximum speed schedules based on the pseudo CI. To ensure that the speeds used within the simulation are reasonable, the minimum and maximum speeds from BADA were further calibrated to represent realistic operating ranges, and the maximum operating speed and Mach number (VMO and MMO) were further limited using a corrected VMO/MMO to take into account additional limitations on the maximum speeds imposed by the FMS. An example of the minimum and maximum Mach numbers and Calibrated Airspeeds (CAS) is provided in Table I, for 2 different altitudes and for four different aircraft types with maximum landing weights.. The TP used by GE was the FMS TP, using the APM and RTA speed profile logic in the certified FMS. Both the Boeing 737 and Airbus (A320 and A330) FMSs were used in the experiment to represent several different types of speed strategies and RTA implementations.

TABLE I. AIRCRAFT SPEED ENVELOPE USED

	B736	**A320**	**A333**	**B773**
Weight (tons)	54,5	64,5	180	220
Min. CAS FL300 (kts)	207	219	225	246
Min. CAS FL350 (kts)	209	224	230	249
VMO (kts) / MMO	340 / 0.82	350 / 0.82	330 / 0.86	330 / 0.89
Corrected VMO (kts) / MMO	330 / 0.80	340 / 0.80	315 / 0.83	315 / 0.86

The use of both BADA and a certified FMS was desired for several reasons. First, the use of the certified FMS TP and APM allows an evaluation of the actual trajectory that will be generated and flown by the aircraft, yielding results that are consistent with what can be expected in actual flights using the implemented RTA algorithms. The BADA simulation is a more generic simulation using speed profiles within the complete speed envelope range of the aircraft. The advantage with BADA is that it can simulate many different aircraft types with different performances. This can be done in an automated way without being dependent on multiple simulation platforms, possibly from different providers.

In both the EUROCONTROL and GE simulations, the following steps were performed for each scenario:

1. Generate the 4D Trajectory for the lead aircraft using a given CI and Cruise Altitude.
2. Compute the RTA for the trail aircraft equal to the Estimated Time of Arrival (ETA) of the lead aircraft plus 90 seconds.
3. Compute the CI for the trail aircraft needed to meet the RTA.
4. Generate the 4D Trajectory for the trail aircraft using the computed CI and given Cruise Altitude.
5. Compute the longitudinal and vertical separation between the lead and trail aircraft at 6 second intervals along the two trajectories.

The boundary conditions for these simulations are shown in Table II. No altitude constraints existed prior to the RTA waypoint, and the only speed restriction prior to the RTA waypoint is a standard descent speed restriction.

TABLE II. SIMULATION BOUNDARY CONDITIONS

Parameter Name	Value
Target Altitude at RTA waypoint (feet)	8000
Target Spacing at RTA waypoint (sec.)	90
Speed limit (knots)	250 below FL100

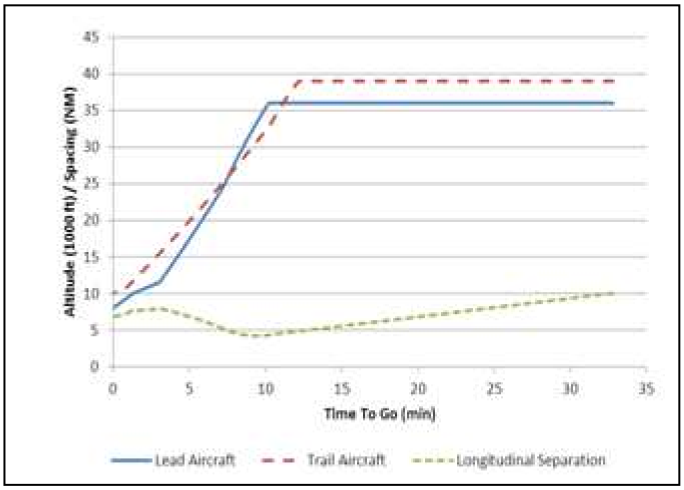

Figure 1. Overview of simulation scenario

A typical simulation scenario is shown in Fig. 1, showing the lead and trail aircraft vertical trajectories along with the longitudinal spacing between the lead and trail aircraft as a function of the lead aircraft's time to go to the RTA waypoint. In all scenarios, the simulation begins with both the lead and trail aircraft in cruise.

