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Dalmau, Ramon ; Sun, J.; Prats, Xavier

Publication date
2021

Document Version
Final published version

Citation (APA)
Dalmau, R., Sun, J., & Prats, X. (2021). *Fuel Inefficiency Characterisation and Assessment due to Early Execution of Top of Descents: A Case Study for Amsterdam-Schiphol Terminal Airspace using ADS-B data*. Paper presented at 14th USA/Europe Air Traffic Management Seminar.

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Fourteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2021)

Fuel Inefficiency Characterisation and Assessment due to Early Execution of Top of Descents

A Case Study for Amsterdam-Schiphol Terminal Airspace using ADS-B data

Ramon Dalmau[§]
Network Research Unit (NET)
EUROCONTROL Experimental Centre
Brétgny-Sur-Orge, France

Junzi Sun
Faculty of Aerospace Engineering
Delft University of Technology
Delft, The Netherlands

Xavier Prats
Department of Physics - Aerospace division
Technical University of Catalonia (UPC)
Castelldefels (Barcelona), Spain

Abstract—**The vertical trajectory plan (altitude and speed) corresponding to the descent phase of a modern airliner is computed by the on-board flight management system while the aircraft is still in cruise. As long as the constraints on the arrival procedure allow, this system plans for an idle descent and the exact location of the (optimal) top of descent (TOD) is determined in this process. In busy terminal airspace, however, air traffic control officers – motivated by the needs to maintain a safe and expeditious flow of aircraft – might require to start the descents before the TOD computed by each particular arriving aircraft. In such situations, most flight guidance systems aim to intercept the original altitude plan from below, by using a shallower descent angle while keeping the speed plan, requiring in this way, additional thrust. This leads, consequently, to higher fuel consumption figures. The objective of this paper is threefold. Firstly, it characterises and quantifies these fuel inefficiencies for an Airbus A320, using accurate aircraft performance data and a trajectory computation software from the manufacturer. Secondly, it proposes a methodology to automatically identify early descents and to extract the key parameters required to compute the fuel inefficiencies by only observing ADS-B (automatic dependent surveillance-broadcast) data. Finally, the method is applied to a case study with 4,139 real ADS-B trajectories in Amsterdam-Schiphol (The Netherlands) terminal airspace; showing that early descents are very frequent and that they increase the fuel consumption by a 5%, in average.**

Keywords—**Continuous descent operations; environmental impact; air traffic control; ADS-B**

I. Introduction

The continuous growth in air traffic, drastically interrupted by the COVID-19 pandemic since early 2020, increased the pressure on the environmental sustainability of air transport. In this context, recent research has focused on investigating new aircraft procedures to reduce the environmental impact during the climb [1]–[3]; cruise [4]–[6]; and descent [7] phases of flight. For the latter, several works have demonstrated that continuous descent operations are successful at reducing the noise nuisance, gaseous emissions and fuel consumption in the terminal maneuvering area (TMA). The optimal descent trajectory, in terms of fuel consumption, consists of an unimpeded descent, from the cruise altitude until the interception of the instrumental landing system glide path, with the engines at idle thrust [8]–[10].

[§]This study was performed while working at the UPC

In modern aircraft, the optimal descent trajectory in the vertical plane – altitude and speed – is planned by the on-board flight management system (FMS), well before the descent is initiated while the aircraft is still in cruise. This computation is done by numerically integrating of the differential equations that describe the dynamics of the aircraft. This integration is typically done backwards, starting at the (known) runway threshold and ending when reaching the cruise altitude: i.e. the (unknown) top of descent (TOD) is found.

The resulting trajectory plan depends on many factors, such as the mass of the aircraft; the cruise altitude; aircraft performance; the weather forecast and the cost index (CI) chosen by the aircraft crew[1]. Furthermore, the descent trajectory will also be shaped by several operational constraints present in standard arrival procedures, especially in busy TMAs, like for instance minimum or maximum speeds or altitudes at certain waypoints. This means that the variability of the exact TOD location is very high, and depends on many parameters, even for the same aircraft type. For instance, [11] addressed the TOD location for a B737 aircraft with 3 different configurations, showing that the presence (or absence) of winglets is a significant factor that affects the location of the TOD. It is worth noting that research is still underway to improve FMS algorithms to better determine the TOD. See for instance the work done in [12], where wind prediction errors are considered in the TOD computation.

During the execution of the flight, the aircraft crew can initiate the descent only after receiving the proper clearance by the air traffic control (ATC) service. ATC officers, however, have no *a priori* knowledge on where the planned TOD lies for each of the incoming flights. Ideally, a *when ready* or *at pilot's discretion* clearance is given, meaning that the aircraft crew is allowed (and expected) to initiate the descent at the TOD location previously computed by the on-board FMS. In some TMAs, ATC officers are typically supported by automated tools when when sequencing and merging arrival flows of aircraft, which might provide TOD estimations, increasing the likelihood to clear descents close to the optimal TOD [13].

[1]The cost index is a parameter that represents the ratio between the cost of time and the cost of fuel. The higher the cost index, the more importance is given to the time and therefore the faster the aircraft speed and steeper the descent.

In this context, research is underway to propose methods to better predict the TOD by these ground-based systems, such as polynomial approximations [13], [14] or machine learning algorithms [15]. Moreover, it is worth nothing that in the near future, applications relying on the extended projected profile (EPP) concept will benefit from detailed 4D trajectory data down-linked from on-board systems, including for instance, the TOD location planned by the FMS [16].

Nevertheless, regardless of the actual knowledge that ATC officers have on the planned TOD location, in congested TMAs they may be forced to clear the descents at a specific locations (or moments in time). This fact is driven by the need to manage complex and busy flows of arrivals and departures, with the ultimate goal to maintain safe separation among all aircraft and expedite the operations in the TMA. Consequently, the actual (executed) TOD will differ from the optimal (planned) TOD computed by the FMS.

If the ATC requests a descent before the optimal TOD (the so called *early descent*), once the descent is initiated, the guidance strategy of the FMS will attempt to intercept the original (optimal) descent path *from below*. This is achieved by maintaining a shallower flight path angle with the elevator control (typically by commanding a specific vertical speed), at the same time that the original (optimal) speed profile is kept with throttle control. For *late descents*, the FMS would try to intercept the original descent path *from above*; by commanding a higher speed at idle thrust, and typically requesting the aircraft crew to use speedbrake devices, in order to increase the rate of descent.

Since the guidance strategy for early descents calls for a non-idle thrust segment until the original planned descent path is intercepted, it is expected that higher fuel figures will be obtained. For this reason, this paper seeks to measure these fuel inefficiencies, as well as to raise awareness regarding the occurrence of early descents in actual operations. It should be noted that the objective of this paper is not to perform an assessment of the factors that cause early descents, nor to propose methods to anticipate them. To the best of the authors knowledge, no previous research has quantified early descents occurrences or their impact in fuel consumption, if compared with descents initiated at the planned TOD.

