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Guaranteed Conflict: when speed advisory doesn't work for Time-based Flow Management

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Abstract—**Time-based Flow Management (TBFM) is one of the core portfolios of the Next Generation Air Transportation System (NextGen). However, according to multiple reports, there is general confusion about the usage and implementation of the time-based capabilities. This paper aims at answering questions about the usage of time-based instructions and speed advisories to maintain safe distances for TBFM. Towards this end, three collectively exclusive types of situation which are "conflict free", "potential conflict" and "guaranteed conflict" are developed to classify the condition of a flow of aircraft. Then, a decision-making process is further proposed using the three classes to increase the use of time-based instructions and speed adjustment and avoid the costly vectoring and path stretching. Furthermore, algorithms are developed to assist the process in identifying the "guaranteed conflict" and resolving the conflict by removing the least number of airplanes from the flow. Lastly, a use case is studied to illustrate the decision-making process and the effectiveness of the proposed algorithms.**

Keywords-Time-based Flow Management; speed advisories; guaranteed conflict; safety

I. INTRODUCTION

The Next Generation Air Transportation System (NextGen) envisions improving the safety and efficiency of airspace operations, while reducing the environmental impacts and increasing the capacity of the air transportation system [1]. At the heart of NextGen is time-based management, e.g., Time-Based Flow Management (TBFM), for Trajectory Based Operations (TBO), an air traffic management system in which every aircraft is represented by a 4-D trajectory (4DT) [2]. A 4DT includes a series of points from departure to arrival representing the aircraft's path in four dimensions: lateral (latitude and longitude), vertical (altitude), and time. With the presence of 4DT, TBFM plays an important role in NextGen's transition from traditional miles-in-trail [3] traffic management to (Extended) Time-based Metering, providing air traffic services to meet a scheduled time at which airborne aircraft should cross a metering point or arc instead of specifying a minimum spacing for flights [4]. TBFM is at the heart of time-based management [5], whose main promise is to relieve ATC workload by issuing crossing time clearances directly to the aircraft and allowing the aircraft to adjust speed autonomously to meet the crossing restriction, instead of issuing speed instructions to pilots to keep the aircraft on time [6]. FAA defines ATC's role in TBFM as "issuing clearances to metered aircraft to meet TBFM-assigned Scheduled Time of Arrival (STA) by using the STA time and speed advisories (***when applicable***)" [7].

However, the key question is: when is "when applicable"? Specifically, (1) when it is applicable to only use time-based 4DT instruction, (2) when speed advisories are required and (3) when both are not sufficient? On one hand, our previous work has shown it is possible to guarantee ***conflict free*** trajectories for certain scenarios only with 4DT instruction, i.e. crossing a waypoint at a specific time (x, y, z, t) [8][36]. On the other hand, we also identified scenarios where 4DT time-based instructions are insufficient, which can be further categorized into two classes: one is called ***potential conflict***, where conflict can be avoided by applying certain speed advisories; the other is called ***guaranteed conflict***, where conflict cannot be avoided by speed adjustment and so altitude or direction change needs to be applied.

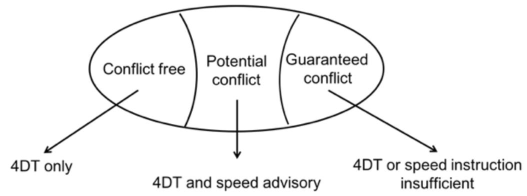

Figure 1. Three classes of situation for a flow of aircraft

Therefore, a flow of aircraft can be categorized into three exclusive classes of situations: "***conflict free situation"***, ***"potential conflict situation"*** and "***guaranteed conflict situation"***. Speed advisory does not matter in both "conflict free situation" and "guaranteed conflict situation", though for different reasons. In "conflict free situation", there are always feasible time-based 4DT instructions that can guarantee conflict free trajectories regardless of the specific speed profile the pilots choose to reach the instructed waypoint. In "guaranteed conflict situation", there is no feasible speed profile to avoid an

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upcoming conflict. The only alternative to avoid a collision is vectoring or "path stretch" [9]. In the "potential conflict situation", time-based 4DT instruction is insufficient to rule out the possibility of conflicts but there are always feasible speed profiles to deconflict the situation.

Explicitly determining these classes helps minimize the unnecessary, costly use of vectoring and maximizing the use of speed adjustment while maintaining safe separation in a traffic flow. First, when airplanes are in "conflict free situation", ATC can simply use 4DT waypoints to guide the airplanes, which reduces ATC's workload by leaving the speed autonomy to pilots/airlines to optimize their own objectives. Second, if airplanes are in "potential conflict situation", speed advisories need to be issued in addition to 4DT waypoints, in order to guide the airplanes away from dangerous conflicting situation. Finally, the "guaranteed conflict situation" shall be avoided by all means. It is the only situation where costly vectoring or holding is necessary to deconflict the situation.

This paper has two main goals. The first is to show how the three classes of situation can help to systematically exploit and utilize time-based 4DT instruction and speed advisory. A decision-making process for TBFM instructions is proposed. The second goal particularly aims to address the "guaranteed conflict situation", which has not been addressed in our previous work, i.e. when speed advisory cannot resolve a conflict. Algorithms for automatic instruction generation for flight deck-based interval management are being developed based on the findings in this paper.

The rest of the paper is organized as follows. Related work is reviewed in Section II, showing that there are confusions about the usage and implementation of the time-based capabilities and the general trend in the work of Conflict Detection and Resolution. In Section III, the decision-making process and "guaranteed conflict situation" are explained in detail using a three-aircraft example to provide insights about the problem. The algorithms to identify the "guaranteed conflict situation" for a flow of aircraft is illustrated in Section IV and the algorithm to remove the least number of aircraft from the flow to resolve a "guaranteed conflict situation" is then explained in Section V. In Section VI, a use-case study is conducted to show how the proposed algorithms assist the decision-making process by identifying guaranteed conflict and resolving it. In the end, the paper is summarized and results are concluded.

