Linear Holding for Airspace Flow Programs: A Case Study on Delay Absorption and Recovery

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***Abstract*—This paper presents a method to introduce linear holding to flights affected by Airspace Flow Program (AFP) initiatives. Trajectories are optimized at their planning stage in such a way that the program performance is improved in terms of delay absorption before the congested area, and delay recovery at the destination airport. This recovery process is studied by comparing the case where the same fuel consumption is fixed as the nominal flight, with several cases where some extra fuel allowances are considered at the flight planning stage. The effects for AFP delayed flights are thoroughly discussed in a case study followed by a sensitivity analysis on possible influential factors. Results suggest that using the proposed method could partially recover part of the AFP delay, even with no extra fuel allowances (e.g., reducing 3.3 min of ground delay and 1.7 min of arrival delay for a typical short-haul flight). When extra fuel is allowed, however, the maximum delay recovery increases up to 10 min for the studied case, which also proves to be more cost-efficient than current operations, when flight speed is increased after experiencing all delay on ground.**

***Index Terms*—Air traffic management, airspace flow program (AFP), linear holding, trajectory based operations.**

I. INTRODUCTION

Adverse weather is a major cause of congestion in the United States National Airspace System (NAS). In order to ensure that the traffic demand does not exceed the capacity under adverse weather conditions, the Federal Aviation Administration (FAA) typically issues air traffic flow management (ATFM) measures; such as miles-in-trail restrictions, aiming to keep a certain (reduced) demand level towards congested areas; or re-routings, which directly avoid them. Nevertheless, if the traffic volume reaches a point where these initiatives are not sufficient, the ATFM personnel may decide to issue more restrictive actions such as Ground Holdings or Ground Stops, in which certain flights are delayed from their scheduled departure times to mitigate the anticipated congestion at the concerned airspace [1]. In this context, the FAA started to implement the airspace flow program (AFP) in June 2006, in which only those flights scheduled to traverse this concerned airspace are subject to pre-departure delays at their origin airport [2]. Among these ATFM initiatives, ground holding is the most common action to absorb the distributed delays and it is also widely used when congestion affects the destination airport, with the FAA ground delay programs (GDPs). Similar initiatives exist in Europe, implemented by the Eurocontrol's Central Flow Management Unit (CFMU).

ATFM regulations, however, are often cancelled before the initially planned ending time, since ATFM decisions are typically conservative when taking into account weather and trajectory prediction uncertainties, for instance[3], [4], [5]. These early cancellations imply that some delayed flights would still be at their departure airport even if the capacity is no longer constrained at the concerned airspace. Typically, the already suffered ground delay cannot be recovered, or can be partially recovered by increasing flight speed leading to extra fuel costs.

To overcome this issue, a cruise speed reduction strategy was proposed by Delgado and Prats [6], where aircraft were allowed to cruise at the lowest possible operational speed in such a way the fuel consumption remained exactly the same as initially planned. In this situation, if the ATFM delays are cancelled ahead of schedule, aircraft already airborne (and flying slower) could speed up to the initially planned speed and recover part of the delay, but without incurring with extra fuel consumption. This linear holding concept was further explored in [7], where the impact of wind conditions was assessed; and in [8], [9], where its potential applicability to GDPs was discussed. More recently, an novel approach using advanced aircraft trajectory optimization techniques was adopted to extend this linear holding strategy to the whole flight (i.e. also accounting for climbs and descents)[10], [11].

As the core method to perform linear holding, speed reduction is one of the speed control strategies that have proven effective for several Air Traffic Management (ATM) scenarios. For instance, [12], [13] presented a speed control approach for transferring delay away from the terminal to the en route phase, from which significant fuel saving on a per flight basis was also yielded. In [14], a pre-tactical speed control was applied to prevent aircraft from performing holding patterns when arriving at a congested airspace, improving both flight efficiency and controller workload level. More widespread applications for conflict management have been under research for decades [15], where the speed control strategy was used, in addition to other effective manners such as path stretching or flight level adjustment for instance [16].

Motivated from the benefits of linear holding when absorbing delays airborne, this paper addresses its potential applicability to AFPs. In previous works mentioned above delay was only recovered in case the ATFM regulation was lifted before scheduled. Hence, the delay recovery was performed at the tactical phase of the flight (once it is known that the regulation is lifted). This generates some concerns regarding network effects and unforeseen conflicts or sector congestion downstream. In this paper, regulated aircraft can recover some arrival delay at the destination airport even if the AFP is kept as planned since delay absorption (before reaching the concerned airspace) and recovery (after overflying the

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concerned airspace) are both planned in the pre-tactical phase of the flight (i.e. at the flight planning stage). This is important since the speed adjustments can be integrated into the (4-dimensional) trajectory negotiation process with the ATFM authority in line with the future trajectory based operations (TBO) paradigm. In this way, potential conflicts and/or sector overloads could be detected in advance and mitigated before the agreed trajectories are tactically executed.

II. MOTIVATION

This section gives a brief comparison between different delay management initiatives and highlights those features that could be used to improve the performance of current AFPs initiatives.

A. *Delay management strategies*

Ground holding is performed at the departure airport, prior to take-off, while airborne holding could be theoretically realized anywhere along the flight. In practice, however, airborne holding is typically performed in specific designated airspace either with path stretching (radar vectoring) or using holding patterns above certain navigation fixes. Linear holding (LH) differs from these typical airborne delay strategies because the aircraft keeps always flying the original route (but at a reduced speed).

Ground holding could provide virtually unlimited holding time and make no difference on the fuel consumption initially planned. Typical airborne holding leads to extra fuel consumption due to the extended flight distance, which also leads to a fairly limited holding time (given that safety related issues may arise from a reduction of the on-board reserve fuel). Finally, the fuel consumption in LH could remain the same as the nominal flight, at the same time the flight benefits from the speed reduction strategy, or turn even lower if the maximum LH time is not required[17].