To ensure that the results were not limited to a single aircraft type, a variety of both Boeing and Airbus aircraft types were used in both the EUROCONTROL and GE simulations. Also, to ensure that the results were not limited to a narrow set of conditions, and to provide statistically relevant results, the wind, lead aircraft speeds (specified by the cost index or pseudo cost index), and cruise altitude were varied. Although the authors considered varying the aircraft gross weight as well, it was determined that the variation of cost index, wind and cruise altitude provided sufficient coverage of applicable speed profiles. Therefore a single nominal gross weight for each aircraft type was used. The lead aircraft's distance from the RTA waypoint was also varied to determine if the distance over which the RTA operation was conducted affected the probability of a loss of spacing. The initial spacing between the lead and trail aircraft at the start of the operation when the RTA was assigned was also varied between 10, 15 and 20 nautical miles (NM). This range of initial spacing was assessed by controllers to be normal for aircraft pairs in cruise likely to be sequenced. The parameters used in the EUROCONTROL simulations are shown in Table III. The combination of all parameters yields a total of 34,560 simulations scenarios performed in the experiment. When a non-zero wind was simulated, it was held constant above FL300 and linearly ramped to 0 knots at ground level, as shown in Fig. 2.

The GE experiment used a similar set of parameters, with the following exceptions:

- The types of aircraft used in the simulation were A320, A333, B733, B738
- All aircraft types used cruise flight levels of FL310, FL330, FL360, FL390
- The actual CI was used rather than a pseudo CI

In addition, simulations were not performed on A320/A333 aircraft following B733/B738 aircraft. As a result, the GE experiment included 25,920 total scenarios.

TABLE III. EUROCONTROL SIMULATION PARAMETERS

Variables	Unit	Values					No.
Type A/C 1 (leading)	-	A320	B736	A333	B773		4
Type A/C 2 (following)	-	A320	B736	A333	B773		4
Initial Distance to RTA A/C1	NM	170	200	230			3
Wind (positive for tailwind)	kts	-80	0	80			3
Pseudo Cost Index A/C1	-	10	30	50	70	90	5
A320 and B738 Cruise FL	FL	310	330	350	370		4
A333 and B773 Cruise FL	FL		330	350	370	390	4
Initial Spacing between A/C1 and A/C2	NM		10	15	20		3
TOTAL COMBINATIONS	-						**34560**

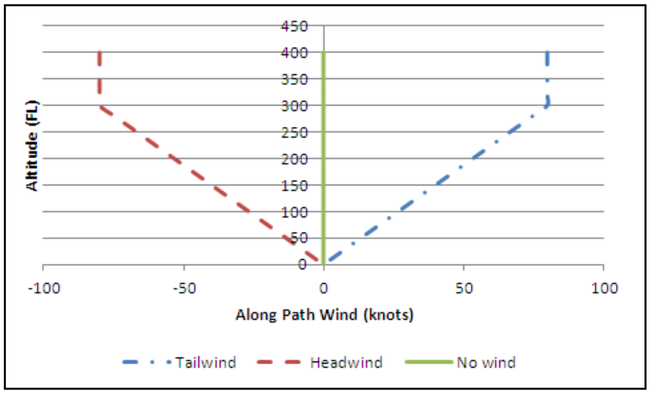

Figure 2. Wind profiles used in simulation

It should be noted that these simulations model the initial trajectory computation to meet a time of arrival constraint, and do not consider closed-loop speed control to compensate for disturbances such as wind forecast error. As such, the results of these simulations are applicable to any time-based metering concept that allows aircraft to fly a speed profile without controller intervention, such as Tailored Arrivals [27] or the SARA [28]. Although airborne TOAC operations will adjust speed to compensate for time errors, these results are intended to be a first analysis of the potential distance reduction in time based operations.

IV. RESULTS AND ANALYSIS

The experiment was initially performed using 90 second target spacing at the metering fix where an altitude constraint of 8000ft was applicable and with true separation minima. Based on the results of this simulation, the experiment was re-run using a target spacing of 120 seconds at the metering fix for certain aircraft pairs which had a higher probability of spacing infringement to evaluate if the larger target spacing affected the results. Finally, based on discussions with air traffic controllers, a variable trend-based spacing criterion was evaluated.

A. 5 NM / 1000 feet / 90 second spacing

The first set of simulations examined the probability of a true separation infringement for two aircraft flying an RTA to a metering fix at 8000 feet. In these simulations, the speed profile for the trail aircraft is computed to give a 90 second spacing at the metering fix. A spacing lost condition is detected as a simultaneous longitudinal spacing of 5NM or less and vertical spacing of 1000 feet or less. This is consistent with current radar separation minima for en route operation (when aircraft are over 40 miles from the radar antenna [26]), and thus represents a true violation of separation minima (although it is recognized that a controller would take action to ensure separation before the minima are encountered – see Section III.C). In reality, a Short Term Conflict Alert (STCA), which is a ground-based safety net, would be triggered whenever the spacing approaches these minima.

