

Hot Spot Identification and Mitigation at Strategic Level by Subliminal Changes in Aircraft Time of Arrival at Junction

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Abstract— This paper presents some results obtained when applying a different criterion in Air Traffic Flow and Capacity Management (ATFCM) measures. The approach is based on reducing the probability of controller's reactive interventions by "hot spot" identification and mitigation at strategic level, by applying minor changes on the aircraft's Times of Arrival (TOA) at the crossing or merging points (junctions). The concept of this strategy is fully aligned with the Trajectory Based Operation (TBO) principles. It is assumed that the changes on the times of arrival only demand very small speed changes to the involved aircraft (A/C). In this assessment, hot spots are established by identifying groups of closely spaced A/C arriving at a junction. A hot spot isolates the set of A/C involved in multiple conflicts, close in their times of arrival at the junction, violating the minimum required "safe" time separation at the junction. The minimum safe time separation is established based on a chosen threshold for the probability of collision obtained by considering the different sources of uncertainties in the aircraft's time of arrival at junction.

Some exercises are proposed and solved by applying this method. The obtained results show its ability to remove the conflicts by applying simple linear optimization programming tool. The effect of this method on the aircraft's operating costs is also analyzed.

This approach also seeks to change the current capacity-limiting factor, established by the number of aircraft occupying simultaneously each sector, to another parameter where the level of traffic complexity, flowing towards junctions, will be identified and mitigated at strategic level.

Keywords—ATFCM, TBO, CD&R, DCB, junction, TOA, hot spot, complexity, operating costs

I. INTRODUCTION

In the last few decades, the aviation industry has experienced a significant growth in air traffic and competitiveness, putting pressure on the Air Traffic management (ATM) capacity and its efficiency. Today, particularly in high traffic density areas in Europe, this traffic growth has determined a certain degree of saturation in airports

and the airspace. In addition, the projected rising demand for air travel has the potential to further increase air traffic congestion and reduce the operational safety and efficiency [1]. When the current ATM system with its conventional Air Traffic Services (ATS) route network and Air Traffic Control (ATC) sectors were designed, the delays on the en-route traffic were not as significant as today [2], [3]. Consequently, this system is failing to cope with the ever-increasing traffic, and has become one of the main limiting factors of the ATM capacity. With the increase of traffic in ATC sectors, the Air Traffic Controllers' (ATCO) workload which increases mainly due to increased number of tactical actions required to avoid conflict between aircraft, has also increased, limiting the number of operations that can be safely attended by the controller [4]. Thus, the capacity of the current ATM system is limited by the amount of simultaneous traffic inside each sector.

To mitigate the above limitations, and increase the ATM efficiency, new initiatives such as those proposed by the Single European Sky ATM Research (SESAR), seek to reform the paradigm for the ATM system [5]. The key element to achieve the change is the Trajectory Based Operations (TBO) concepts, under which air traffic demand and capacity balancing (DCB) practices can be improved through aircraft trajectory management at strategic level. This involves identifying long time in advance incompatibilities between aircraft trajectories and negotiating alternatives with the airspace users, in order to minimise controller's tactical interventions to increase the airspace capacity [6]. Elements of this concept are the basis of this paper.

Identifying potential conflicts and mitigating them at strategic level would bring an increase in airspace capacity, a decrease in en-route delays and a reduction in ATC workload. The method presented in this paper seeks to change the current capacity limiting factor, established by the number of aircraft occupying simultaneously each sector, to other criteria where the level of traffic complexity [7], [8], [9], flowing towards

airspace junctions, will be identified and mitigated at strategic level.

The method focusses on reducing the probability of controller's reactive interventions based on "hot spot" identification and mitigation at strategic level. In the mitigation process, instead of changing the initial aircraft trajectory, the method produces minor speed changes as the control variables computed before the flight to provide an adjustment on aircraft's Time of Arrival (TOA) at the junctions, in order to have a de-randomized and well-behaved (conflict free) traffic. This will enable improvements in airspace capacity/safety.

The main framework of the approach used in this paper, has been developed and presented by the current authors in a journal paper titled "Development of a new method for ATFCM based on trajectory based operations" provided in [10], which has been submitted to the Journal of Aerospace Engineering and currently under peer review. In order to better contextualise the results presented here, a few relevant concepts described in the above paper are revisited and summarised in Section II of this paper whilst, Section III presents the results, the analysis and the discussion, followed by conclusion summarised in Section IV.

