



AIR TRAFFIC MANAGEMENT REQUIREMENTS AND PERFORMANCE PANEL (ATMRPP)

TWENTY SEVENTH WORKING GROUP MEETING

Montreal, Canada, 27 to 31 October 2014

Agenda Item 1: Trajectory Based Operation (TBO)

Time adherence in TBO

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SUMMARY

The concept of the trajectory is a fundamental element in realising the vision of the SESAR Research and Innovation Programme. In order to deliver the benefits envisaged through the implementation of an ATM network based on Trajectory Based Operations (TBO), it is necessary to understand the many inter-dependent factors, often creating conflicting priorities between an individual Airspace User and the wider ATM network.

This paper elaborates on these inter-dependent factors, and examines the temporal aspect of TBO. It considers the level of adherence that Airspace Users must achieve to ensure that TBO functions to the benefit of Airspace Users and ATM network alike.

The paper begins by describing TBO, and some of the many inter-dependent factors that impact the ability of TBO to operate efficiently. Using the results of validation exercises, the paper describes in detail selected situations that reveal the impact of temporal adherence.

The paper refines the TBO concept by identifying the TBO parameters that enable to optimally balance flexibility for Airspace Users versus predictability required from an ATM perspective.

A second SESAR paper outlines the basic architectural principles for trajectory information sharing in TBO, including ground-ground trajectory exchange as well as RTCA SC-227/ EUROCAE WG-78 recently standardized air-ground downlinking of the Extended Projected Profile (EPP).

This paper builds on SESAR's earlier presented ATMRPP working papers WP601 (Toulouse, March 2014) and WP632 (Tokyo, July 2014).

1. INTRODUCTION

The concept of the trajectory is a fundamental element in realising the SESAR¹ vision. The ultimate goal is a trajectory based ATM system where partners optimise business and mission trajectories through common 4D trajectory information and users define priorities in the network. It initiates 4D based business and mission trajectory management using system wide information management and air-ground trajectory data exchange² to enable tactical planning of conflict free route segments.

In order for SESAR to deliver the benefits envisaged through the implementation of an ATM network based on Trajectory Based Operations (TBO), it is necessary to understand the many inter-dependent factors, often creating conflicting priorities between an individual Airspace User (Airspace Users) and the wider ATM network.

This paper examines the temporal aspect of TBO, and considers the level of adherence that Airspace Users must achieve to ensure that TBO functions to the benefit of Airspace Users and ATM network alike.

The paper begins by describing TBO, and some of the many inter-dependent factors that impact the ability of TBO to operate efficiently. Using the results of SESAR validation exercises, the paper describes in detail selected situations that reveal the impact of temporal adherence.

- *Chapter 2 provides the introduction to Trajectory Based Operations in a SESAR context. It explains the need for predictability, linking it to the layered planning approach and identifying the need to balance between flexibility and predictability.*
- *Chapter 3 explains how flights are optimized in an atmosphere that turns out to be different from what had been forecasted, what the Flight Management System (FMS) capabilities are available for time adherence purposes with what accuracy, and what the impact is of adherence on fuel usage.*
- *Chapter 4 explains the relationship between flight time and fuel consumption in flight operations. It distinguishes between operational measures for the en-route phase and for the arrival phase.*
- *Chapter 5 looks into different potential ATM applications of time adherence requirements in TBOs. First the use of target times for separation purposes is discussed, explaining how inaccuracy of time adherence capabilities leads to the need for an additional buffer in conflict resolution tools. The following section explains the application of time target to Demand and Capacity Management (DCB). The chapter ends with elaborating the usage of time targets for arrival management*

¹ In general a distinction is required between the “SESAR Deployment Manager” and the “SESAR Research and Innovation Programme”. In the context of this paper, whenever SESAR is mentioned, it should be read as the “SESAR Research and Innovation Programme”.

² After take-off, the aircraft system transmits an update of the FMS-predicted 4D trajectory to the ATM ground system. This is used for updating the NOP. The NOP ensures that identical copies are distributed to all interested parties that have been granted access through the SWIM. The trajectory prediction computed onboard feeds the ground tools (Trajectory Predictor, Arrival Management tool for metering purposes, medium term conflict detection, etc). During the flight, the update of the reference trajectory (RBT/RMT) is automatically triggered when the trajectory predictions continuously computed by the aircraft system differ from the previously shared trajectory predictions more than the thresholds defined in Trajectory Management Requirements (TMR).

processes, and how the balance between runway pressure, holding stack delay and upstream time targets should be carefully balanced in order to avoid a loss of runway capacity. Finally, the need to tailor time adherence tolerances (RTA time window) for specific purposes is identified as an area requiring further research.

- *The last chapter summarises all previous and demonstrates that adherence to the RBT is not a goal in itself but rather the continuously negotiated and revised reference. It concludes by showing that the uncertainty inherent in a system as complex as a busy ATM network requires flexibility in the application of adherence to time targets and highlights the need for ATM systems and procedures to be able to use this flexibility to maintain optimum network performance while matching as closely as possible the individual airspace user business model driven operational performance needs.*

2. TRAJECTORY BASED OPERATIONS

2.1. Increasing predictability

The objective of TBO is to enable a safe and expeditious handling of increased traffic load by improving the predictability in the ATM system while maintaining efficiency. By continuously sharing and updating an air-ground synchronised view of the expected remainder of the trajectory for a flight between all ATM stakeholders, all are enabled the awareness to better anticipate on the events that are about to happen, increasing the overall performance of both the flight and turn around processes.

Data communication enables the revision of the trajectory through clearances and both forecast and now-cast³ information as the flight progresses whilst making best use of the airborne and ground capabilities to make sure that the (Four Dimensional) 4D-trajectory flight-plan is updated and as such consistent between air and ground systems.

2.2. The layered planning approach

TBO consists of a range of ATM functions which operate across the whole ATM system, from demand and capacity balancing (DCB), advanced flexible use of airspace (AFUA), limiting complexity usually by asset/resource capacity configurations and de-confliction of traffic flows, all the way to tactical separation provision and safety nets acting on individual trajectories.

All those processes have to be able to deal with limiting factors that vary over time, like meteorological events (e.g. thunderstorms or volcanic ash clouds), varying availability (e.g. night curfews, airspace closure or conditional routes) or varying capacity (e.g. sector and runway configurations).

³ Forecasts are predictions about a future state. Now-casts are observations about a current state.

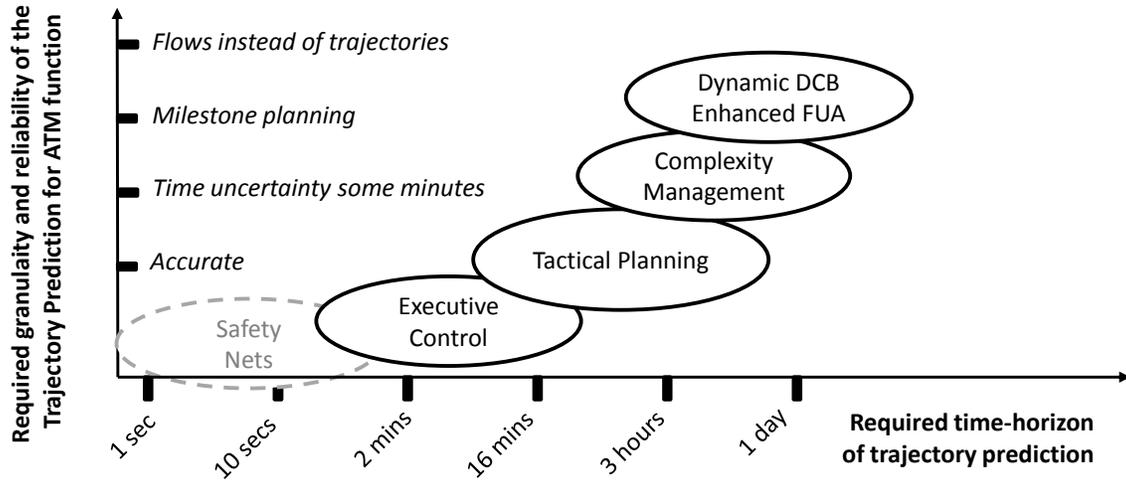


Figure 1: A layered planning approach [ref.1]

2.3. The application of constraints; flexibility versus predictability

The ATM processes mentioned above, may apply constraints to a flight to ensure all flights can be handled safely and efficiently within those limiting factors. Operating in a TBO environment gives clear visibility of those limiting factors, which may appear to the individual flight as time targets or lateral or vertical boundary constraints along the trajectory.

At one extreme, ruthlessly insisting on total adherence to the RBT as once negotiated and therefore static baseline, the very flight efficiency enabled by evolving airborne systems will be compromised. At the other extreme, by allowing complete flexibility to the Airspace Users, the efficiency of the ATM network could be reduced which, in turn, would have an impact on Airspace Users business goals. There is, therefore, a need for a balance between the actual need of the ATM system and the needs of individual airspace users.