The results of the EUROCONTROL and GE simulations are summarized in Table IV. In each cell, the EUROCONTROL results are shown on top and GE results on bottom. The results are shown for all aircraft pairs, and are also broken out by the type of leading aircraft and type of trailing aircraft. For the EUROCONTROL simulations, A320 and B736 are considered to be Medium aircraft, while A333 and B773 are considered to be Heavy aircraft. For the GE simulation, A320, B733 and B738 aircraft were considered to be Medium aircraft while an A333 was considered to be a Heavy aircraft. The RTA is considered to be achievable if the speed profile results in the target spacing at the metering fix with a tolerance of +/- 10 seconds. The only reason the RTA would not be achievable is if the speeds needed to achieve the target spacing are outside of the allowable speed envelope. The spacing infringement results are presented as a percentage of the scenarios in which the trail aircraft was able to meet the RTA. For example, 28,443 of the 34,560 total aircraft pairs were able to achieve the RTA (82.3%). Of those flights, 1398 aircraft pairs incurred a spacing infringement. This is 4.9% of the "valid" aircraft pairs, and 4.0% of all aircraft pairs in the simulation. The former value is the one presented, as it represents the percentage of aircraft that would actually fly the RTA.

The results summarized in Table IV provide some interesting insights relative to both the likelihood of an RTA being achievable as well as the potential for a spacing infringement between two aircraft flying to a metering fix. First, in both simulations approximately 82% of aircraft were able to meet the 90 second target spacing at the metering fix, and less than 5% of those aircraft incurred a separation infringement where spacing was reduced below 5NM and 1000 feet. The probability of a separation infringement was lower in the GE simulations, but is explained primarily by the fact that only A333 aircraft were used in the Heavy category in the GE simulation, so a smaller sample of Heavy Behind Heavy and Heavy Behind Medium aircraft pairs were simulated.

In addition, both simulations show similar trends as the initial spacing between aircraft is increased. In both cases, a lower initial spacing corresponds to a higher probability that the target spacing of 90 seconds can be achieved by the trail aircraft. This makes sense intuitively since the magnitude of the speed change needed to meet the target spacing increases as the initial spacing increases (the trail aircraft needs to speed up more to meet its RTA if the initial spacing is increased). Moreover, the probability of an intermediate spacing infringement decreases as the initial spacing increases. This result is also as expected.

In both the EUROCONTROL and GE simulations, the probability of a separation infringement increased when the initial distance to the RTA waypoint of the lead aircraft increased, while the probability of the RTA being achievable by the trail aircraft remained essentially the same. Additionally, the probability of separation infringement increased when there was headwind and decreased when there was tailwind. In general, the probability for the trail aircraft to meet its RTA decreased slightly if headwind was present, while the opposite was observed for tailwind. The differences in separation infringement probability in these various conditions can be explained intuitively by the fact that there is more time available for trends to develop if the flight time is increased due to the higher distance to fly or the presence of headwind.

TABLE IV. SIMULATION RESULTS, 90 SECOND TARGET SPACING (EUROCONTROL RESULTS ON TOP, GE RESULTS ON BOTTOM)

		Initial Spacing			
		10NM	***15NM***	***20NM***	***Total***
All Aircraft	***RTA Achievable***	87.6% 86.4%	84.6% 80.9%	74.7% 73.7%	**82.3%** **80.3%**
	RTA Achievable & Spacing Lost	10.0% 5.0%	3.1% 1.8%	1.0% 1.1%	**4.9%** **2.8%**
Medium Behind Heavy	***RTA Achievable***	95.0% 80.3%	86.8% 75.9%	74.3% 70.4%	**85.4%** **75.5%**
	RTA Achievable & Spacing Lost	0.0% 0.7%	0.0% 0.2%	0.0% 0.0%	**0.0%** **0.3%**
Medium Behind Medium	***RTA Achievable***	95.7% 85.1%	93.3% 78.4%	80.5% 69.7%	**89.8%** **77.8%**
	RTA Achievable & Spacing Lost	1.6% 4.6%	0.3% 3.1%	0.0% 2.0%	**0.7%** **3.3%**
Heavy Behind Heavy	***RTA Achievable***	86.2% 100.0%	83.9% 98.9%	73.5% 93.9%	**81.2%** **97.6%**
	RTA Achievable & Spacing Lost	0.7% 0.0%	0.0% 0.0%	0.0% 0.0%	**0.3%** **0.0%**
Heavy Behind Medium	***RTA Achievable***	73.6% 100.0%	74.4% 95.1%	70.5% 91.1%	**72.8%** **95.4%**
	RTA Achievable & Spacing Lost	44.6% 22.8%	13.8% 0.6%	4.3% 0.0%	**21.1%** **8.2%**

Examining the results relative to the type of leading and trailing aircraft also provides interesting insight. When the trailing aircraft is a Heavy, there is a much lower probability of achieving the RTA than when a Medium aircraft is trailing. This is explained by the fact that the minimum operational speeds for a Heavy aircraft are significantly higher than the ones for a Medium aircraft (see Table I). In addition, the Heavy aircraft is often able to reach higher cruising altitudes resulting in a Heavy trailing aircraft being unable to reduce its speed enough to meet an RTA behind a slow Medium leading aircraft. This situation is aggravated when the Medium aircraft is flying at a low cruise altitude.

