FUEL BURN BENEFITS OF ALTITUDE OPTIMIZATION STRATEGIES IN THE CRUISE PHASE OF LONG-HAUL FLIGHTS

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ABSTRACT

This paper focuses on the vertical profile of the cruise phase of long-haul commercial flights covering legislation, operational standards, communications, surveillance, flight planning and performance aspects. Two case studies are presented: the first one describes and compares an actual vertical profile of a flight and an optimised one, with detailed calculations as well as results estimation; the second one compares two vertical profile optimization procedures strategies. Small modifications in how cruise phase of a flight is operated airlines can achieve cost reductions, mitigate environmental impacts, and contribute to airspace efficiency.

Keywords: Altitude Optimization, Emissions Reduction, Fuel Conservation, Long-Haul Flights, Vertical Profile.

1. INTRODUCTION

Improving aircraft operational efficiency has become a dominant issue in air transportation, as the recent social and political climate has pushed for reduced environmental impact.

Scientific evidence of global climate change increased awareness on the importance of pollutant gases emissions such as CO_2, resulting in a significant pressure to reduce emissions. Air transport is responsible for 2% of man-made carbon emissions annually (IATA, 2014). But the industry recognizes that it must work ever harder on behalf of the environment to achieve long-term sustainability, which will give the industry a license to grow. In 2009, therefore, the industry - comprising airlines, business aviation, airports, airplane manufacturers, and air navigation service providers (ANSP's) - committed to a united approach in reducing emissions that includes three carbon emissions goals (IATA, 2014):

- Improving fuel efficiency an average of 1.5% annually to 2020;
- Capping net emissions through carbon-neutral growth from 2020; and
- Cutting net emissions in half by 2050, compared with 2005.

In 2014 the fuel impact on the operating costs of the global airline industry was $226 billion (accounting for 32,3% of operating expenses at $101,4/barrel of oil), which is near five times the fuel bill of 2003 at $44 billion (that accounted for only 13,6% of operating expenses at $28,8/barrel), (IATA, 2015).

Environmental concerns provide further motivation for fuel conservation as climate and air quality impacts from hydrocarbon fuel combustion gain greater scientific and social prominence. There are various techniques to control fuel related environmental impact with varying implementation timelines and potential benefit. These include new aircraft technology, retrofits to existing aircraft technology, alternative jet fuel and propulsion technology, major infrastructure improvements and operational mitigation (Jensen and Hansman, 2014).

Efforts to modernize aircraft technology are limited by the extremely slow and expensive process of adopting new aircraft, which can take decades (Kar, Bonnefoy and Hansman, 2010). Major infrastructure improvements like the Single European Sky ATM Research (SESAR) in Europe or the Next Generation Air Transportation System (NextGen) in North America promise efficiency improvements but also face long implementation timelines. Operational mitigations are useful due to the potential for rapid implementation and low capital expenditure, although the long-term benefit is generally less than other technology-driven solutions. Prior work in academia and industry has identified many potential operational mitigations, including barriers to implementation and potential benefits.

Operational strategies for fuel conservation are those that involve the way an aircraft is flown, handled on the ground or managed in the air traffic control (ATC) system. They are implementable without modification to aircraft structures or engines, but may require investment in avionics, infrastructure and training. These strategies can be implemented in all phases of flight.

This paper begins with an introduction to environmental aspects and fuel savings, then the objectives are set, and the scope defined. The second section depicts legislation, and the operational aspects for vertical trajectory management, communication and surveillance technology tools. On the third section, the case study of NATCLM and all the technology needed to perform the flight trials are described, as well the estimation of savings and results from the flight trials. The fourth section presents another case study, the ISAVIA one, and its results. On the fifth session, a comparison between the two case studies, NATCLM and ISAVIA, is presented, as well as some concluding remarks. As a conclusion, the sixth section contains final remarks and perspectives for future research.