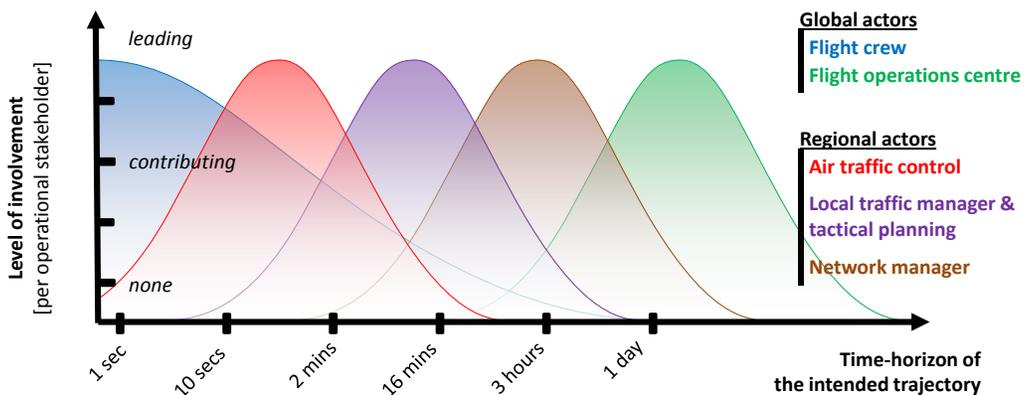


Figure 2: Multi-actor framework to manage the flight's trajectory [ref. 1]

Increasing performance of the overall system is therefore not simply a matter of freezing a plan and ensuring that all aircraft follow that plan. It requires planned trajectories to be continuously refined and revised during the execution phase, based on latest data, observations and predictions, in order to find the optimum balance between sometimes conflicting demands from different stakeholder perspectives: the flight itself; the airlines⁴; the ATM network; and Air Traffic Services. The concept itself has to allow for flexibility while simultaneously maintaining predictability in order to continuously optimise overall network performance. Finding this optimum requires an iterative collaborative decision making process involving all actors [ref.1].

2.4. Validation results

SESAR validates the interaction of all ATM processes in the layered planning approach through simulations and live trials. This has led to initial insights into finding the balance between flexibility versus predictability in the TBO concept. The implications of the levels of adherence in different phases of flight and in different operational circumstances vary, and with it the answer to the question “what is optimal?” may change.

Live trials are conducted in a mixed environment that contains both aircraft capable of FMS controlled adherence to constraints, and aircraft that are not. In a final TBO concept, all aircraft are assumed to be capable of accurately adhering to constraints. Also, live trials reveal some insight into the behaviour of individual airlines or flights as to how well they are willing and able to comply with target times; Various Airspace User Business Models may show different behaviour. To understand the implications and significance of the validation results on the final TBO concept, their results need to be considered in the context of higher equipage levels.

2.5. Hypothesis

Continuous corrections of the multi-aircraft system in its entirety are required to keep the system stable and safe. This does not by definition lead to a conflict between predictability and flexibility. For most purposes the only relevant element of predictability is milestone planning *with tolerance levels tailored* to a specific ATM function.

For example, from an Airspace Users perspective, time constraints could limit the user’s ability to optimize the flight according to its flight scheduling priorities. From a network or ATC perspective, full 4D-trajectory adherence may not be strictly required to meet the need; adhering to a limited set of 4D constraints with tolerance levels that depend on the operational need is sufficient.

Situations may occur at any time where changes in reality exceed the boundaries within which the systems can be adjusted to meet the plan. Examples include significant unexpected weather changes, unplanned runway closure, engine failures, etc. In those cases trajectories will need to be re-planned and all constraints need to be re-considered.

⁴ The individual airline’s Flight Operations Centre (FOC) is a key stakeholder who has full awareness of the attributes of each single flight and of the efficiency of its own network. Therefore, the airline is a key determinant to make TBOs truly contribute to the overall effectiveness of the ATM system.

One could for example adhere to a target time within a defined range (time interval) for arrival at a metering fix, and simultaneously allow for fluctuations (within limits) in speed to keep the flight optimized in a varying atmosphere, or add lateral or vertical constraints triggered by the need for conflict resolution.

3. THE FMS – FUEL VS TIME

3.1. The Cost Index

In today’s operations Airspace Users almost always use the Cost Index (CI) to enable an aircraft to manage the flight in a manner that best meets the airline’s business need. Understanding its use is key to understanding TBO. This section describes the use of CI.

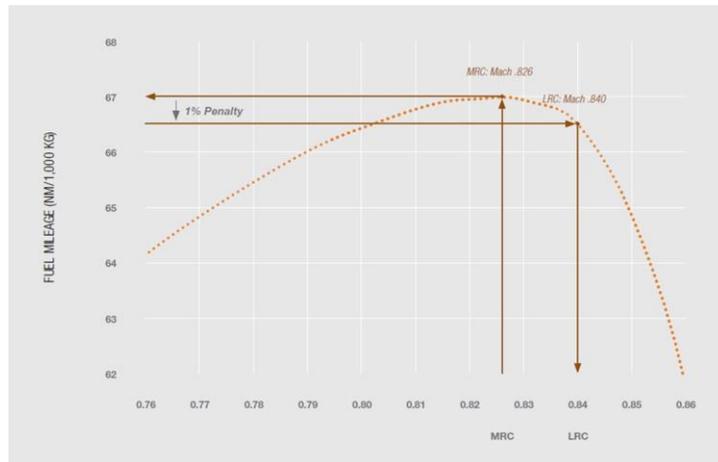


Figure 3: Relationship between speed and fuel usage [Ref. 3].

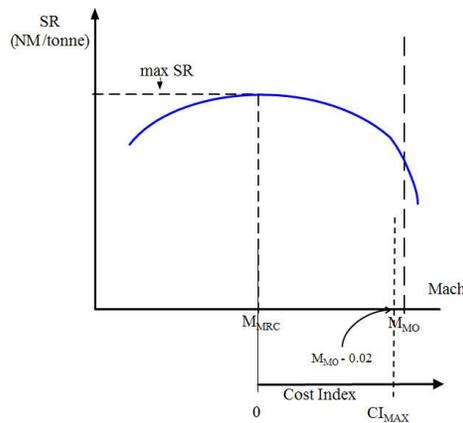


Figure 4: Specific range for given mass and altitude⁵

⁵ MMRC = Max Range Cruise Mach Number, MMO = Max Operating Mach Number, SR = Specific Range = fuel/ traversed distance = Fuel Milage in the USA

The CI [Ref. 3] is the ratio of the time-related cost of an airplane operation and the cost of fuel. Its value reflects the relative effects of fuel cost on overall trip cost as compared to time-related direct operating costs. A CI of zero results in maximum range airspeed and minimum trip fuel, ignoring any cost related to time. A maximum value for CI results in minimum flight time, ignoring any fuel related cost considerations.

The flight crew enters the company-calculated CI into the FMS. The FMS then uses this number and other performance parameters to calculate climb, cruise, and descent speeds to optimise the flight from a total fuel vs. time/cost perspective. These speeds are called economy climb, cruise and descent speeds, commonly abbreviated “Econ speed”. Different CI scales/ranges are in use by different FMSs, with 0-500 and 0-999 being the most common. Regardless of the range used by any particular FMS, Zero CI (CI 0) always corresponds to maximum range speed, i.e. speed is adjusted to cover the required track with minimum fuel, and therefore will give maximum range for the available fuel.

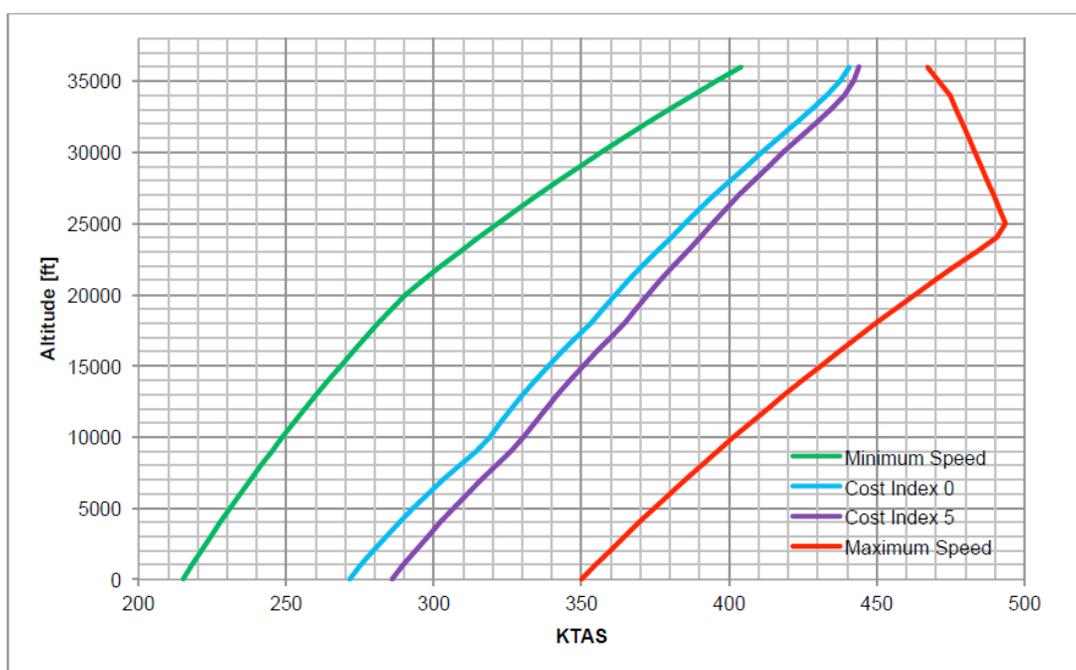


Figure 5: Relationship between CI, speed and altitude

Negative CI values with speeds below maximum range speed are not available for selection, since they would mean that the aircraft would be flown slower than maximum range speed, with fuel consumption per time unit being below that for a zero CI, but fuel per distance unit being higher. The minimum (non-selectable) CI would be a negative CI that would correspond to maximum endurance speed, which is the speed that will maintain the aircraft flying the longest time, but will take it less far than maximum range speed