II. RELATED WORK

A. Time-based operation

As far as the general framework of time-based operation is concerned, the conditions to use time-based instructions and speed-based instructions are unclear to the best of the authors knowledge. FAA's order JO 7210.3AA [10] prescribes that TBFM is the expanded use of time-based metering, allowing the routine use of Performance Based Operations and ***only applying spacing when needed***. It is consistent with FAA's Performance Based Navigation (PBN) strategy to continue transition from distance-based to time-based and speed-based air traffic management [11]. It is important to note that there is a general lack of understanding about what a NAS Time-based Scheduling and Management system means from the perspectives of both Air traffic and System adaptors, which coincides with the findings in [12] that there are general confusions about the usage and implementation of the time-based capabilities.

Based on the document reviewed [13-15], though the exact detailed algorithm of TBFM is not open to the public and names of the modules where the functions reside in differ, it is certain that Schedule Time of Arrival (STA) will be calculated first and then airplanes will be given speed advisories to catch each STA at the respective Constraint Satisfaction Point (CSP). More specifically, [16] claims the TBFM system uses trajectory modeling functions to build a sequence and schedule of aircraft joining an arrival flow and provides a time schedule at meter reference points (MRPs). Its sub-function of speed advisories suggests airspeeds that ATC can provide to an aircraft to help meet its frozen scheduled time of arrival (STA) at an MRP. [17] touches upon the time-based and speed-based concepts by studying the difference and interaction between schedule-based management and spacing-based management at CMPs. [18] discusses the concept of operation for Interval Management, which is basically a speed-based decision-making tool to assist ATC to maintain STA and conduct relative spacing. More similar work can be found in [19, 20]. None of the work reviewed considers how to use STAs in TBFM to effectively eliminate conflicts in the first place and only use speed advisory as a reserve to avoid possible collision.

B. Conflict detection and Resolution (CD&R)

There are two major types of CD&R model: centralized and decentralized. For the decentralized model, [21] did an review on decentralized CD&R in air traffic managemnt system. They put forward 10 criteria, such as agent selection, agent action and agent interaction, to compare different decentralized air traffic operation model. More decentralized work can be found in [22-24].

As far as the centralized air traffic model which is used in this paper, there are two main types of models: discrete space and continuous space. As a discrete approach, [25] defined for each airplane a "protected air zone (PAZ)", a 3D space that is not supposed to overlap with other airplanes'. Moreover the airspace is divided into grids the same size of PAZ. [26] formulated the air-traffic collision detection and resolution problem as the search for a maximum clique of minimum weight in a specific graph linking conflict-free maneuvers. [27] mapped the congestion area to a corresponding graph based on the minimum reliable distance threshold, resolving potential conflicts using Graph Coloring method.

Continuous models are more frequently used in the work of CD&R. Most of the continuous models recognize the uncertainty in aircraft motion and environment; however, one of the main distinctions are in the assumption of velocity, i.e. constant velocity or varying velocity. A large volume of work is based on the assumption of constant velocity. [28] proposed methods to determine the time, positions, and distance of closest approach for two vehicles following arbitrary trajectories by assuming "uniform motion", i.e. constant velocity. [29] applied an optimal control method to CD&R. The conflict situation between aircrafts is detected on the basis of forecast of their motion, and the values of aircraft velocities are constant and assumed to be known. More work assuming constant velocity can be also found in [30] and [31]. Other work addresses varying velocity. [32] represented the uncertain varying speed with Space-Time Prism (STP). Conflict detection is performed by verifying whether the STPs intersect or not, and conflict resolution by planning a conflict-free space–time trajectory avoiding overlapping. [33] put forward a speed uncertainty model based on the assumptions that actual speed may differ from nominal value, say *v*, within a certain error percentage *e*, which means the speed is bounded by [(1-*e*)*v*, (1+*e*)*v*]. Based on the classification, the model used in this paper is a centralized continuous one with varying velocity, which is the most realistic among all.

In summary, the current literature of CD&R, regardless of types of model assumed, mostly focus on how to use velocity to avoid conflict or optimize an object. None of them explicitly addresses the condition where velocity control is incapable of deconflicting aircraft, and more importantly, how the work can improve the use of the time-based concept.

III. Problem Analysis

This section first provides a geometric interpretation of traffic flow through a three-aircraft scenario to help the reader gain intuition about the problem. Then, an observation about how this problem can be formulated as an optimization problem to increase scalability is briefly discussed. Finally, the decision-making process for TBFM instructions is proposed.

A. The three-aircraft scenario

Figure 2 Three-aircraft scenario

As shown in Fig.2, three airplanes AC1, AC2 and AC3 fly in the same 3D trajectory, i.e. a flow. At the *t=0*, the respective positions and velocities along the 3D flow are ($S1(0)$, $S2(0)$, $S3(0)$, $v1(0)$, $v2(0)$, $v3(0)$), where $S1(0) > S2(0) - D$, $S2(0) > S3(0) - D$ and $v1(0) < v2(0) < v2(0)$. D is an acceptable minimal distance between airplanes and without losing generality is assumed *D*=0. For purposes of illustration, we assume all airplanes' velocity are bounded from below and above by $[\underline{v}, \bar{v}]$, respectively, and acceleration by $[-\underline{a}, \bar{a}]$, where $\underline{v} > 0, \bar{v} > 0, \underline{a} > 0$ and $\bar{a} > 0$. In general, these are unrealistic assumptions. However, the algorithms in Section IV and V are more realistic, with the ability to handle airplanes with different boundary conditions, i.e. different flight envelopes.

