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VERTICAL FLIGHT EFFICIENCY

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SUMMARY

This paper estimates the impact of Air Traffic Management (ATM) on vertical flight efficiency

Keywords

Air Traffic Management		Vertical Flight Efficiency	Interrupted descent
Flight level capping	ATM	Interrupted climb	FL

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1 INTRODUCTION

The purpose of this technical note is to estimate the impact of ATM on vertical flight efficiency.

The vertical profile of a flight may be subject to systematic and tactical constraints preventing the aircraft from flying its optimum flight profile, which generates fuel penalties.

Systematic vertical flight profile constraints have several origins. The Route Availability Document (RAD)[1] is a 400-page document listing the conditions under which a given route can be used. The aforementioned Airspace Action Plan proposes that RAD constraints be reduced by 10% in 2008.

Constraints may also be stipulated in letters of agreement describing, inter alia, how traffic should be handled between adjacent centres. For example, short flights are often subject to flight level capping and are therefore not authorised to climb to their optimum altitude.

Vertical flight inefficiencies can be split up into 2 components:

- Flight level capping: the flight can't reach its optimum cruising level during the flight
- Interrupted climb/descent: during the climb or descent phase, the flight is kept at a suboptimal flight level (Intra-flight vertical inefficiencies)

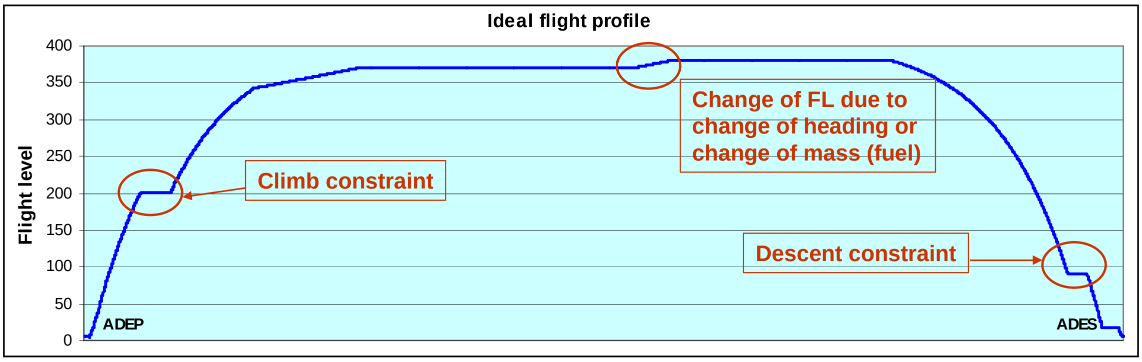

Figure 1: Vertical profile of real flights (with constraints)

[1] www.cfmu.eurocontrol.int/cfmu/opsd/public/standard_page/operational_services_rad.html.

2 FLIGHT LEVEL CAPPING

2.1 Introduction

Flight level capping generally occurs on short-distance flights to keep those flights below the over flying traffic. Appendix 3 of the RAD document contains a long list of city pairs with level cap.

2.2 Method and key results

Constraints between airports (city pairs) are detected and extracted from the CFMU database. Based on these extracted city pairs, flights are marked as constrained or unconstrained.

The fuel impact of flight level capping constraints has been estimated using the results of a simulation that was run by DSNA as part of the SESAR project.

The following table summarizes the results.

Number of city pairs subject to flight level constraints.	16000
Percentage of flights on constrained city pairs	11.8%
Additional fuel per impacted flight (kg)	50 kg
Additional fuel per flight (Europe average) (kg)	6 kg

Table 1: Flight level capping constraints

2.3 Analysis

16000 airport pairs subject to Flight level capping have been extracted from the CFMU database by selecting all flight level constraints that apply between two airports (or group of airports). Some selective checks have been performed to verify that the results were consistent with the list of city pairs subject to flight level capping described in the RAD document.

A flight level capping constraint typically applies from a group of airports to another group of airports, for instance all flights from Amsterdam airport group (7 airports) to Paris airport group (7 airports) shall stay below FL 240. This constraint therefore applies potentially to 49 (7x7) airport-pairs although there is no traffic or at least no regular traffic on most of them. At European level 16 000 city pairs are subject to flight level capping although only 634 have more than 1 flight per day on average (see Table 2).

Volume of traffic	Number of constrained airport-pairs
All	16 000
At least one flight a week	2 746
At least one flight a day	1 320
More than 1 flight a day	634

Table 2: Volume of traffic on constrained airport-pairs

Over the year, flights on city-pairs subject to flight level capping represent 11.8% of the total traffic. This percentage varies during the year between 9% and 14%. It is some 2% higher during the week than at weekends and 2% to 3% higher in winter than in summer (Figure 2).