The FMS will use the user-entered CI in order to calculate a predicted trajectory prior to flight (including speeds for all airborne phases of flight), the quality of this predicted trajectory is dependent on both the quality of the forecasted meteorological conditions that are input in the FMS and on the FMS algorithms used. Once the flight is airborne there are differences between predicted and actual meteorological conditions, the

trajectory may need to be revised in real time. This means that the same aircraft with the same user-entered CI and flying on the same route will typically fly slower⁶ in a higher headwind scenario than compared to the originally planned speed, based on a lower head wind.. Fuel consumption variation is not directly proportional to CI, as shown in the figure below: at lower CI values a small increase in CI will provide considerable time savings without a very large fuel penalty, whereas with CI close to the upper limit, a slight increase in CI to save a bit of time en-route can cause a disproportionate increase in fuel costs.

Airlines usually use a default CI, which in the current economy is often very close to zero due to the high cost of fuel. Some airlines may have different default CI for certain routes or certain individual aircraft, e.g. some may use a higher CI in the early morning, when delays have a higher knock-on effect, some may use higher CI on airframes on a lease contract that charges proportionately to off-block time, etc.

The CI of an individual flight may be different from the default company CI for a number of reasons: a flight that is behind schedule may or may not be flown faster depending on what the business impact of it being late would be.



Figure 6: Fuel required for speeding up, as a function of the CI

This practice is called Dynamic Cost Indexing (DCI), and has been the object of agent-based modelling in the SESAR exploratory research project “Complex Adaptive Systems for Optimization of Performance in ATM”, abbreviated to CASSIOPEIA.

⁶ A clear distinction between True Airspeed (TAS) and Ground Speed (GS) is required: If headwind is stronger, the aircraft will fly at a faster TAS or Mach number, but typically will still fly at a slower GS than if there was no headwind (i.e. Mach number is increased to make up for some of the slowdown caused by headwind. If the aircraft is not operating with a CTA/CTO, the aircraft will not adjust its speed to meet a constraint, however it will make small adjustments if e.g. the headwind is stronger than the forecasted head wind, typically inserted prior to flight.

Not surprisingly, CASSIOPEIA’s findings suggested that DCI is beneficial, but may stop being so if fuel prices continue to soar. They also explored different DCI strategies, and found that it may be more beneficial to leave some residual delay (which in their model was 10 minutes) rather than try to recover all delay above a certain threshold by flying faster. CI is a business parameter that is unknown to the ATM system. It is important to realise that requiring a flight to change speed for ATM purposes forces the airspace user to ignore their CI setting. Flying above desired CI will increase fuel usage, flying below desired CI will increase flight time.

3.2. Uncertainty in wind and temperature

Because of wind and temperature forecast errors, ground and airborne predictions are subject to deviations. Deviations from forecasted gridded wind and temperature could be correlated with many aspects including height and the stability of the atmosphere itself and as such these deviations vary in time and space.

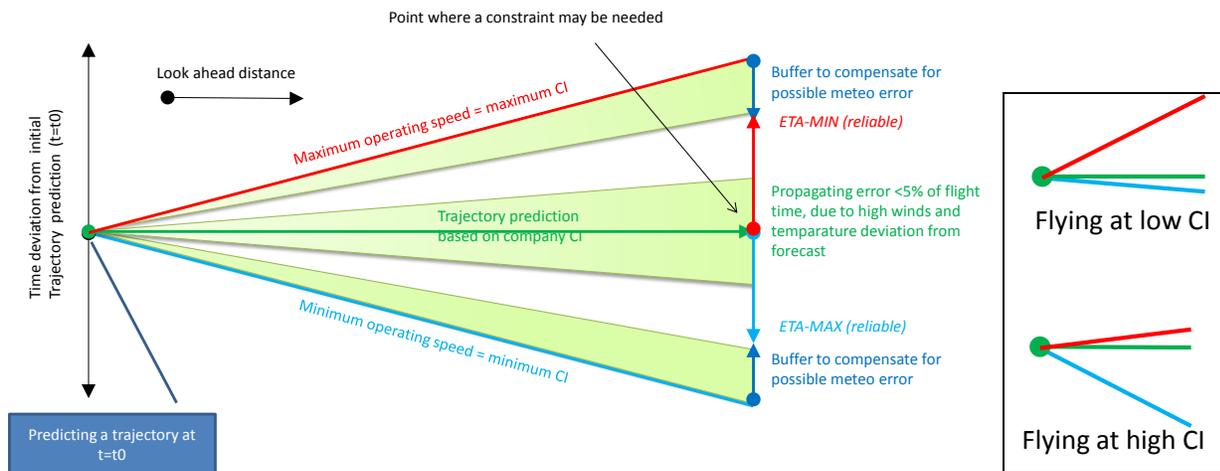


Figure 7: The relation between meteorological uncertainty and the ETA min/max⁷

A lot of studies were undertaken in various regions of the work and aiming to quantify the time deviation between the initial planning of the FMS and the real flown trajectory. Most of them concur on the fact that when the aircraft is using its CI, and not flying to a time target, the time error (deviation between its predicted time over a waypoint and its actual time over a waypoint) at 2 sigma (95% of the time) is less than 5% of the Time To Go (TTG). For example, on a predicted 100 minute flight time, the actual flight time varies on average between 95 and 105 minutes [ref.4].⁸

⁷ Note that time is not to scale, and that flight at minimum operating speed gives maximum endurance. In this case minimum CI is negative, and is an internal FMS parameter (i.e. can't be selected by the user)

⁸ In today's nominal conditions, the time error in open loop is very low, with larger errors to be expected in typically strong wind conditions (jet streams). If not flying in a jet stream, an accuracy of ± 1 to 2 minutes on a flight for 5,5 hours (open loop) can be achieved from Scandinavia to the Canary Islands (typically a lot of cross wind). One of the future challenges is to deal with TBO operation in the vicinity of jet streams.

Availability of the FMS predictions to the ground potentially enables significantly improving the ground predictability without necessarily constraining the airplane, i.e. without additional fuel burn.

If, for a specific operational need (like queue management in dense TMA), the ATC requires the airplane to comply with a specific time objective, the i4D FMS has the capability to reach a specific waypoint with a precision of (+/- 10 seconds) and thus reducing this deviation of 5% of the TTG as is explained in the following section on the RTA function.

This percentage deviation will be reduced still further as the benefits of SESAR’s 4DWxCube begin to be felt in SESAR’s step 1. This concept will enable the sharing of more frequent ground-based weather forecasts, air and ground-based weather observations, and wind vector information uplinked in finer granularity, which can be used by the FMS⁹ to improve trajectory prediction. In parallel research continues to quantify the “acceptable meteorological uncertainty” compatible with the ultimate TBO concept. This research is tightly linked to the concept of time adherence tolerance (section 5.4).

3.3. FMS Required Time of Arrival (RTA) function

In today’s operation, when lateral and vertical FMS navigation mode in combination with auto thrust are engaged, the FMS has a capability to adhere to one single time constraint at a time: the Required Time of Arrival (RTA) functionality. The RTA may apply to climb phase, cruise phase or descent phase¹⁰.