Note that the *x* axis can be seen as a vector in R^3 space, representing the directional progression of the "flow" in three dimensions. In an earth-centered inertial coordinate system, the "flow" can be a straight-line of air corridor, or any curved path with altitude changes and turns such as in the standard routes for arrival and departure. Another possible interpretation of "*x*" here is just one dimension in 3D space. Speed and acceleration have to be decomposed and projected to this single dimension and conflict is then defined as the intersection of all the three dimensions at the same time. In this paper, we use the former interpretation; however, the results can also be extended to the latter interpretation.

B. Guranteed conflict

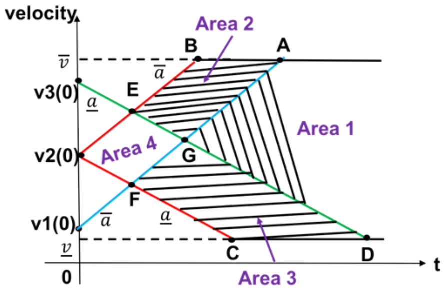

Figure 3 Geometric representation of the guaranteed conflict problem

To analyze the "guaranteed conflict", we consider the best-case scenario (in terms of separation). If the conflict cannot be avoided in the best case, then it must be a guaranteed conflict. Fig. 3 is a geometric representation of the concept. The best case is: the leading aircraft, AC1, accelerates with $\bar{a}$ until reaching and maintaining speed $\bar{v}$ from point A. The trailing aircraft AC3 decelerates with $\underline{a}$ until reaching and maintaining speed $\underline{v}$ from point D. The two extreme speed trajectories that the middle aircraft, AC2, can fly is, starting at v2(0), to accelerate with $\bar{a}$ until reaching and maintaining speed $\bar{v}$ from point B and decelerate with $\underline{a}$ until reaching and maintaining speed $\underline{v}$ from point C. v1(0)A intersects with v2(0)C at point F and v3(0)D at point G. v2(0)B intersects with v3(0)D at point E.

Obviously, there are only four areas where AC2 can be: the open area to the right of AGD, the closed area of ABEG, DGFC and v2(0)FGE. For simplicity, they are called Area 1, Area 2, Area 3 and Area 4, respectively.

Area 1: if AC2 is in Area 1, then at any timestamp its speed is less than AC1's and greater than AC3's. Because AC1 accelerates at the greatest rate and AC3 decelerates at the greatest rate, if AC2 can successfully make into Area 1, then it is impossible to have conflict anytime thereafter. It is actually a conflict free zone.

Area 2: if AC2 is in Area 2, then at any timestamp its speed is greater than AC3's. Similarly, it won't have conflict with AC3 anytime thereafter because AC3 decelerates at the greatest rate.

To avoid conflict with AC1, the best AC2 can do is to decelerate at rate $\underline{a}$. All points within Area 2 can find respective points on line EG to better deconflict the situation. In other words, EG dominates Area 2 for best-case scenarios. If the guarantee conflict happens in Area 2, it must happen at its boundary, i.e. line EG. **Area 3** is similar with Area 2.

Area 4: Hence, if there is guaranteed conflict in the three-aircraft scenario, it must be happening in Area 4, including its boundary. As shown in Fig. 3, Area 4 is bounded by two possible trajectories: v2(0)EG and v2(0)FG. Since the area under v2(0)EG is always the greatest at any timestamp from t=0 to point G, thus it is the most advanced trajectory of all possible trajectories. Similarly, v2(0)FG is the least advanced trajectory.

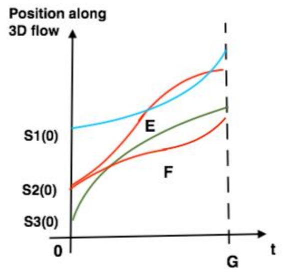

Figure 4 An intuitive explanation of conflict in Area 4

There is an analytical way to precisely predict potential conflict in Area 4. However, since the goal here is to understand the nature of this problem, we present here an intuitive explanation shown in Fig. 4. The analytical derivation will be shown in future work.

The blue convex line represents AC1's accelerating trajectory to point G of Fig. 3. The green concave line represents AC3's decelerating trajectory to point G. The area bounded by the red lines is the Area 4 in Fig. 3. Note that, the lower red line is comprised of a concave line of the first half and a convex line of the second half, which represents the path of v2(0)FG in Fig. 3. The upper red line represents the path of v2(0)EG in Fig. 3. Based on Fig. 4, it is easy to see that there are three possibilities that a guaranteed conflict exists.

Possibility 1: The blue line and the green line intersect at some point when conflict happens. Intuitively, this means the leading aircraft AC1 and the trailing aircraft AC3 has a guaranteed conflict. Obviously, in this situation no matter how AC2 flies, it cannot deconflict the situation.

Possibility 2: In certain time interval, area bounded by the red lines is completely above the blue line. In other words, during that time interval, the lower red line is above the blue line, intuitively meaning the middle aircraft AC2 has guaranteed conflict with the leading aircraft AC1. Similarly, **Possibility 3** is the middle aircraft AC2 has guaranteed conflict with the trailing aircraft AC3.