When evaluating the probability of a spacing infringement, a Heavy aircraft following a Medium aircraft results in the highest probability of a spacing infringement in both simulations. This can again be explained by the natural difference in speed envelopes between the aircraft types. For example, while a B773 typically cruises with Mach numbers of around 0.84 (with 0.89 being the real limit), the A320 and B736 are operationally limited to Mach numbers below 0.80 (with 0.82 being the real limit). However, the Calibrated Airspeeds during the descent phase of flight of those two different aircraft types are in the same order of magnitude.

Although this categorization was done based on aircraft weight, a distinction based on the aircraft's speed envelope may be more appropriate for the purpose of time-based operations. Hence, considering the maximum operational cruise Mach numbers as presented in Table I (0.8 for B736 and A320 versus 0.83 respectively 0.86 for A333 and B773), the terminology Medium versus Fast would actually be more appropriate instead of Medium versus Heavy.

B. 5 NM / 1000 feet / 120 second spacing

The use of 90 second target spacing at the metering fix provides a probability of a spacing infringement of approximately 5% for all aircraft pairs in both simulations. However, when looking at the types of lead and trail aircraft, it is clear that the probability is much higher for a Heavy aircraft following a Medium aircraft than it is for other aircraft pairs.

In an attempt to reduce the separation infringement rate for the particular aircraft pairs that showed an increased separation infringement rate in the first simulation, a larger target spacing was used for those aircraft pairs. In the second simulation 120 second target spacing at the metering fix was used for a Heavy behind Medium aircraft pair. All other aircraft pairs were still assigned 90 second target spacing at the metering fix.

The results of the second simulation are summarized in Table V. Only the overall results and the results for the aircraft pairs with the 120 second target spacing are provided, since the results for all other aircraft pairs are the same as in the first experiment. In both experiments the overall probability of achieving the RTA remained the same. Interestingly, however, in the EUROCONTROL experiment the probability of a Heavy aircraft achieving the larger spacing target behind a Medium aircraft actually decreased from 73.6% to 69.1% for a 10NM initial spacing while it increased from 70.5% to 74.1% for a 20NM initial spacing. This is as expected; if the target spacing increases, the most optimal initial spacing to achieve an RTA also shifts. Thus, the likelihood of achieving the RTA depends not only on the initial spacing but also the target spacing. As expected, increasing the target spacing from 90 to 120 seconds also resulted in a significant reduction in the probability of a spacing infringement in both the EUROCONTROL and GE experiments, from 21.1% to only 9.2% and from 8.2% to 4.6%, respectively. Moreover, the probability of a spacing infringement is significantly lower for a 15NM and 20NM initial spacing than for a 10NM initial spacing. This indicates that there are certain initial conditions depending on the target spacing that are much more conducive to RTA operations than others.

In this experiment, the minimum distance from the RTA waypoint of the lead aircraft where a spacing infringement occurred was also recorded. The distribution of these distances from the EUROCONTROL experiment is shown in the histogram in Fig. 3 and for the GE experiment is shown in Fig. 4. Both graphs are very consistent, indicating that the maximum number of separation infringements occurred at a distance of around 60 to 80NM to the RTA waypoint and most infringements even occurred at a distance to the RTA waypoint greater than 50NM. These results indicate that if aircraft were flying separate lateral profiles that merge onto a common procedure with a merge point less than 50NM from the RTA waypoint, the number of spacing infringements would be cut significantly. However, because infringements near the merge point might reduce controller acceptability, a merge point closer to the RTA waypoint might be the best option.

TABLE V. SIMULATION RESULTS, 120 SECOND TARGET SPACING FOR HEAVY BEHIND MEDIUM (EUROCONTROL RESULTS ON TOP, GE RESULTS ON BOTTOM)

		Initial Spacing			
		10NM	*15NM*	*20NM*	*Total*
All Aircraft	***RTA Achievable***	86.5% 86.4%	84.8% 81.2%	75.6% 73.3%	**82.3%** **80.3%**
	RTA Achievable & Spacing Lost	4.9% 4.1%	1.3% 1.8%	0.4% 1.1%	**2.3%** **2.4%**
Heavy Behind Medium	***RTA Achievable***	69.1% 100.0%	75.3% 99.3%	74.1% 86.4%	**72.8%** **95.2%**
	RTA Achievable & Spacing Lost	21.4% 13.1%	5.5% 0.0%	1.5% 0.0%	**9.2%** **4.6%**