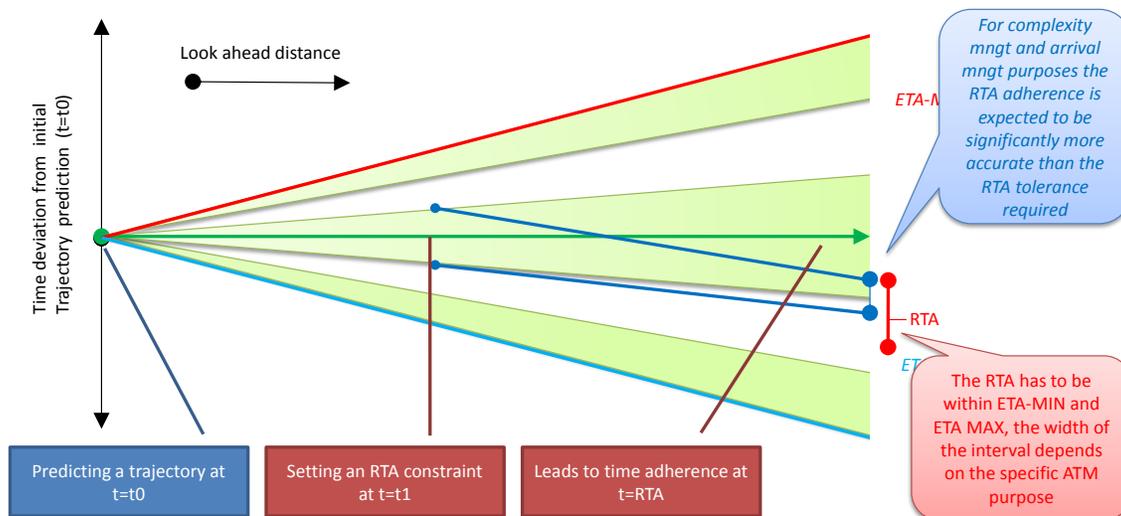


Figure 8: Distinction between required RTA interval and FMS RTA accuracy

When an RTA exists, the pilot entered CI is overruled. The FMS computes a “pseudo CI” that allows the A/C to meet the RTA. This pseudo CI includes the full range of selectable positive CI values, as well as the non-

⁹ Requires the improved i4D FMS capabilities, in which the number of winds and temperatures were increased to enable better predictions which immediately impact the profile computation.

¹⁰ Not all FMSs today have the capability to apply RTA functionality in climb or descent. Also, of those able to apply in descent, not all can apply RTA below a certain altitude.

selectable negative CI values all the way to maximum endurance speed. Then, using this “pseudo CI”, it computes a “Performance Speed”¹¹ that replaces “Econ Speed”. When an RTA exists, “Performance Speeds” are updated if the time error predicted at the RTA waypoint (with current performance speed) goes beyond a threshold. In SESAR step 1, requirements on the RTA function have become more demanding, and i4D equipped aircraft (SESAR FMS prototypes) are capable of adhering to a time constraint with +/- 10 seconds 95% of the time¹². This has been demonstrated in SESAR’s i4D trials and simulations: SESAR exercises VP-472 and VP-478.

The i4D-capable FMS is able to calculate, in deviate from its planned flight, what the maximum and minimum (latest and earliest) time over a certain fix could be. This is called the RTA min/max reliable window, or the ETA min/max window¹³, see figure 7. An interrogation-like capability has been included in the latest published EUROCAE WG-78 standards (ATN Baseline 2) as a separate ADS-C contract set up specifically for the ETA min/max interrogation¹⁴. This allows the ATM system to interrogate the FMS on its RTA achievable window over a waypoint at any time. RTA achievable intervals for a waypoint 30 flight-minutes ahead have been found to be typically around 5 or 6 minutes wide when associated to the descent phase (e.g. SESAR i4D flight trials). In level flight, ETA min/max intervals are narrower than in the descent phase.

3.4. Controlled Time of Arrival (CTA) or Controller Time Over (CTO)

Controlled Time of Arrival (CTA) or Controlled Time Over (CTO) is a new concept of ATC clearance, currently under research in SESAR. A CTO/CTA¹⁵ is issued by ATC to an aircraft in flight, and it is a requirement that the flight reaches a certain waypoint at a certain time. SESAR prototype i4D FMSs are currently capable to adhere to this time constraint with a specific tolerance of ± 10 seconds. As with any other clearance, flight crews are required to advise ATC if at any time they realise they will be unable to comply. A CTO/CTA clearance is only uplinked if it falls within the RTA reliable interval, which initially makes CTOs/CTAs achievable with a confidence rate of 95%. The use of this type of time constraints is currently under validation in SESAR, with applications on separation/de-confliction management, complexity management, as well as arrival management being investigated.

The possibility of applying multiple constraints to a trajectory is being investigated. This concept has the potential to create inefficient flight profiles, if not carefully applied. Consequently, when investigating the nature of such constraints, the efficiency of the whole flight profile should be considered. In addition, even

¹¹ Also known as "Target Speed" or "RTA Target Speed"

¹² Assuming the difference between actual and forecast wind along the route is less than 10 KT

¹³ Flight at minimum operating speed gives maximum endurance. In this case minimum CI is negative, and is an internal FMS parameter (i.e. can't be selected by the user)

¹⁴ The ETA min/max is visible to the crew, and without an ADS-C contract the parameters alternatively could be reported over R/T.

¹⁵ The CTO and CTA are technically the same, the latter being only differentiated when we specifically address the arrival phase.

though the FMS itself may be capable of flying to a 10-second tolerance, the actual tolerance needed to deliver the operational concept may be different, or even variable, depending on the specific situation.

4. FLIGHT TIME VERSUS FUEL BURN IN FLIGHT OPERATIONS

The cost of fuel remains, and is likely to remain, a key factor in the way airlines choose to fly. It is not always the highest priority, due to other changing business priorities, but it is nevertheless always an important consideration. The impact on fuel consumption of various ATC techniques is complex and subtle, and understanding these subtleties is important to refining TBO.

In this section, for illustration purposes, the order of magnitude of impact on fuel of different ATM actions is presented. Calculations were made using the aircraft performance software tool for an Airbus A320 family aircraft, assuming optimum cruising level FL360, Cost Index 5, typical given gross mass, no wind and standard ISA environment.

In the arrival phase, there are also significant differences from a fuel perspective among different delay absorption methods. The most fuel-efficient way to delay an aircraft is by using CTA, followed by low-level low-speed lateral extension or orbital hold. In summary, the respective arrival delay examples in the paper, starting at a point approx. 200 NM before the runway and delay by 2 minutes gives the following penalties for our example aircraft:

Measure to establish 2 minute delay at Initial Approach Fix (IAF)	Fuel impact	Time impact
Lateral extension allocated and implemented at high altitude (before ToD)	78 – 82 kg	+ 2 min
“Point merge” lateral extension allocated at FL100	83 kg	+ 2 min
Orbital delay 2 minutes, one “360° turn” at the CTA point 30 NM before the runway	89 kg	+ 2 min
Using CTA allocated in the en-route phase 200 NM before runway <i>Note: Maximum delay that could be absorbed with CTA only was 4.2 minutes/+32 Kg.</i>	2 kg	+ 2 min

Table 1: Relation between delay strategies for AMAN purposes and fuel consumption

Additional delay might be absorbed through linear holding if the aircraft descends earlier, which means a lower True Airspeed (TAS) is possible. In this case, assuming early descent and maximum endurance speed, up to 8.6 minutes of delay can be absorbed, at a cost of 193 Kg (assuming delay is absorbed at FL200). Alternatively, using the figures from table 1, it can be shown that the same amount of delay may be absorbed by CTA first (4.2 minutes/+32 Kg.) followed by lateral extension/holding at FL100 (4.4 minutes/+214 Kg.), which add up to 246 Kg.

For the en-route phase, in general, the report suggests that the most efficient way to separate aircraft from a fuel efficiency perspective is by lateral separation, followed by a vertical separation. Usage of CTO is costly fuel-wise when speeding up the aircraft and costly time-wise when slowing it down. In summary the respective en-route examples in this paper, using a conflict point 200 NM downstream gives the following penalties for our example aircraft:

Measure to establish 7 NM separation 200 NM downstream	Fuel impact	Time impact
Lateral separation 7 NM, initiated 200 NM before conflict	1,4 kg	+ 4 sec
Vertical separation by descending 1000 ft.	7 kg	+ 12 sec
Creating separation by CTO 7 NM, speeding up	46 kg	- 57 sec
Creating separation by CTO 7 NM, slowing down	6 kg	+ 57 sec
Maintaining separation by CTO, encountering a wind error of -15 kts after 100 NM	42 kg	+ 0 sec

Table 2: Relation between en-route conflict resolution solutions and fuel consumption

It is worth highlighting that in current practice both a lateral offset and a vertical instruction for separation are unlikely to be initiated by ATC with an anticipation of 200 NM. This is a natural consequence of uncertainty: controllers may detect a conflict far in advance, but will usually wait to take action as the problem may solve itself, for example as a consequence of meteorological fluctuations. Lateral offsets are often initiated no earlier than 50 NM before the conflict point, which results in a slightly higher penalty (+0,975 NM / + 5,5 Kg / 16 sec). If the descent from FL360 to FL350 were also to be delayed until 50 NM before the point of conflict, however, the fuel penalty would then be as low as 1,75 Kg. However, assessment of vertical deviation must be qualified taking also into account whether the aircraft may or may not go back to its optimum cruise level after the point of conflict, which of course will depend on both whether the level is still available and how much flight time there is left before TOD.

In the future and subject to further research, as airspace demand increases, the impact of uncertainty in meteorological information could be reduced by an early application of vertical or horizontal constraints on a particular waypoint. Management of uncertainty through safe clearances instead of time adherence is outside the scope of this paper. For a discussion on safe clearances see the preceding ATMRPP paper WP-601 presented by SESAR.