C. *Scalability*

An obvious problem of the analysis presented above is that it is unscalable as the number of aircraft increases. However, one can observe certain similarities between the logic of solving the example above and the Simplex Method in solving linear programs. To manually solve the feasibility problem, we are essentially trying different corner solutions on the acceleration/deceleration decisions at discrete time points and checking its feasibility of constraints on velocities and positions. This resembles the phase-I method, which concentrates on the corner of a relaxed linear program and determines its feasibility. Therefore, inspired by the three-aircraft example, we will propose a conflict detection routine that generalizes the manual derivation above. As we will see in Section IV, the formulation will be a linear program for which many efficient solvers exist. Upon solving the conflict detection linear program, it will return one of two possible results. The first is that such a linear program is *infeasible*, which indicates the *existence of guaranteed conflict*. The second possible result is that such linear program is *feasible*, which indicates the conflict can *possibly* be avoided by adopting certain speed profile and acceleration/deceleration schedule, if the feasible solution is practical enough.

However, because the model used to identify "guaranteed conflict" is based on the best-case scenario, it is possible that the solution (in terms of speed profile and acceleration/deceleration schedule) created by the linear program – introduced momentarily – is so aggressive that it is in fact not desirable to follow. Therefore, a dedicated strategy for "potential conflict situation" is still desirable to generate practically executable speed advisories in parallel, even if the result for the "guaranteed conflict" identification is feasible. This dedicated strategy is out of the scope of this paper. The majority of current literature is about this topic. We will also address this problem in the future.

D. *The decision making process*

In this subsection, we show in general how the ATC instruction is made in our process, as well as what role guaranteed conflict plays in the entire decision-making process.

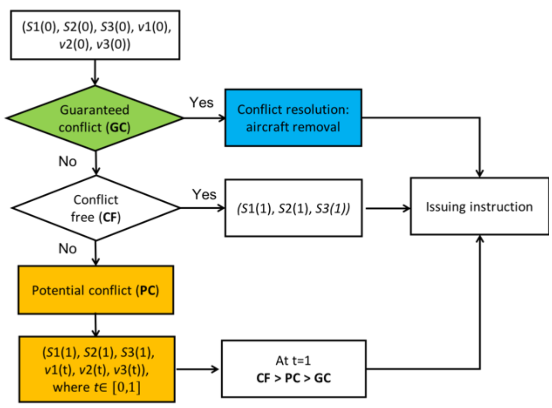

Figure 5 The decision-making process for TBFM instructions based on the three classes of situation

In the process, ATC gives instructions periodically at each decision-making point in time. Note that the determination of the time interval between two decision points needs further investigation at this point, but it has to be shorter than the look-ahead time introduced momentarily in the next section.

Fig. 5 is at decision-making point 0. First, with the information of ($S1(0)$, $S2(0)$, $S3(0)$, $v1(0)$, $v2(0)$, $v3(0)$), ATC needs to evaluate whether the current condition is in the "guaranteed conflict situation" (the green diamond in the figure). If yes, then he/she shall decide with the assistance of automation which airplane/airplanes need to be removed from the traffic flow (the blue block in the figure), so that the least amount of aircraft are vectored. The green diamond and blue block are the focus of this paper and will be discussed in detail in the following sections.

Second, if the current condition is not in the "guaranteed conflict situation", ATC must evaluate whether conflict-free trajectories can be achieved by only issuing the 4DT instructions, which is addressed in our previous work [8][36]. If not, it is in the "potential conflict situation" (the yellow block), where speed advisories as well as the 4DT instructions are necessary to avoid conflict in the coming time duration. The instruction for the "potential conflict situation" is in general constructed in the form of ($S1(1)$, $S2(1)$, $S3(1)$, $v1(t)$, $v2(t)$, $v3(t)$), $t\in[0,1]$. Although out of the scope of this paper, a dedicated strategy should be created to generate practical speed advisories for this situation, for the reason stated in Subsection C.

Third, with the information of ($S1(1)$, $S2(1)$, $S3(1)$, $v1(1)$, $v2(1)$, $v3(1)$), it is possible to evaluate the classes of situation for the time duration **after** next decision point. The instruction ($S1(1)$, $S2(1)$, $S3(1)$, $v1(t)$, $v2(t)$, $v3(t)$) is preferred to guide the traffic flow into "conflict free situation (CF)" or at least "potential conflict situation (PC)", rather than the "guaranteed conflict situation (GC)" for the next decision point. The algorithms to classify different situations can be used in the step and the most favorable possible instruction will be issued after the evaluation.

Lastly, the entire process is repeated at the next decision point.

From this point, Section IV continues with the infeasible case which indicates "guaranteed conflict", and we will further develop a formal Binary Integer Programming (BIP) model in Section V for the minimum number of aircraft to deviate from the traffic in order to resolve the conflict.

IV. GUARANTEED CONFLICT

A. Problem definition

"Guaranteed conflict" means a conflict in an air traffic flow cannot be resolved through speed adjustment alone. One of the challenges of modeling aircraft trajectory in continuous space is that it can fly at any speed continuously within its capability during any length of time. However, it is possible to get a relatively good estimation by discretization. Specifically, we discretize the time horizon of interest into smaller time intervals and assume within each time interval the airplane can only accelerate or decelerate at a constant rate. With appropriate time intervals, this assumption results in a relatively tight, yet conservative, over-approximation. The problem is defined as follows.