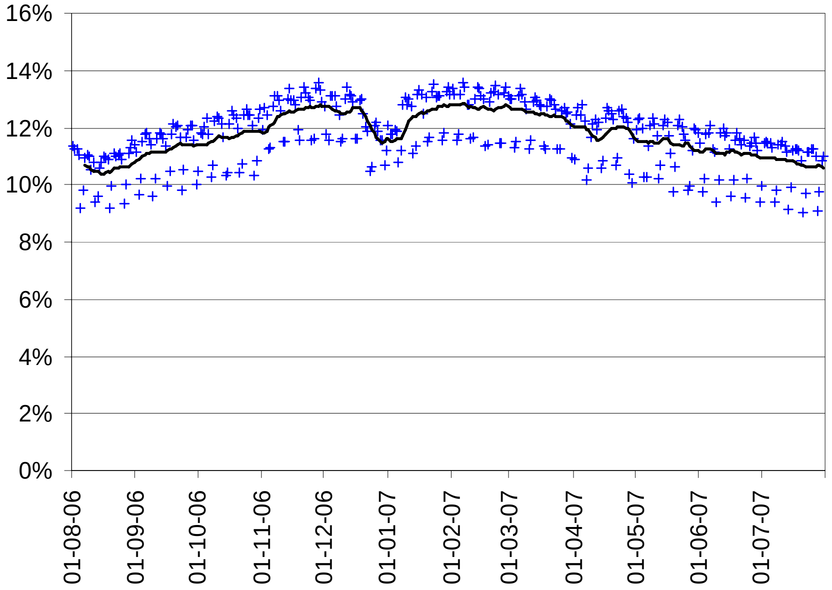

Figure 2: Annual distribution of vertically constrained flights

Figure 3 shows the distribution of constrained flights as a function of the city pair distance. City pairs subject to flight level capping, are mainly situated between 0 and 600 NM. In the 200-300 NM band the number of constrained flights represents nearly one third of the total traffic within that band.

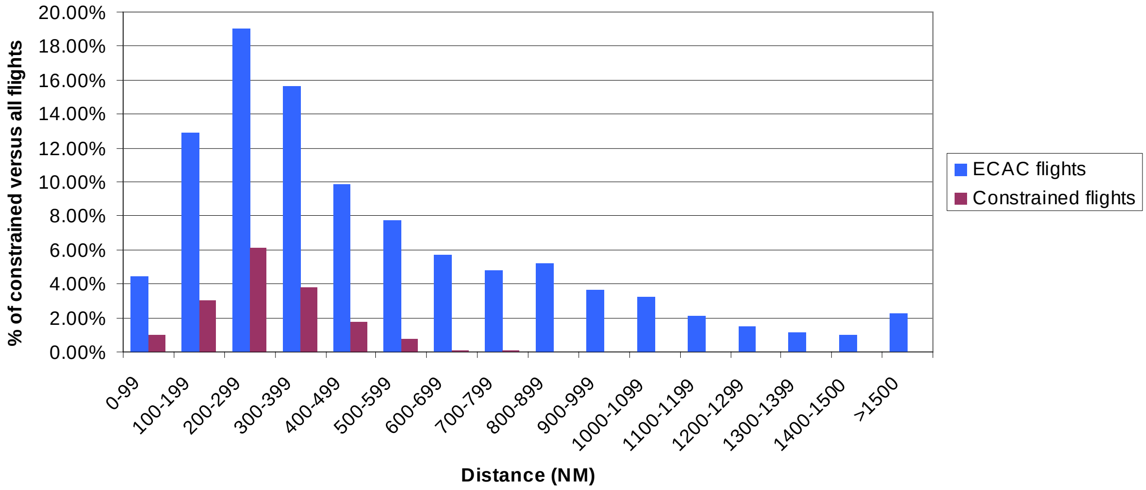

Figure 3: Distribution of vertically constrained flights by stage length

The maximum flight level allowed on constrained city-pairs ranges from FL80 to FL350; but, as can been seen in Figure 4, the majority of the constrained flights lies in the range FL240-FL340.

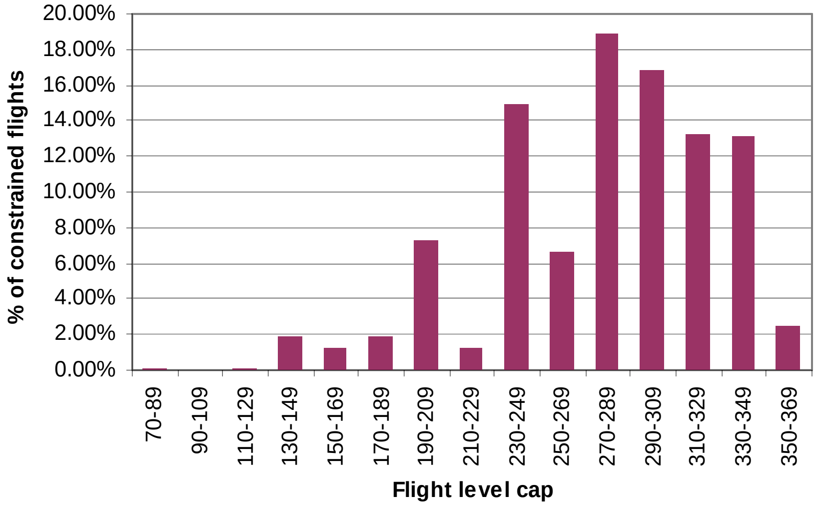

Figure 4: Maximum Flight level allowed

Figure 5 and Figure 6 plot the flight level distributions observed on constrained city pairs (in yellow) against unconstrained city pairs (in blue) for a similar distance

For turboprops (Figure 5) the flight level capping is rarely a constraint. The vertical limit (in red on the graph) is generally well above the normal cruise level

