



# Maximizing airborne delay at no extra fuel cost by means of linear holding



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## ABSTRACT

This paper introduces a linear holding strategy based on prior works on cruise speed reduction, aimed at performing airborne delay at no extra fuel cost, as a complementary strategy to current ground and airborne holding strategies. Firstly, the equivalent speed concept is extended to climb and descent phases through an analysis of fuel consumption and speed from aircraft performance data. This gives an insight of the feasibility to implement the concept, differentiating the case where the cruise flight level initially requested is kept and the case where it can be changed before departure in order to maximize the linear holding time. Illustrative examples are given, where typical flights are simulated using an optimal trajectory generation tool where linear holding is maximized while keeping constant the initially planned fuel. Finally, the effects of linear holding are thoroughly assessed in terms of the vertical trajectory profiles, range of feasible speed intervals and trade-offs between fuel and time. Results show that the airborne delay increases significantly with nearly 3-fold time for short-haul flights and 2-fold for mid-hauls to the cases in prior works.

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## 1. Introduction

Ground holding, the practice of delaying the take-off of a flight due to anticipated congestion at the destination airport (or at some airspace along the route), is motivated by the fact that it is less expensive and safer than holding in the air (Richetta, 1991). By less expensive, it means less fuel is consumed waiting at the apron with the engines off than delaying the aircraft in the air by means of holding stacks or path stretching instructions given by air traffic control (ATC). By safer, it means that the aircraft is not burning (reserve) fuel unnecessarily and by the fact that ATC workload is decreased in the airspace(s) where aircraft are required to lose time. Waiting on ground, however, has the inconvenience that if the delay is no longer necessary and thus cancelled before initially planned (due to the unexpected improving of congestion or weather for instance) (Cook and Wood, 2010; Ball et al., 2010; Inniss and Ball, 2004), the grounded aircraft are still at departure airports and the already delayed time on departure cannot be recovered (or can be partially recovered by increasing flight speed, leading to extra fuel consumption if compared with the initially planned flight).

To overcome this issue, a speed reduction strategy was proposed by Delgado et al. (2013) where aircraft were allowed to cruise at the lowest possible speed in such a way the fuel consumption remained exactly the same as initially planned. In this situation, if the delays are cancelled ahead of schedule, aircraft already airborne and flying slower, can speed up to the initially planned and recover part of the delay without extra fuel consumption. Previously, this strategy was explored by Prats

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and Hansen (2011), but aimed at partially incurring in the air, by flying slower, the assigned ground delays. Ground delayed aircraft were enabled to fly at the minimum fuel consumption speed (typically slower than nominal cruise speed initially chosen by the airline), performing in this way, some airborne delay at the same time fuel was saved with respect than the nominal flight. Thereafter, more related work to the strategy has been done discussing such as the impact to Ground Delay Programs (GDPs), the effects from en route wind and the potential applicability for handling air traffic flow (Delgado and Prats, 2014, 2013, 2012).

Other than the typical airborne delay (holding pattern or path stretching), this kind of linear holding means that only speed is adjusted and the planned route remains the same. Furthermore, in line with the concept of trajectory based operations (TBO), as proposed in SESAR and NextGen programs, delays could be allocated in form of controlled times of arrival (CTA) at different designated waypoints along the route (Klooster et al., 2009; Smedt et al., 2013). In this way, linear holding could be seen as a complementary air traffic flow management (ATFM) strategy, in addition to ground holding, pre-tactical re-routing or strategic deconfliction initiatives (Ruiz et al., 2014). Then, through a dynamic speed management along the route, the arrival time at different waypoints could be tactically adjusted in response to uncertainties.

As the core method to perform linear holding, speed reduction is essentially one of the speed control methods that have proven successful for several air traffic management (ATM) scenarios. For instance, Jones et al. (2013, 2015) 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 Günther and Fricke (2006), a pre-tactical speed control was applied en route to prevent aircraft from performing airborne holding patterns when arriving at a congested airspace, with both flight efficiency and controller workload reported improved. Similar but more at tactical level, aircraft in Australia (2007) were required to reduce their speed to avoid arriving at the airport before its opening time to reduce unnecessary holdings. More widely, the applicability of speed control with regard to the conflict resolution problem has been discussed for decades, and typically it was implemented along with other approaches such as path changing (Tomlin et al., 1998) or flight level assignment (Vela et al., 2009). With metering operations under TBO, aircraft trajectories are tactically managed to their schedules across meter points, through speed control or path extension based on accurate trajectory predictions and modifications, which raises the critical need of concern about uncertainties (such as aircraft-specific parameters and predicted winds), as has been studied in Kirkman et al. (2014). Regarding terminal procedures (where aircraft are typically climbing or descending), however, speed control has been mainly used for (tactical) separation purposes. (see for instance in Barmore, 2006; Xu et al., 2016).

This paper extends the work done in Delgado et al. (2013), Delgado and Prats (2012, 2013, 2014) by proposing a linear holding strategy that not only takes into account the cruise phase, but also considers climb and descent phases. The inclusion of climb and descent will increase the overall capability of delay absorption and even make it appealing for short-haul flights, as climb and descent often represent a considerable percentage of the total trip distance. Through the use of aircraft trajectory optimization techniques, the differences on efficiency of performing linear holding during each flight phase will be fully utilized, in such a way to generate the optimal trajectory realizing the maximum airborne delay. Since changes of flight trajectory have a direct effect to fuel consumption, which is one of the main safety issues and operating costs airlines have concerns about (Cook and Tanner, 2011), this maximum airborne delay is computed with the pre-condition that the delayed flight must burn the same (or less) quantity of fuel than the original flight, when planned before receiving the ATFM regulation.

## 2. Linear holding at no extra fuel cost

Current on-board flight management systems enable airlines to optimize the aircraft trajectory in terms of DOC (Direct Operating Costs, including both fuel and time related costs) (Airbus, 1998) by means of the Cost Index (CI), which represents the ratio between time-based cost and the cost of fuel (Roberson and Pilot, 2007). In this paper, optimal trajectories computed with a given CI would be regarded as the nominal flights, and labeled as Case-0.

### 2.1. The linear holding concept

In order to explain the LH concept, it is appropriate to start with a short comparison between the two commonly seen holding practices in current ATM: ground and airborne holding, along with the proposed cost based linear holding, as shown in Fig. 1.

In terms of fuel consumption, typical airborne holding would consume more fuel due to the extended flight track (the deviation of actual trajectory to the initially planned) (Belkoura et al., 2016), whilst holding on the ground should make no difference with the planned fuel. For LH a trade-off is possible between fuel and time, depending on the speed adjustment strategy.

Due to the increased extra fuel, the airborne holding time is fairly limited if compared with ground holding, taking account that safety related issues may arise from a reduction of the on-board reserve fuel. On the other hand, the LH time should depend on several factors, such as aircraft type, flight distance, payload and cruise flight level, and requires a detailed analysis (as done in Section 3 of this paper). Although a reasonable amount of extra fuel allowance could bring a considerable increase of the maximum LH time, this option is out of the scope of this paper and the pre-condition is that LH must be done at no extra fuel cost.

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