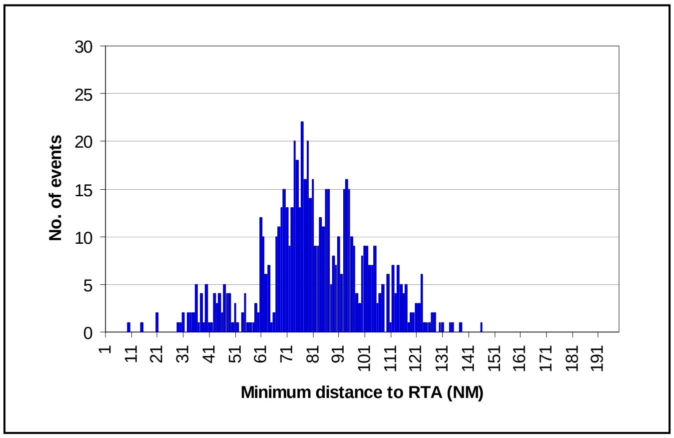

Figure 3. EUROCONTROL distribution of spacing infringement location, experiment #2.

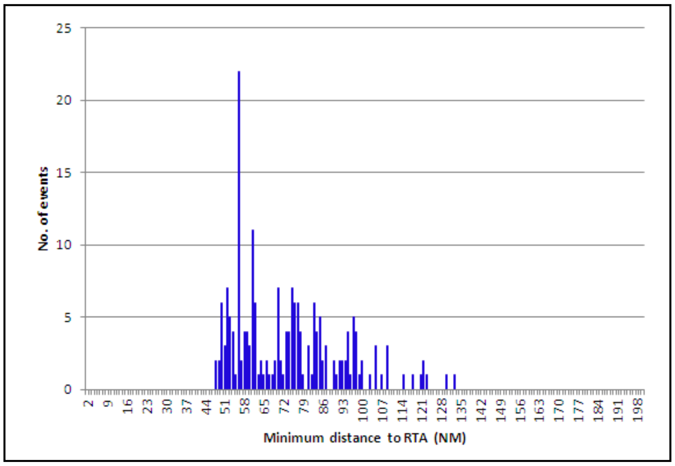

Figure 4. GE distribution of spacing infringement location, experiment #2.

C. *Trend-Based Separation*

The first two experiments conducted quantified the probability of a true separation infringement (if not detected and handled by the controller). It is, however, highly likely that a controller would take action to ensure separation well before the separation minima were encountered and quantifying only the probability of true separation minima infringement does not provide full insight into the impact on controller workload in RTA operations. On the contrary, controllers who were consulted during the experiments reported that the highest workload during these kind of operations would come from the requirement to monitor the traffic flying towards an RTA, without the possibility to provide active control in at least one dimension (for example by imposing a descent rate, heading or speed to the aircraft). Active control would become necessary if the spacing decreases below a value that is judged as “comfortable” by the controller. This value is obviously well above the separation minima and might depend on conditions such as individual controller judgment, traffic density, relative aircraft groundspeeds, etc. Controllers also reported that they would like to be assisted by a support tool which could relieve them partly from passive monitoring during RTA operation. Thus, there is great value in an experiment that quantifies the likelihood that the aircraft spacing would reduce below a certain value (the separation minima with an added buffer) at which the controller will have to take action to ensure separation is maintained.

Unfortunately there is no single metric that can be used to quantify when a controller will take active control over an aircraft. Several different mechanisms to capture this were considered, such as a more conservative spacing criterion (for example, 7NM and 5000 feet). However, after consultation with both current and former air traffic controllers, it was determined that a trend based criteria was most applicable for this experiment. The trend based metric is meant to capture when a loss of separation appears likely in the near future. The trend based algorithm used in this experiment is summarized in Fig. 5. In this experiment, a 3 minute look-ahead time was used (Alert_Time = 180 sec) and a 30 second filter was used for the rate of change of the longitudinal and vertical spacing (dt = 30 sec). The standard separation minima were used as the limit criteria (LS_Lim = 5NM, VS_Lim = 1000 feet). The output for one scenario where an A333 is following an A320 is shown in Fig. 6. Both the current separation and the predicted value in 3 minutes are plotted for both the horizontal and vertical separation, as well as when an alert is triggered. In this example, an actual 5NM spacing infringement never occurs, but due to the rate of change of spacing reduction an alert is triggered approximately 15 minutes after the RTA has been assigned, shortly after the trail aircraft has started its descent.