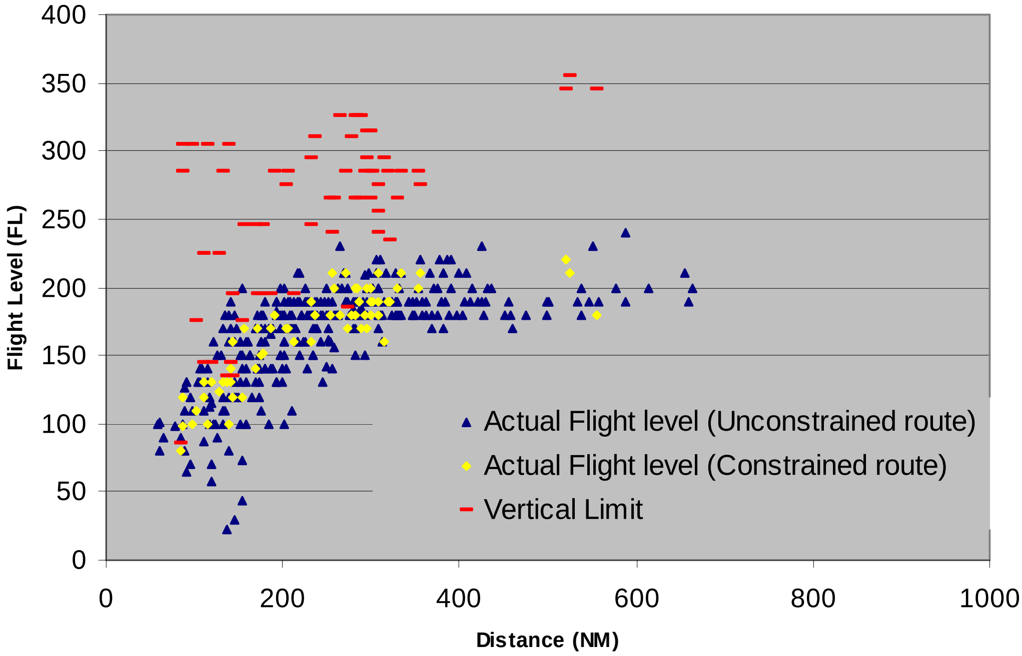

Figure 5 Comparison of un/constrained flights -Turboprop (ATR 72)

For Jet (Figure 6) the graph shows a small number of city pairs with a flight level cap (red hyphen) significantly below the typical flight level observed on an unconstrained city pair (blue dot). The flight level distribution of constrained flights (yellow plot) is not far from the distribution of unconstrained flights (blue dot).

On some occasions, the actual flight level (yellow dot) exceeds the maximum limit. The explanation for that may be either that the constraint was actually only applying to a specific route or that the pilot was authorised by the air traffic controller to climb above the maximum limit.

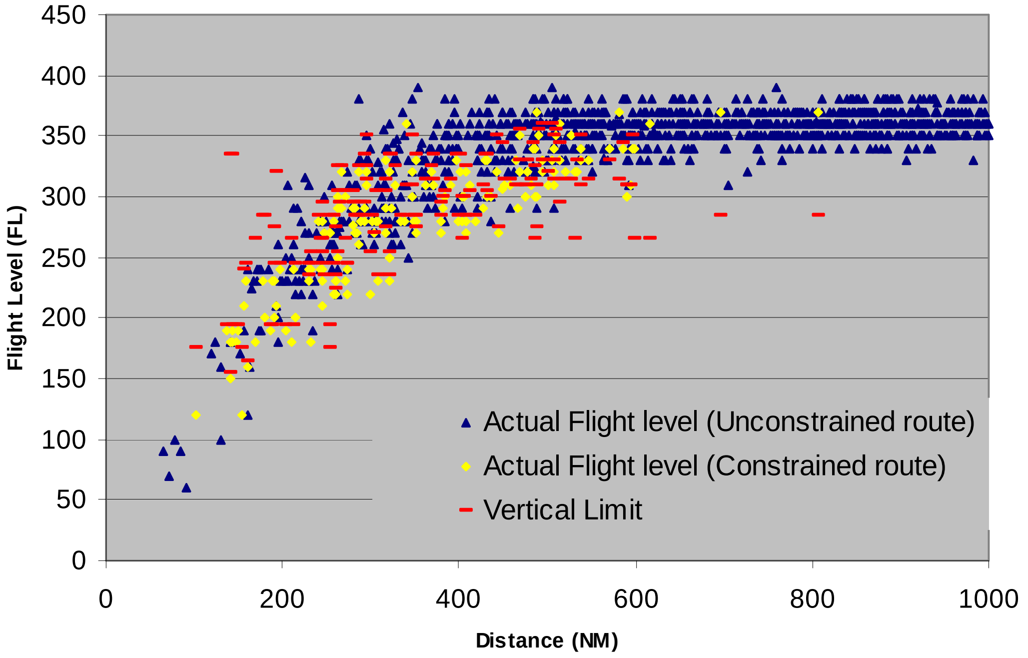

Figure 6: Comparison of constrained/unconstrained flights – Jet (A320)

2.4 Fuel impact

The estimation of the fuel impact has been made using results of an experiment done by DSNA in the context of SESAR which consisted in simulating aircraft movements along the following scenarios:

- Reference scenario representing actual (or augmented) traffic, at their Requested Flight Level (i.e. respecting the flight level constraints);
- Optimum scenario where flight constraints were removed and where the simulated aircraft were allowed to fly at their fuel optimal flight levels.