In this paper early descents are simulated for an Airbus A320 using the trajectory computation tool embedded in the Airbus Performance Engineering Programs (PEP) suite, which rely on very accurate aircraft performance data. For each early descent, the resulting fuel consumption is compared with that of the corresponding idle-thrust trajectory starting at the planned (and optimal) TOD. This allows us to quantify the fuel differences from a theoretical point of view.

Then, a large sample of real aircraft trajectories obtained from automatic dependent surveillance–broadcast (ADS-B) records in Amsterdam-Schiphol (The Netherlands) TMA is used to provide an initial insight of the frequency of early descents, and the estimation of the fuel inefficiencies produced. Thus, a contribution of this paper is also to present a methodology to automatically identify early descents and to extract the key parameters required to compute the fuel inefficiencies from ADS-B data.

II. Aircraft Trajectory Planning and Execution

In order to quantify the fuel inefficiencies due to early top of descents in aircraft trajectories, one must know how descents are planned and executed by a typical flight management system (FMS). Before starting the descent, the FMS generates the most cost-efficient trajectory plan that complies with all operational constraints (including potential constraints depicted in the arrival/approach procedure). Then, during the execution of the trajectory, the FMS has a variety of guidance modes to follow the trajectory plan and to react in case deviations from the plan occur. The planning and guidance strategies presented in this paper reflect the behavior of the Airbus A320 (and arguably most of the Airbus models), as described in the flight crew operations manual (FCOM) [17]. It is worth noting that Boeing 737NG [18] and B757 [19] models use analogous planning methodologies and guidance strategies during early descents. Accordingly, the information presented herein is likely to be used by a very large percentage of airliners currently in operations.

This section describes the mathematical process that underpins the computation (planning) and execution (guidance) of realistic aircraft trajectories. Section II-A is devoted to trajectory planning, which a twofold objective: firstly, the method explained here is representative of the computation done by the on-board FMS when planning trajectories; secondly, this trajectory computation framework would be used to simulate idle-thrust and early descent trajectories in Section III, aiming at quantifying the fuel impact of early descents (the main motivation of this paper). Then, Section II-B focus on the guidance strategies relevant for this paper.

A. Trajectory Planning and Simulation

The motion of an aircraft in the vertical plane can be described by the following system of ordinary differential equations (ODEs), assuming continuous vertical equilibrium:

$$\begin{aligned} \frac{\mathrm{d}v}{\mathrm{d}t} &= \dot{v} = \frac{1}{m}\left[T(\pi, v, h) - D(v, h, m)\right] - g\sin\gamma, \\ \frac{\mathrm{d}h}{\mathrm{d}t} &= \dot{h} = v\sin\gamma, \\ \frac{\mathrm{d}s}{\mathrm{d}t} &= \dot{s} = v\cos\gamma, \\ \frac{\mathrm{d}m}{\mathrm{d}t} &= \dot{m} = -q(T, v, h), \end{aligned} \tag{1}$$

where the state vector, $\boldsymbol{x} = [v,\, h,\, s,\, m]^T$, is composed of the true airspeed, the geometric altitude, the along path distance and the mass of the aircraft; and the generic control vector of this model, $\boldsymbol{u} = [\pi,\, \gamma]^T$, is given by the engine throttle and the aerodynamic flight path angle (FPA). T is the total thrust delivered by the aircraft engines, D is the aerodynamic drag, g is the gravitational acceleration, and q is the total fuel flow.

Note that two degrees of freedom must be closed in order to integrate Eq. (1) along time. However, they are seldom given in terms of throttle (π) and flight path angle (γ) functions of the time. Instead, the aircraft trajectory is typically divided in different phases or segments, and most of them are operated at constant Mach or constant CAS (callibrated airspeed).

In some cases descents could be specified at a constant vertical speed (VS) and deceleration/acceleration segments are computed keeping a constant energy share factor[2]. Thus, in a more generic formulation, two path constraints (c_1 and c_2) shall be taken into account to mathematically close Eq. (1), rather than just assuming a given control vector $\boldsymbol{u}$:

$$c_i(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}) = 0; \quad i \in 1, 2, \tag{2}$$

where $\boldsymbol{p}$ is a vector of known parameters, also known as intents [20], e.g., the CAS in a constant CAS segment, the VS in a constant vertical speed segment, etc.

Equations (1) and (2) together form a system of differential-algebraic equations (DAEs) that fully describe a trajectory in the vertical plane. Unless π and γ are given as a known input control, it will be always needed to compute them first in order to transform the original set of DAEs to a system of ODEs suitable for numerical integration.

Wrapping up, a trajectory is defined as a sequence of consecutive phases. For each phase, two aircraft intents shall be given to specify the two path constraints mentioned above, along with at least one *exit condition* that will trigger the transition to the next phase. Moreover, certain models that are implicit in Eq. (1) could change in different phases, in order to consider, for instance, different flap/slat configurations, the deployment of the landing gear, the use of speedbrakes, etc.

1) Cruise: In cruise, aircraft typically fly at constant Mach (M) and constant pressure altitude (h_p), which is the altitude displayed by the barometric altimeter, which assumes the International Standard Atmosphere (ISA) model. Thus, the two path constraints of Eq. (2) will be given as:

$$\begin{aligned} c_1 &\equiv \frac{\mathrm{d}M}{\mathrm{d}t} = \frac{\partial M}{\partial h}\dot{h} + \frac{\partial M}{\partial v}\dot{v} = 0, \\ c_2 &\equiv \frac{\mathrm{d}h_p}{\mathrm{d}t} = \frac{\partial h_p}{\partial h}\dot{h} = 0, \end{aligned} \tag{3}$$

with

$$M = \frac{v}{\sqrt{\gamma_a \tau R}}, \tag{4}$$

where γ_a is the specific heat ratio of the air, τ is the temperature of the air, and R is the perfect gas constant; and

$$h_p = \begin{cases} \frac{\tau_0}{\lambda}\left(1 - \left(\frac{p}{p_{ref}}\right)^{\frac{R\lambda}{g}}\right) & \text{if } h < h_{11} \\ h_{11} - \frac{R\tau_{11}}{g}\ln\left(\frac{p}{p_{11}}\right) & \text{if } h \geq h_{11}, \end{cases} \tag{5}$$

where τ_0 is the standard temperature at sea level, λ is the ISA temperature gradient, h_{11} is the ISA tropopause altitude, p is the pressure of the air and p_{ref} is the altimeter setting.