N aircraft fly in a flow, labelled as $1, \dots, N$orderly, as well as **M+1** timepoints $\mathrm{t}_0, \mathrm{t}_1, \dots, \mathrm{t}_M$ of fixed length **T**. For each airplane i, $V_i(t_o)$ and $S_i(t_0)$ are the initial velocity and initial location and $D_i(t_k)$ is a constant acceleration/deceleration decision throughout time interval $[t_k, t_{k+1}]$. Given a set of decisions $D_i(t_0), \dots, D_i(t_M)$, the velocity at time point t_k is

$$V_i(t_k) = V_i(t_0) + T\ \textstyle\sum_{j=0}^{k-1} D_i(t_j).$$

And for arbitrary $t_k < t < t_{k+1}$, the velocity can be derived as

$$V_i(t) = V_i(t_k) + (t - t_k) D_i(t_k).$$

Derived from the velocity, we could find the formula for location at preset timepoints is

$$S_i(t_k) = S_i(t_0) + \mathrm{kTV_i(t_0)} + T^2 \textstyle\sum_{j=0}^{k-1} (k - j - \frac{1}{2}) D_i(t_j).$$

Similarly, for arbitrary $t_k < t < t_{k+1}$, the location is

$$S_i(t) = S_i(t_k) + (t - t_k) V_i(t_k) + \frac{1}{2}(t - t_k)^2 D_i(t_k).$$

For each airplane i, choose $D_i(t_0), \dots, D_i(t_M)$ so that $S_i(t) - S_{i-1}(t) \geq 0$ is always true for the entire time horizon of interest. If no such $D_i(t_0), \dots, D_i(t_M)$ exists, then a "guaranteed conflict" is identified.

Two parameters that are worth mentioning are T and t_M. T is to discretize the continuous spectrum of time for approximation. The smaller T is, the more accurate that the approximation model will be, but is more resource demanding as well. Furthermore, smaller T also means that the pilots have to adjust the velocity more frequently, which can be unrealistic or undesirable. The determination of T requires further investigation at this time. But once it is decided, the proposed algorithm can be used readily. $\mathrm{t}_M * T$ is the look-ahead time for the trajectory prediction. Furthermore, to be applied to the decision-making process of Fig. 5, the look-ahead time has to be longer than the time interval between ATC's two adjacent decision-making points. Even if the look-ahead time is the same length as the decision-making interval, ATC may successfully deconflict the situation before the next decision-making point, but only to find unavoidable immediate conflicts right at the next decision-making point.

B. Identifying "guranteed conflict"

In this subsection, the identifying "guaranteed conflict" problem is translated to the infeasibility problem of an optimization problem. If the optimization problem is infeasible, then it means guaranteed conflict exists between at least a pair of aircraft before t_M, independent of any possible speed adjustment by any/all aircraft. If feasible, the solution could be used as the speed advisories in "potential conflict zone". The optimization problem is constructed as follows.

For all $i \in \{1, \ldots N\}$, all $k \in \{1, \ldots M\}$ and all t,

$$\min_{D(t)} f\big(D(t)\big) \tag{1}$$

$$\begin{aligned}
&\text{subject to} && S_i(t) - S_{i-1}(t) \geq 0 \\
&\text{max velocity} && V_i(t) \leq \overline{V_i} \\
&\text{min velocity} && V_i(t) \geq \underline{V_i} \\
&\text{max acceleration/deceleration} && D_i(t) \leq \underline{D_i} \\
&\text{min acceleration/deceleration} && D_i(t) \geq \underline{D_i} \\
& && |D_i(t_k) - D_{i-1}(t_k)| \leq \widetilde{D_\iota} \\
& && D(t) = \{D_i(t_k)\} \text{ for all } i, k.
\end{aligned}$$

Since we are only interested in the feasibility of the optimization problem, the objective function does not play an important role here since it has no impact on feasibility. As a result, it could take multiple meaningful and informational formulations. An ideal objective function would factor in efficiency and safety in a balanced manner. For example, one option is,

$$f\big(D(t)\big) = \alpha \textstyle\sum_{\text{all } i,k} D_i^2(t_k) + \beta \textstyle\sum_{\text{all } i,k} |S_i(t_k) - S_{i-1}(t_k)|$$

where the first term relates to the intensity of acceleration/deceleration and could serve as a measure for fuel consumption; and the second term relates to the distance between each pair of neighboring aircraft and could serve as a measure for airspace usage. The positive penalty parameters α and β are tuned to find a balance between these two factors.

Note that the change of acceleration/deceleration rate between adjacent time interval is bounded within certain range, i.e. $|D_i(t_k) - D_{i-1}(t_k)| \leq \widetilde{D_\iota}$. It is to prevent sudden and violent acceleration/deceleration during short period of time, which is a realistic assumption in real operation for both the passenger experience and the constraints due to continuous flight dynamics.

C. *Computational efficiency*

Observe that, given initial locations, velocities and time interval T, all constraints in (1) are linear in decision variables $D_i(t_j)$. This convenient fact enables us to detect its feasibility in polynomial time, by either formulating its dual problem or utilizing certain Phase-I method. [34]

One advantage of having a polynomial runtime is its flexibility with the size of time interval and time horizon. Since the number of decision variables increases linearly as we extend the time horizon with fixed T or decrease T with a fixed horizon, the runtime increases with such operation in a polynomial fashion. This property is desirable in practice and can be used to build an adaptive scheme to control the time interval optimally in crowded airspaces.

However, it is significant that, even though the feasible region has a simple and well-studied geometry, the objective function decides computational complexity as well. For linear or convex objective functions (e.g. our example in the last section,) certain interior point methods have been proven to have a polynomial runtime. The Simplex Method performs generally well in practice for linear programs despite an exponential runtime. On the other hand, (1) with a non-convex objective function will most likely have an exponential runtime and cannot be solved in an efficient manner.

V. Conflict Resolution

Speed adjustment cannot resolve a "guaranteed conflict", thus removal of one or more airplanes from the traffic flow has to be applied. However, sometimes it is not easy to decide which airplane/airplanes is causing the problem in the traffic flow. In this section, we introduce a model that efficiently decides which aircraft to remove from the current flow at the decision point, and further makes the remaining aircraft conflict-free.