In both scenarios the fuel consumption was computed assuming a nominal take-off weight, standard weather conditions and an unconstrained climb or descent to/from the cruising level.

The simulation was run on a single day using data from 17 July 2005.

The study concluded, after comparing the 2 scenarios, that vertical flight inefficiencies generated about 3% of additional fuel burn in ECAC in 2005, (4% with 2020 traffic sample). However looking at the results in more detail, this difference appears to be in most of the cases not caused by ATC constraints but rather by data availability and accuracy.

Differences between the Flight Level requested by the airline and the optimum flight level computed using the simulation tool might be due to a number of factors such as: weather conditions, the aircraft weight and/or the policy of the airline, all of which have an influence on the optimum flight profile. The lack of precise information on those parameters is likely to be the cause of most of these differences.

In order to assess more accurately the real impact of flight level capping, the following table presents the results of the SESAR simulation depending on whether the flight is flying on a constrained city pair or not.

ECAC	Unconstrained city pairs	Constrained city pairs	Total
Number of flights	24 540 90%	2 630 10 %	27 170 100%
Percentage of distance flown	95%	5%	100%
Average Take Off Weight	65t	43t	63t
Fuel burn	96.9%	3.1%	100%
reference scenario	112 064 tons	3 584 tons	115 649 tons
optimum scenario	108 588 tons	3 449 tons	112 038 tons
Fuel difference	3 476 tons	135 tons	3 611 tons
	3.2%	3.9%	3.2%

Table 3: Constrained versus unconstrained flight (1 day of data)

On this particular day, flights on constrained city-pairs represented 10% of the traffic but only 5% of the distance flown within ECAC and 3.1% of the total fuel burn. The fuel burn was in excess of 135 tons (+3.9%) compared to the computed optimum.

As shown in the previous paragraph the percentage of traffic on constrained city pairs varies over the year. If we consider the average utilisation over the year and assume that the fuel penalty per flight (about 50 kg) remains constant the impact of flight level capping represents some 6 kg on average per flight in Europe.

Percentage of flights on constrained city pairs	11.8%
Additional fuel per impacted flight (kg)	50 kg
Additional fuel per flight (Europe average) (kg)	6 kg

Table 4: Impact of flight level capping European average

If on average the impact of flight level capping appears to have a very limited impact (less than 0.2%), the situation can be different for regional airlines operating a fleet of regional jets. For instance Brit Air has 21% of its flights subject to flight level capping for a total fuel increase of some 1.4%.

2.5 Limitations

It should be noted that although the computed fuel difference relates to constrained city-pairs only, part of this difference might still be caused by data precision issues. This figure shall therefore be considered as an upper bound.

Some flights for instance have an optimum flight level below the flight cap and are therefore not constrained by ATC. Disregarding those flights already reduces the fuel difference by 10%.

On the other hand, only constraints that were defined between from an airport (or an airport group) to another airport (or airport group) were extracted. It cannot be excluded that there exist other city pairs not subject to flight level capping where flights cannot reach their optimum flight level because of constraints/restrictions on routes. The analysis of the observed maximum flight level as a function of the city-pair distance presented in Figure 6 tends however to prove that those cases should be limited.

3 INTERRUPTED CLIMB/DESCENT

3.1 Introduction

During the climb phase, interruptions can occur mainly due to operational reasons, for instance to avoid entering congested sectors, or to facilitate the separation with crossing traffic. That means that the flight will maintain a lower (and uneconomical) altitude for a given time, until the pilot receives clearance to climb to a higher (i.e. more economical) flight level.

Similar constraints may apply in the descent phase obliging the flight to leave its cruising level earlier than the optimum top of descent.

Furthermore for some airports there could be a level-off segment at low altitude before intercepting the glide slope and/or waiting stacks where the flights await their final approach clearance.

In the latter case, and in all cases where a level-off segment is the result of the need to sequence aircraft on the runway, a distinction should be made between the impact of the time constraint and vertical flight efficiency. The cost of airborne delays will be addressed separately and will include the costs induced by the additional time and distance flown. This study on vertical efficiency only addresses the extent to which a given airborne delay has been achieved in the most efficient way.

3.2 Method and key results

In order to assess the impact of vertical flight inefficiencies due to interrupted climb/descent, parts of the trajectory where a plane is stable at a sub-optimal flight level have been identified. A sub-optimal flight level is a level below the maximal observed flight level of a flight. The climb or descent phase of a flight is thus interrupted.

For the purpose of this study a level off segment is defined as a portion of the trajectory made of two or more consecutive points where the rate of climb/descent between two subsequent points is smaller than 200ft/min.

In order to filter out segments that may be due to changes in cruise level, long level-off segments of more than 20 minutes have been filtered out.

In the absence of the flight level constraint, the distance flown at the sub-optimal flight level could have been flown at a more economic flight level; to compute the fuel impact, BADA was used to estimate the difference in the fuel consumption between the sub optimal flight level and the cruise level. This difference has then been multiplied by the length of the level-off segment.

The main results are summarised in the following table.