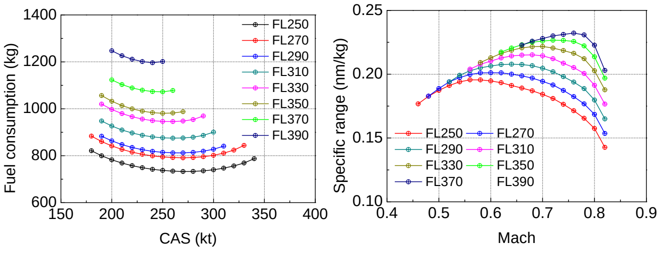
To illustrate the relationship between fuel consumption and LH time, Fig. 1 shows for an Airbus A320 the aggregate fuel consumption in climb and descent phases versus the Calibrated Airspeed (CAS), and the specific range versus cruise Mach. Data was extracted from the Airbus Performance Engineers' Program (PEP) software suite using a typical aircraft mass. According to Fig. 1, given a flight phase, and for each flight level, there exists a speed such that the fuel consumption is minimized. Yet, since aircraft operators also consider time-related costs when planning their flights (i.e. direct operating costs -DOC- including both fuel and time related costs) [18], higher speeds are preferred despite consuming some more fuel. These airline preferences regarding the DOC are typically reflected by the Cost Index (CI), an input parameter of current on-board flight management systems (FMS) that represents the ratio between time-based cost and the cost of fuel [19].

Thus, if the aircraft operator chooses to fly with a nominal speed faster than the minimum fuel speed (i.e. at a Cost Index greater than zero), there will exist a range of slower speeds with a fuel consumption equal or lower than the fuel consumption attained when flying at the nominal speed (see 1). Consequently, this would allow to perform some linear holding at no extra fuel cost (or with some fuel savings). This is the key concept that motivates the applicability of trajectory optimization to enhance AFPs initiatives presented in this paper.

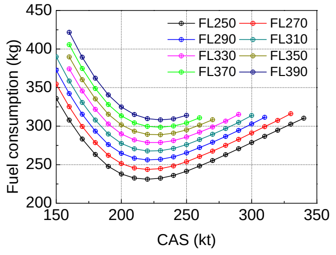
B. *Airspace flow programs (AFP)*

As stated in [1], AFPs are one of the ATFM initiatives that marked a significant milestone in en-route traffic management in the United States NAS. It identifies constraints in the en route system, develops a real-time list of flights that are filed into the Flow Constrained Area (FCA), and distributes Expected Departure Clearance Times (EDCTs) to meter the traffic demand through that area. An AFP might be used, for example, to reduce the rate of flights through an ATC center when that center has reduced en-route capacity due to severe weather, replacing miles-in-trail restrictions with a required re-routing, managing airport arrival fix demand or controlling multiple airports within a terminal area. Compared with GDP, an AFP does not unnecessarily delay flights to an airport that do not pass through the en route region of reduced capacity [20], [2].

Currently, once a flight is captured in an AFP, an EDCT will be assigned to that flight based on certain slot allocation algorithm [21], which aims at entirely absorbing all the assigned delay by means of ground holding at the origin airport. Nonetheless, with the paradigm shift from an airspace-based ATM to trajectory based operations, delays could eventually be assigned directly in form of Controlled Time of Arrival (CTA) or Over (CTO) at the FCA [22], instead of being wholly imposed on the pre-departure time by means of an EDCT. In such a way, as shown in Fig. 2, a flight affected by an AFP delay could reduce its ground holding (i.e., take off earlier than the EDCT), and then perform the necessary LH to experience



(a) Climb phase (b) Cruise phase



(c) Descent phase

Fig. 1: Relationship between fuel consumption and flight speed in different flight phases. Note: cruise specific range (SR) is the distance an aircraft travels per unit of fuel consumed.

the rest of the delay airborne in order to meet the assigned CTA (or CTO) at the particular FCA.

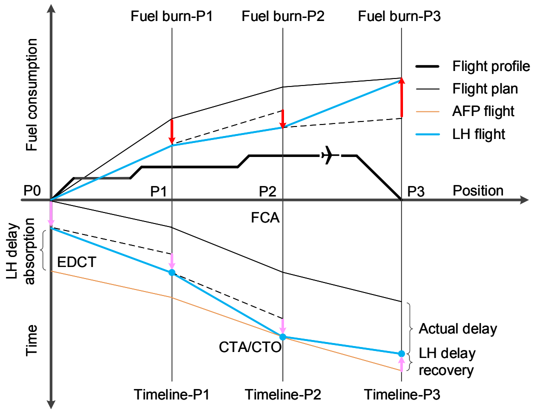


Fig. 2: Schematic of linear holding applicability in an AFP.

As discussed in Sec. II-A, this could be done at the same time some fuel is saved. After passing the FCA, it would be possible to take advantage of the saved fuel to accelerate along the rest of the trajectory to recover part of the delay at the destination airport. Different from a GDP, in which CTA is assigned at the arrival airport, the arrival time at the destination airport for a flight captured in an AFP is not enforced, making this delay recovery process feasible and legitimate.

Furthermore, convective weather may occur at multiple airspaces simultaneously, leading to more than one constrained areas identified (by different AFP) to meter the traffic demand through each corresponding area. Additionally, a flight could be eventually captured in both a GDP and an AFP at the same time, where the former has constraints closer to the airport and the latter specifies an FCA somewhere in the route. Under current operations, assigned delays will be transferred to the departure airport. In the United States a GDP has higher priority than an AFP, such that the EDCT arising from a GDP will override that one coming from an AFP.

If in the future the EDCT enforcement is replaced by a CTA (or CTO) enforcement, this hierarchy principle may apply as well (but is out of the scope of this paper). Since AFPs are aimed to identify constraints in the en-route domain of the NAS, this paper will only take account the issued en route FCA as the constrained airspace.

Finally, it is worth noting that AFPs are issued based on convective weather predictions which might be not correct as always and could be subject to timely updates, and in turn, would impact the AFP delayed flights. As such, the robustness of the method proposed in this paper needs to be clarified given that the increased airborne traffic density (as ground holding is reduced via LH) will have more aircraft in the air potentially affected by any incorrect weather predictions.