A. *Airplane removal scheme*

Similar to our discussion in Section III, detecting the existence of conflict manually is cumbersome in the first place; deciding which aircraft to remove and make the rest conflict-free only adds another layer of nonintuitive reasoning and more complexity. Therefore, we extend (1) and use a Binary Integer programming (BIP) formulation to find the minimal effort resolution of existing conflict. The underlying idea is to find the conflict resolution that incurs minimal effort by enumerating all possible scenarios of how many and which aircraft to remove from the flow. It can be systematically formulated and effectively solved as the following BIP:

$$\min_{I_i} \sum_{i=1}^{n} I_i \tag{2}$$

$$\begin{aligned}
&\text{subject to } S_i(t) - S_{\max_j j<i, j\in K}(t) \geq B \text{ if } i \in K \\
&\text{max velocity} \quad V_i(t) \leq \overline{V_i} \\
&\text{min velocity} \quad V_i(t) \geq \underline{V_i} \\
&\text{min throttle/brake} \quad D_i(t) \leq \overline{D_i} \\
&\text{min throttle/brake} \quad D_i(t) \geq \underline{D_i} \\
&|D_i(t_k) - D_{i-1}(t_k)| \leq \widetilde{D_\iota} \\
&I_i = 0 \text{ if } i \in K \\
&I_i = 1 \text{ if } i \notin K \\
&\text{for all } i \in \{1, \ldots N\}, \text{ all } k \in \{1, \ldots M\} \text{ and all } t, \\
&\text{where } S, V_{\max_j j<i, j\in K}(t) \text{ is small if } j \text{ is not defined}
\end{aligned}$$

Like (1), the same set of constraints still applies to all airplanes; constraints related to safety distance are removed for those who are commanded to leave the flow at the beginning. Additional constraints can be added at the same time; e.g. $I_i = 0$ for some i mandates the i^{th} aircraft to stay on the trajectory. The objective function here can take alternative forms as well but it is beyond the scope of this paper.

B. Solving (2)

First note that (2) is always feasible because keeping none or one aircraft trivially solves the conflict. However, unlike (1) which can be solved efficiently, obtaining the exact optimal value for (2) as a Binary Integer Programming problem can almost always take an exponential number of iterations. In practice, a BIP of moderate size (10 planes and 100 periods, for example) takes less than a minute on a home-use laptop. For larger problems, approximation algorithms are often a compromise between runtime and optimality; for example, an exact BIP algorithm on (2) will use 1 minute and optimally removes 2 aircraft from the trajectory, while an approximation algorithm uses only 10 seconds but sub-optimally remove 3 aircraft instead. These approximation algorithms produce a resolution in a timely manner at a cost of suboptimality. A survey of similar optimization problems and approximation algorithms can be found in [35].

VI. USE-CASE STUDY

In this section, we illustrate with a demonstrative example how the decision-making process of TBFM works in general and the role that the proposed algorithms for “guaranteed conflict” and “airplane removal” play in the process. Note that the use case studied in this section is only for the purposes of illustration, while the decision-making process in Section III and the proposed algorithms in Section IV and Section V can apply in general to all the time-based metering and sequencing problems for TBFM.

A. Use-case settings

Seven airplanes and two decision-making points are involved in this use case, as shown in Fig. 6 and Fig. 7. We assume the speed is bounded within [0.7 Mach, 0.86 Mach] and the acceleration/deceleration bounded within [-0.05g, 0.15g]. The time duration between decision-making points is set to be 5 minutes, look-ahead time is set to 10 minutes and the discretized time interval to be 1 minute. The min/max change rate of acceleration/deceleration between two adjacent time intervals is set to be [-0.1g, 0.1g]. Note that the algorithms are able to handle different speed bounds and acceleration/deceleration bounds for different airplanes, and the homogeneity of airplanes in the example is only for demonstration. Furthermore, the uncertainty is not rigorously explored and evaluated in this paper because this paper aims to explain the concept of the TBFM decision-making process and the algorithms for “guaranteed conflict”. The effect of uncertainty will be more thoroughly investigated in future work.

B. Results

1) First decision-making point (t=0)

As shown in Fig. 6, six airplanes (i.e. AC1, …, AC6) fly the left route to reach the fixpoint, marked as S=0, to land at the runway. Another airplane, currently on holding pattern, is scheduled to reach the fixpoint through the right route after AC6 passes the fixpoint. Hence, AC7 is not in conflict with traffic flow at this point. The state of the six aircraft at t=0 is shown in Table 1.

Table 1 The states of the traffic flow at t=0

	AC1	AC2	AC3	AC4	AC5	AC6
S(0)/km	-157	-161	-169	-173	-177	-180
v(0)/Mach	0.76	0.82	0.78	0.74	0.72	0.80

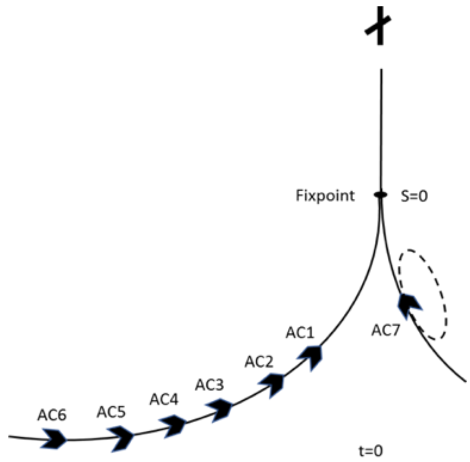

Figure 6 Aircraft state at the first decision point (t=0)

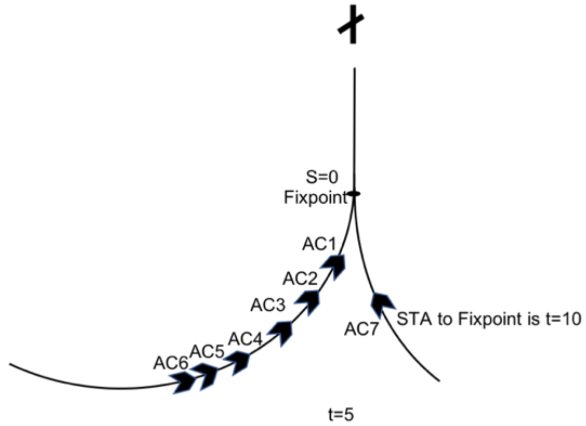

Figure 7 Aircraft state at the second decision point (t=5)

Obviously, if the aircraft fly with the current speed, there will be multiple conflicts at certain points in the future.