2) Idle descent at a constant speed: As commented before, as long as the constraints on the arrival procedure allow, the FMS plans for an idle descent, which typically starts with a constant Mach descent, followed by a constant CAS descent. The values of Mach and CAS, respectively, are taken from pre-computed tables and aim to minimise a compound cost function of fuel and time, given the current flight conditions. The transition from the Mach to the CAS descent phase is known as the *cross-over altitude*, where the true airspeed is the same for the given Mach and CAS. For these two phases, the two path constraints of Eq. (2) will be given as:

$$\begin{aligned} c_1 &\equiv \frac{\mathrm{d}(\cdot)}{\mathrm{d}t} = \frac{\partial(\cdot)}{\partial h}\dot{h} + \frac{\partial(\cdot)}{\partial v}\dot{v} = 0, \\ c_2 &\equiv \pi = 0, \end{aligned} \tag{6}$$

where $(\cdot)$ is either Mach or CAS; and CAS is computed by the aircraft assuming ISA conditions and adiabatic compressible air flow at sea level:

$$\text{CAS} = \sqrt{\frac{2p_0}{\mu\rho_0}\left(\left(\frac{p}{p_0}\left(\left(\frac{\mu v^2}{2R\tau}+1\right)^{\frac{1}{\mu}}-1\right)+1\right)^{\mu}-1\right)}, \tag{7}$$

where $\mu = {}^{(\gamma - 1)}/_{\gamma}$, and p_0 and ρ_0 are, respectively the standard pressure and density values at sea level.

Then, at lower altitudes the FMS plans several phases that account for several decelerations, the deployment of flap/slats, the interception of the instrumental landing system (if any), etc. For the purposes of this paper, however, it is not needed to model theses phases since they will be the same for both the nominal trajectory and the simulated early descent.

3) Descents at a given vertical speed and constant speed: As it will be discussed later in Section II-B3, when an early descent is initiated, the guidance system of the FMS immediately commands a segment at constant speed and constant vertical speed (i.e. pressure altitude rate) aiming at intercepting, from below, the nominal trajectory path. This type of trajectory is not actually *planned* by the FMS, which has computed an idle-thrust trajectory as described above. Yet, for the purposes of this paper and to derive the results presented in Section III it is necessary to simulate these kind of trajectories in order to compute the fuel consumption.

It is worth noting that a first segment of constant Mach and constant vertical speed will be executed right after the actual TOD (earlier than that initially planned by the FMS). Then, if the nominal trajectory path has not been yet intercepted when reaching the cross-over altitude, a second segment will be flown at constant CAS and constant vertical speed. Thus, for this case, the two path constraints of Eq. (2) are:

$$\begin{aligned} c_1 &\equiv \frac{\mathrm{d}(\cdot)}{\mathrm{d}t} = \frac{\partial(\cdot)}{\partial h}\dot{h} + \frac{\partial(\cdot)}{\partial v}\dot{v} = 0, \\ c_2 &\equiv \frac{\mathrm{d}h_p}{\mathrm{d}t} = \frac{\partial h_p}{\partial h}\dot{h} = \text{VS}, \end{aligned} \tag{8}$$

where $(\cdot)$ is either the commanded Mach or CAS, and VS is the commanded vertical speed.

B. Trajectory Guidance

The guidance part of the FMS embeds the logic that will be executed to follow the previously planned trajectory. Typical aeroplanes have two independent actuators to steer the movement along the vertical plane: the elevator and the engine throttle. This means that among all the different (planned) variables that define a 4D trajectory, the guidance function of the FMS has to *choose* which two should be followed (or tracked) with the two actuators. For example, the guidance

[2] a parameter that specifies the ratio of the available thrust that is allocated to gain/loose kinetic energy as opposed to gain/loose potential energy

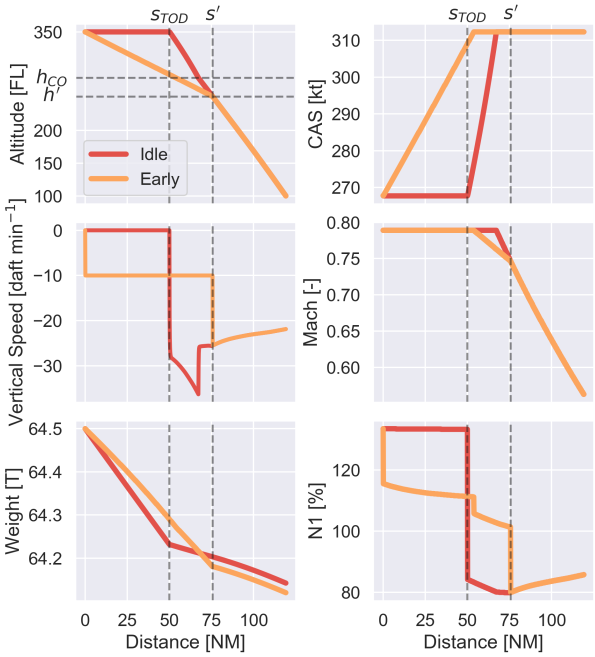


Figure 1: Comparison of idle-thrust and early descent

strategy could command the elevator to follow the path plan (i.e. the planned altitude along the climb/descent), while the throttle actuator could follow the planned throttle.

Assuming the FMS had perfect models when planning the trajectory, this would lead to the same 4D trajectory (and fuel consumption) as theoretically planned. Nevertheless, in a real flight, different sources of uncertainty would be present, such as aircraft performance models, weather forecasts, actuator dynamics, etc. This means that the other variables that are not followed by the guidance system will differ from the plan. In the previous example, where the path and throttle plan were commanded (and therefore followed by the actuators), the aircraft will not follow the planned speed schedule due to uncertainties, and the final fuel consumption would also differ from the computed one at the planning stage. In case, for instance, that throttle plan and speed schedule is commanded, then the actual path will differ from the planned one in presence of uncertainty.

The guidance function of the FMS contains in fact a quite complex logic of different guidance modes and strategies that are switched from one to another during the flight, depending on the deviations with respect to the plan.

1) Cruise: In cruise, the elevator is in charge to keep a constant pressure altitude, and the throttle is set to keep the commanded speed (typically Mach). Therefore, the actual throttle might differ from the planned one due to uncertainty.

2) Idle descent at a constant speed: Once reaching the planned TOD, the thrust is set to idle (i.e. the throttle plan is followed) and the elevator takes control of maintaining the speed schedule: Mach is followed first, and once the cross-over altitude is reached, CAS is followed instead. Typically, CAS remains constant until reaching FL100, where in most TMAs a speed limitation is enforced and consequently, the FMS will command a deceleration. In case of uncertainty, the aircraft would deviate from the planned path. Depending on these deviations the FMS would change the guidance commands to increase or decrease the descent rate, and therefore, the speed plan will not be longer followed.

In this paper we focus only in this initial descent, from the cruise altitude to FL100, since we assume that early descent trajectories will intercept the nominal descent path well before FL100. Figure 1 shows different characteristics of a typical idle-thrust descent trajectory (red lines) for an Airbus A320, as a function of the relative flight distance to the start of an hypothetical early descent. The early descent guidance strategy (orange line) is explained in the next section.