Let us consider two scenarios for unexpected weather situations: turning better or worse than initially forecast. For the better case, obviously, with increased airspace capacities available there is no need to further regulate the controlled flights including those performing LH airborne. In some circumstances, ATC instructions such as short-cuts could be applied to those flights to take advantage of the advanced unoccupied slots, while the grounded aircraft (not performing LH) might be still holding in the departure airport. For the worse case, on the other hand, although the aircraft performing LH took off earlier than the nominal EDCT, the CTA/CTO at the border of FCA will be still the same as with ground holding, due to the airspeed reduction (see Fig. 2). In other words, if the areas of (unforeseen) reduced capacity, close to or at the downstream of the FCA (as in most of the cases), require further movements such as holding patterns and diversions (under conventional operations), the same will happen to the aircraft performing LH as to those with only ground holding.

III. TRAJECTORY OPTIMIZATION FOR AFPS

Incorporating linear holding in an AFP is modelled in this paper as a two-stage trajectory optimization process. During the first stage, the operator computes the optimal trajectory in terms of DOC for the nominal flight plan (denoted by *nom* flight in this paper). Then, assume some delay is assigned to the *nom* flight due to an AFP (denoted by *AFP* flight). During the second stage, a new optimal trajectory is generated such that the delay recovery is maximized (denoted by *LH* flight). In both stages the optimization of the aircraft trajectory is formulated as an optimal control problem and solved by means of direct collocation numerical methods. This section briefly summarizes how this problem has been customized for the application presented in this paper. For more details on this methodology, the reader may refer to [23] and the references therein.

A. *First stage: nominal flight*

The optimization of aircraft trajectory requires the definition of a mathematical model representing aircraft dynamics and flight performance, along with a model for certain atmospheric parameters. This paper considers a point-mass model, an enhanced performance model using manufacturer certified data and the International Standard Atmosphere (ISA) model.

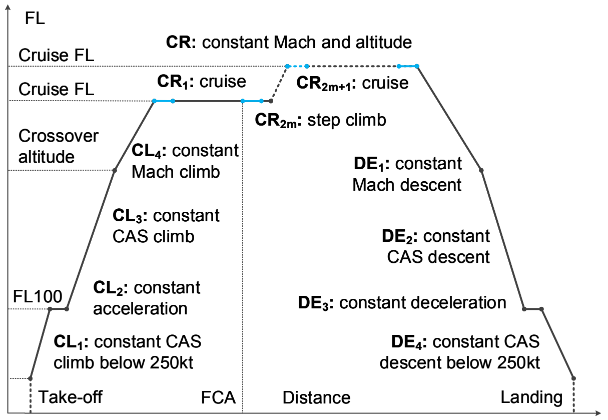


Fig. 3: Vertical profile model in the trajectory optimization tool

A generic vertical trajectory can be partitioned into several segments $i \in \{1, \cdots, N\}$, where different constraints may apply. For each segment defined over a time window $[t_0^i, t_f^i]$ the state vector $\boldsymbol{x}^{(i)} = [v\ s\ h\ m]$ is composed, respectively, of the true airspeed (TAS), along path distance, altitude and mass of the aircraft; the control vector $\boldsymbol{u}^{(i)} = [T\ \gamma]$ includes the aircraft thrust and flight path angle. As explained in Sec. II-A, the objective of the trajectory optimization for the *nom* flight is to minimize the DOC, modelled as a compound cost function J over the whole time window $[t_0^{(1)}, t_f^{(N)}]$ as follows:

$$J = \int_{t_0^{(1)}}^{t_f^{(N)}} (FF(t) + CI)\mathrm{d}t \tag{1}$$

where $FF(t)$ is the fuel flow and CI is the Cost Index.

The optimization constraints come from different aspects, while the first important set are the dynamics of the aircraft itself (the point-mass model). Then, some algebraic event constraints fixing the initial $\boldsymbol{x}(t_0^{(1)})$ and final $\boldsymbol{x}(t_f^{(N)})$ state vector must be satisfied. In this paper, the initial and final points are taken, respectively, at the moment the slats are retracted (after taking off) and extended (before landing). The remaining parts of take-off and approaching are not optimized due to the heavy constraints from operational procedures. Some bounds (known as box constraints) on the control variables are specified as follows:

$$\gamma_{min} \leq \gamma \leq \gamma_{max} \tag{2}$$

where γ_{min} and γ_{max} are aircraft dependent scalars. However, the maximum T_{max} and minimum T_{min} thrust are not scalars but functions of the state variables. Therefore, this control is bounded by additional path constraints:

$$T_{min} \leq T \leq T_{max} \tag{3}$$

Similarly, box constraints for the state variables are not required, since they are bounded by generic path constraints on auxiliary variables, such as the Mach number (M) and the Calibrated Airspeed (CAS or V_{CAS}):

$$M_{GD} \leq M \leq MMO;\ V_{GD} \leq V_{CAS} \leq VMO \tag{4}$$

where MMO and VMO are the maximum operational Mach and CAS, respectively, and M_{GD} and V_{GD} are green dot speeds [24], which approximate the best lift to drag ratio speed in clean configuration.

In order to ensure the continuity of the trajectory composed by different segments, a set of link constraints must be defined at the final point and initial point of each segment, on all the state variables:

$$\boldsymbol{x}^{(i)}(t_f^{(i)}) = \boldsymbol{x}^{(i+1)}(t_0^{(i+1)});\ i = 1, ..., N-1 \tag{5}$$

Next, additional path and event constraints on the flight profile, which are flight segment dependent, must be considered in order to guarantee the optimized trajectory is consistent with typical ATM operations and regulations. These constraints are summarized in Fig. 3.

It should be noted that before each cruise flight level, a short cruise segment less than 1 min is added, allowing in this way proper speed adjustments (as shown with the blue lines in Fig. 3). A similar segment is also added after the FCA and at the end of the last cruise segment. These allow, respectively, to accelerate to recover delay and to adjust the speed for an optimal Mach descent. More mathematical details on the formulation of this flight profile can be found in [23]. In addition to the flight vertical (and speed) profile, a flight route must be defined either in terms of Great Circle Distance (GCD) between city-pair airports, or by using air traffic services (ATS) route waypoints and published procedures (such as standard instrumental departures and arrivals).