To put these figures on additional fuel usage in perspective: The average profit on a (short-haul) flight is around 1000 EURs [ref 5, 6]. Assuming a fuel cost of 9 EUR/10 Kg (which is quite accurate), gaining 8 minutes in an 800 NM flight would cost approximately 165 EUR (4 times 46 Kg of fuel).

From a fuel-efficiency perspective, it can be concluded that for en-route it is generally most efficient to solve conflicts using lateral extension or vertical separation. Absorbing delay in the arrival phase is completely different: since the total flight time to be flown by each flight is an independent variable determined by its landing slot, total fuel-burn can only be minimised by flying the aircraft slowly while still in clean configuration. Slow-down CTA clearances and early descent followed by flight at maximum endurance speed are both going to contribute to smaller fuel consumption numbers. When all delay cannot be absorbed by those two methods, path stretching or holding will need to be used. In such cases, there is only a small difference between absorbing delay at high altitude compared to doing so at lower altitude (see table 1 above).

5. TIME ADHERENCE IN TBO

The use of arrival times is key to TBO and is the focus of this paper. There are a number of different ways that the fourth dimension can be applied in TBO, and it is necessary to review these and examine how they impact trajectory management. That is the purpose of this section.

5.1. Time Adherence for Separation Purposes

As was seen in Chapter 4, different operational circumstances can result in time control not always being the most efficient mechanism for resolving conflicts in terms of fuel consumption. However, in SESAR Step 1, the concept of applying automatic allocation of time constraints is being investigated in a circumstance where separation could be ensured without controller intervention. The concept is called “Trajectory Adjustment through Constraints in Time” or TRACT.

TRACT applies to the en-route phase only; it incorporates uncertainty by providing CTOs to ensure a separation between the uncertainty envelopes of CTO-constrained flights, which is motivated by the ± 10 seconds uncertainty of RTA (10 seconds at a speed of 450 Knots correspond to 1.25 NM).

The target separation of the TRACT tool currently under validation in SESAR incorporates an additional 1 NM buffer, so that a 6 NM separation is targeted for validation in a 5 NM minimum radar separation environment. The need for buffers is linked to the expectation that the conflict will happen several minutes ahead (25 minutes ahead according to the current TRACT concept) and can be solved with a reasonable confidence by a CTO instruction that is expected not to change.

TRACT could be used to increase separation between two aircraft (for instance from 4,9 Nm to 6,7 Nm), enabling the controller to consider the conflict as solved when he receives the aircraft on his frequency. CTO allocation needs to be done well in advance of the point of conflict, regardless of whether TRACT is used to create separation between two aircraft that would otherwise be closer than the established separation minimum or to increase separation between two aircraft that would already be safely separated without TRACT.

The need for separation buffers may be avoided by using closed-feedback loop processes to control the execution of separation provision tasks. At each process loop, the crossing point becomes closer, and therefore uncertainty over the future trajectory is reduced, and assessment of whether separation will actually be safe becomes more reliable. At each process loop, further action can be taken to ensure safe separation if deemed necessary. Close to the conflict point, uncertainty becomes negligible, and therefore in the last process loop-cycles separation can be guaranteed tactically with virtually no buffers.

This closed-feedback loop process is actually a formalization of the way controllers provide separation without buffers in current operations. It is however worth highlighting that there is no conceptual incompatibility between the use of closed-feedback loop processes and introduction of increased automation into ATM separation provision processes. Using such processes to eliminate the need for buffers could significantly improve the performance of TBO.

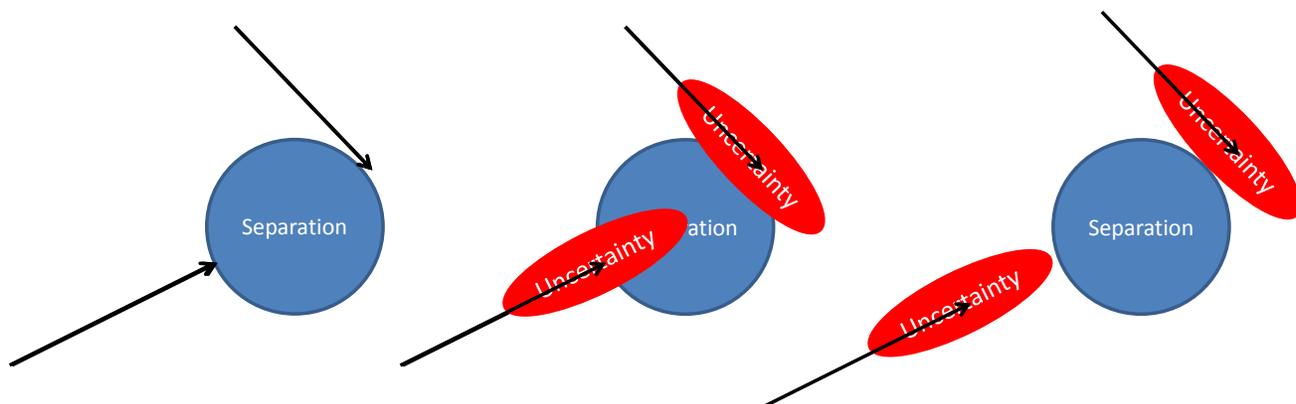


Figure 9: Additional separation to compensate for inaccuracy in time adherence

The balance of fuel cost against the operational benefits of using speed changes to solve en-route conflicts in each particular case will, of course, depend on the amount of the required speed change as well as whether it is an increase or decrease. In some cases, TRACT will merely constrain aircraft to their estimated times, turning them into CTOs in order to bound their temporal uncertainty, and in this case fuel impact will be neutral as long as the actual meteorological conditions are what was forecast. In other cases, minimal speed changes will be necessary, and fuel impact will be accordingly negligible. Large speed changes will be unlikely to be found beneficial for the reasons explained above.

5.2. Time Adherence for Demand and Capacity Balancing: the Concept of Target Times

Before departure, Estimated Elapsed Times (EET) to all waypoints along the routes are calculated by both NM, AOC and the FMS. EETs are the flight-times between all waypoints in the flight plan, and take into account aircraft performance data, as well as weather forecast, known altitude constraints, etc. Information sharing in order to use the best of each of those three sources of EETs is an important goal of SESAR, and the outcome will be more accurate EET calculation. If EETs are added to planned take-off time, the result is a list of planned times over waypoints all the way to landing time at the destination airport. These define the trajectory in the time dimension.

As long as take-off time has been in accordance with the flight plan and the atmosphere behaves as forecasted, a flight will overfly waypoints along its route at the time it was planned to prior to departure, and ultimately land at the time it was expected to¹⁶. Even in the final TBO concept, a flight may deviate from its pre-departure planned times taking off earlier or later than planned, requiring a recalculation of estimates over all waypoints.

In either case (take-off time deviation or atmosphere different from forecast), and having re-assessed the need for constraints from congested sectors or arrival airport based on the updated trajectory prediction, the flight

¹⁶ In current operations, the late addition of departure and arrival routes (SID and STAR) has a significant effect to the estimated times over each waypoint and for landing.

may be required to adjust its speed schedule to meet the needs from a complexity management or arrival management perspective.

The RTA function could be used by airspace users to comply with adherence requirements, but this does not preclude use of tolerance levels that are different from the ± 10 seconds adherence to time constraints that the SESAR i4D RTA function provides (see figure 7).

Derivation of CTOT from congested airspace time constraints

In current European operations, when demand over a particular fix or sector exceeds capacity during the planning phase, the Network Manager (NM) assigns target times to spread demand. Target times over an arrival metering fix are called Target Times of Arrival (TTA), whereas target times that do not regulate arrival flow to an airport are called Target Times Over (TTOs). The NM uses EETs to calculate a Calculated Take-off Time (CTOT) backwards from the latest target time assigned to the flight (TTO or TTA), and aircraft are required to take off in a window of -5/+10 minutes around their CTOT. No specific adherence to TTO/TTA is then required during the flight execution phase, and actually Airspace Users do not even know their target times, although they do know where along their route excess demand has caused them to be asked to delay their departure to the CTOT; the CTOT is associated to the flow constrained area that has the Most Penalising Regulation (MPR). Airspace Users are allowed a certain degree of negotiation of target times in current operations (e.g. slot swapping), and SESAR's future operational concept greatly broadens Airspace Users participation in this process through an iterated improvement of the trajectory jointly performed by the NM and the individual Airspace Users. This includes, but is not limited to, the User Driven Prioritisation Processes (UDPP).