	Percentage of flight impacted	Additional fuel per impacted flight	Additional fuel per all flights
Interrupted climb	19%	15 kg	3 kg
Interrupted descent	42%	33 kg	14 kg
Total			17 kg

Table 5: impact of vertical flight inefficiencies due to interrupted climb/descent

3.3 Data source

Currently there are three types of vertical profile information (FSD, ARU and CPR) with increasing level of detail and all with their limitations.

Vertical Profile Type	Description	Advantages	Disadvantages
PRISME (FSD)	Filtered ARU profile information	Systematically stored	Level of detail not sufficient
CFMU (ARU)			- not systematically stored/accessible - false stages
CPR	Correlated Position Reports	Level of detail	Not systematically stored/accessible

Table 6: Vertical profile information

The profile stored in PRISME is a simplified version of the original CFMU flight profile. In this lighter version, only those points corresponding to a waypoint or geographic position are present, intermediate points corresponding to a change in the vertical profile between two waypoints have been filtered out. The lack of precision in the vertical dimension is a clear limitation in the context of this study.

The original idea was to use the complete flight profile as received from the CFMU.

Analysis of the results showed that more than half of the computed fuel inefficiencies were actually due to very short segment in the climb or descent. Those short segments were generally absent in the original CPR data received. Although it should be feasible to correct the CFMU profile by doing some post processing of the data received, it has been found easier to use the original CPR data.

The results presented in this paper are based on one day of CPR data (12 July 2007).

3.4 Analysis

The traffic sample for that day is composed of 26 624 flights. On those flights some 36 000 level-off segments have been isolated. 30% of those occur before the flight has reached its maximum level and 70% after.

Figure 7 shows the distribution of the duration of level-off segments before any filtering. Some 5% of occurrences have a duration of more than 20 minutes. These long level-off segments account for slightly more than 20% of the fuel difference.

Long level-off corresponds to a change of flight level during cruise. This may occur as a result of a change in the parity of the routes followed by the flight. A majority of long level-off however occurs in climb. Those changes in flight level are in fact the result of normal cruise management. During the course of the flight, fuel is burned and the aircraft becomes lighter and requests to climb to the next flight level in order to stay as close as possible to its optimum flight level.

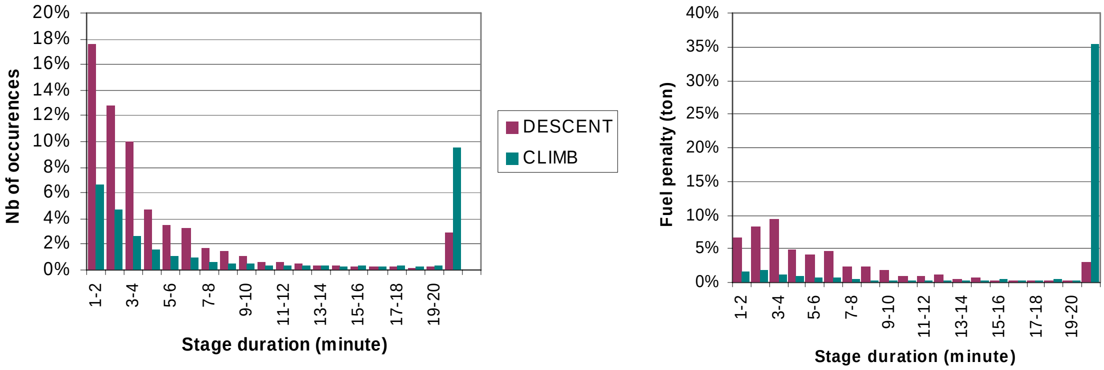

Figure 7: Distribution of the duration of level-off segment

Figure 8 confirms that long level-off (in light blue on the graph) are done at a flight level close to the maximum flight level and are therefore most likely to be a choice of the pilot rather than the result of an ATC constraint.

DIFF_FL	0-5 min	5-10 min	10-15 min	15-20 min	>20 min	Grand Total
<25 FL	1481	588	330	331	2272	38.7%
25-49 FL	863	226	71	50	313	18.0%
50-74 FL	622	80	30	15	44	12.1%
75-99 FL	316	35	5	1	8	8.3%
100-124 FL	293	19	6	2	5	6.3%
125-149 FL	140	5	1		1	3.3%
150-174 FL	153	5	1	1		2.6%
175-199 FL	136	3		1		1.6%
>200	719	35		1		9.2%
Total	77.9%	6.2%	2.5%	2.2%	11.3%	100.0%