In this illustrative example, the idle-thrust descent starts 50 NM after the early descent, at the optimal TOD, which distance is denoted by s_{TOD}. Prior to the TOD, the fuel consumption is relatively high due to the engine thrust needed to sustain a steady speed while flying at the cruise altitude (see the mass profile in the bottom-left cell of Fig. 1. Right after the TOD, the engines are set to idle thrust (see the revolutions of the engine fan, N1, in the bottom-right cell of Fig. 1 and the elevator ensures that the initial Mach is maintained down to the cross-over altitude (h_{CO}). Under this guidance mode, the vertical speed ranges between -3,000 and -3,500 ft min^{-1}. At the cross-over altitude (around FL280 for this particular example), the elevator follows a constant CAS of 312 kt (see the top-right cell of Fig. 1) down to FL100. The engines remain at idle thrust all along the descent and, consequently, the mass of the aircraft slowly decreases after the TOD.

3) Descents at a given vertical speed and constant speed: As anticipated before, when the pilot initiates the descent before the (optimal) TOD computed by the FMS planning function, the FMS immediately attempts to intercept from below the nominal planned trajectory. Thus, the descent must be performed with a flight path angle shallower than that of the idle-thrust trajectory. Rather than descending at a determined flight path angle, however, early descents are typically commanded at a specific vertical speed. Regarding the speed, early descents are performed by adhering to the speed profile that was originally intended [17]. That is, at a given altitude, the guidance system will follow the Mach or CAS of the idle-thrust trajectory at the same altitude. This method guarantees that, when the idle-thrust trajectory is intercepted from below, the actual speed is the same as the intended one, allowing the optimal descent to be resumed.

If the nominal planned trajectory is intercepted before reaching the cross-over altitude, then thrust is set to idle and the elevator takes the speed control to maintain a constant Mach number down to the cross-over altitude, thereafter following the guidance strategy presented above. Otherwise, at the cross-over altitude the elevator keeps the desired vertical speed and the throttle switches to maintain a constant CAS. The last phase, which starts either at the cross-over altitude or when intercepting the idle-thrust descent trajectory, consists of flying with the throttle at idle and at constant CAS.

Figure 1 shows various characteristics of an early descent (orange lines), as a function of the flight distance. In this illustrative example, the early descent trajectory intercepts the corresponding idle-thrust trajectory at h', sightly below the cross-over altitude. Before the interception, the fuel consumption of the early descent is lower than that of the idle-thrust trajectory while the latter is still in cruise. After s_{TOD}, however, the idle-thrust trajectory is more fuel-efficient because of the lower thrust (see the bottom-right cell of Fig. 1). Note that after the interception, the fuel consumption of the idle-thrust and the early descent trajectories are almost identical, since both are flying with the engines at idle and following the same speed profile.

Rearranging Eq. (8) we obtain:

$$\begin{aligned} \dot{h} &= \text{VS}\left[\frac{\partial h_p}{\partial h}\right]^{-1} = f_1\text{VS}, \\ \dot{v} &= -\frac{\partial(\cdot)}{\partial h}\left[\frac{\partial(\cdot)}{\partial v}\right]^{-1}\left[\frac{\partial h_p}{\partial h}\right]^{-1}\text{VS} = f_2(\cdot)f_1\text{VS}, \end{aligned} \tag{9}$$

where $(\cdot)$ is either the commanded Mach or CAS and VS the commanded vertical speed. Then, by substituting this expression in the ODE system given by Eq. (1):

$$T = D + \frac{m}{v}[g + vf_2(\cdot)]f_1\text{VS}. \tag{10}$$

Note that a T higher than T_{idle} is typically required in these conditions, and thus the fuel consumption increases. In fact, for a given altitude, mass, and true airspeed, the required thrust to maintain a constant CAS or Mach is proportional to the vertical speed. Note that in this paper only the phase of descent and the cruise segment right before the TOD are considered, thus the vertical speed will be equal (in cruise) or lower than zero all along the trajectory. Accordingly, the closer to zero the commanded vertical speed, the more thrust is required to keep constant the commanded Mach or CAS.

Wrapping up, the fuel inefficiencies due to early top of descents in aircraft trajectories mainly depend on: (1) the value of s_{TOD}, (2) the fuel consumption of the nominal trajectory in cruise (which in turn depends on the cruise altitude, speed and mass), and (3) the fuel consumption of the nominal and early descent trajectories at idle-thrust (which mainly depends on the speed and altitude profiles).

III. Fuel Consumption Sensitivity Assessment with Simulated Early Descent Trajectories

The Airbus PEP (Performance Engineering Program) software suite has been used to assess the fuel consumption sensitivity due to early TOD in aircraft trajectories from a theoretical point of view. Airbus PEP allows to compute aircraft trajectory plans using accurate performance data from the manufacturer, as well as trajectory prediction and optimisation algorithms similar to those installed in the real FMS. Note, however, that the same kind of study could be also accomplished by using other aircraft performance models, such as the Base of Aircraft Data (BADA), and the trajectory planning and simulation methods described in Section II-A.

First, the optimal descent trajectory plan (at idle-thrust) of an Airbus A320, from the cruise altitude down to FL100, has been computed for a wide variety of flight conditions.

Each flight condition is determined by the combination of three input parameters: the mass of the aircraft at the TOD (m_0), the cruise altitude (h_0) and the cost index (CI). In this analysis, the following values have been considered for each one of these parameters, considering their typical range in actual operations: 64,500 and 70,500 kg for m_0; FL300, FL320, FL350 and FL370 for h_0; and 0 (i.e., maximum range), 20, 40 and 60 kg min^{-1} for the CI. For each possible combination of these three parameters, the optimal descent trajectory plan has been computed and the following attributes haven extracted: the optimal speed profile (i.e., Mach-CAS pair, which mainly depends on the CI), the optimal position of the TOD, and the optimal fuel consumption.

Then, for each one of these optimal (idle-thrust) descent trajectory plans, four hypothetical early descent trajectories have been simulated by using the same m_0 and h_0, as well as the optimal speed profile that was extracted from the optimal trajectory plan. In this experiment, the four early descent trajectories start the descent 10, 25, 50 and 75 NM before the optimal TOD, respectively, and thereafter fly with a vertical speed while following the original (optimal) speed profile until intercepting the corresponding idle-thrust trajectory plan from below. After the interception, the idle-thrust trajectory plan is resumed and executed down to FL100. In this study, the vertical speed intent, VS, during the early descent segment has been set to -1,000 ft min^{-1}, according to [17] and [18].