CTOT adherence rates

In current European operations non-regulated flights departure tolerance window is -15/+15 minutes, and this shrinks to -5/+10 minutes for regulated flights (i.e. flights with a CTOT). It could be expected that non-regulated flights would depart at a less precise time, but would also be less prone to accelerate or request shortcuts en-route than those that have been delayed on the ground. EUROCONTROL assesses monthly on CTOT adherence rates, reporting against the target of at least an 80% adherence rate. The actual adherence rate in 2013 was 88%. In some cases, areas where NM-forecast demand does not exceed capacity but is close to the capacity limit, CTOTs are issued in order to narrow the departure uncertainty window. Likewise, when an area is regulated due to forecast demand actually exceeding capacity in a certain timeframe, the so-called hotspot, regulations are put in place for a time period starting a few minutes earlier and ending a few minutes later than the hotspot. In this way, departure times are less uncertain for flights expected near but not actually during the hotspot period, and so chances that they end up *slipping* into the hotspot are smaller.

Limitations of the effect of CTOT on congested airspace

As discussed in section 4, airlines sometimes use DCI to accelerate flights to compensate for all kinds of delay, including delayed CTOTs. If acceleration happens before the MPR area in a CTOT-delayed flight, the aircraft may reach the MPR area earlier than its assigned TTO/TTA, which is actually cancelling the effect of the NM-imposed ground delay and may lead to a safety issue by causing the MPR area to be overloaded. The SESAR step 1 concept includes the communication of planning TTOs/TTAs to Airspace Users. The optimal way to ensure that aircraft do not accelerate or request direct routings to ATC to compensate for ground delay is still subject of investigation. From a NM-perspective, the easy answer would be to not only communicate TTOs/TTAs to aircraft, but also turn them into time constraints, with tolerance intervals to be defined but

possibly less strict than the 10 seconds used for CTOs/CTAs. This solution may be costly from a fuel perspective than is strictly required for this purpose, for the reasons discussed in Section 3, even if tolerance requirements are much less strict than ten seconds. It also implies that a process for TTA maintenance needs to be implemented to avoid unnecessarily constraining aircraft for areas where flow control issues are no longer current.

Adherence to pre-departure set time constraints in congested airspace (FAIRSTREAM)

The SESAR's step 1 demonstration project "FABEC ANSPs and Airlines in SESAR Trials for Enhanced Arrival Management", funded by SESAR and abbreviated to FAIRSTREAM, investigated the TTA adherence concept with real flights in 2013. Flight crews of CTOT-constrained aircraft were told what their TTA was and were waived their CTOT: they could take-off at the time they chose to, and were asked to try to adhere to their TTA as much as possible. Flight crews would enter the TTA at the relevant position in the FMS while the aircraft was still on the ground, and the FMS would give them a departure time so that the TTA would be met with the aircraft flying at its Airspace Users-preferred CI. Departure airports tried to accommodate flights participating in the trial so that they could depart at the time they had calculated they needed to as much as possible. Aircraft couldn't, of course, take off always at precisely the time they had calculated. This take-off time deviation was due not only to the fact that aircraft needed to be fit into the departure sequence, but also to non-ATM reasons, like ground handling taking longer than planned. Once airborne, different strategies were used by flight crews to try to meet the TTA when a deviation from take-off time had occurred. In most cases, flight crews chose to make up for delay by speeding up without using the RTA function, in order to avoid wasting fuel with very high CIs (i.e. they increased their CI, but not all the way to the top of the available range). Some late-departing flights actually used the RTA function to meet the TTA, and this resulted in very high fuel consumption numbers to gain 5 minutes in a 1 hour (Toulouse-Paris) flight.

Adherence to pre-departure set time constraints in congested airspace (VP-632)

The same concept was investigated in SESAR's step 1 exercise VP-632: flight trials with aircraft with TTAs for regulating arrival counts into Palma de Mallorca airport. Flights coming into Palma de Mallorca from the UK and Germany that had been delayed on the ground were cleared direct by upstream French controllers that were unaware that the flight had a TTA over Palma de Mallorca Terminal Manoeuvring Area (TMA). Aircraft that flew according to such direct clearances arrived earlier than their TTA. Some trial flights did not request direct clearances, or maybe even rejected direct clearances spontaneously given by ATC, in order to respect their TTA. Not surprisingly, adherence improved significantly for the non-direct flights, but it was at the expense of increasing track miles and fuel consumption, and TTA dissemination was found to be useless unless flight crews actively tried to adhere to it.

In both FAIR STREAM and VP-632 TTA adherence was considered good if the fix was reached with ± 3 minutes. Rates of less strict adherence (± 6 minutes, etc.) were also recorded. Upcoming SESAR activities will look into what adherence tolerance target is adequate for DCB purposes.

5.3. Time Adherence in Arrival Management Processes

Airports comprise the most common choke point in the ATM system, and time management has long been used to smooth the flow and to try to reduce congestion by, for example, ensuring that aircraft arrive at a metering fix sufficiently spread out in time to reduce the likely need for holding while maintaining runway

pressure. In the SESAR TBO concept, this process is refined through the availability and use of more predictable arrival times, which enable better arrival management.

5.3.1. *Building an arrival sequence with an Arrival Manager (AMAN)*

Arrival Managers (AMAN) take as input each flight's estimate over a metering fix as well as a configurable arrival rate, and assign each flight a time over a metering fix. The assigned time may be before or after the aircraft's ETA. In SESAR's concept of operations step 1, this assigned time may be either passed to the controller in the form of a Time-To-Lose/Time-To-Gain (TTL/TTG) advisory, or may be passed directly to the aircraft in the form of a time constraint, called Controlled Time of Arrival (CTA), which will be inserted as an RTA in the FMS. SESAR fosters the CTA process, and the TTL/TTG when the CTA is not possible; this is fundamental for the AU. AMANs take aircraft into account when they enter what is called the AMAN¹⁷ horizon, which is measured in flight-minutes before the metering fix.

TTG advisories can be implemented by controllers by requiring that aircraft maintain a higher speed than their FMS had scheduled. This forces the aircraft to arrive at the metering fix before it was scheduled by flying faster than the aircraft operator would want to, and carries a fuel penalty which can be rather significant¹⁸. As an example, an AIRBUS 320 with typical gross mass and flying at low cost-index 5 that is required to gain 3 minutes may increase fuel consumption in the descent phase by 90 Kg. Likewise, CTAs requiring aircraft to fly faster than their CI-determined speed schedule have a comparable cost in fuel. Flying faster is not possible when the aircraft is already flying at a very high CI.

STARs often include turns that are designed to de-conflict arrival and departure flows. In such cases, TTG advisories may also be implemented by path shortening within the STAR if traffic permits. Path shortening within the STAR should have a positive impact on fuel consumption, but this may not be so if the aircraft is not given the direct clearance early enough to allow it to optimize its descent.

The primary use of AMAN systems when aircraft need to lose time is when the number of inbounds exceeds the available landing runway capacity. Short AMAN horizons serve the purpose of helping controllers manage the metering fix holding stack, by assigning stack departure times which controllers can pass on to aircraft as Estimated Approach Clearance time (EAC) / Expected Approach Time. Longer AMAN horizons allow for upstream delay sharing, so that aircraft with large delay apportionment can absorb some of it before entering the holding stack. SESAR activities have been centred on the extension of the AMAN horizon.

AMANs do not reduce total delay, but support controllers to optimize delay management. AMAN may be used to reduce flight time if aircraft departing from airports within the AMAN horizon are considered in the arrival sequence before departure, and when assigned delay take off later in order to absorb some of delay on the ground instead of during the flight. For aircraft that do not absorb delay on the ground, flight time remains the same with or without AMAN, but it is reasonable to expect that the use of CTA will have a positive impact on fuel consumption. This expectation is based on AMAN providing a time-to-land estimate in

¹⁷ Sometimes called XMAN – Extended Range Arrival Management

¹⁸ However, flying faster IS POSSIBLE and may be in the airline's interest, even when burning extra fuel in descent, so as to get a good place in the sequence.

advance, that if known by the FMS should allow for better descent planning. One of the difficulties for realising this is that when there is delay, traffic density is likely to be high, and therefore separation requirements will greatly limit the aircraft's chances to descend as planned. Even if self-management of descent speeds is not fully possible, AMAN can be used to support operational procedures that foster reduced engine-thrust settings and consequently result in less fuel consumption.

5.3.2. Preventing under-utilization of the runway during inbound peaks: the concept of over-delivery

When demand exceeds capacity¹⁹, i.e. during inbound peaks, and arrival traffic is delayed (i.e. forced to fly longer in order to land after their ETA), it is not acceptable that there are any gaps in the approach sequence, or that there is extra time between any pair of aircraft. In order to avoid such gaps, it is necessary to ensure a certain degree of over-delivery. In AMAN systems, over-delivery rate is regulated through off-line defined internal parameters: the 'runway pressure parameter' is the amount of delay to be absorbed *after* the metering fix through speed control or vectoring, and the 'holding stack-delay parameter' is the amount of delay to be absorbed *in lower airspace before or over* the metering fix holding stack, or equivalently at the Point Merge or Trombone structure in TMAs featuring such layouts.