B. Second stage: AFP delayed flights with no LH

Based on the 4-dimensional (4D) trajectory found for the *nom* flight, a capacity reduction is assumed en route, requiring to issue an AFP at a specific FCA located at a flight distance d from the departure airport ($D - d$ is the remaining distance to the arrival airport where D is the whole flight distance). Resulting from the AFP, the *nom* flight is captured in the program list with a Δt delay assigned. Then, the CTA for the *AFP* flight at the FCA will be $t_{FCA} = t_{FCA \cdot nom} + \Delta t$, where $t_{FCA \cdot nom}$ is the time at which the *nom* flight planned to arrive at the FCA.

Apparently, the only difference of the *AFP* flight, with respect to the *nom* flight, lies on the timeline which takes a parallel movement from the latter one, so as to transfer all the Δt on the EDCT, keeping the other 3D trajectory unchanged. Yet, as a consequence of enduring some delay on ground, the operator of the *AFP* flight may be inclined to increase the flight speed after the FCA even if more fuel than initially planned has to be burnt in order to recover part of the delay at the arrival airport. This is sometimes necessary for aircraft operators trying to guarantee, for instance, connecting passengers and/or to mitigate reactionary delays as much as possible.

In this context, it is considered in this paper that the aircraft operator will plan (at dispatch level) for $\omega\%$ extra fuel than the total trip fuel as initially scheduled for the nominal flight. Then, not only the timeline but the whole 4D trajectory of the *AFP* flight will change if compared with the *nom* flight. It is worth noting that regarding this $AFP + \omega\%$ flight, an earlier arrival time at the FCA could be technically achieved provided that the CTA is not (currently) enforced. However, aimed at future TBO, it is more realistic to fix CTA at the FCA, only permitting delay recovery at the arrival airport where no capacity reduces.

For the $AFP + \omega\%$ flight, the trajectory optimization problem will maximize the delay recovery (i.e. minimizing the arrival time t_f), instead of minimising the function written in Eq. 1. Besides all optimisation constraints already used when generating the *nom* flight (see Sec. III-A), this new trajectory will consider as well the following restrictions:

$$t_0 = t_{0 \cdot nom} + \Delta t \tag{6}$$

$$t_{FCA} = t_{FCA \cdot nom} + \Delta t \tag{7}$$

$$s(t_{FCA}) = d \tag{8}$$

$$\int_{t_0^{(1)}}^{t_f^{(N)}} FF(t)dt \leq [m(t^1_{0 \cdot nom}) - m(t^N_{f \cdot nom})](1 + \omega\%) \tag{9}$$

Eq. 6 and 7 specify that the assigned delay Δt is fully realized in terms of the EDCT at origin airport, and the CTA at the FCA, respectively. Eq. 8 ensures the flight arrives at the FCA meeting the assigned CTA. Eq. 9 imposes the maximum fuel consumption allowed which equals to the total trip fuel burnt in the *nom* flight (difference between initial and final aircraft mass) plus the ω allowance.

C. *Second stage: AFP delayed flights with LH*

As explained before, with the LH strategy the aircraft can experience less ground holding and depart earlier than the initially assigned EDCT, absorbing the remaining delay airborne and still meeting the CTA at the FCA (and with some eventual fuel savings due to the reduced speed). After passing the FCA, the *LH* flight is able to use this saved fuel to increase speed and recover as much delay as possible at the arrival airport. Like in the *AFP*+$\omega\%$ flight previously presented the aim of the *LH* flight is also to maximize delay recovery.

Regarding the optimisation constraints, however, the key difference compared with the *AFP* flight is that the EDCT for the *LH* flight is no longer enforced. Thus, besides all constraints listed in Sec. III-A for the *nom* flight, equations 7, 8, 9 are also enforced, while Eq. 6 is replaced by $t_0 \geq t_{0 \cdot nom}$ just to ensure that the *LH* flight does not depart the origin airport before its initially scheduled time.

IV. ILLUSTRATIVE EXAMPLES

In this section, the application of trajectory optimization in AFP is simulated by using the above mentioned method. Sec. IV-A presents the numerical results for a given case study, representing a realistic AFP in the NAS. Then, a sensitivity experiment is conducted to reveal possible factors having impacts on the performance, with results analyzed in Sec. IV-C in terms of delay absorption and delay recovery.

A. *Effects for a specific AFP delayed flight*

The case study for this paper is shown in Fig. 4, where a flight from MSP (Minneapolis-Saint Paul) to JFK (John F. Kennedy) airport is scheduled to fly through a pre-coordinated (known as "canned") AFP, passing an FCA frontier named FCAA05. From MSP to FCAA05, the flight (great circle) distance is 350nm, and from FCAA05 to JFK it is 544nm. An Airbus A320 model is used in this study assuming a typical passenger load factor of 81% [6] and a CI of 45 kg/min.

The following additional assumptions have been considered in this case study: 1) a 20 min AFP delay is assigned at FCAA05; 2) no wind conditions are considered; 3) only even flight levels are used (FL260 as the lowest altitude); and 4) cruise step climbs are allowed (if any) with 2,000ft steps.

Results for the cases with no extra fuel included (i.e., the *AFP* and *LH* flights) are presented in Fig. 5, showing the true airspeed (TAS), flight timeline, vertical profile, and various representations of the fuel cost (including the unit, aggregate and difference) taking the *nom* flight as the baseline.

Due to the TAS variation (as shown in Fig. 5a), LH is realized and thus part of the delay is absorbed airborne before the FCA (at 350nm), satisfying the CTA (at 70 min) with a shorter ground holding if compared with the *AFP* flight (see Fig. 5c). As discussed in Sec. III-B, when extra fuel is not allowed, the AFP flight shares the same trajectory with the *nom* flight except for the timeline, and thus, an anticipated parallel movement of 20 min on flight timeline can be observed as shown in Fig. 5c.

In addition, some fuel is saved before arriving at the FCA (at around 70 min), as shown in Fig. 5d, because of the lower selected climb and cruise speeds (leading to lower unit fuel consumption as shown in Fig. 5b). Afterwards, this fuel saved is burnt after the FCA till the final arrival (see the difference on fuel consumption versus the *nom* flight in Fig. 5d), contributing to a higher TAS for descent, a steeper vertical descent profile (leading to an extended cruise distance), and an earlier arrival time (see Fig. 5c).