II. SUMMARY OF THE MAIN APPROACH FRAMEWORK CONCEPTS

A. ATM Operational Network Topology and Junction Definition

In this approach, the ATM operational network is described as a set of fixed internal and external nodes, directed links among nodes and intersection points of these links (Junctions) as depicted in Fig. 1. Each internal node (i, j, \dots), presented by a square is a sink and source points of traffic flow, representing the physical volume of airspace occupied by a Terminal Manoeuvring Area (TMA). The external nodes (k, l, \dots) represented as circles are also simultaneously the sinks and sources of the traffic, representing entry/exit points of the airspace under consideration. Links represent planned Aircraft (A/C) trajectory tracks, where the (unidimensional) continuity principle will be applied along them if they do not arrive to any junction. Finally, junctions are dynamic or fixed locations where two or more links are expected to converge. An intersection of links will only be considered as a junction if it is

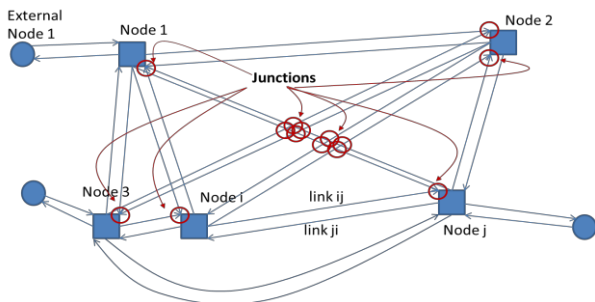


Figure 1. Airspace Topology and Junction Definition

“active”, that is; when a set of two or more A/C are expected to arrive within a small and well-defined time interval limit among any pair of them.

The geometry of a Junction can be characterised by its physical intersection of links [11]. If a junction has m incoming links and n outgoing links, then for $n=m$, it is referred to as a crossing point, when $m>n$, it is referred to as a merging point and when $n<m$, it is referred to as a distribution or a fork junction.

Assuming that all outbound traffic (q_{ij}) flows emerging from node i towards all other nodes j , and all inbound traffic (q_{ji}) flows arriving from all nodes j coming to node i satisfy the limiting throughput criteria (QI_i for inbound traffic) and (QO_i for outbound traffic). Thus, considering all nodes (N), the following equation can be stated for each node (i):

$$QI_i \geq \sum_{j=1, j \neq i}^{N-1} q_{ji}; QO_i \geq \sum_{j=1, j \neq i}^{N-1} q_{ij} \quad (1)$$

Where, QI_i and QO_i are a priori known, possibly time dependant, maximum allowed flow values for each node (i). Managing the TMA capacities in terms of inbound and outbound maximum flows (QI_i and QO_i) supported by Extended Arrival Management/Departure Manager (E-AMAN/DMAN) is considered as boundary condition of the problem. For ATFCM purposes, all the required information from these nodes is provided for the above criteria. In other words, all the following discussion refers to airspace beyond the limits of the TMAs borders. The equation on the left in (1) also applies to the (active) junctions. That is to say; the whole maximum arriving traffic to the junction (m) shall be equal or smaller than the junction inbound flow capacity (QI_m). However, situations where (QI_m) is exceeded are also analysed in this paper.

B. The minimum required time separation at the junction (τ)

In this paper, hot spots are established by identifying groups of closely spaced A/C arriving at a junction. A hot spot isolates the set of A/C involved in multiple conflicts, close in their times of arrival at the junction, violating the minimum required “safe” time separation (τ) at junction. Since (τ) is determined at strategic level, before the execution of flights, its accuracy will depend on the degree of the adherence of the actual to the planned trajectory. The planned trajectory may suffer from various sources of uncertainties, causing errors in aircraft TOA at a junction [12]. These uncertainties involve vertical, lateral (cross-track) and longitudinal (along-track) deviations. Additionally, the uncertainties due to initial time or scheduling also affect the A/C TOA at the junction. By assuming that these deviations are statistically independent or uncoupled, an analysis has been performed, to quantify all different sources of these uncertainties when transferred as TOA uncertainties of A/C i and j trajectories to the junction. A complete derivation of these uncertainties is provided in [10], and the resulting standard deviations of these uncertainties are summarised in Table 1.

TABLE I. SUMMARY OF ASSUMED REQUIRED TOA STANDARD DEVIATIONS

Uncertainty at the junction	Standard deviation specifications & Required Operation/performance conditions	
	A/C TOA standard deviation specification	Required condition
A/C Lateral deviation	$\sigma_{T1i,j} = \sqrt{2} \times \frac{\sigma_{LD}}{V_{i,j} \times \sin(\alpha_{ij})} = 30 \text{ sec}$	Crossing angle $\alpha \geq 20^0$ and RNP1
Initial time deviation	$\sigma_{T2i,j} = 1 \text{ min}$	N/A
Along-track time deviation	$\sigma_{T3i,j} = \frac{d_{i,j}}{2} \times \sigma_{V_{i,j}} = 1 \text{ min}$	A/C is CTA equipped
Combined Time Deviation	$\sigma_T = 1.5 \text{ min}$	Combination of the above conditions