The optimal fuel consumption extracted from each idle-thrust trajectory plan has been compared with those of the 4 associated early descent trajectories. Furthermore, the altitude at which each one of the early descent trajectories intercepts the corresponding idle-thrust trajectory plan (h') has been also computed, aiming to identify its relationship with the distance at which the early descent trajectory starts from the optimal TOD (Δs) and the three parameters of the simulation.

Figure 2 shows the altitude drop (Δh), measured as $h_0 - h'$, that would be required to intercept the idle-thrust trajectory plan from below, as a function of the distance at which the early descent starts from the optimal TOD . Each row shows the results for one of the two masses considered in the study, while each column shows the results for a given cruise altitude. Within a cell, each line corresponds to a CI.

As expected, for a fixed combination of the three parameters, the earlier the descent starts from the optimal TOD (i.e., the higher the Δs), the more the altitude drop required to intercept the idle-thrust trajectory plan from below (Δh). Interestingly, for a given mass and cruise altitude, the relationship between Δs and Δh is almost linear, being the slope determined by the CI: The lower the cost index, the steeper the slope. In other words, the slower the optimal speed profile, the lower the altitude at which the idle-thrust trajectory plan is intercepted from below for the same Δs.

This observation is coherent with what one could expect by analysing the basic equations of motion: while the Airbus A320 executes the early descent at a fixed VS of -1,000 ft min^{-1} (independently of the CI), the descent rate of the idle-thrust trajectory plan is proportional to the true airspeed, as described by Eq. (1). Accordingly, the early descent trajectory, flying with a VS of -1,000 ft min^{-1}, would intercept before a fast idle-thrust trajectory plan than a slow one.

Figure 3 shows the fuel consumption difference between the early descent trajectories and the corresponding idle-

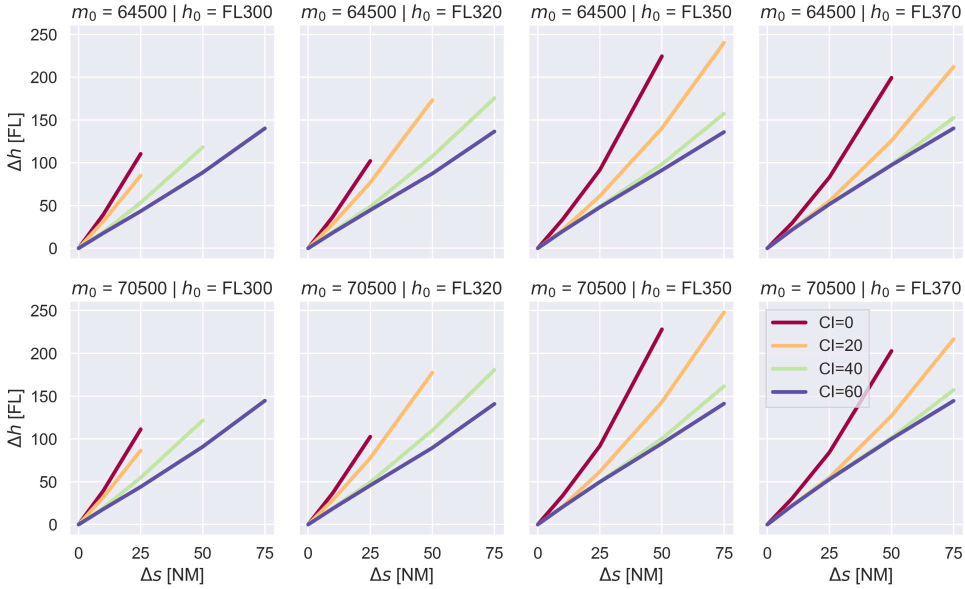
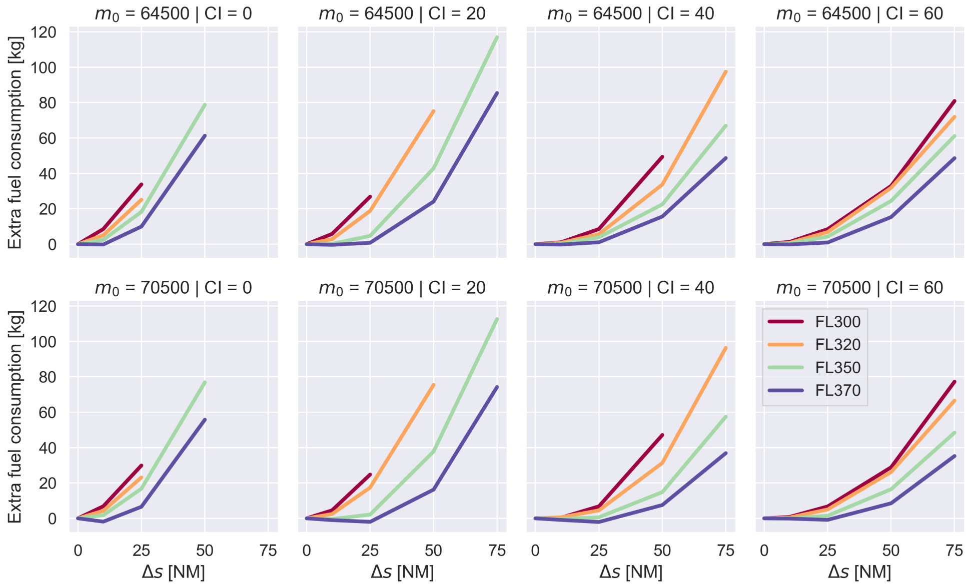
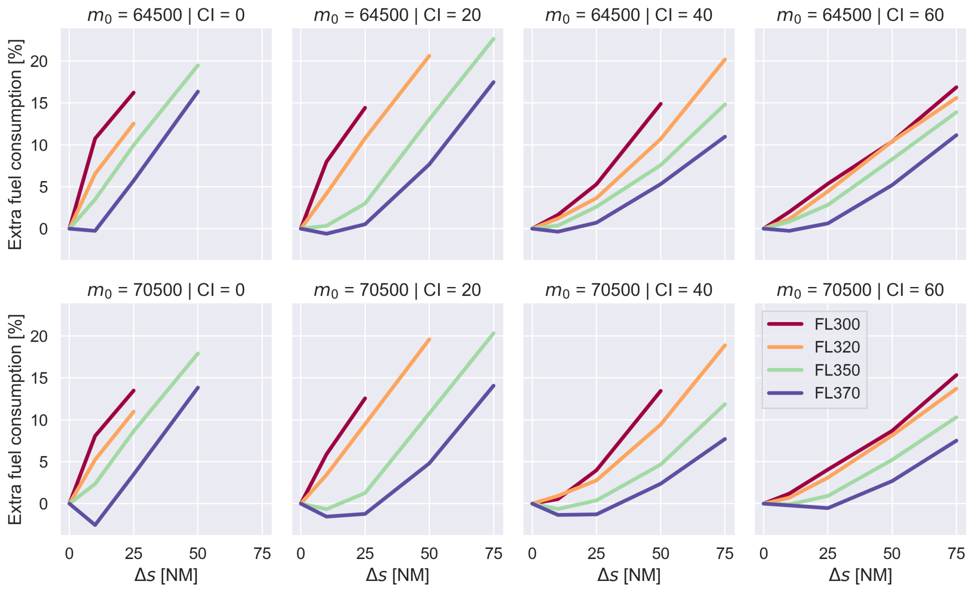