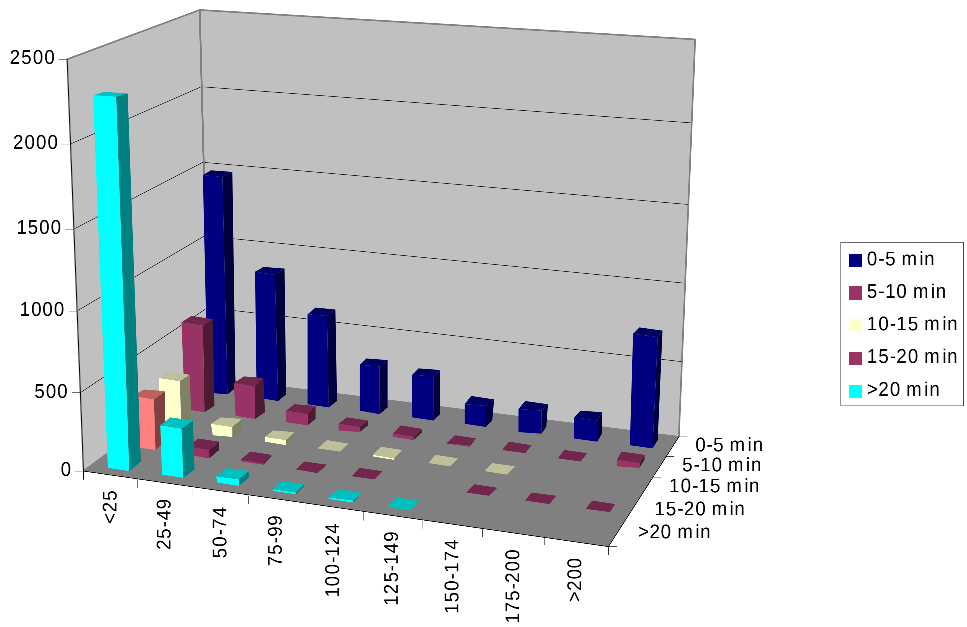

Figure 8: Distribution of level-off in climb

Level-offs of more than 20 minutes have therefore been excluded from the analysis.

As shown inFigure 9 and Figure 10, despite the filtering of level-off segments longer than 20 minutes, there remain quite a few segments in the cruising phase. As a consequence the overall results are likely to be somewhat overestimated.

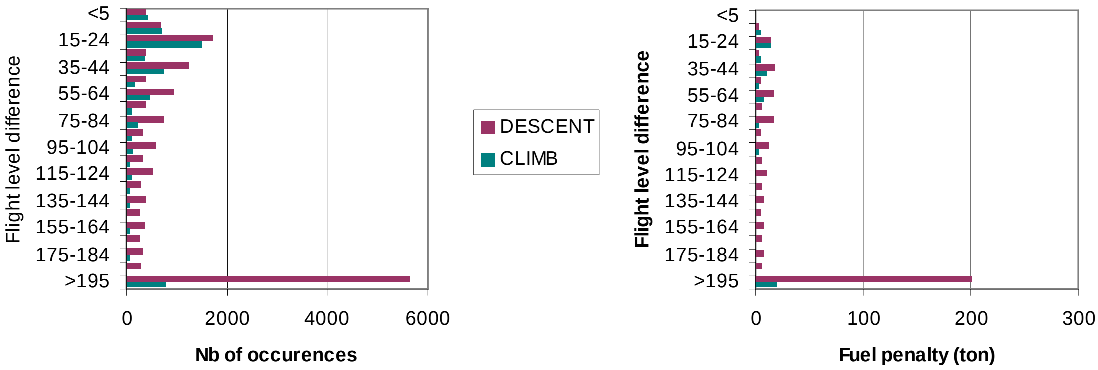

Figure 9: Flight level differences between the level-off and the top of flight

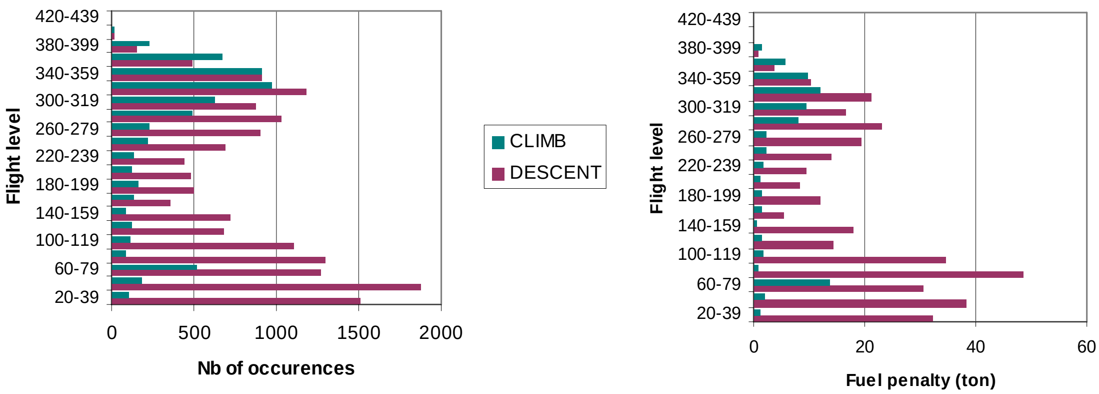

Figure 10: Flight level at which the flight is levelling off

Figure 10 also shows that a significant proportion of level-off segments during the descent phase are taking place below FL100. Most of them correspond to holding patterns or to path stretching in the terminal area. As mentioned earlier, the cost of the additional time and distance flown due to airborne delay will be addressed separately. The vertical inefficiencies addressed in this study only address the extent to which the delay has been achieved in the most efficient way.

3.5 Fuel impact

The fuel impact of level-off has been estimated by looking at the fuel economy that would have been achieved if the flight had been flying the same distance at the flight maximum altitude.

	Number of flights impacted	Additional fuel per impacted flight	Additional fuel per all flights
Interrupted climb	19%	15 kg	3 kg
Interrupted descent			
Above FL 100	28%	27 kg	8 kg
Below FL 100	20%	31 kg	6 kg
Total			17 kg

Table 7: Fuel impact of interrupted climb/descent

The list shown in Appendix 2 presents the vertical flight inefficiencies for the top 25 airports on that particular day. Not surprisingly, vertical flight inefficiencies are concentrated around the main airports. The top 25 airports handle 35% of the ECAC traffic but are responsible for 73% of the vertical flight inefficiencies. There exists however some important differences across airports, the vertical flight inefficiencies exceed 50 kg/flight at London Heathrow while it is less than 10kg/flight at Barcelona and Paris Charles de Gaulle.