Trigger an alert if:

- If (time to RTA waypoint ≤ 3 minutes):
  Criteria_1 is TRUE
- Else if (time to RTA waypoint > 3 minutes):
  Criteria_1 is TRUE OR Criteria_2 is TRUE

Where:

Criteria_1 = (LS ≤ LS_Lim) AND (VS ≤ VS_Lim)
Criteria_2 = (Pred_LS ≤ LS_Lim) AND
(Pred_VS ≤ VS_Lim)
LS = Current longitudinal spacing
VS = Current vertical spacing
LS_Lim = Longitudinal separation limit
VS_Lim = Vertical separation limit
Pred_LS = Predicted longitudinal spacing in Alert_time
= LS + Alert_time*d(LS)/dt
Pred_VS = Predicted vertical spacing in Alert_time
= VS + Alert_time*d(VS)/dt
Alert_time = lookahead time for the prediction

Figure 5. Summary of trend based separation algorithm.

TABLE VI. SIMULATION RESULTS, 120 SIMULATION RESULTS, TREND BASED ALERT (EUROCONTROL RESULTS ON TOP, GE RESULTS ON BOTTOM)

RTA Achievable & Spacing Alert	**Initial Spacing**			
	10NM	***15NM***	***20NM***	***Total***
All Aircraft	7.7%	2.7%	0.8%	**3.9%**
	4.5%	1.5%	0.9%	**2.4%**
Medium Behind Heavy	0.0%	0.0%	0.0%	**0.0%**
	1.0%	0.4%	0.1%	**0.5%**
Medium Behind Medium	3.3%	1.0%	0.3%	**1.6%**
	3.9%	2.3%	1.6%	**2.7%**
Heavy Behind Heavy	2.1%	0.5%	0.1%	**0.9%**
	0.4%%	0.0%	0.0 %	**0.1%**
Heavy Behind Medium	31.3%	10.2%	2.9%	**14.4%**
	20.4%	0.6%	0.0%	**7.5%**