2. STATE OF ART

2.1 ICAO RULES FOR SEPARATION AND MINIMA

Vertical separation is obtained by requiring aircraft using prescribed altimeter setting procedures to operate at different levels

expressed in terms of flight levels (FL) or altitudes in accordance with the Altimeter Settings Procedures of ICAO. The vertical separation minimum (VSM) shall be (ICAO, 2007):

(a) A nominal 300m (1.000ft) below FL290 and a nominal 600m (2.000ft) at or above this level, except for in (b) below; and
(b) Within designated airspace, subject to a regional air navigation agreement: a nominal 300m (1.000ft) below FL410 or a higher level where so prescribed for use under specified conditions, and a nominal 600m (2.000ft) at or above this level.

2.2 STANDARDS FOR THE USE OF VERTICAL AIRSPACE

The optimal vertical profile of a flight depends on several factors, the aircraft type, aircraft gross weight, environmental conditions (mostly the temperature and wind evolution), flight plan (FPLN) and ATC interventions.

All the phases of a flight are filled within the ICAO flight plan, including horizontal elements of the vertical profile expected/ preferred by the air user (ICAO, 2007). The OFP also contains all characteristics of the flight (airways, times of overfly of waypoints, distances between waypoints, tracks, FL's, fuel consumption, aircraft weights, air speeds, ground speeds, etc.). This operational flight plan (OFP) is the basis for the flight execution. Every ATS along the flight routes receives a copy of the ICAO FPLN so the ground services have full pre-flight information about the planned vertical profile of a flight (SESAR, 2010).

2.3 DATA-LINK SERVICES CONSIDERED FOR VERTICAL AIRSPACE MANAGEMENT

Firstly, the Automatic Dependent Surveillance - Contract (ADS-C) is a tool used by air traffic services (ATS) in which aircraft automatically transmit, via a data link, data derived from on-board navigation systems. According to the ICAO Doc. 4444 (ICAO, 2007) the ground systems shall provide for:

- the transmitting, receiving, processing and displaying of ADS-C messages related to flights equipped for and operating within environments where ADS-C services are being provided; the display of safety-related alerts and warnings;
- position monitoring (the aircraft's current position as derived from ADS-C reports is displayed to the controller for air traffic situation monitoring);
- conformance monitoring (the ADS-C reported current position or projected profile is compared to the expected aircraft position, which is based on the current flight plan. Along track, lateral and vertical deviations that exceed a pre-defined tolerance limit will permit an out-of-conformance alert to be issued to the controller); and
- flight plan update (i.e. longitudinal variations that exceed pre-defined tolerance limits will be used to adjust expected arrival times at subsequent fixes).

Secondly, the Automatic Dependent Surveillance - Broadcast (ADS-B) is a surveillance system based on the ability of the aircraft to periodically and automatically broadcast a set of data, its state vector as minimum. This data can be received by any user, either aircraft or ground-based, within range of the broadcast that choose to receive and process the ADS-B information.

Thirdly, Controller-Pilot data link communication (CPDLC) is an ATC communication tool that uses a data link to establish communication between air traffic controllers (ATCo) and pilots.

3. NATCLM CASE STUDY

3.1 INTRODUCTION

The Atlantic Interoperability Initiative to Reduce Emissions (AIRE) is an agreement between the European Commission (EC) and the Federal Aviation Administration (FAA) of the United States of America. It is a project that aims to reduce CO_2 emissions by taking advantage of ATM best practices and new

technologies, it expects to accelerate the implementation of environmentally friendly procedures for all flights and to validate the benefits of these improvements. The SESAR Joint Undertaking (SESAR JU) is responsible for the management of AIRE from a European perspective (SESAR JU, 2010a). The project includes a set of activities for aircraft vertical trajectory optimization in the oceanic domain.

3.2 FLIGHT TRIALS

Several flights between Europe and North, Central and South America provided data and derived results for the project. The demonstrations were carried out inside one of the Oceanic Flight Information Regions (FIR) that compose the North Atlantic Region defined by ICAO.

Some flights were supported by the Air Navigation Service Provider (ANSP) that manages and follows the FIR where the trials were taking place to allow for an extension of the flight profile optimization.

Data link communications were used to support the flight trials. So, it was required for the execution of the optimization commands that all aircraft taking part in the trials were equipped with Future Air Navigation Systems (FANS).

All flight trials were conducted exclusively with ADS-C / CPDLC certified flights and were handled expeditiously by the operators involved regarding all current standards and practices. None of the flight trials were constrained by any reason other than safety or ICAO regulations. In total, fifty flights, by the several airlines involved in the project were optimized.