The results in Table I are obtained by assuming Gaussian distribution for all of these uncertainties. The required minimum (safe) time interval (τ) at a junction is derived from a given predefined probability of collision (P_C), computed by convolving the two associated probability density functions (pdfs) for A/C (i, j) for the time of arrival (t) to the junction such that:

$$P_C = \frac{1}{\sqrt{2\pi(\sigma_{Ti}^2 + \sigma_{Tj}^2)}} \exp\left(-\frac{(\tau_p)^2}{2(\sigma_{Ti}^2 + \sigma_{Tj}^2)}\right) \quad (2)$$

Where $\tau_p = t_i - t_j$, t_i and t_j are the times of arrival at the junction for aircraft i and j , while σ_{Ti} and σ_{Tj} are the total standard deviation of uncertainties for aircraft i and j respectively.

The required minimum (safe) time interval (τ_p) between their expected TOA for a given P_C then results in:

$$\tau_p = \sqrt{-2(\sigma_{Ti}^2 + \sigma_{Tj}^2) \ln[P_C \times \sqrt{2\pi(\sigma_{Ti}^2 + \sigma_{Tj}^2)}]} \quad (3)$$

If the expected (nominal) time interval (τ_0) is equal or greater than the above computed value (τ_p), there will be no additional time interval required. Otherwise, the demanded time increment shall be:

$$\tau = \tau_p - \tau_0 \quad (4)$$

Fig. 2 shows the required TOA interval (τ_p) for different global standard deviations ($\sqrt{(\sigma_{Ti}^2 + \sigma_{Tj}^2)}$) in the TOAs for A/C i and j at the junction with different chosen probability of collisions (P_C). By assuming a constant TOA interval (τ_p) between consecutive A/C, the maximum inbound flow at the

junction (the frequency of traffic) can be directly derived as: $QI_m = 1/\tau_p$, it can be deduced from Fig. 2 that in order to maintain a probability of collision below 10^{-3} and a junction capacity close to 6 A/C per hour, a global TOA uncertainty of 3 minutes or less will be required. This TOA standard deviation value however, can only be achieved under specific operational and aircraft capability conditions.

From Table 1, uncertainties due to lateral deviations, given in terms of standard deviation ($\sigma_{T1i,j}$), depends on the navigation performance accuracy (given by σ_{LD} or RNP), A/C ground speed ($V_{i,j}$) and angle between A/C trajectories/tracks ($\alpha_{i,j}$). In [10], TOA standard deviations were calculated for different A/C speeds and crossing angles. The results shows that for A/C with a speed greater than 200 knots such as that of most typical commercial A/C, and for crossing angle between tracks greater than 20^0 , the relative lateral TOA standard deviation is: $\sigma_{T1i,j}/\sigma_{LD} < 1 \text{ min/NM}$ [10]. The accuracy criteria for RNP-X involves a standard deviation of $\sigma_{T1i,j} = X/2$. This means that when an aircraft is flying under PBN with RNP-X procedures, the associated standard deviation is $X/2$. For instance, RNP1 involves a standard deviation of $\sigma_{LD} = 0.5 \text{ NM}$. This then result in TOA standard deviation of: $\sigma_{T1i,j} < \sigma_{LD} 1 \text{ min/NM} = 30 \text{ s}$, which is adopted in Table 1.

Concerning the initial time/scheduling deviations ($\sigma_{T2i,j}$) as presented in Table 1, this variable can hardly be known a-priori. According to the Eurocontrol Performance Review Report (PRR) 2014[13], 0.9 minutes per departure due to local ATC departure delays at the gate and 3.5 minutes' delay per departure due to additional taxi-out time were registered at the top 30 busy airports in Europe in 2014. However, some on-going research projects such as the airspace User Driven Prioritisation Process (UDPP) and Airport Collaborative Decision Making (A-CDM) [14], seek to reduce significantly the level of this inefficiency to a target of about 30 seconds. Although the previous average values sensitivities are not known, in this paper, an initial/scheduling time standard

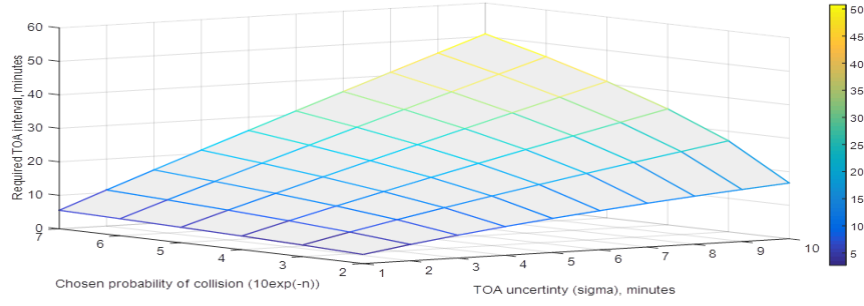


Figure 2. Required TOA interval for different collision probabilities and TOAs standard deviation for the involved A/C

deviation of around 1 minute ($(\sigma_{T2i,j})$, $\sigma_{T2i,j} = \pm 1$ minute) has been adopted.