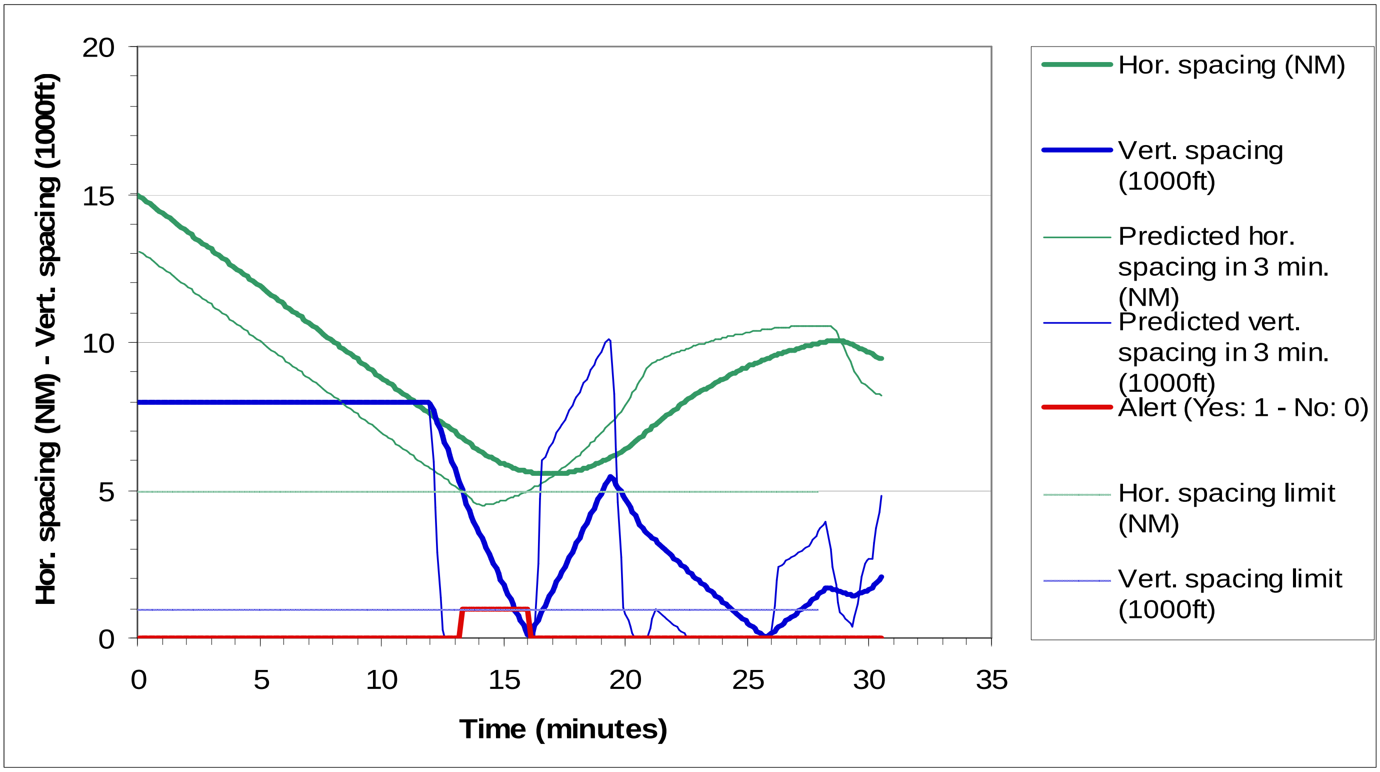

Figure 6. Example of spacing evolution, predictive spacing evolution with 3 minutes look-ahead time and triggering of alert to controller: A320, cruise FL310, M 0.70 / CAS 280kts followed by A330, cruise FL390, M 0.78 / CAS 265kts, no wind, 2 minutes target spacing.

The distribution of the distance from the RTA waypoint when the alert was triggered is shown for the EUROCONTROL experiment in Fig. 7 and for the GE experiment is shown in Fig. 8. These histograms are slightly different from the histograms for the second experiment shown in Figs. 3 and 4. Specifically, both histograms are somewhat flatter for the trend based spacing alert, and appear to be slightly more evenly distributed between 60 and 120NM.

The results of the simulations using the trend based alert criteria are shown in Table VI. In these simulations, the target spacing at the metering fix was 120 seconds for the aircraft pairs with a high rate of spacing infringement (a Heavy following Medium) and 90 seconds for all other aircraft pairs. As expected, the alert rate increased when compared to the strict separation minima experiment. Although the infringement rates are still relatively low overall, they have almost doubled in some cases, just because of the fact that controller action has to be anticipated well before separation minima are actually encountered.

Thus, with the trend based alert criteria using a look-ahead of 3 minutes, the overall rate of aircraft which would not incur any type of spacing alert remains quite high at over 96%. Moreover, the distribution of the location of the trend based alert indicates that a vast majority of the alerts remain 50NM or farther from the RTA waypoint, consistent with the distribution in the separation minima case. The probability of a spacing alert between the merge point and the RTA waypoint is shown as a function of the merge point distance from the RTA waypoint in Fig. 9. The figure indicates that the probability of an alert remains almost constant at less than 0.3% for a merge point that is less than 50NM from the RTA waypoint, but increases sharply for a merge point between 50 and 100NM, from the RTA waypoint.

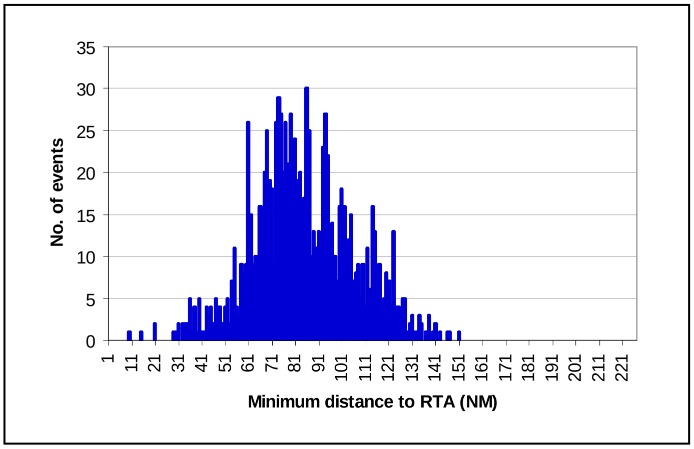

Figure 7. EUROCONTROL distribution of spacing infringement location, trend-based alert.

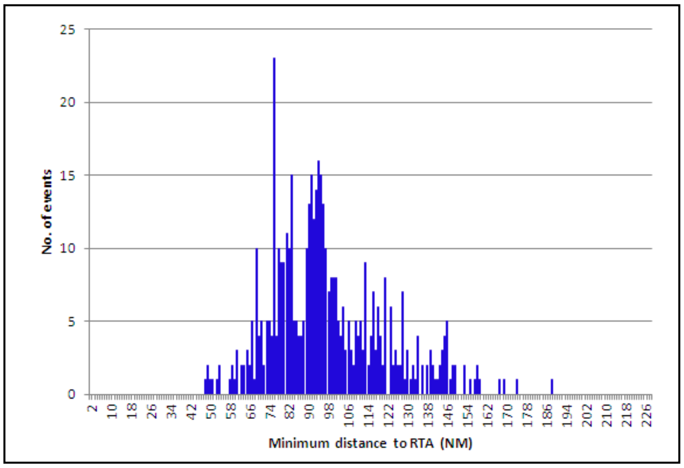

Figure 8. GE distribution of spacing infringement location, trend-based alert.