Figure 2: Interception altitude of early descents



(a) Absolute fuel inefficiency



(b) Relative fuel inefficiency

Figure 3: Fuel inefficiency due to early top of descents

thrust trajectory plan. Figure 3(a) shows the fuel consumption difference in absolute terms. The relative fuel consumption difference, if compared to the optimal fuel consumption of the idle-thrust trajectory plan, is shown in Fig. 3(b). Positive numbers indicate a higher fuel consumption. Different from Fig. 2, in Fig. 3 each cell shows the results for a different combination of mass and CI (the two parameters for which more variance on the fuel consumption difference was observed). Within a cell, each line corresponds to a different altitude, and results are shown as a function of the distance at which the early descent trajectory starts from the TOD.

According to Fig. 3(a), and independently of the combination of parameters, the earlier the aircraft starts the descent from the optimal TOD, the higher the extra fuel consumption if compared to that of the corresponding idle-thrust trajectory plan. For a given mass, a given cruise altitude and a given distance from the optimal TOD, increasing the CI reduces the extra fuel consumption, presumably because the idle-thrust trajectory plan is intercepted at a higher altitude (as shown in Fig. 2) due to the faster speed profile of the trajectory plan.

Similar to Fig. 2, the effect of the mass is residual, if compared with that of the other factors considered in this analysis. All in all, the relationship between the early descent distance (Δs) and the extra fuel consumption is polynomial.

In general, the extra fuel consumption (both in absolute and relative terms) when the aircraft starts the descent 10 NM before the optimal TOD could be considered small. Yet, even small amounts of fuel savings become significant at aggregate level, especially when considering the high volume of traffic that is operating every day. Furthermore, Figure 3 shows that, when the Δs is high, the extra fuel consumption cannot be neglected. In fact, the results of this theoretical assessment show that the extra fuel consumption due to early top of descents in aircraft trajectories could be as high as 120 kg (for an extreme case with Δs of 75 NM), representing a 20% increase when compared to the corresponding idle-thrust trajectory plan in the same flight conditions.

The results presented in this section were obtained by computing the optimal trajectory plan (at idle-thrust), and then comparing its fuel consumption with that of several (simulated) early descent trajectories under the same flight conditions, each one starting at a different distance before the (known) optimal TOD. In *real-life*, however, the optimal trajectory plan (and the associated TOD) is only known by the on-board FMS, which data are propriety of the airline and are not publicly available. Actually, only the executed trajectory can be captured from surveillance data, but the not plan.

Consequently, when using surveillance data as the only source of flight data (which is the most common situation), one must address several issues in order to quantify the fuel consumption impact due to an early descent: (1) the fuel consumption of the executed trajectory is not explicitly present in the data, and therefore must be estimated somehow; (2) it is not straightforward to identify whether an aircraft has started the descent before the optimal TOD or not, because the optimal TOD is unknown a priori (as it is the trajectory plan); (3) assuming that the fuel consumption of the executed trajectory and the optimal TOD were known, one would still need access to the optimal speed profile in order to estimate the optimal fuel consumption. Unfortunately, only the executed speed profile is available in the surveillance data.

The first issue can be effectively solved by using algorithms of fuel estimation from surveillance data, as proposed in [21]. Next section describes fundamental methods to automatically detect early descents from surveillance, as well as to extract the key parameters required to quantify their fuel impact, thus addressing the second and third issues, respectively.

IV. Early Descent Detection and Key Parameters Extraction

The guidance strategies used during an early descent are known, and one can use this valuable information to (1) detect early descents by observing the altitude and vertical speed profiles, and (2) extract all necessary parameters required to estimate the fuel consumption impact.

A. Early Descent Detection

Figure 4 shows the vertical speed of an Airbus A320 with the engines at idle assuming a typical descent mass of 58 tonnes, which roughly corresponds to 90% of the maximum landing mass (MLM). The vertical speed is presented as a function of the altitude and true airspeed of the aircraft, and several speed profiles are illustrated (typical, fast and slow).

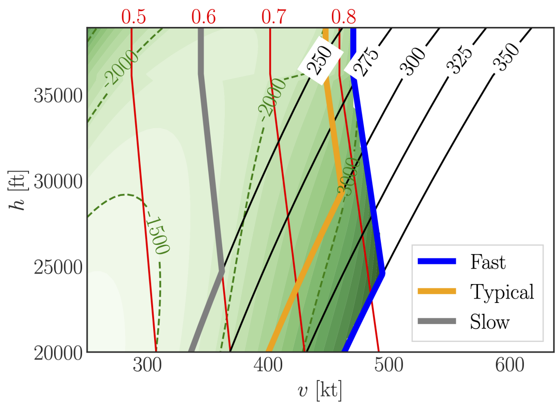


Figure 4: Vertical speed for an Airbus A320 with the engines at idle (this figure was generated by using the Airbus PEP)

According to Fig. 4, the vertical speed of an Airbus A320 with the engines at idle for a typical descent mass is lower that -2,000 ft min^{-1} for most operational speed profiles, well below the -1,000 ft min^{-1} corresponding to the interception phase of an early descent trajectory. This indicates that an aircraft descending with a vertical speed of -1,000 ft min^{-1}, no matter its altitude or speed, is applying some throttle.

The method proposed in this paper is based on the fact that, during an early descent, the guidance system commands a constant VS of -1,000 ft min^{-1} until intercepting the idle-thrust trajectory plan from below. Thereafter, the engines are set to idle and one could expect a sudden increase of the descent rate (i.e., a more negative vertical speed).

In this study, we employ a sliding window of 10 second at the start of the actual descent trajectory as captured from the surveillance data (i.e., when the aircraft *leaves* the cruise altitude). We apply a simple linear regression on the altitude data within this time window. The vertical rate is estimated as the slope of this linear regressor. The mean absolute error between this estimated vertical rate and vertical rate reported in the ADS-B is then calculated and the following two criteria are evaluated to determine the occurrence of an early descent:

1) The difference between the estimated vertical rate and -1,000 ft min^{-1} is smaller than 150 ft min^{-1}
2) The mean absolute error of the estimated vertical rate and ADS-B vertical rates is smaller than 150 ft min^{-1}

With the sliding window, the start (at the cruise altitude, h_0) and end (at the interception altitude, h') of early descent can be identified. In Figure 5, the result of such detection process is illustrated using a real trajectory from ADS-B data.