For the along track deviation ($\sigma_{T3i,j}$), it is assumed in this paper that the A/C are equipped with an on-board Controlled Time of Arrival (CTA) functionality with the accuracy of ± 30 seconds. As suggested in [14], the use of this CTA accuracy value is more effective for dynamic Demand & Capacity Balancing (DCB) than the one of Targeted Time to Overfly/Targeted Time to Arrival (TTO/TTA) accuracy (± 3 minutes). However, even relaxing the CTA accuracy ($\sigma_{T3i,j} = \pm 30$ seconds to $\sigma_{T3i,j} = \pm 1$ minute, an acceptable result can be still achieved.

Based on the above assumptions, the resulting final combined TOA standard deviation $\sigma_T = 1.5$ minutes is obtained as shown in Table 1. This value is then used to revisit the required TOA interval for different collision probabilities. For these TOA standard deviations, the minimum time interval between two consecutive A/C, derived from (3), is presented in Fig. 3 for different probabilities of collision (P_C). As shown in Fig. 3, the probability of collision of 10^{-5} requires a minimum time interval of around 9 minutes which permits the junction's inbound traffic flow of up to 6 A/C an hour. This value for the collision risk is then retained, by considering it will strongly reduce the probability of ATC tactical intervention to remove conflicts.

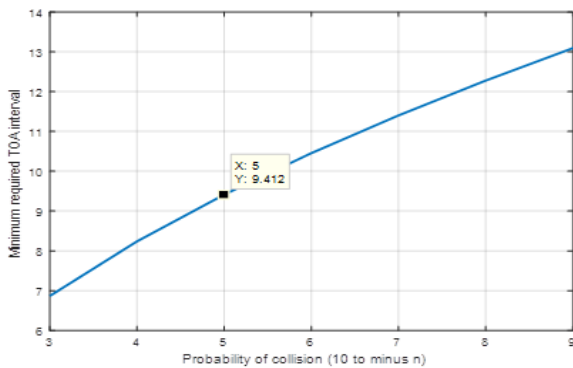


Figure 3. TOA interval for different probabilities of collision at the junction

Based on the above derived required minimum time separation between any two consecutive aircraft at junctions of $\tau=9$ minutes, hot spots can be identified in the initial Reference Business Trajectories (RBTs) by the Network Manager (NM), this identification includes the expected TOAs for the involved A/C.

The Air Traffic Flow and Capacity Management (ATFCM) mitigation actions are based on establishing the new TOA to the junctions for all A/C that remove conflicts. The computation of these times is based on basic Linear Programming (LP) optimization, where the total amount of distance-weighted speed changes is minimised and the initial target departing and arrival times at final destination are maintained (as constraints). A maximum allowed speed change is also imposed. These new times shall be issued by the NM to the A/C to be included within the new RBT as requested target TTOs for crossing points, and TTA to TMAs entry points. A detailed derivation and description of the linear optimisation tool developed for this method is provided in [10].

In the following section, some new exercises are proposed and solved to analyse the performance and applicability of this method. In all the exercises, the flight distance of 900NM and an initial nominal speed of 420knots before and after junction have been considered for each flight.

III. DISCUSSION & RESULTS

A. Number of in-bound A/C arriving to the junction in a bunch that can be realistically de-conflicted

It can be acknowledged that, the reactive nature of the current ATM system favours tactical de-conflicting measures such as heading and flight level changes over speed control [3]. This is mainly due to significant anticipation time required by speed control, and limited possible speed changes, compatible with aircraft performance. This preference is manifested especially when conflicts or severe congestions are locally detected. But when hot spots are identified long time in advance as proposed in this paper, it allows to use A/C speeds as control variables to mitigate them (producing small changes on the junction's TOA at the strategic level), assuming that the changes on TOA only demand very small speed changes from the involved aircraft