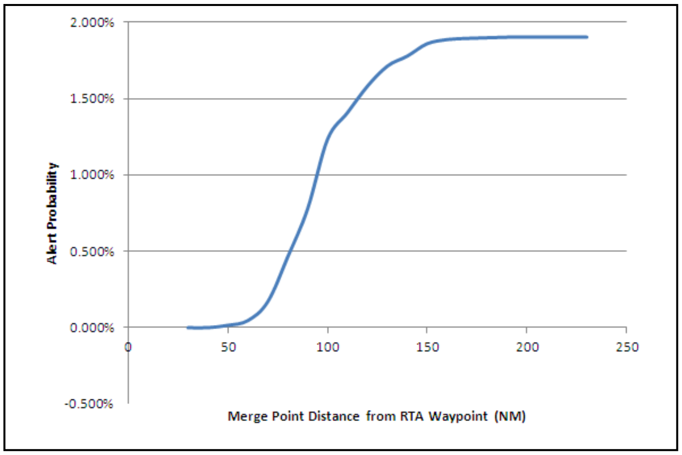

Figure 9. Probability of separation alert based on merge point location, GE simulation.

V. RECCOMENDATIONS AND NEXT STEPS

The simulations show that the likelihood a trail aircraft can meet a time constraint when initially 10 to 20 nm behind the lead aircraft is approximately 82%. Moreover, there are certain initial conditions – such as aircraft type, cruise altitude, speed of the lead aircraft, initial spacing, target spacing and winds – that provide a much higher probability of achieving the time constraint than others. The likelihood of a separation infringement for a 90 second target spacing is approximately 5%, but the probability is significantly reduced if the target spacing for certain aircraft pairs is increased. The percentage of aircraft that could not meet an RTA indicates that some type of controller support aid would be beneficial to identify appropriate aircraft and target spacing criteria for RTA assignment. In addition, controllers have expressed the need for a monitoring support tool to assist them with CTA operation, because passive monitoring of aircraft flying towards CTAs might be more workload-intensive than providing active control to establish spacing between the aircraft.

Simulations analyzing the probability of a trend-based spacing alert based on the rate of change of the spacing reduction and a 3 minute look-ahead, show an higher alert rate when compared to the ones based on actual separation infringement. Increasing the look ahead from 3 to 5 minutes was investigated in one simulation performed by EUROCONTROL and GE. Obviously this increased the alert rate further but also resulted in a large number of nuisance alerts with relative spacings greater than 10NM at the time of the alert, without leading to a real separation infringement later on. This indicates the importance of a good design of the Decision Support Tools. Providing key parameters from the aircraft, such as the target speed, could further enhance these DSTs.

Furthermore, for the purpose of distance reduction analysis, distinguishing aircraft by speed envelope, as opposed to weight class, may be more appropriate.

These results also show that the highest probability of separation infringement occurs when the lead aircraft is more than 50 nm from the RTA waypoint. The use of separate lateral profiles with a merge point less than 50 nm from the RTA waypoint could also be beneficial in time-based operations, provided that airspace is available and remaining conflicts at the merge point are dealt with operationally by controllers, supported by monitoring tools and DSTs.

These simulations did not take into account wind forecast error or closed-loop control to compensate for time errors. Further simulations modeling these factors could be performed to evaluate the impact of wind errors on the ability to meet an RTA and the likelihood of a separation infringement.

Finally, these simulations were based on typical performances of Medium and Heavy aircraft types. As in SESAR, Initial 4D functionality is being developed as well for regional aircraft (for example turboprops), it would be interesting to evaluate the impact of these aircraft on the concept of CTA operation.

VI. SUMMARY AND CONCLUSIONS

EUROCONTROL and GE have performed simulations examining the likelihood of a time constraint at a metering fix in descent being achievable, as well as the probability that a spacing infringement would occur while maneuvering to meet that time constraint. A large number of conditions were used, giving over 30,000 aircraft pairs in the comparison. For a target spacing at the metering fix of 90 seconds, approximately 82% of the aircraft pairs can meet their assigned RTA, and 5% of those cases would encounter some loss of separation if no active control were exerted to ensure separation. Heavy aircraft following Medium aircraft have the highest probability of a separation infringement because of the different speed and descent profiles of those two types. Increasing the target spacing at the metering fix to 120 seconds for those aircraft pairs decreases the probability of an infringement by over 50%. If a trend-based alerting criterion based on the rate of change of longitudinal and vertical separation over a 3 minute look-ahead is used, a higher rate of alerts will be seen which reflects more realistically the amount of actions a controller would need to undertake to ensure separation. To keep controller workload at acceptable levels, the use of controller decision support and monitoring tools, coupled with the provision of aircraft derived data such as the aircraft speed profile, could be extremely useful in supporting these types of CTA based operations.

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