First, according to the decision-making process explained in Fig. 5, the “guaranteed conflict” algorithm, illustrated in Section IV, is applied to identify guaranteed conflict in the traffic flow. Again, the key point in the algorithm is to test the feasibility subject to the constraints, which is not affected by the specific form of the objective function. In this example, the objective function (3) is defined particularly from the perspective of the passenger experience, to minimize the change of speed for each of the airplane. $D_i(t_k)$ is the acceleration/deceleration rate of ACi at time interval t_k.

$$\min \sum\nolimits_{\text{all } i,k} D_i^2(t_k) \quad (3)$$

$$\begin{array}{rl} \text{subject to} & S_i(t) - S_{i-1}(t) \geq 1 \\ \text{max velocity} & V_i(t) \leq 0.86 \\ \text{min velocity} & V_i(t) \geq 0.7 \\ \text{max acceleration/deceleration} & D_i(t) \leq 0.15g \\ \text{min acceleration/deceleration} & D_i(t) \geq -0.05g \end{array}$$

$$|D_i(t_k) - D_{i-1}(t_k)| \leq 0.1g$$

$$D(t) = \{D_i(t_k)\} \text{ for all } i, k.$$

Second, a feasible solution for the optimization problem above is found, meaning speed adjustment is sufficient to avoid conflict for the aircraft flow. The solution, in form of the speed advisories for all the six airplanes, is shown in Fig. 8. Again, a dedicated strategy for this potential conflict situation is advised, even though it is out of the scope of this paper. For purposes of illustration, we simply assume the airplanes follow the speed profiles generated from (3), there will not be any conflict in the next 10 minutes. The distances among each two adjacent airplanes, as shown in Fig. 9, are always greater than the defined minimal distance, 1 km.

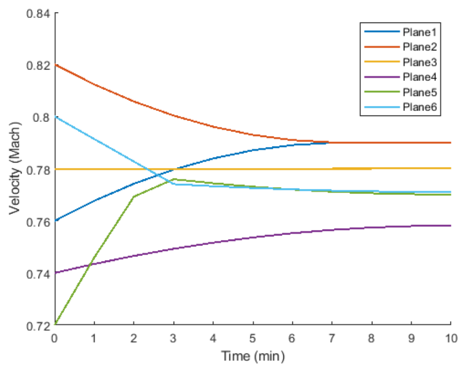

Figure 8: Speed Advisories made at t=0 for the 10-minute look-ahead time

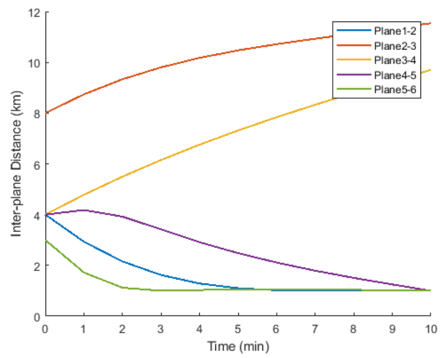

Figure 9: Predicted interplane distances of the 10-minute look-ahead time if the speed advisories generated from (3) at t=0 are followed

2) The second decision-making point (t=5 min)

The position and speed of the traffic flow at the second decision-making point (t=5 min) can be easily calculated by using the speed advisories. Table 2 shows the aircraft states.

Table 2 The aircraft states at t=5

	AC1	AC2	AC3	AC4	AC5	AC6
S(5)/km	-77.8	-79.9	-89.4	-96.7	-97.2	-100.2
v(5)/Mach	0.787	0.793	0.780	0.751	0.773	0.773

Say there is some emergency happening in AC7 at the second decision-making point, hence it is cleared to cross the fixpoint before all the six aircraft in the flow. Its assigned STA to the fixpoint is at t=10, as shown in Fig. 7. Because of this change, there is a question about whether the six aircraft flow can be successfully delayed accordingly only using speed adjustment.

First, as prescribed in the decision-making process, the "guaranteed conflict" algorithm is applied. A new objective function (4) is adopted to find the most delayed position that AC1 can achieve while still maintaining safe distance among all the 6 aircraft in the flow. Again, the selection of the objective function (4) is irrelevant in terms of identifying the guaranteed conflict, because it does not affect the feasibility of the optimization problem.

As a result, the predicted position of all the aircraft at t=10 is shown in Table 3. Obviously, AC1 and AC2 are both across the fixpoint before AC7's STA. Hence, there is guaranteed conflict in the flow and aircraft has/have to be removed to resolve the conflict.

$$\min S_1(10) \tag{4}$$

$$\begin{array}{rl} \text{subject to} & S_i(t) - S_{i-1}(t) \geq 1 \\ \text{max velocity} & V_i(t) \leq 0.86 \\ \text{min velocity} & V_i(t) \geq 0.7 \\ \text{max acceleration/deceleration} & D_i(t) \leq 0.15g \\ \text{min acceleration/deceleration} & D_i(t) \geq -0.05g \end{array}$$

$$|D_i(t_k) - D_{i-1}(t_k)| \leq 0.1g$$

$$D(t) = \{D_i(t_k)\} \text{ for all } i, k.$$

Table 3 The predicted aircraft positions at t=10

	AC1	AC2	AC3	AC4	AC5	AC6
S(10)/km	1.38	0.15	-9.12	-16.05	-18.67	-21.59

Secondly, we resolve this conflict by removing the aircraft by using the "airplane removal scheme" illustrated in Section V. The objective function (5) is to minimize the number of aircraft removed and a new constraint $S_{\min_i I_i=0}(t=10) \leq 0$ is added to the optimization problem, to make sure the first plane (after removal) to cross the fixpoint after t=10. The results show that only AC2 needs to be removed to resolve the conflict.