3.3 RESULTS AND DISCUSSION

During any commercial flight, the air temperature, air density and wind velocity can be recorded. As these values are not known before the flight and they are needed for filling the flight plan, forecast values, given by the meteorology are used instead. Other important parameters like the exact weight of passengers, luggage and remaining fuel, are never certain.

To reduce the uncertainty of the results, the specific range deviation was determined for different segments of the flight, which makes it possible to determine an average performance factor to apply to all predictive performance calculations.

For all trials the actual fuel consumption was compared with the predicted fuel consumption for the prevailing conditions and with predicted fuel consumption in the cases where the current techniques were used.

To determine the actual fuel consumption the data extracted from the flight data recorders was used, integrating it in time instantaneous readings of the relevant parameters. The fuel consumption figure was compared with the fuel quantity readings, which allowed to determine how much fuel was used between the initial and final instants considered.

The prediction of fuel consumption for the prevailing conditions was made using the manufacturers Performance Programs (Jensen and Hansman, 2015). Calculations were performed in a sequence of 100ft climbs plus cruise segments at increasing flight levels, from the initial weight at a given level, until the optimum weight to climb another 100ft is attained.

So, for the prediction of fuel consumption for the current climb technique, it was used a Performance software, by calculating a cruise segment from the start of the cruise until the point where optimum weight for a 2.000ft step climb is attained, plus a climb of 2.000ft, plus a cruise segment until the same point where the cruise climb would be finished (SESAR JU, 2010a).

For the estimation of savings, an A330-202 aircraft was used. And the steps were calculated at a weight that leads the aircraft to be at the optimal weight for the average altitude of the altitude between the steps. These yields results are expected to be valid for other aircraft types in a qualitative way. Three different optimization strategies were tested, besides the current operational situation:

- Case 0, was a step climb of 1.000ft, from FL360 to FL370 followed by a cruise segment at FL370 and then step climb from FL370 to FL380;
- Case 1, was a 2.000ft step climb from FL360 to FL380;
- Case 2, was a series of 100ft steps each followed by a cruise segment; and

- Case 3, was a continuous climb at a rate as close as possible to the one that makes the aircraft follow the path of optimum altitude versus weight (in this case 10ft/min). This, in theory, could be called the actual Cruise Climb Technique, although it proved to be far from ideal.

Table 1 summarizes the results obtained, considering the following conditions too:

- Cruise at Mach 0,80;
- Climb at maximum rate;
- Initial weight: 205.300kg, which is close to the optimum weight for FL360 (205.270kg); and
- Final weight: 186.400kg, which is the optimum weight for FL380.

Table 1: Estimation of savings - Summary (SESAR JU, 2010a)

	Case 0 (1.000ft step)	Case 1 (2.000ft step)	Case 2 (100ft step)	Case 3 (Slow climb)
Distance from [205.300; 186.400] kg (NM)	1.596,8	1.595,3	1.597,9	1.565,8
Extra distance to case 2 (NM)	1,1	2,6	0,0	32,1
Extra fuel for distance for case 2 (kg)	12	29	0	360
Final weight (kg)	186.388	186.371	186.400	186.040
Fuel increase for case 0 (kg)	0	17	-12	348
% increase for case 0	0,00	0,09	-0,06	1,84
Fuel increase for case 1 (kg)	-17	0	-29	331
% increase for case 1	-0,09	0,00	-0,15	1,75
Fuel increase for case 2 (kg)	12	29	0	360
% increase for case 2	0,06	0,15	0,00	1,90

From Table 1 it can be concluded that there are potential savings of 0,06% when flying as specified in Case 2 comparing to Case 0. If a comparison is made to Case 1 the potential fuel savings reaches 0,15%.

3.4 REMARKS

The fact that there are so many changes in some of the variables during any flight and that these savings are of such a low magnitude, precludes the use of a methodology based in global parameters like the fuel spent per flight, even if it is corrected for payload and meteorological differences.

To make an analysis based on the factors above mentioned, it would be necessary to have data from a larger number of flights, during a very long period and this is simply not feasible due to the current state of on-board equipment and to the burden it would impose on pilots. Such a burden would increase risks in terms of operational safety.