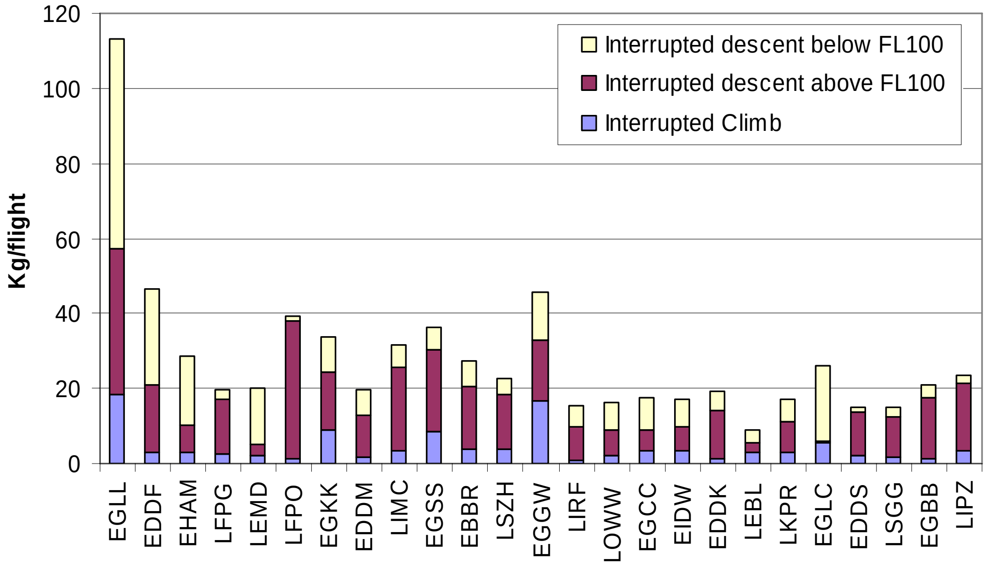

Figure 11: Fuel impact per airport

3.6 Limitation

Two types of limitations are described below:

a) The fuel impact of level-off has been estimated by looking at the fuel economy that would have been achieved if the flight had been flying the same distance at the flight maximum altitude.

The method used to estimate the additional fuel due to level-off segment assumes that the flight would have flown the same distance at the optimum altitude. This method is not really correct when the level-off segment is caused by the need to delay an aircraft. In this case the problem is not anymore to travel a given distance as close as possible to the optimum altitude, but to “lose” a given amount of time in the most efficient way.

Looking at the difference in terms of consumption per nautical miles rather than fuel flow per hour leads to an overestimation of the impact of interrupted descent. This is particularly the case below FL100 where the level off is most likely to be due to time constraints.

b) Information received by the CFMU varies from country to country, the time between two successive CPR is one minute in most countries but three minutes in France and Germany. In the latter countries a level-off of less than three minutes may not be detected.

4 CONCLUSIONS

Vertical inefficiencies result from the inability of flights to fly an optimum vertical profile.

This paper has focussed on two types of constraints that ATC may impose on a flight:

- flight level capping which obliges short flights on some city pairs to stay below a certain level and;
- interrupted climb or descent.

Figure 12 summarises the results presented in this paper. Those results warrant some comments.

Type of constraints	Percentage of traffic impacted	Additional Fuel per impacted flight	Additional fuel per flight
Flight level capping	12%	50 kg	6 kg
Interrupted climb	19%	15 kg	3 kg
Interrupted descent	42%	33 kg	14 kg
Total vertical inefficiencies			23 kg

Figure 12: Summary results

Flight inefficiencies are measured from a single flight perspective. In reality a flight is not alone in the sky. From a system point of view, trade-off exists between flight efficiency and safety/capacity. It's neither feasible nor optimum to suppress all flight inefficiencies.

Vertical flight inefficiencies are difficult to estimate with accuracy. Take off weight, MET condition, aircraft operators' policy can have significant impact on the optimum profile. A number of limitation/simplifications presented have been highlighted in this paper some of them are likely to lead to a significant overestimation of the impact. The results presented here should therefore be considered as an upper-bound.

The overall impact of vertical flight inefficiencies is estimated at some 23kg per flight on average over Europe. This represents an increase of less than 0.6% of the fuel burn. Furthermore it should be noted that the two main sources of vertical inefficiencies are "Flight level capping" and "Interrupted descent", two items for which the uncertainty is the highest. The actual value may be significantly lower.

Although vertical flight inefficiencies generate some negative impacts they remain relatively small when compared to other known types of inefficiencies (horizontal, taxi-time, airborne delays).