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By imposing realistic maximum speed changes threshold that are compatible with aircraft performance (e.g. 6% or 10%) as a constraint, a number of aircraft in a bunch inbound an active junction that can be successfully de-conflicted without exceeding the above threshold can be determined. This is particularly important, in determining the performance of the proposed mechanism based on minor TOA changes when traffic density at junctions is high, such as on busy merging points. A bunch of aircraft inbound a junction, is understood in this paper as a sequence of two or more aircraft planning to arrive to the junction within a given period of time, representing the air traffic demand of the junction for that period of time. Therefore, if a bunch of aircraft is arriving to the junction with 9 minutes of separation between any two successive aircraft, the junction would be operating on its full nominal throughput. Fig. 4, shows box and whisker plots for the optimized speed changes to remove potential conflict at a junction for different numbers of aircraft in a bunch inbound a junction. The initial time separation interval (τ_0) between any two consecutive aircraft at the junction before the minor speed

changes defined in (4) is randomly generated within the range of [0-9] minutes following a uniform distribution. This variable represents the interdependency of time stamps at the junction on aircraft trajectories defined in the flight plans. This range of [0-9] minutes implies that each aircraft is initially in a conflict.

To compute the speed changes in Fig. 4, the linear optimization model is applied in order to achieve the previously established collision probability between any two consecutive aircraft of 10^{-5} , which requires a minimum time interval between aircraft of around 9 minutes at a junction.

As shown in Fig. 4, for a bunch of 6 A/C, the obtained speed changes are all below 6% threshold. As the number of in-bound aircraft increases, so it does the required optimal speed changes. When the number of aircraft in a bunch is increased to 7 A/C and then to 8 A/C, the 6% threshold is exceeded (about 50th percentile is within the 6% threshold) and all A/C in both situations are within the 10% threshold. When the number of aircraft is increased to 9 A/C in a bunch, both thresholds are exceeded. This implies that if a maximum speed change of 6% and 10% is required for $\tau_0 = [0-9]$, the number of aircraft in a bunch inbound a junction must not exceed 6 and 8 respectively. This exercise can be performed for any τ_0 interval and any speed change threshold reflecting a particular traffic situation at junction and a required aircraft performance to determine a corresponding number of aircraft that can be realistically de-conflicted.

Fig. 5 shows the speed changes obtained from the optimizer before and after the junction (percentage of nominal A/C speed) per aircraft, when the number of in-bound aircraft to the junction is increased to 12 and 15 respectively. It is shown from this figure that the middle 6A/C and 8A/C meet their respective 6% and 10% speed change threshold, certainly

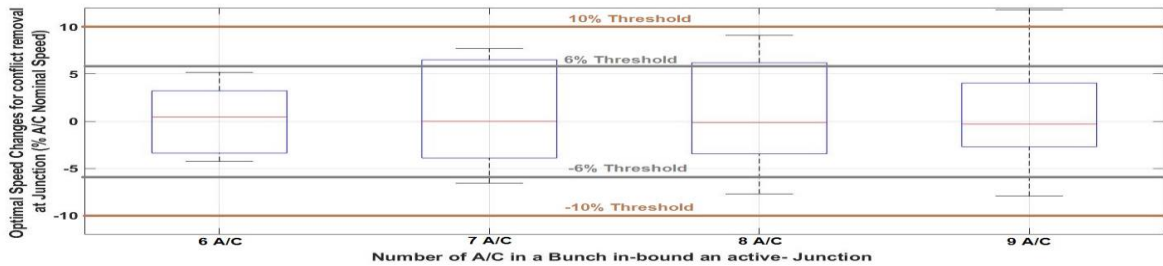


Figure 4. Optimal Speed Changes for Different Number of Aircraft in a Bunch In-bound a Junction

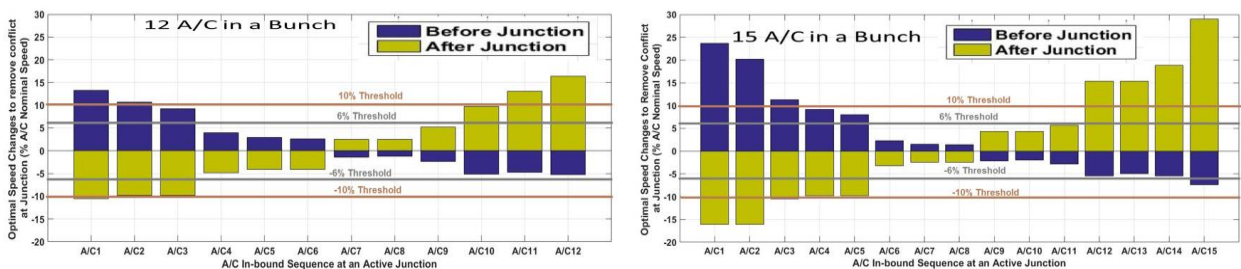


Figure 5. Speed changes per aircraft for 12A/C and 15 A/C in a bunch

supporting the results portrayed in Fig. 4.