The methodology used, changing from climb to cruise modes and back, was validated through this analysis, which proved that the estimation of savings was in line with the actual data obtained from the flight trials.

Enhancements to the ATM system can be done quickly and easily, under the control of the local ANSP and would allow for immediate benefits. Changes to the AIDC protocol would require coordination within the NAT region and would allow for the continuation of the optimized trajectory across FIR boundaries. Changes in the avionics systems could also help a faster implementation of more efficient vertical profiles in large scale.

4. ISAVIA CASE STUDY

4.1 INTRODUCTION

As a part of the AIRE project, the case of ISAVIA also aims to demonstrate, through simulation and flight trials, the benefits that can be obtained if more efficient flight profiles are used. The flight trials performed for this project had the goal of validating practical actions that could be employed in the present or soon that would lead to fuel savings.

4.2 FLIGHT TRIALS

The typical cruise flight of a jet aircraft involves a sequence of level segments

increasing in altitude as fuel is burned. The steps in altitude are typically 1.000ft, 2.000ft, or 4.000ft depending on the constraints of the airspace where the aircraft is flying. A step climb is typically made when the flight efficiency between two candidate altitudes is approximately the same. At that point, the optimal altitude is approximately at the mid-point between the two altitudes (SESAR JU, 2010b).

There is a potential for increased fuel savings by allowing aircraft to continuously fly their optimal cruise altitude. This is known as cruise climb and is a continuous climb in the cruise phase of a flight that optimizes the vertical profile in terms of fuel consumption. The flight altitude is continually increased to ensure that the aircraft is at its optimum altitude as its weight decreases due to fuel burn.

Because of limitations in the current avionics systems, flying a Cruise Climb is an arduous process of continuous configuration while climbing and so, making it an option that is not feasible for the flight trials. The cruise climb rate of approximately 10 to 15ft/min was approximated by a climb rate of 100ft/min. This approximation is named Limited Cruise Climb. Figure 1 shows how a reduced climb rate is used to approximate a Cruise Climb. After the ATC clearance, the pilot sets the climb rate of 100ft/min instead of the standard 500ft/min. For all the 14 flights trialed, the climbs were performed at a fixed Mach speed of M0.80 in a B757-200 (SESAR JU, 2010b).

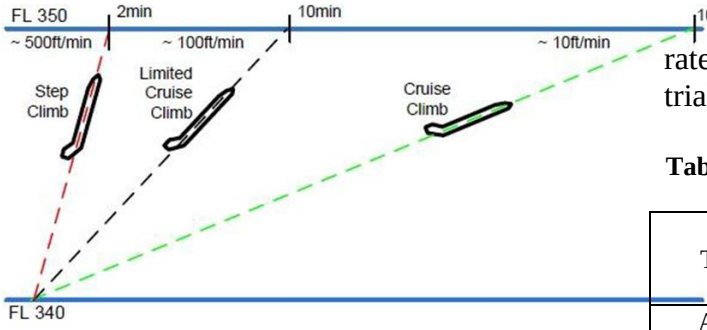


Figure 1: Difference between cruise climb, limited cruise climb, and regular step climb (SESAR, 2010a)

4.3 RESULTS AND REMARKS

The benefit from the limited cruise climb technique is calculated at around 330kg of fuel. Table 2 shows the average fuel savings and total fuel savings from the 14 flight trials.

Table 2: Summary of the results obtained (SESAR JU, 2010b)

	Number of flights	Average savings (kg)	Total savings (kg)
Limited Cruise Climb	14	330	4260

From the results obtained by the flight trials performed by ISAVIA, another technique that can be used to further optimize the vertical profile of a flight was validated. This technique can be employed with the current state of the systems (ground and airborne) and is only dependent on traffic conditions and clearance from the ATC.

5. FLIGHTS PROFILES COMPARISON

5.1 INTRODUCTION

For a comparison of case studies, it is necessary to find some common ground where comparing would make sense and contribute to the development of the state of the art. Thus, three main points of comparison where chosen:

- Flight profile;
- Results; and
- Operational Feedback;

5.2 FLIGHTS PROFILES

The flight profile tested for NATCLM was a division of a 2.000ft step climb into twenty 100ft steps climbs, climbing at a 250ft/min climb rate. By doing this, the goal was to remain as close as possible to the theoretical most efficient flight profile.