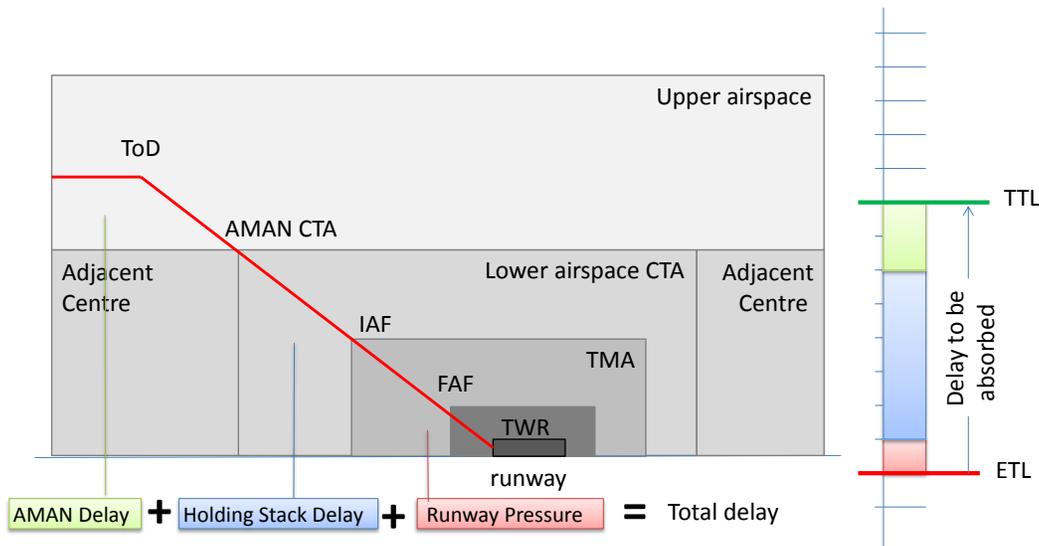


Figure 10: Delay parameters related to arrival management

Both runway pressure time and holding-stack time should not be shared upstream. In SESAR activities different values have been used for these. As an example, a holding-stack delay parameter of 5 minutes (the value used at SESAR's step 1 VP-244 (London TMA)) would not show a TTL advisory to en-route controllers for any delay below 5 minutes, and would show them a TTL for the delay-minutes in excess of 5 minutes, so the last five minutes of delay were to be absorbed at the holding stack. Delay sharing can also be regulated through proportional delay apportionment: the more delay there is, the higher the percentage of delay to be

¹⁹ This is likely to be caused by variations from original schedules, but in some cases may be due to overselling landing rights.

shared upstream. In SESAR’s VP-244 (Rome TMA) a combination of absolute and relative parameters was used, the rule being that 20% of delay above 2 minutes was to be absorbed upstream.

When the arrival manager planned time is sent to aircraft as a CTA, the use of a holding-stack delay parameter would potentially cause aircraft having flown to a time constraint to still need to hold at the IAF. A CTA requiring aircraft to speed up followed by holding would not be acceptable, whereas a slow-down CTA followed by holding would be. This potentially makes the use of holding-stack parameters inappropriate for CTA operations that may require speed-up instructions. In SESAR’s step 1 VP-485 (i4D arrival management in Malmö ATCC) the only delay-sharing limit was a 1 minute runway pressure parameter, and no delay was left to be absorbed in the holding stack. If the use of CTA is limited to slow-down CTAs, there is obviously no problem in planning for any number of minutes in the holding-stack over the metering fix.

For aircraft handled through TTL/TTG, an AMAN planned time ahead of the aircraft estimate to the fix will result in a TTG advisory. This may be handled by controllers by path shortening and/or by instructing aircraft to maintain high speed during descent. The latter would result in a descent profile similar to a CTA whose compliance requires high speed.

5.3.3. *The impact of delivery accuracy*

The need for over-delivery is directly related to the need to avoid loss of movements on a congested runway as a consequence of variations in arrival time due to previously discussed uncertainty issues. The highest delivery accuracy that is currently available is the ± 10 seconds 95% of the time provided by the FMS RTA function. It is important to realise, though, that the SESAR operational concept is not to build the approach sequence based on CTA only; the sequence is always composed of CTA aircraft intertwined with TTL/TTG (non-CTA) aircraft. I4D-equipped aircraft may need to be handled by TTL/TTG for various reasons, the two most common ones being: self-management of descent speed not possible due to separation provision constraints; and AMAN planned time outside the RTA achievable interval. Between two successive CTA-delivered arrivals, a 20-second gap can be expected if delivery is within the ± 10 seconds, and even larger gaps may happen if one of the aircraft is among the 5% that will be delivered more than 10 seconds off their AMAN planned time.

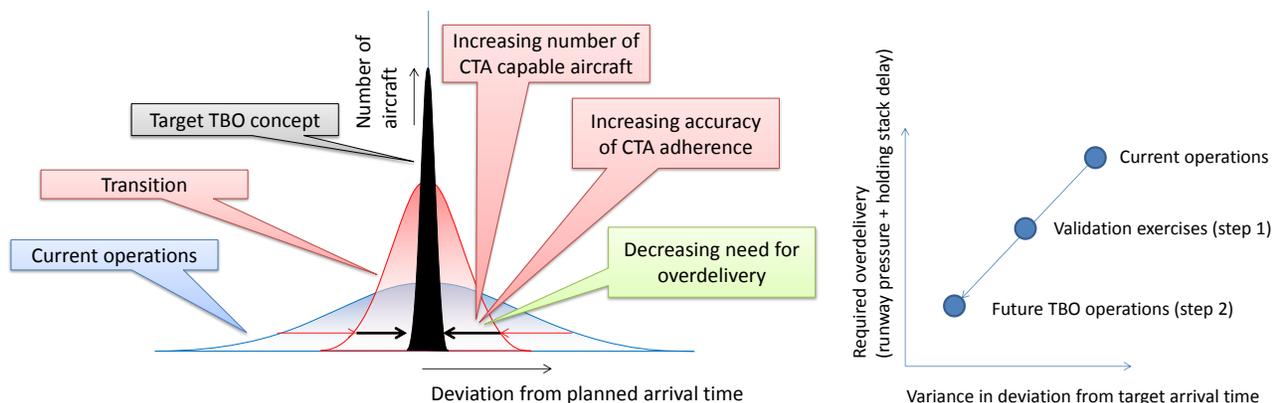


Figure 11: Evolution of variance in arrival time deviations towards target TBO concept

The better the adherence to AMAN planned times over the metering fix, the less need for over-delivery there will be, as this will have a knock-on improvement in the smoothness of arrival sequences, leading to reduced holding or vectoring as a result of fluctuations in the arrival sequence or the need to compensate for excessive over-delivery.

5.3.4. *Using TTA as an AMAN parameter*

As discussed in section 3, TTA adherence may be costly for an Airspace Users. For this reason, concepts looking into adding some kind of TTA adherence requirement with a certain tolerance, even if it is a less stringent one than the CTO/CTA-like +/- 10 seconds, need to offer an advantage to those Airspace Users that comply with their target time over those that don't. Airspace Users would want some guarantees for priority when adhering to TTA before starting adjusting flying parameters to adapt to it. An option that is currently under discussion in SESAR would be giving priority in the arrival management algorithm to TTA-complying flights over those that do not comply. This concept is called TTA into AMAN. However, the complexity of the arrival management process that has just been described demonstrates that this option is not as straightforward as its name seems to suggest. Research has commenced in SESAR to investigate this issue further.

5.4. Tailoring time adherence tolerances for each specific purpose

Sections 5.1, 5.2 and 5.3 discuss potential uses of imposing time adherence requirements to aircraft for ATM purposes. The goal of this exercise is to illustrate how requiring that aircraft conform to their planned trajectory in time may be used for ATM purposes, and why the level of tolerance with which such conformance will need to be required will depend on the specific application to be used. Further research on the required target time tolerance level is planned in SESAR.

As shown in section 5.1, adherence to time constraints can be used for separation provision. In this case, adherence tolerances result in uncertainty over the aircraft position, which will need to be accounted for in the separation minima to be used. For this reason, high accuracy in meeting time constraints will need to be required in order to make better use of airspace capacity.

Arrival management processes ultimately aim at producing a landing sequence where aircraft are as close as it is safe for them to be, and may thus benefit of smaller tolerance intervals than DCB processes, which only need to ensure that traffic density in a specific area remains manageable for controllers. The figures 12 and 13 illustrate the different accuracy needs for DCB against Arrival Management applications, as well as the difference in timing for setting the target time.