B. Monotonic Increase of Speed/TOA Changes When $\tau_0 \leq [0-9]$

As previously stated, when $\tau_0 \leq [0-9]$, all aircraft in a bunch are initially in a conflict at the junction, which implies that TOA changes are required for each aircraft in order to achieve the required minimum separation. For 8A/C for instance, as shown in Fig. 6, seven intervals of a minimum of 9 minutes separation between each pair of successive aircraft are required in order to remove successfully all conflicts. To achieve this, it follows that an interval of at least $7 \times 9 = 63$ minutes at a junction is required between the first (A/C1) and the last aircraft (A/C8) in a bunch.

In Fig. 6, two initial separation situations are illustrated. One when time interval is within $\tau_0 = [0-7]$ minutes providing a particular random initial separation of [2 5 6 4 0 5 2] minutes between (AC1&AC2.....AC7&AC8) respectively, resulting in an initial separation interval between the first and last A/C of 24 minutes (shown by the top line), and another when the time interval is within $\tau_0 = [0-3]$ minutes proving a particular random initial separation of [1 2 3 2 0 2 1] minutes for the same aircraft, resulting in an initial separation interval between the first and last A/C of 11 minutes (shown by the bottom line).

It is shown from Fig.6 that in each of the two initial situations, it is necessary to change the TOA of the first and last aircraft greater enough to obtain an interval of at least 63 minutes between them (middle line). This is done in order to provide the required minimum safe time scale on which all other aircraft's TOA can be effectively changed to achieve the required minimum safe separation between all of them of 9 minutes. As shown in Fig. 6, it follows that the first and last few successive aircraft in both situations will usually require TOA changes longer than the required minimum separation,

while the middle aircraft require TOA changes just enough to achieve this minimum separation.

Comparing the TOA changes for the two situations: The TOA changes for time intervals within $\tau_0 = [0-7]$ minutes are shown by solid lines above middle line while TOA changes for time intervals within $\tau_0 = [0-3]$ are shown by dashed lines below the middle line in Fig. 6. It can be derived that the stronger the initial time stamp interdependency/closeness (i.e. the smaller the τ_0) of aircraft trajectories at the junction before TOA changes are applied, the more longer are the TOA changes required for the first and last few aircraft, while the TOA changes for the middle aircraft are merely increased. This behaviour is also reflected in the optimal speed changes obtained for the above two situations shown in Fig. 7. From Fig. 7 it can be observed that when τ_0 is decreased from $[0-7]$ minutes to $[0-3]$ minutes, the speed changes required to remove the conflict strictly increases monotonically for the first and last few aircraft in a bunch while almost linear for the middle aircraft.

The above monotonic increase in the speed/TOA changes can be attributed to the fact that when τ_0 decreases below $[0-9]$ minutes, the demand of arriving traffic is above the junction's inbound flow capacity QI_m . This may particularly occur at merging junctions where the incoming traffic is confined into higher density outbound routes. This behaviour is usually observed in all other single server queuing systems, where the traffic delay grows towards infinity when the traffic arrival rate exceeds the servers inbound flow capacity.

C. Modulation of Speed/TOA Changes and Steady State Condition

With the above monotonic behaviour of speed/TOA changes when τ_0 decreases below $[0-9]$ minutes, the proposed new ATFCM mechanism maybe unrealistic if the current