Figure 6 shows the cases when 1% and 2% of the total trip fuel is added at dispatch level (i.e., the *AFP+1%*, *AFP+2%*, *LH+1%* and *LH+2%* cases). Here, the assigned delay is partially recovered for all of these flights, with the same CTA (at 70 min) satisfied at the FCA (see Fig. 6c). Next, if compared to the *AFP+1%* and *AFP+2%* flight, higher cruise speeds (and thus higher unit fuel consumption, see Fig. 6b) can be selected after the FCA for the *LH+1%* and *LH+2%* flights, respectively (see Fig. 6a), as a result of the fuel saved from LH before the FCA (see the difference on fuel consumption versus the *nom* flight in Fig. 6d). Therefore, more time can be recovered at the arrival airport. In other words, with the same amount of fuel included, the *LH* flight will still perform better

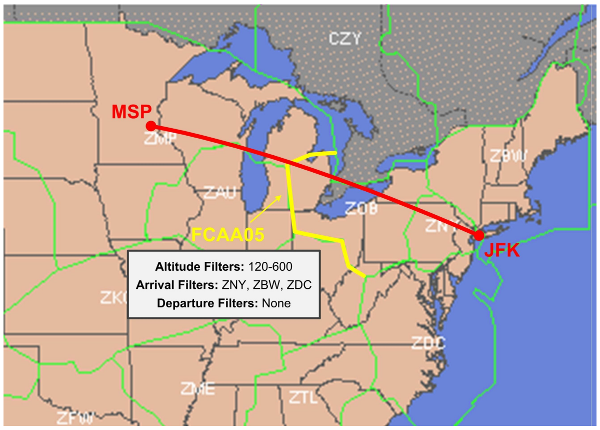
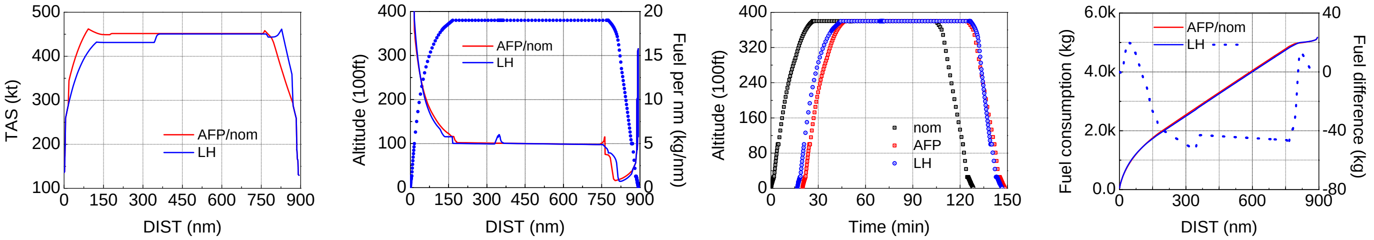
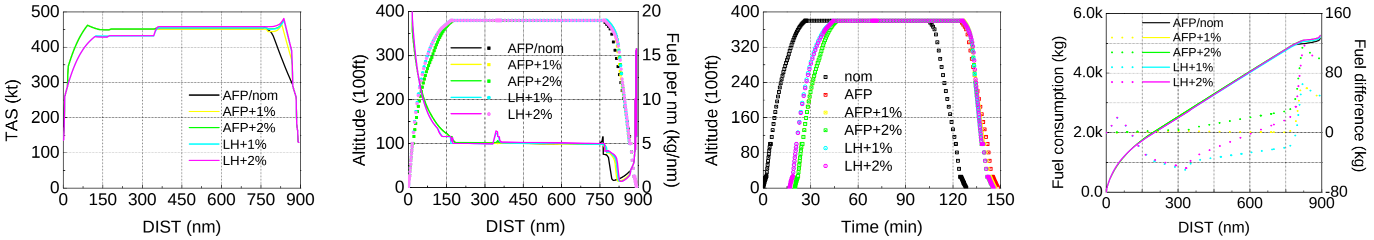


Fig. 4: A sketch of flight "MSP-JFK" passing the AFP flow constrained area FCAA05 (defined by the western boundary of ZOB and the eastern boundary of ZID air route traffic control centers).



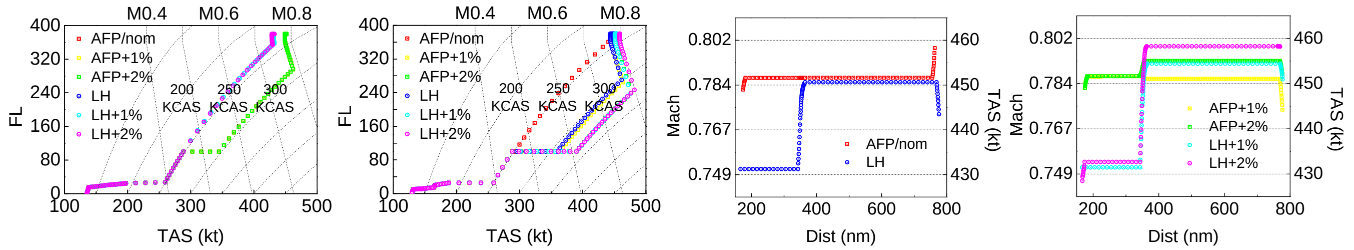
(a) True airspeed (b) Trajectory and unit fuel cost (c) Flight timeline (d) Aggregate fuel consumption

Fig. 5: Comparison between the *nom*, *AFP* and *LH* trajectories (at no extra fuel cost)



(a) True airspeed (b) Trajectory and unit fuel cost (c) Flight timeline (d) Aggregate fuel consumption

Fig. 6: Comparison between the *AFP* and *LH* trajectories (with 1% and 2% of extra fuel allowances)



(a) Climb phase (b) Descent phase (c) Cruise phase (no extra fuel) (d) Cruise phase (extra fuel)

Fig. 7: Speed profiles for the different flight phases

TABLE I: Summary of results for each case study.