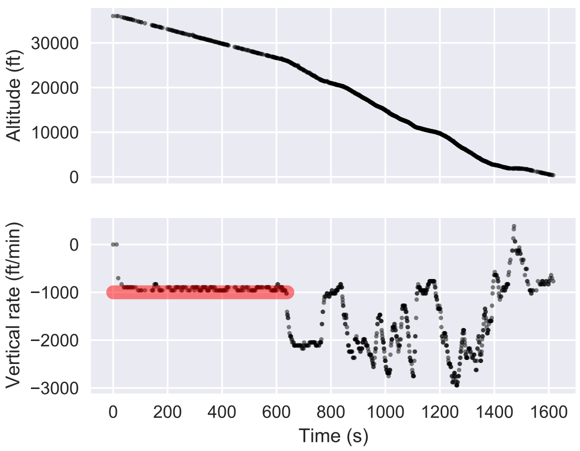


Figure 5: Detecting an early descent from ADS-B data

B. Key Parameters Extraction

When using real surveillance data, the trajectory plan is unknown (and the TOD). Yet, it can be inferred by exploiting the fact that it was computed at idle-thrust and using the speed profile observed in the actual (early descent) trajectory.

By observing the surveillance data, it is possible to detect the constant Mach and constant CAS segments of the descent, and then extract their Mach and CAS parameters, respectively (i.e., the speed profile). In this study, we employ two piece-wise regression models to detect the constant Mach and CAS segments. The Mach profile is described by using two linear pieces. The CAS profile consists of a linear and a quadratic piece, due to the high non-linearity in speed for the final approach segment. The model can be described as follows:

$$f_{mach}(t) = \begin{cases} M & t \leq t_m \\ -k_1 \cdot (t - t_m) + M & t \geq t_m \end{cases} \quad (11)$$

$$f_{\text{CAS}}(t) = \begin{cases} \text{CAS} & t_m \leq t \leq t_c \\ -k_2 \cdot (t - t_c)^2 + \text{CAS} & t \geq t_c \end{cases} \quad (12)$$

where t_m and t_c are the (unknown) times where the constant Mach and constant CAS segments start, respectively; and $k1$ and $k2$ are regression model coefficients which also need to be estimated by minimising the mean square error between the model described by Eqs. (11) and (12) and the observed data.

In Figure 6, the result of such extraction process is illustrated using a real trajectory obtained from ADS-B data.

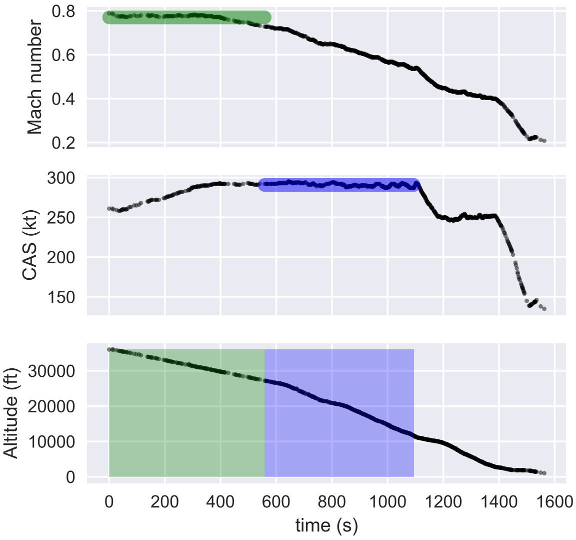


Figure 6: Detecting speed profile from ADS-B data

The cruise altitude can be also obtained easily from surveillance data. Finally, estimating the mass is not straightforward, especially during the phase of descent. However, as discussed in Section III, the effect of the mass on the fuel consumption impact is residual if compared to that of the other factors. Therefore, using a typical descent mass should not significantly impact the results of the assessment.

Knowing the speed profile, the interception altitude h' (extracted by using the method described in the previous section) and a *guess* for the mass, it is possible to generate the hypothetical idle-thrust trajectory plan: starting at h', and integrating backwards the ODEs of Eq. (1) with the two constraints of Eq. (6) (using the extracted CAS and Mach) until reaching the cruise altitude h_0 at the the estimated TOD. Note that this strategy requires an aircraft performance model (e.g., BADA) and a solver of DAEs to integrate the trajectory.

In this paper, however, a different strategy has been adopted: the results obtained from the trajectories simulated with Airbus PEP have been used to fit an interpolator. The *key* parameters (all of them extracted from surveillance data) required to query the interpolator and assess the fuel consumption impact of a real early descent, previously detected by using the method described in Section IV-A, are:

- h_0: cruise altitude,
- Δh: altitude drop, i.e., $h_0 - h'$
- CAS: callibrated airspeed of the descent,
- M: Mach of the descent,
- m_0: mass of the aircraft at the top of descent.

V. Case Study for Amsterdam-Schiphol TMA

This Section combines the theoretical results presented in Section III and the methods proposed in Section IV to perform an initial assessment of the fuel consumption impact due to early TOD for Airbus A320 aircraft descending at Amsterdam-Schiphol airport (EHAM) from 1$^{\text{th}}$ to the 30$^{\text{th}}$ of

April 2018. In total, 4,139 complete descent trajectories were extracted from ADS-B data.

First, the early descents in the traffic sample were detected by using the method described in Section IV-A. The remaining trajectories were filtered out. Then, for each one of the detected early descents, the key parameters where extracted by using the method described in Section IV-B. Finally, the nearest-neighbor interpolation method (also known as proximal interpolation) was used to estimate the fuel consumption impact caused by each one of the detected early descents.

The data points of the interpolator were populated with the data obtained from the simulations performed with Airbus PEP. The coordinates of each data point correspond to the (h_0, Δh, CAS, M, m_0) of one early descent simulations, and the data point value is the associated absolute (or relative) extra fuel consumption, with respect to the corresponding idle-thrust trajectory plan that starts the descent at the TOD.

For each one of the detected early descents (from ADS-B data), the interpolator was evaluated with the key parameters extracted from the real trajectory, re-scaling points to unit cube before performing interpolation. As mentioned in Section IV-B, estimating the aircraft mass during the descent is not straightforward. Theoretical results shown in Section III, however, suggested that the effect of the aircraft mass in the fuel consumption impact is marginal if compared to that of the other influencing factors (e.g., the speed profile). For this reason, a mass m_0 corresponding to the MLM was assumed for all ADS-B trajectories when evaluating the interpolator.

1) Illustrative Example: Figure 5 shows the altitude and vertical speed profiles of a real descent, which was sampled from the set of trajectories obtained from ADS-B data. Figure 6 shows the speed profile of the same trajectory.