$$\min_{I_i} \sum_{i=1}^{n} I_i \tag{5}$$

$$\text{subject to } S_i(t) - S_{\max_j j<i, j\in K}(t) \geq 1 \text{ if } i \in K$$

$$\begin{array}{rl} \text{max velocity} & V_i(t) \leq 0.86 \\ \text{min velocity} & V_i(t) \geq 0.7 \end{array}$$

$$\text{max acceleration/deceleration } D_i(t) \leq 0.15g$$
$$\text{min acceleration/deceleration } D_i(t) \geq -0.05g$$
$$|D_i(t_k) - D_{i-1}(t_k)| \leq 0.1g$$
$$S_{\min\limits_{i} I_i=0}(t = 10) \leq 0$$
$$I_i = 0 \text{ if } i \in K$$
$$I_i = 1 \text{ if } i \notin K$$
$$\text{for all } i \in \{1, \dots N\}, \text{all } k \in \{1, \dots M\} \text{ and all } t,$$
$$\text{where } S, V_{\max\limits_{j} j<i, j\in K}(t) \text{ is small if } j \text{ is not defined}$$

Finally, after AC2 is removed, the rest of the aircraft flow are fed back into objective function (4) again to find the most delayed position for AC1. As a result, a feasible solution is found. The speed advisories for the remaining 5 aircraft are shown in Fig. 10 and it can ensure all aircraft crossing fixpoint after t=10. We could observe that AC1 decelerated at full capacity to avoid reaching the fixpoint before t=10 and succeeded. As shown in Fig. 11, all the remaining 5 aircraft can cross the fixpoint after AC7's STA (t=10). The distances among each two adjacent airplanes, as shown in Fig. 12, are always greater than the defined minimal distance, 1 km. As a result, we can resolve the conflict and allow AC7 to cross at an inevitable cost of removing AC2 from the flow.

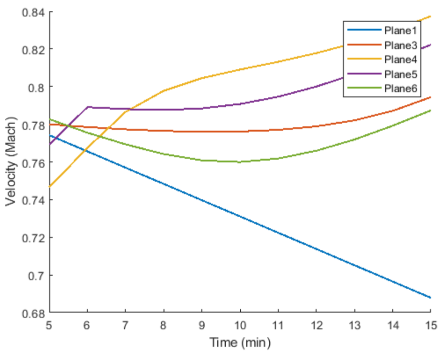

Figure 10: Speed advisories after removing AC2 made at t=5 for the 10-minute look-ahead time

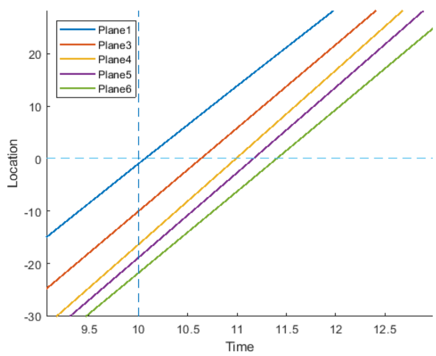

Figure 11: Predicted fixpoint crossing time of the aircraft flow after removing AC2

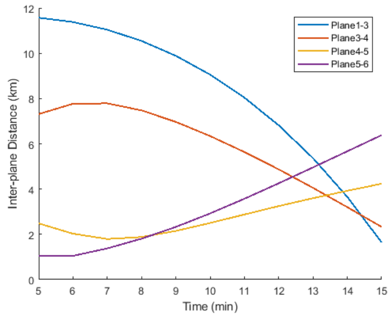

Figure 12: Predicted interplane distances of the 10-minute look-ahead time if the speed advisories generated from (4) at t=5 are followed

VII. CONCLUSION

This paper aims to understand how to systematically exploit and utilize the time-based instructions for TBFM. First, a scheme is developed to classify a flow of aircraft into three types of situation: "conflict free situation" where the 4DT instruction (without speed advisories) is enough to keep a safe distance among aircraft, "potential conflict situation" where speed advisories are necessary to avoid potential conflict, and "guaranteed conflict situation" where aircraft has/have to be removed from the flow to resolve the conflict. A decision-making process about how to give TBFM instruction based on these three classes is then provided and explained using a three-aircraft scenario. Second, the "guaranteed conflict situation" is studied in greater detail. An algorithm to identify "guaranteed conflict" is proposed as a feasibility problem of a linear program. A scheme formulated as a Binary Integer Program to resolve the guaranteed conflict by removing a subset of the aircraft in the flow is then developed. Finally, a use case consisting of seven aircraft and two decision-making points is studied to show how the algorithms of identifying "guaranteed conflict" and resolving the conflict by "airplane removal" assist in the general decision-making process. The results show that the "guaranteed conflict situation" can be efficiently identified and effectively resolved by the proposed algorithms.

Compared with current literature, our approach is better not because of better speed advisories, but because instructions, i.e. 4DT waypoints, speed advisories and path stretching, are determined based on the specific type of situation that the aircraft flow resides in. Following the decision-making process supported by the algorithms proposed in this paper, ATC's workload can be reduced, pilots are given more autonomy over speed control, and costly path stretching can be minimized to improve the performance and safety of the airspace operation.

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