Cases	Total			MSP		FCA		JFK	
	Dist (nm)	Fuel (kg)	Time (min)	ETD/EDCT (hh:mm:ss)	GH (min)	ETA/CTA (hh:mm:ss)	Delay abs. (min)	ETA (hh:mm:ss)	Delay rec. (min)
nom	894	5167	128.4	**0:00:00**	-	**0:49:50**	-	**2:08:24**	-
AFP	894	5167	128.4	**0:20:00**	20.0	**1:09:50**	0.0	**2:28:24**	0.0
LH	894	5167	130.0	**0:16:41**	16.7	**1:09:50**	3.3	**2:26:40**	1.7
AFP+1%	894	5217	126.5	**0:20:00**	20.0	**1:09:50**	0.0	**2:26:31**	1.9
LH+1%	894	5217	129.0	**0:16:41**	16.7	**1:09:50**	3.3	**2:25:39**	2.7
AFP+2%	894	5267	125.6	**0:20:00**	20.0	**1:09:50**	0.0	**2:25:33**	2.9
LH+2%	894	5267	128.3	**0:16:38**	16.6	**1:09:50**	3.4	**2:25:00**	3.4

for the *AFP* delayed flights than only increasing flight speed after the FCA.

Table. I summarizes the numerical results of the key parameters for all the flights of this case study. It can be noticed that, by performing LH, 1.7 min of the AFP delay can be recovered when arriving at JFK, at no extra fuel cost, which accounts for nearly 8.5% of the total delay assigned. Meanwhile, 3.3 min of the delay can be absorbed airborne by LH, saving 16.5% of the GH (ground holding) as supposed to perform at MSP. With 1% (50kg) and 2% (100kg) extra fuel allowed, 1.9 min and 2.7 min can be recovered respectively without LH, but all of the 20 min of AFP delay have to be fully realized on ground. On the other hand, with LH performed at a similar delay absorption (3.3 min and 3.4 min), the delay recovery can be extended to 2.9 min and 3.4 min, respectively, which makes an increase of 0.8min and 0.5min with respect to each of the above two cases where LH is not in effect.

It is worth noting that the amount of achievable delay

TABLE II: Main parameters for each flight phase before reaching FCAA05.

Cases	Take-off			Climb				Cruise_1					Total		
	Dist (nm)	Fuel (kg)	Time (min)	Dist (nm)	Fuel (kg)	Time (min)	av. TAS (kt)	Dist (nm)	Fuel (kg)	Time (min)	av. TAS (kt)	SR (nm/kg)	Dist (nm)	Fuel (kg)	Time (min)
AFP/nom	4	176	2	170	1721	25	411	176	895	23	451	0.196	350	2793	50
LH	4	176	2	162	1646	26	375	184	924	26	431	0.199	350	2745	53
AFP+1%	4	176	2	171	1725	25	411	175	894	23	451	0.196	350	2795	50
LH+1%	4	176	2	163	1649	26	376	183	924	26	431	0.198	350	2749	53
AFP+2%	4	176	2	171	1728	25	411	175	894	23	451	0.196	350	2798	50
LH+2%	4	176	2	163	1651	26	375	183	926	25	431	0.197	350	2753	53

TABLE III: Main parameters for each flight phase after reaching FCAA05.

Cases	Cruise_2					Descent				Landing			Total		
	Dist (nm)	Fuel (kg)	Time (min)	av. TAS (kt)	SR (nm/kg)	Dist (nm)	Fuel (kg)	Time (min)	av. TAS (kt)	Dist (nm)	Fuel (kg)	Time (min)	Dist (nm)	Fuel (kg)	Time (min)
AFP/nom	413	2058	55	452	0.201	122	237	20	360	8	80	3	544	2375	79
LH	426	2114	57	451	0.202	110	228	17	390	8	80	3	544	2422	77
AFP+1%	427	2114	57	451	0.202	109	229	17	392	8	80	3	544	2422	77
LH+1%	427	2144	56	454	0.199	108	244	16	403	8	80	3	544	2468	76
AFP+2%	426	2142	56	455	0.199	109	248	16	404	8	80	3	544	2469	76
LH+2%	419	2144	55	458	0.196	116	291	17	410	8	80	3	544	2514	75

recovery, along with the delay absorption, appears to be not such remarkable (for around several minutes) that could be expected to largely reduce the initially assigned AFP delay. Even so, it still proves to be always more efficient (at the same fuel cost) than the case where ground holding is fully experienced followed by burning more fuel to speed up (as commonly done nowadays). In other words, with the aim of recovering the same delay, implementing the LH strategy will contribute to some fuel saved. In fact, given the exponential relation between aircraft speed and fuel consumption (recall Fig. 1), a relatively small increase of delay recovery could incur much more costs on fuel, as will be discussed in Sec. IV-C. Furthermore, considering the simple procedure (at the airline dispatch level) of the proposed strategy, it could be effectively realized in practical, and thus the accumulative delay recovery of various AFP delayed flights shall mount remarkably.

B. Detailed trajectory analysis

In order to better understand the changes of trajectories for the above cases, a further discussion is presented in this section analyzing separately the climb, cruise and descent phases. Fig. 7 shows the different speed profiles. As expected, the *LH* flight (including *LH+1%* and *LH+2%* flight) selects the lowest CAS (250kt) during the constant CAS climb segment, while the *nom* flight, along with the *AFP* flight (including *AFP+1%* and *AFP+2%* flight) all choose 300kt (see Fig. 7a). During the descent phase, as shown in Fig. 7b, the *nom* flight selects 250kt, while the *AFP+1%*, *LH+1%*, *AFP+2%* and *LH+2%* select speeds from 300kt to VMO, orderly. It is worth noting that the higher the climb/descent CAS, the lower the crossover altitude will be to change to/from the climb/descent Mach number.

As for the cruise phase, both the *LH* flight and *AFP+1%* flight select lower cruise Mach after the FCA than the *nom* flight, as shown in Fig. 7c and 7d, respectively. Given that both of the flights have delay recovered at final arrival (see Table I), the recovery process is actually realized only in the descent phase. The reason is due to the fact that the trade-off of fuel and time, as presented in Fig. 1, differs between each flight phase, and the descent is more fuel efficient than the cruise (see also the unit fuel consumption in Fig. 5b and Fig. 6b). In this way, increasing the descent speed incurs less fuel consumption than cruise speed, but keeping increasing will in turn lower its marginal efficiency.