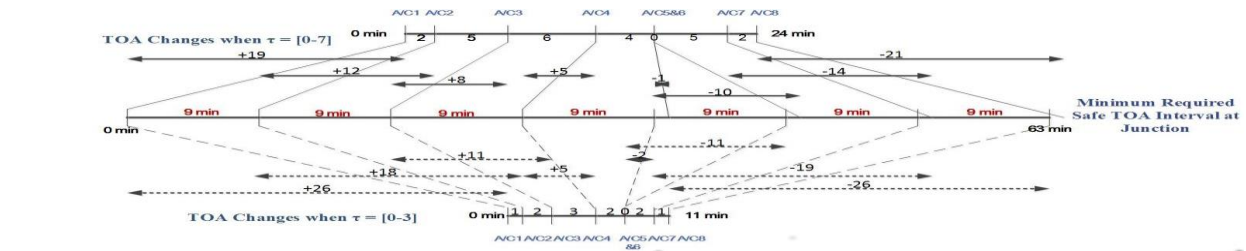


Figure 6. Monotonic Increase of TOA changes when $\tau_0 \leq [0-9]$

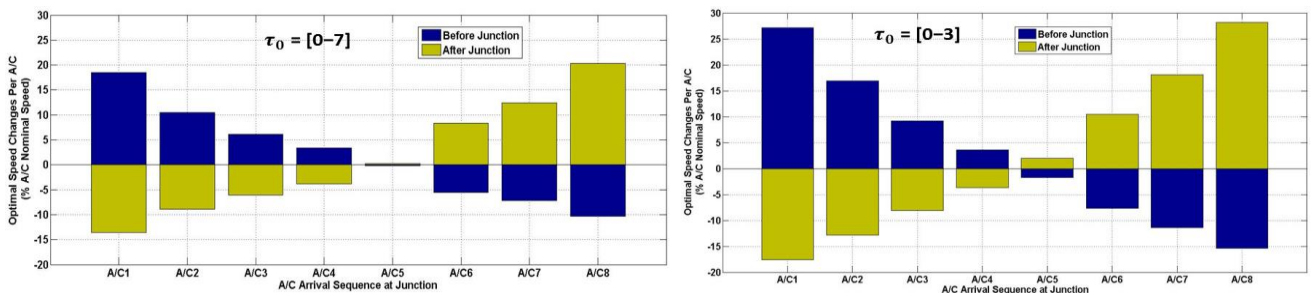


Figure 7. Monotonic Increase of TOA changes when $\tau_0 \leq [0-9]$

confining fixed conventional ATS route network was to be maintained. It is then assumed in this paper that aircraft are flying following free routing airspace (FRA), where the number of routes intersections is spread, and then the traffic density at junctions (except those in the nodes entry points) drops down. For crossing point junctions, the conventional situation usually will have actual flow (within each link) far below its limit. Under these circumstances, the situations where τ_0 interval is above [0-9] minutes can be realistically assumed, allowing some aircraft in a bunch to be initially sufficiently separated at junctions.

For those aircraft that are initially sufficiently separated, their separation can be reduced to exactly minimum safe separation (9 minutes) to allow a modulation of speed/TOA changes among all aircraft. Thus, the problem becomes a traffic de-randomization problem and the junction's utilization/throughput is maximised by speeding up and slowing down arriving traffic to achieve exactly the minimum "safe" time interval among A/C arriving from different links. This removes the previous monotonic behaviour, hence, providing some degree of fairness. Fig. 8 shows the optimal speed changes when a bunch of 8 in-bound aircraft at a junction is considered for $\tau_0 = [0-12]$ minutes and $\tau_0 = [0-15]$ minutes.

The results in Fig. 8 show that as τ_0 is increased above [0-9] minutes, the above monotonic behaviour in the required speed changes for the first and last aircraft in the bunch arriving to the junction is subsequently changed into an oscillated behaviour.

When $\tau_0 \geq [0-18]$ minutes, the junction's inbound flow capacity QI_m exceeds the arriving traffic demand and the optimal speed changes reaches the stable steady state. When $\tau_0 = [0-18]$ minutes, since the initial separation between any two successive aircraft is randomly generated in this interval, the average initial separation between aircraft is close to 9 minutes which is the required minimum safe separation at the junction.

D. Effects of the Proposed Method on the Flight Operating Costs

The flight operating costs in commercial aviation can be divided into fuel costs, flight time dependent costs and fixed costs. The fixed costs such as crew and landing fees are independent of the flight speed, while fuel and time costs vary

as a function of the flight speed. Users have different operating objectives, and hence, the flight operating cost optimization is proprietary and varies from one user to another. Some users may prefer timely flights while others are more concerned with fuel savings. To achieve this trade-off, different flights use different Cost Index (CI) through an optimization process with a common objective function given by: Total cost = (Fuel costs) + CI × (Time Costs).

Given that, CI is proprietary of the user and cannot be easily known, it is assumed in this paper constant and the same for all flights. Moreover, one important attribute of the optimization model developed for the ATFCM method in this paper, is that it preserves the aircraft's Targeted Time of Arrival (TTA) [10], and therefore, does not affect the aircraft's time related costs. Hence, the speed changes obtained by the model only affects the amount of fuel consumed. To analyze these effects, a benchmark scenario is considered the nominal fuel consumption the aircraft would consume if its initial planned nominal speed was not to be changed, assuming that its nominal speed is the optimal speed for its fuel consumption such that any change on this speed will result into excess fuel consumption.

The A320 is chosen for all aircraft in this analysis. This is because it is a typical mid-range aircraft, used worldwide, either operated by low-cost or legacy carriers. It is acknowledged that the aircraft fuel consumption varies with the weight and flight altitude, but in order to have significant results, it is assumed that the weight of the aircraft throughout the flight is the average weight of the aircraft during cruise and a flight level of 37000ft is selected and unchanged during the flight. The Eurocontrol Base of Aircraft Data (BADA) aircraft performance model is used to extract the aircraft performances used to compute the fuel consumption. Fig.9 shows the average change (excess) in fuel consumption per aircraft in a bunch of 6, 9, 12, and 15 aircraft for different values of τ_0 ([0-9],[0-12],[0-15],[0-18]) when the speed changes are applied to remove the conflict at the junction.