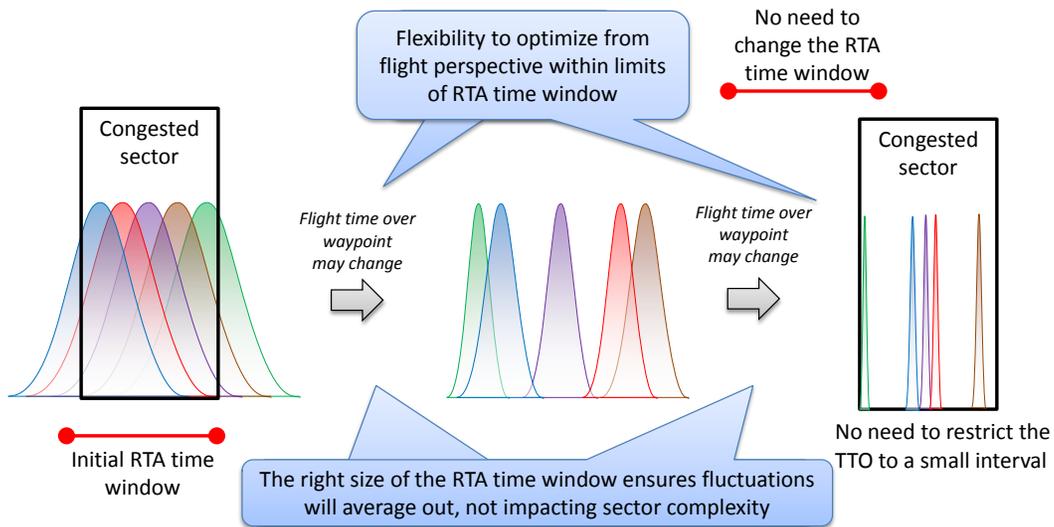


Figure 12: Finding a convenient RTA tolerance level that serves complexity management

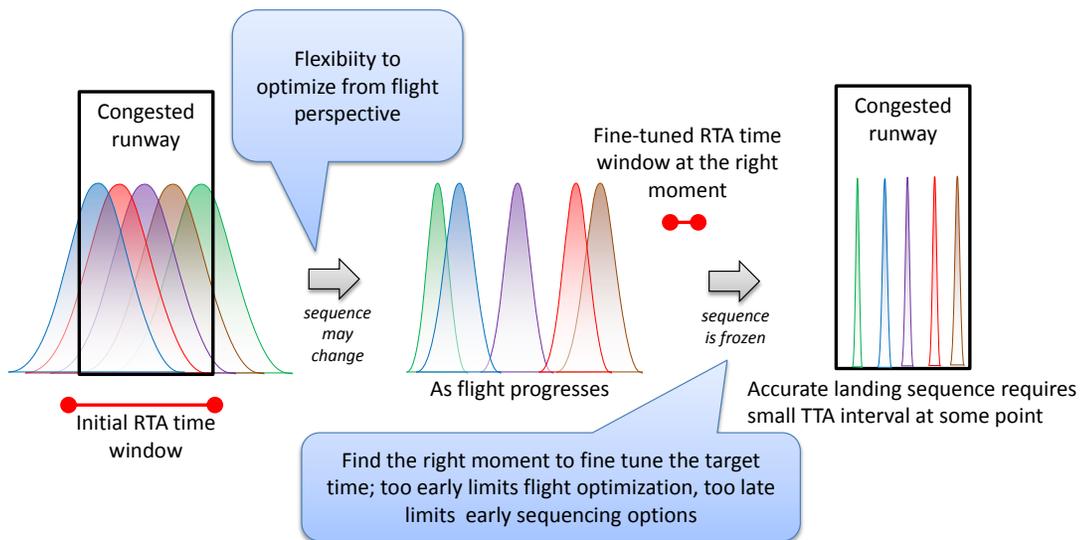


Figure 13: Finding the right moment to set an RTA that still serves arrival management

6. CONCLUSIONS

Increasing predictability starts with a more accurate management of departure times. Once airborne, the TBO environment will lead to a greater predictability of arrival sequences which, when flown with increased precision by highly efficient aircraft, will reduce the need for techniques such as extended time buffers or arrival over-delivery.

There is a need to balance the often-competing needs of stakeholders. Specifically, the need for system predictability, and adherence to the plan, should be balanced against the need to allow Airspace Users to benefit from the aircraft's ability to manage a fuel-efficient flight. By refining a flight's trajectory as the flight progresses and applying time target windows at the time they are required and tailored to the specific need for an ATM purpose, the balance between these needs can be optimised. The *width of the target time window* is a significant element in balancing flexibility versus predictability for the optimisation of demand versus planning and control purposes, and should be carefully selected. Also, the *timing for freezing the target time* plays a particular role in this balancing and would therefore equally be a parameter requiring careful selection. Both parameters will be subject of further investigation within SESAR.

Time is already used extensively in arrival management, and this forms an important component of SESAR's TBO concept. The notions of target times (as planning tools) and time constraints (as instructions to aircraft) should remain distinct in order to allow the ATM system of systems to retain as much flexibility as possible until the need for a flight to be constrained at all is determined.

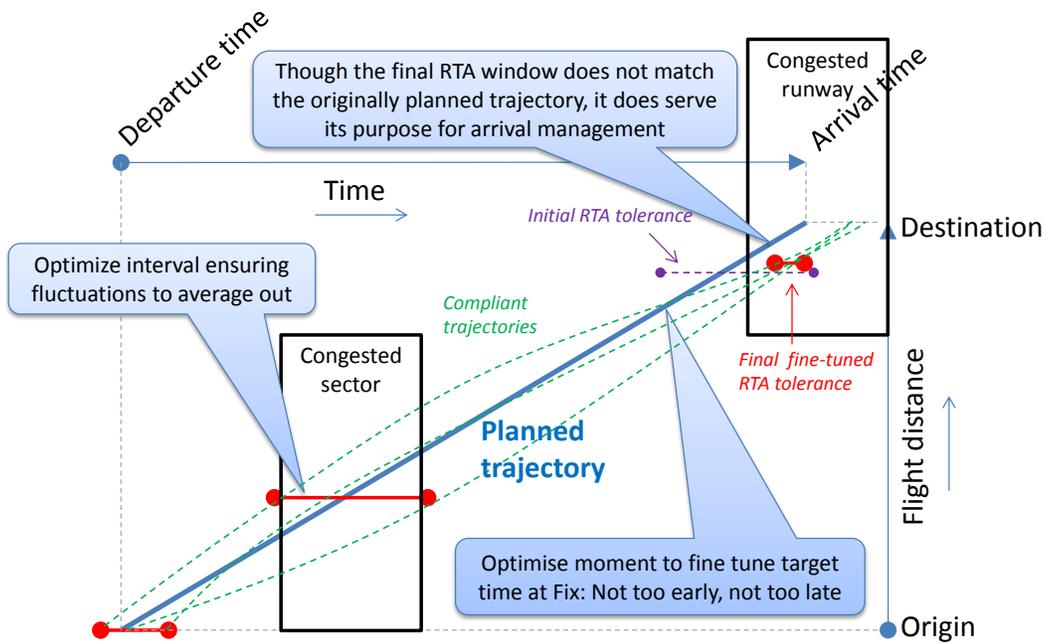


Figure 14: The optimum between flexibility and predictability

Both TTL/TTG-only or combined CTA-TTL-TTG²⁰ AMAN systems need to ensure a certain amount of over-delivery to the arrival metering fix in order to avoid gaps in the approach sequence, which would result in runway under-utilization. Over-delivery may cause aircraft that reach the metering fix at their AMAN-planned time to still need to absorb some additional delay. This will be acceptable for aircraft that have been already

²⁰ As stated before, SESAR fosters the CTA process, and the TTL/TTG when the CTA is not possible; this is fundamental for the AU, as this TTL/TTG generates "push-pull" flights, and causes unnecessary fuel burn.

required to absorb delay during their descent through TTL or slow-down CTA, but may not be so for those who have been required to descend at higher than desired speed, be it by CTA or TTG²¹. In such cases, use of CTA should be carefully considered, since it could be less flexible than TTG. The need for over-delivery is a consequence of uncertainty, and it is therefore reasonable to expect that it can be reduced by reducing uncertainty.

Successful implementation of TBO is key to realising the SESAR vision. As well as defining the mechanisms for using time values in trajectory management, SESAR projects are also discovering that the dynamic nature of the ATM network requires certain flexibility in the need for adherence to trajectory times, depending on the application. At one extreme, ruthlessly insisting on total adherence, the very flight efficiency enabled by evolving airborne systems could be compromised. At the other extreme, by allowing complete flexibility, the efficiency of the ATM network could be reduced which, in turn, would have an impact on Airspace Users business goals. There is, therefore, a need for a balance between the actual need of the ATM system of systems and the needs of individual Airspace Users.

7. ACTION BY THE MEETING

The meeting is invited to:

- a) note and review the contents of this working paper;
- b) incorporate these considerations into the continued development of the TBO concept
- c) incorporate in particular the following notions:
 - o The TBO concept shall promote increased predictability whilst retaining a level of flexibility that allows operators to fly as closely as possible to their business need.
 - o The tolerance range of any target time should be commensurate with the ATM function it serves and should be decoupled from aircraft system capability.
 - o The timing for freezing any target time should be delayed as late as possible commensurate with the ATM function it serves.

— END —

²¹ Additional delay after already having adapted speed to upstream delays, are not favorable to Airspace Users. In the final TBO concept delay sharing between en-route, arrival and approach segments should be fully transparent. Airspace Users expect that this can be achieved by application of one time constraint only.

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