Therefore, when less (or no) extra fuel is allowed, descent is prior than cruise for delay recovery, but when more fuel is appended, cruise phase is involved, as revealed by the *AFP+2%*, *LH+1%* and *LH+2%* flight in Fig. 7d. It is also worth mentioning that the extended cruise distance caused by the steeper descent profile (due to higher descent speed) also accounts for delay recovery, as enlarging cruise phase will keep the flight flying at high altitude and high speed as much as possible.

Summing up, delays can be recovered by means of two contributions: enlarging the cruise phase (retarding the top of descent) and increasing speed in the descent. The specific changes within different flight phases before and after the FCA are summarized in Tables II and III, respectively. Note that take-off and landing phases (out of the scope of optimization) are fixed in this study.

As presented in Table II, for each of the *LH* flight, nearly 75kg of fuel are saved during the climb phase, reducing climb distance by 8nm. Among this saved fuel, 29kg is allocated to the cruise phase to compensate with that extra 8nm of cruise distance. In total, the fuel is saved for nearly 48kg untill the

TABLE IV: Independent variables in the sensitivity analysis.

Category	Variables	Baseline	Min	Max	Step	Num
Scenario	City pair distance (nm)	*1000*	500	2000	20	76
	FCA position (%)	*50*	25	75	1	51
	AFP delay (min)	*10*	10	10	-	1
Aircraft	CI (kg/min)	*30*	5	100	1	96
	Aircraft payload (%)	*80*	0	100	1	101
	Extra fuel buffer (%)	*all*	0	unlimited	-	8

FCA, realizing 3 min of delay absorption. As for the rest of the trajectory, increases on descent speeds can be found in Table III, if compared with the baseline (*AFP/nom* flight). However, due to the reduction of marginal efficiency, as discussed previously, these increases on descent speeds turn slower after more extra fuel appended, while cruise speeds start increasing, driving down the corresponding specific ranges (SR). It is also interesting to notice that, after the FCA, the *LH* flight (including *LH+1%*) is quite similar to the case of adding every 1% of extra fuel to the *AFP* flight, as shown in Table III.

C. Extension of the case study: sensitivity analysis

The effects of some independent variables to the amount of delay absorption and delay recovery are presented in this section. Table IV shows the relevant variables and their associated ranges considered for this sensitivity study. It can be noticed from Fig. 8 that with regards to delay absorption, the differences between various extra fuel are quite small when the allowances lower or equal than 10%. However, this does not imply that the LH time has no relation with the amount of extra fuel included (see the maximum LH that can be realized at certain fuel consumptions in [10]).

For the AFP case, LH is implemented aimed at saving fuel, not realizing the maximum airborne delay, before arriving at the FCA. Therefore, when large amounts of fuel appended, like in the unlimited case (i.e. removing Eq. 9 from the optimization), it can be seen that the assigned AFP (10 min fixed in the experiments) would be entirely absorbed besides the objective of minimizing arrival time at the destination airport.

On the other hand, notable distinctions on the delay recovery can be observed from Fig. 8 as a function of the extra fuel allowed, especially for a remarkable change from 0% to 1%, which indicates the recovery time can be almost doubled (even more in some cases) with only 1% increase of the total fuel consumption. However, keeping adding extra fuel cannot bring always large increase on delay recovery as from 0% to 1% (see for instance the cases ranging from 10% to unlimited fuel allowance), because higher speeds tend to be more fuel-costly (see Fig. 1), and the maximum operating speed (also dependent on the altitude) is enforced (see Eq. 4).

Moreover, observing the cases with an extra fuel allowance greater than 10% it can be noticed that even with large amounts of fuel included, the delays that can be recovered are still quite small. Depending on the specific case, the actual extra fuel consumed when setting an unlimited allowance would range approximately from 20% to 30%. All this suggests that accelerating aircraft speed much higher than initially scheduled is not very efficient, in terms of fuel consumption, to recover delays airborne.

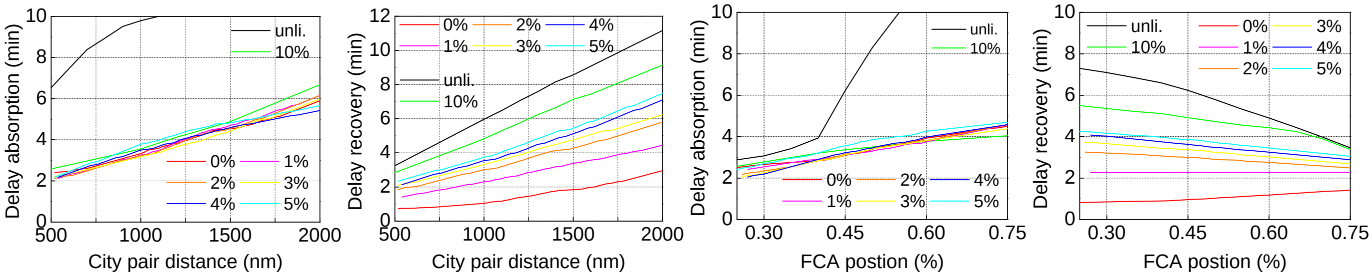
Specifically, for the case of 0% extra fuel, the amount of recovered delay (realized after the FCA) is lower than the delay absorbed before the FCA, meaning that the fuel savings from a certain minutes of delay absorption are lower than the extra fuel needed to recover the same amount of delay. Recall the relationships between fuel consumption and flight speed shown in Fig. 1. As discussed previously, airlines would also consider time-related costs besides the cost of fuel (see Eq. 1), and thus the initially planned speeds are typically higher than the minimal-fuel speed (see the extreme points in Fig. 1). Therefore, on the same fuel consumption level, the interval of speed reduction should be much larger than that of increasing speed, which makes recovering delays more difficult than absorbing delays airborne.