From Fig.9, it can be seen that for $\tau_0 \geq [0-9]$, the average change in fuel consumption is below 6% for all aircraft bunches, for $\tau_0 = [0-9]$ the changes are above 6% and below 10% for 12A/C and 15A/C in a bunch, while for $\tau_0 = [0-18]$, the changes are below 3% for all aircraft bunches.

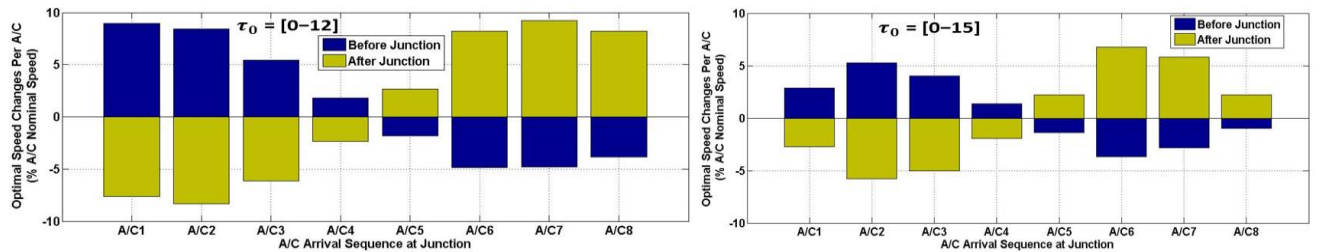


Figure 8. Oscillated behavior of speed changes when $\tau_0 \geq [0-9]$

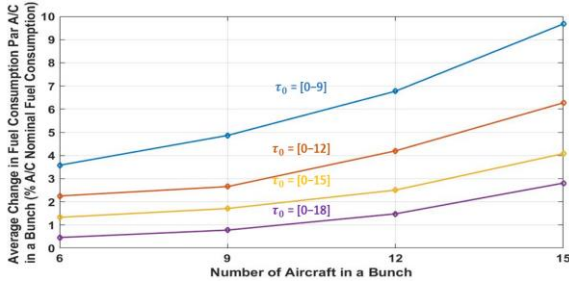


Figure 9. Excess fuel consumption due to Speed/TOA changes

IV. CONCLUSION

The implementation of direct routes and free routing airspace, applied to high-density airspace, are changing the traffic flow patterns, forcing both, ATFCM and ATC to change. ATC sector occupancy and dynamic sectoring are some steps in that direction, but they are still anchored in the conventional concept “airspace based operations” rather than in the new one “TBO”. This paper analyses a new metric for the demand measure, based on hotspots identification and, as well, derives a method for establishing the corrective actions to mitigate them at strategic level, fully aligned with the TBO concept.

Hotspots are here defined as “active” junctions, where a bunch of two or more flights are expected to cross their trajectories with less than a well-defined minimum time interval, demanding a special attention by ATC and, likely to produce reactive corrective actions. Based in the initial RBTs, these hotspots are identified by the NM; this identification includes the expected TOAs for the involved A/C. The minimum “safe” time interval used in this paper has been 9 minutes for a probability of collision of 10^{-5} under specific operational and aircraft capabilities providing a specific level of uncertainty in the A/C’s TOA at the junction.

The ATFCM mitigation actions are based on establishing the new TOA to the junctions for all A/C that remove conflicts, the computation of these times is based on basic LP optimization, where the total amount of distance-weighted speed changes is minimized and the initial target departure and arrival times are maintained (as constraints). A maximum allowed speed change is also imposed. Based on the desired speed change threshold, a number of in-bound A/C arriving to the junction in a bunch that can be realistically de-conflicted is established.

The results show a good performance in terms of the A/C speed/TOA changes feasibility and the complete removal of nominal conflicts for different samples of traffic demand in-bound to the junction.

It has been shown that when the arriving traffic demand reaches the junction’s inbound flow capacity, the required speed/TOA changes increases monotonically. This behavior is better observed in all other single server queuing systems, where the traffic delay grows towards infinity when the traffic

arrival rate (taken as inverse of service mean time) is close to the servers inbound flow capacity. To change this behavior, specific traffic demand and operational conditions are established to provide oscillated behavior of speed/TOA changes, hence, providing some degree of fairness. The conditions under which speed/TOA changes reach the stable steady state have been also established.

The TTO/TTA time changes shall be issued by the NM to the A/C to be included within the new RBT as requested target times to overfly (TTOs) for crossing points, and target times to arrival (TTA) to TMAs entry points.

Finally, the assessment also included the effect of the speed/TOA changes obtained by the proposed method to remove conflict on the flight operating costs for different traffic demand at the junction.

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