From Table 3 the average cruise climb rate for an A330 like the one used in the flight trials can be obtained.

Table 3: Cruise climb rate of climb for several aircraft (SESAR JU, 2010b)

Type	Distance between 2.000ft altitude step (NM)	Climb rate Mach 0,80 (ft/min)
A300	1.000 – 1.100	16,8
A310	1.150 – 1.250	14,7
A320	1.200 – 1.300	14,1
A330	1.500 – 1.650	11,2
A340	1.500 – 1.650	11,2
A340-500/600	1.600 – 1.700	10,7

With the information on the cruise climb rate from Table 3 and the information presented

opportunely for NATCLM, the graph from Figure 2 was built, using a climb rate of 500ft/min for the step climb, 11,2ft/min for the cruise climb and 250ft/min climb for the 100ft step climbs.

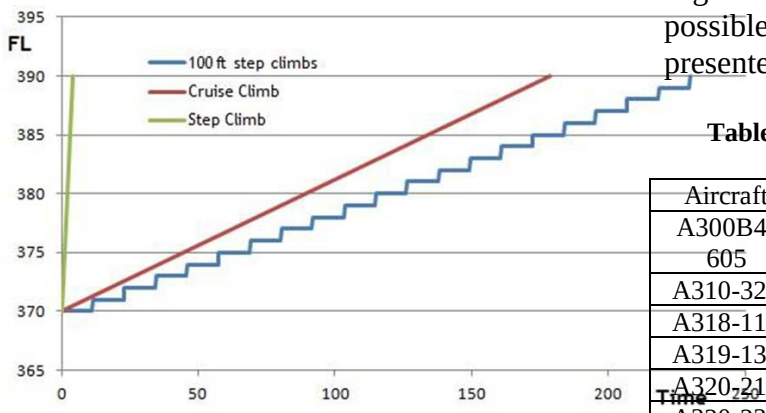


Figure 2: Time needed for a 2.000ft altitude change for an A330

From Figure 2, it can be observed that the approximation of the cruise climbs by 100ft steps, although a good approximation, it stays always below optimal altitude.

For the ISAVIA flight trials, a step of 1.000ft was performed at 100ft/min. Although information of the actual cruise climb rate for the B757 is not given, it is estimated at between 10 and 15ft/min (SESAR JU, 2010b).

Taking advantage of Figure 1 and modifying it for another cruise climb rate, Figure 3 was obtained.

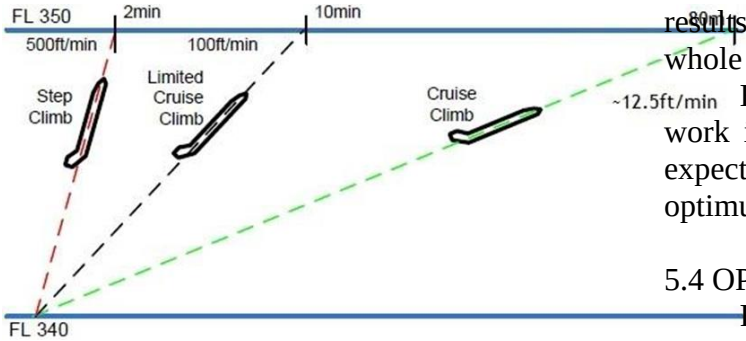


Figure 3: Time needed for a 1.000ft altitude change for a B757

It is observed from Figures 2 and 3 the times spent climbing for the two techniques trialed.

Performing a 2.000ft altitude change by climbing in 100ft step climbs at a climb rate of 250ft/min, takes 50 min more than if the same climb would have been done in a cruise climb mode. It takes more time because of the cruise segments between the climbs. The 1.000 ft climb at 100 ft/min is around 70 min faster than if the same altitude change would have been performed in a cruise climb.

For a better understanding of why all flights should be performed at or the closer possible to optimum altitude, Table 4 is presented.