1) City pair distance: As shown in Fig. 8a and 8b, both delay absorption and recovery are positively correlated with the city pair distance. The longer the flight distance, the more time is available to perform LH, and thus the more delay can be absorbed and recovered after passing the FCA. Moreover, LH also proves to be appealing for short-haul flights, as with respect to 500nm distance, the flight can even take-off 2 min earlier with almost 1min delay recovered.

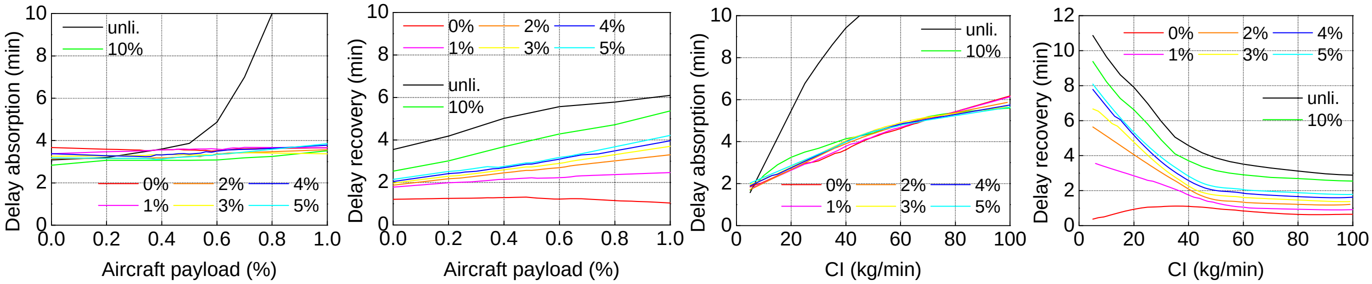
2) FCA position: According to Fig. 8c, the FCA position and the delay absorption are positively correlated regardless of the extra fuel included. However, as the extra fuel increases, the relation with delay recovery turns from positive to negative. Fig. 8d suggests that if no extra fuel is allowed, a longer distance from departure airport to the FCA is better for delay recovery. On the contrary, when extra fuel included, that distance (with fuel saved) weighs less and less than the other distance that is from the FCA to arrival airport, in terms of delay recovery.

3) Aircraft payload: With aircraft payload increasing, the delay absorption (see Fig. 8e) remains constant, which is due to the fact that the optimal flight speed is barely affected by aircraft mass, but the fuel consumption is affected notably. Therefore, for each extra fuel allowance the actual amount of added fuel is increasing with payload, which is why the delay recovery is even higher for heavier aircraft (see Fig. 8f). However, at 0% extra fuel, a slightly decline can be observed. Since the aircraft mass is reducing with the fuel burned along flight distance, a higher payload will leave a heavier aircraft mass for the delay recovery process (after the FCA), consuming more fuel, in such a way the time can be recovered reduces on some level.

4) Cost index: According to the definition of CI (see Sec. II-A), the higher the CI, the more importance will be given to the trip time and the faster the optimal flight speed will be. As a result, for higher CI, more speed reduction can be achieved, and thus more delay can be absorbed, as shown in Fig. 8g. Nevertheless, as for the delay recovery, an interesting change can be noticed at no extra fuel allowance, i.e., the maximum delay recovery occurs at CI around 40 kg/min, as shown in Fig. 8h, but when extra fuel included, higher CI leads to even less delay recovered instead.



(a) City pair distance: delay absorption (b) City pair distance: delay recovery (c) FCA position: delay absorption (d) FCA position: delay recovery



(e) Aircraft payload: delay absorption (f) Aircraft payload: delay recovery (g) Cost index: delay absorption (h) Cost index: delay recovery

Fig. 8: Delay absorption and recovery sensitivity when performing LH for different extra fuel allowances

When the fuel is limited (e.g., extra fuel at 0%), first increasing CI, from 5 to 40 kg/min, brings a growth on fuel consumption than initially planned, providing more fuel to be saved by LH before the FCA, leading to a higher delay recovery after the FCA. Then, with CI keeping increasing, the initially planned speed (nominal speed) continues increasing too, but the speed in the delay recovery process is approaching the upper bound of maximum operational speed, such that their interval will turn narrow, and thus the delay recovery will reduce. Meanwhile, if extra fuel appended (e.g., 1% to unlimited allowance), the recovery speed can reach up to the maximum no matter how the initial CI changes, such that the delay recovery will always decline following the growth of CI.

V. CONCLUSIONS AND FURTHER WORK

Inspired by the forthcoming trajectory based operations paradigm, an aircraft trajectory optimization technique was presented in this paper in order to introduce linear holding (LH) to partially absorb air traffic flow management (ATFM) delays due to airspace flow programs (AFP). It is shown how some fuel can be saved before reaching the congested airspace, which can be allocated to recover delay once this constrained area is overflown. It is worth noting that the implementation is focused on the pre-tactical operations, aimed at improving the overall AFP performance by means of enhancing the efficiency of each individual flight (trajectory) planning.

Fuel consumption accounts for the largest part of airline operating costs, and also generates greenhouse gas emissions bringing adverse environmental issues, which makes it one of the major drivers of current research efforts in air transportation. Results in this paper show that, without extra fuel consumption, the delay assigned in an AFP could be partially absorbed and, eventually, recovered. Even small amounts of them per flight will become significant when considering the cumulative effect for numerous AFP delayed flights: according to statistics data published in [25], there have been 79 AFPs at annual average issued in the NAS for the past 5 years, and the number is still growing, with 177 in 2015 year and 208 in 2016 year. Results also indicate that if some extra fuel consumption is allowed, performing LH still presents some cost-efficiency benefits than simply increasing flight speed after enduring all the delay on ground.

The proposed strategy could be easily combined with other initiatives focusing to improve the aircraft operator's cost-efficiency, such as airlines' waiting for passengers concepts under hub operations [26], or the strategy to neutralize additional delays subject to ground holding [11].

Future work will aim at the simulation in realistic scenarios. Since AFPs are typically issued in response to severe weather conditions, the wind and non-standard atmospheres, which always have great effects on real flights, should be taken into consideration. Moreover, it is also necessary to explore a pre-tactical ATFM method incorporating trajectory negotiation processes (as already discussed in [27], [28]), in order to extend the strategy of this paper from individual flight analysis to an operation of multiple flights.

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