Flight Phase	Additional Time	Additional Fuel burn	
Vertical inefficiencies	~0	23 kg	0.6%
Horizontal inefficiencies	4 min	150 kg	3.8%
Airborne delay	2-5 min	100-250 kg	2.5%-6.0%
Taxi-in/Taxi out	1-3 min	13-40 kg	0.3%-0.9%
Total	7-12 min	300-500kg	7%-11%

Figure 13: Vertical inefficiencies compared to other fuel inefficiencies

APPENDIX 1: FLIGHT LEVEL CAPPING - TOP 25 CITY PAIRS

ADEP	ADES	FL max	Flights	Total Fuel(kg)	FUEL Penalty		% Increase
					kg	Kg/Flight	
LFMN	LFPO	285	26	60 756	4 756	183	8%
LICC	LIML	265	13	50 222	2 911	224	6%
LFPO	LFML	335	18	38 599	2 676	149	7%
LFML	LFPO	285	17	36 147	2 675	157	8%
LEMD	LEPA	305	26	56 504	1 883	72	3%
EGLL	LSZH	275	12	36 686	1 805	150	5%
EDDF	LFPG	245	18	32 125	1 792	100	6%
LEBL	LFPO	325	8	25 238	1 791	224	8%
LSZH	LEBL	295	6	15 357	1 474	246	11%
LFPG	LFML	335	12	30 685	1 424	119	5%
LEBL	LFPG	345	12	35 974	1 419	118	4%
EDDF	EGLL	335	18	57 661	1 412	78	3%
LIPZ	LEBL	310	5	18 187	1 345	269	8%
LFMN	LFPG	300	11	24 800	1 291	117	5%
LEBL	LIMC	310	8	23 570	1 244	156	6%
LFTH	LFPO	285	7	18 691	1 228	175	7%
LFBD	LFPO	285	13	22 768	1 226	94	6%
EGLL	LSGG	320	8	22 344	1 223	153	6%
LEBL	LIPZ	310	5	17 800	1 219	244	7%
EHAM	LFPG	245	17	27 633	1 166	69	4%
LFBZ	LFPO	285	5	11 714	1 140	228	11%
LFML	LFPG	300	11	29 107	1 135	103	4%
LEPA	LEMD	305	25	48 264	1 091	44	2%
LFMT	LFPO	285	7	15 742	1 082	155	7%
LSGG	LEBL	300	6	13 642	1 080	180	9%

APPENDIX 2: INTERRUPTED CLIMB/DESCENT: TOP 25 AIRPORTS

Airport	Departure	Fuel penalty total		Interrupted Climb			Interrupted Descent above FL100			Interrupted descent below FL100		
		kg	kg/flight	kg	kg/flight	% flight impacted	kg	kg/flight	% flight impacted	kg	kg/flight	% flight impacted
EGLL	687	77 847	113.3	12 716	18.5	48%	26 465	38.5	49%	38 666	56.3	64%
EDDF	712	33 000	46.3	2 042	2.9	12%	12 839	18.0	44%	18 119	25.4	34%
EHAM	688	19 662	28.6	2 196	3.2	22%	4 770	6.9	32%	12 696	18.5	35%
LFPG	843	16 581	19.7	2 008	2.4	12%	12 351	14.7	35%	2 222	2.6	6%
LEMD	731	14 785	20.2	1 608	2.2	11%	2 020	2.8	18%	11 157	15.3	45%
LFPO	373	14 717	39.5	539	1.4	8%	13 562	36.4	58%	616	1.7	3%
EGKK	405	13 683	33.8	3 686	9.1	32%	6 225	15.4	47%	3 772	9.3	24%
EDDM	654	12 755	19.5	1 148	1.8	17%	7 344	11.2	47%	4 263	6.5	26%
LIMC	393	12 474	31.7	1 370	3.5	23%	8 768	22.3	63%	2 336	5.9	21%
EGSS	306	11 080	36.2	2 621	8.6	46%	6 646	21.7	66%	1 813	5.9	18%
EBBR	402	10 918	27.2	1 493	3.7	23%	6 693	16.6	59%	2 732	6.8	26%
LSZH	393	8 856	22.5	1 459	3.7	28%	5 803	14.8	54%	1 594	4.1	20%
EGGW	192	8 773	45.7	3 237	16.9	57%	3 074	16.0	57%	2 462	12.8	49%
LIRF	511	7 747	15.2	506	1.0	8%	4 556	8.9	33%	2 685	5.3	16%
LOWW	424	6 875	16.2	967	2.3	22%	2 807	6.6	42%	3 101	7.3	29%
EGCC	352	6 231	17.7	1 156	3.3	20%	2 061	5.9	26%	3 014	8.6	37%
EIDW	312	5 278	16.9	1 120	3.6	24%	1 961	6.3	26%	2 197	7.0	16%
EDDK	249	4 837	19.4	320	1.3	10%	3 157	12.7	35%	1 360	5.5	12%
LEBL	549	4 830	8.8	1 697	3.1	19%	1 270	2.3	17%	1 863	3.4	16%
LKPR	272	4 667	17.2	784	2.9	26%	2 213	8.1	41%	1 670	6.1	31%
EGLC	159	4 117	25.9	853	5.4	72%	96	0.6	15%	3 168	19.9	94%
EDDS	250	3 732	14.9	514	2.1	17%	2 938	11.8	42%	280	1.1	12%
LSGG	248	3 667	14.8	448	1.8	17%	2 650	10.7	49%	569	2.3	15%
EGBB	172	3 627	21.1	222	1.3	18%	2 787	16.2	58%	618	3.6	32%
LIPZ	141	3 320	23.5	482	3.4	21%	2 508	17.8	42%	330	2.3	6%