The method proposed in Section IV-A classified this trajectory as an early descent, due to the long segment at -1,000 ft min^{-1} executed after the actual top of descent at FL360. This segment at constant VS stops at FL260, where the aircraft intercepts from below and resumes the (presumably) idle-thrust trajectory plan. The difference between the cruise altitude (FL360) and the altitude where the idle-thrust trajectory plan is intercepted (FL260) represents an altitude drop of 10,000 ft.

The method proposed in Section IV-B was used to extract the speed profile, effectively detecting a Mach of 0.79 and a CAS of 290 kt. Assuming a mass corresponding to the MLM, the key parameters of this illustrative early descent are: h_0: FL360; Δh: 10,000 ft; CAS: 290 kt; M: 0.79; and m_0: MLM.

The nearest-neighbor strategy, applied to the fitted interpolator with the key parameters listed above, suggests that this early descent trajectory burned 20 kg (6%) more fuel than the corresponding (and unknown) idle-thrust trajectory plan.

2) Aggregated Results: From the 4,139 trajectories in the traffic sample, 868 early descents were detected by using the method presented in Section IV-A, which represents a 21% of the total number of trajectories in the traffic sample.

Figure 7 shows the distribution of key parameters for the 868 early descents detected in the traffic sample. According to Fig. 7, FL340 and FL360 were the most common initial altitudes, followed by FL330 and FL380; the distribution of CAS has a peak at 275 kt, with a mean value of 290 kt; the distribution of Mach has a peak at 0.79, with a mean value of 0.78; the distribution of altitude drop is positively skewed, with a peak around 5,000 ft and a mean value of 6,000 ft.

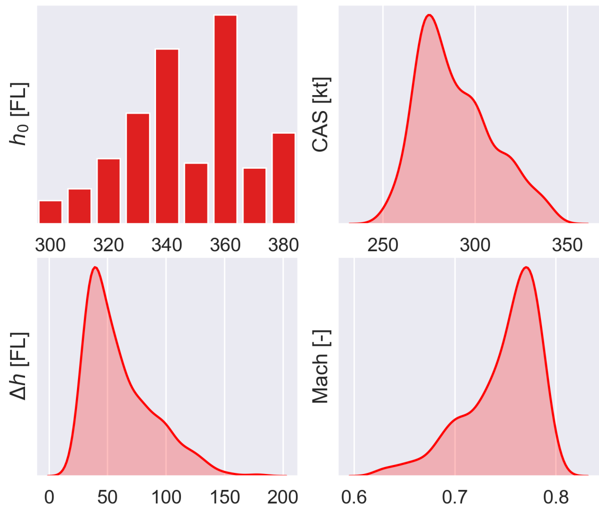


Figure 7: Key parameters of the early descents detected in the traffic sample obtained from ADS-B data

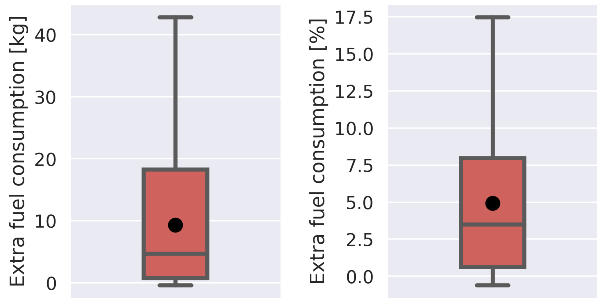


Figure 8: Fuel consumption impact due to early TOD for the early descents detected in the traffic sample obtained from ADS-B data

Figure 8 shows a *box-plot* of the extra fuel consumption in absolute (left plot) and in relative terms (right plot). Remember that the extra fuel consumption of each one of the 868 early descents detected was obtained by evaluating the nearest-neighbour interpolator, which was fitted with the data from the Airbus PEP simulations, with the key parameters extracted from the corresponding ADS-B trajectory. In this kind of plot, the box shows the quartiles of the data, and the whiskers represent a multiple (in this case 1.5) of the innerquartile range (IQR). The horizontal bar inside the box indicates the median value, and the black-filled circle represents the mean. According to Fig. 8, the estimated mean extra fuel consumption caused by early top of descents in Airbus A320 trajectories in the TMA of EHAM during the month of study was around 10 kg, which represents a 5% increase when compared to the fuel consumption of the corresponding idle-thrust trajectory plans. The median of the distribution was 5 kg, which represents a 3.5% increase. Interestingly, Fig. 8 also shows that 25% of the early descents caused an extra fuel consumption higher than 19 kg (roughly 8% increase).

VI. Conclusions

This paper characterised and assessed the fuel consumption impact due to *early descents* (i.e., when the pilot starts the descent before than initially planned). Two important reasons behind early descents are: (1) the fact that air traffic control (ATC) officers do not know the exact position of the optimal top of descent (TOD) calculated by the on-board flight management system (FMS); and (2) the fact that their main focus is on the safety of the arriving traffic flow, rather than the fuel consumption efficiency of a single flight.

Because the equations describing the dynamics and performance of the aircraft are very nonlinear, various simplifications would be required to obtain at an analytical solution for fuel consumption along the descent. The error introduced by such simplifications, however, may be larger than the fuel consumption difference between early and idle-thrust descents. For this reason, the theoretical impact on fuel consumption has been performed through numerical simulations, using an accurate trajectory prediction tool from the manufacturer.

Despite revealing that early descents are common and that their impact on the fuel consumption is not negligible, the causes of their occurrences were not investigated in this study. Future work could combine recordings of ATC transmissions with surveillance data in order to effectively understand under which circumstances early descents are requested. An extension of the work presented herein could also take advantage of the large amount of data that is publicly available nowadays to find a correlation between the complexity of the traffic in the terminal airspace and the frequency of early descents, as well as potential patterns with other variables, such as those related to weather, the airline, and/or the hour of the day. Understanding the factors that drive early descents will be a first necessary step towards minimising their negative impact.

It should be noted that the results of the fuel consumption impact characterisation performed in this paper were obtained by assuming standard atmospheric conditions and disregarding winds. Future work should quantify the sensitivity of these fuel consumption impact figures with the weather variables (e.g., by considering the effect of the longitudinal wind and/or the temperature in the controlled simulations), as well as validate the figures with flight data recorder (FDR) values.

Furthermore, the assessment with real surveillance data was performed for one single terminal maneuvering area (TMA) and for just one month. Thus, the results obtained are limited to the investigated TMA and time period, and cannot be generalised. In the future, the same type of evaluation may be done across a wide range of TMAs over a long time span, with the aim of discovering variations in the occurrence and consequences of early descents through TMAs and seasons.

Finally, it should be noted that the room for improvement in terms of fuel consumption is higher in the climb and cruise phases of flight. Yet, the time and cost required to put in place the procedures and technology that would provide such benefits is notable. The goal of this research is to raise awareness about the frequency of early descents, and to encourage ATC to simply respect the optimal TOD as much as possible in order to reduce the fuel consumption impact.

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