Table 4: Specific range penalty for not flying at optimum altitude (AIRBUS, 2004)

Aircraft	+ 2.000ft	- 2.000ft	- 4.000ft	- 6.000ft
A300B4-605	2,0 %	0,9	3,4	9,3
A310-324	1,9	1,4	4,4	9,3
A318-111	0,7	1,6	5,0	10,0
A319-132	1,0	3,0	7,2	12,2
A320-211	**	1,1	4,7	9,5
A320-232	1,4	2,1	6,2	12,0
A321-112	2,3	1,4	4,6	15,2
A330-203	1,8	1,3	4,2	8,4
A330-343	3,0	1,0	3,2	7,2
A340-212	1,4	1,5	4,0	8,0
A340-313E	1,5	1,6	5,2	9,5
A340-642	1,6	0,6	2,2	5,1

** Above Maximum Altitude

5.3 RESULTS

All in all, 29kg of fuel savings were obtained in the NATCLM project, while 330kg were obtained from the ISAVIA flight trials.

Besides the differences in the aircraft used for the flight and the flight profile, it is also important to note that the NATCLM results account for only a segment of 1.600 NM. The results yielded from ISAVIA account for the whole flight.

Even if it is not expected that fuel savings work in the same way for every aircraft, it is expected that the penalties for not flying at the optimum altitude might be similar.

5.4 OPERATIONAL FEEDBACK

From the pilot's point of view, it was considered that the procedure from ISAVIA requires less workload from the pilots. Although, pilots from both cases agree that if a real cruise climb is to be flown, avionics systems should include a function for automatic execution of the cruise climb.

ATC did not raise any issue with the procedures in any of the cases, although with the current ATM system, the optimization of the vertical profile in the way of these case studies has limited clearance opportunities.

5.5 CONCLUSION

From this section, we conclude that the procedure tested by ISAVIA:

- Yields better savings;
- Has an easier implementation if compared to the procedure from NATCLM, given that it can be executed automatically by the current state of flight instruments; and
- Requires less workload from the pilots, as, once again, it can be executed automatically, while for the NATCLM, every climb had to be performed manually.

Thus, it may be concluded that given the current state of equipment, whether on board or on the ground, the limited cruise climb technique is a better approximation of a cruise climb, then the 100ft step climbs at 250ft/min plus cruise segment.

6. CONCLUSION

6.1 FINAL REMARKS

The main purpose of this paper was to quantify the fuel efficiency benefits achievable through a better altitude profile management during the cruise phase of flight. This was achieved through the development of a strategy that would approximate a vertical profile to the theoretical most efficient one. Which is to fly as close as possible to a cruise climb.

It was defined in the NATCLM case that the cruise climb would be approximated by a series of 100ft step climbs during a FL change of 2.000ft. For the estimation of the savings that resulted from the optimization, the fuel burn from the twenty 100ft step climbs that were actually flown was compared to the predicted 2.000ft climb that would have been flown in the same conditions.

The vertical profiles chosen for the flight trials, while not being the most efficient from a theoretical point of view, turned out to be a decent approximation, yielding savings in the order of 0,15% which for the segment analised translates into 29kg of fuel saved.

With the introduction of the ISAVIA's case, which yielded savings of around 330kg, it became possible to perform a comparison between the two procedures. Through this comparison it was concluded that a limited cruise climb profile is a better approximation of a cruise climb than 100ft steps at 250ft/min of climb rate.

Even if the savings obtained don't look like much, it is necessary to reinforce that everyday there are thousands of long haul flights with cruise segments of over five hours. If these fuel savings are looked at from an industry wide point of view and this kind of optimization starts being applied more often, the benefits would add up to very significant savings.

6.2 FUTURE RESEARCH

One believes that a combination of the two procedures presented in this paper would be very interesting. As the two techniques were already tested, it proves that the current state of the on-board and ground systems, would not impose a problem to test this possibility.

The combined technique would be to perform the twenty 100 step climbs, just like it was presented previously but at the limited cruise climb rate of 100ft/min, and with a shorter cruise segment between climbs, to maintain always the aircraft even closer to its optimum altitude. It is expected that the savings associated with this solution would increase too.

Furthermore, slight changes to the on-board and ground systems would allow a system wide optimization of flight profiles soon.

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