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ANALYSIS AND OPTIMIZATION OF CLIMB PERFORMANCE WITH VARIABLE TRAILING EDGE WING

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Abstract. *This work focuses on developing a study of the aerodynamic impact of variable camber wings on the performance of a regional aircraft. The variation of camber on the wings is done by independent deflections of ailerons and flaps from -5 ° to 5 ° in order to reduce the total drag in flight. Through analysis based on Boundary Layer Wing Body (BLWF) software, it was observed reductions in induced drag, wave drag and trim drag. Due to the predominance of short routes on the regional aviation around the world, the climb segment gains notorious importance in the total cost of an airline, so an iterative procedure based on design of experiments was developed in order to optimize the climb performance of the aircraft for each of the three typical missions proposed, analyzing the impact of variable camber. For a short mission of 500 nm, the optimization of the climb segment is responsible for most of the fuel economy. On long missions, the climb segment loses importance and gains on the order of 1% -2% in fuel consumption are verified due to reduction of wave drag in flight situations with high CL and Mach. Finally it is evident the importance of a correct choice of climb schedule on short routes while the benefit of variable camber is more evident on long range missions.*

Keywords: *Performance, Aerodynamics, Morphing, DOE*

1. INTRODUCTION

With the constant increase of fuel price and its impact on the direct operating cost of major aircraft fleets, the necessity of aerodynamics improvement and new operational procedures becomes mandatory to keep the desirable profit margin.

The variable trailing edge wing concept is already studied by major aircrafts manufacturers such as Boeing and Airbus and by research centers as NASA and Universities around the world. The main objective is the reduction on induced, wave and trim drag by constantly modifying the wing's camber. The purpose of this work is to change the wing camber by deflections of ailerons and flaps within +/- 5^{o} and analyze its impact on aircraft fuel consumption.

Besides the technological advances of these new aerodynamic concepts, it is known that the majority of airliner's world typical routes lies within a 500 nm range (Mirosavljević, P et al., 2009), a typical regional short route. In this scenario the climb phase of any airliner gains importance and its optimization by changing operational procedures becomes an interesting way of achieving a desired reduction on aircraft operating costs.

Combining the performance gains of variable camber wing and an optimized climb schedule, a viable way of maintaining an airliner's profit is achieved in an increasing total cost scenario and competitive environment.

2. PAST EXPERIENCES

The variable camber wing concept started since the beginning of the aircraft era. The first aircrafts ever built took credit of constantly varying wing torsion to accomplish desired maneuvers.

In modern aircrafts, two research projects gain notorious evidence on combining the aircraft manufactures efforts allied with public research institution to demonstrate the benefits of variable camber on aircraft performance, stability and control.

2.1 Mission Adaptive Wing

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In 1985 the mission adaptive wing concept (MAW) was tested in a F-111 aircraft in a research project with NASA, the United States Air Force and Boeing.

Figure 1 - F-111 with mission adaptive wing (Poonsong, 2004)

The wing was manufactured by Boeing and had a variable trailing and leading edge section that contributed to the constant camber variation which adapted the aircrafts configuration for each mission condition.

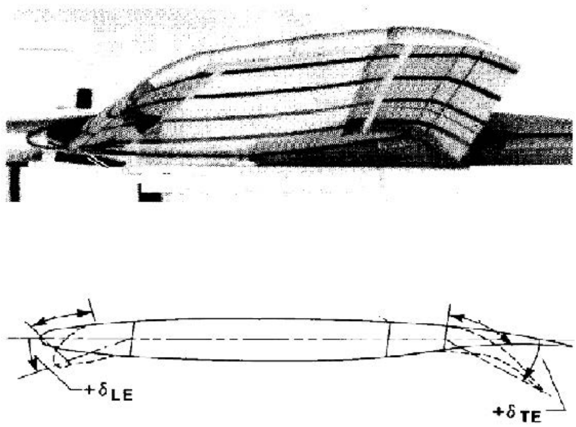

Figure 2 - Mission Adaptive Wing (MAW) (Poonsong, 2004)

A total of 59 flight tests were made, between 1985 and 1988, which proved a 7% of drag reduction on the cruise operating point and reductions of up to 20% at conditions outside the normal flight envelope.

2.2 Lockheed Martin L-1011

A research project made by NASA and Lockheed Martin shows the benefits of variable camber on a civilian subsonic aircraft.

A methodology based on wind tunnel testing and theoretical modeling was proposed in order to verify the gains in the lift to drag ratio on subsonic flight (Mach 0.6) and transonic flight (Mach 0.83).

The research showed an improvement of 1-3% on the lift to drag ratio at typical cruise conditions and benefit up to 9% at non usual operating points (Bolonkin, 1999).

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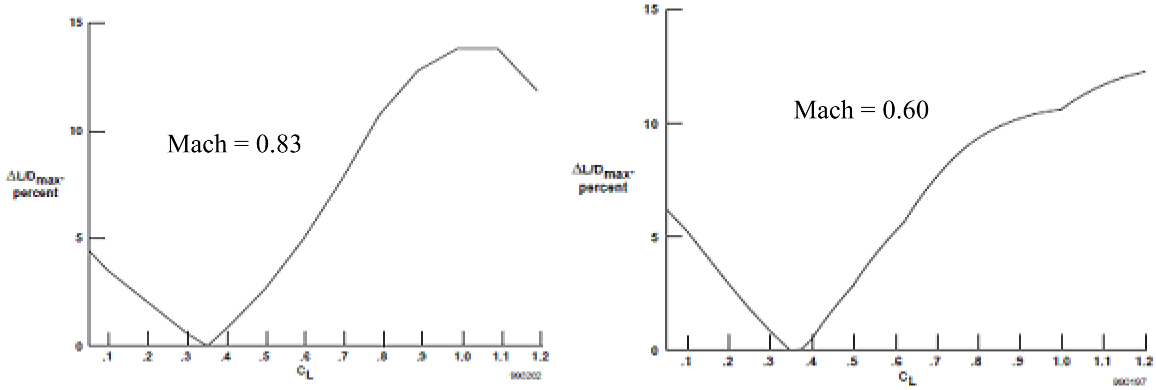

Figure 3 - L-1011 lift to drag ration improvement (Bolonkin, 1999)

3. THE DRAG THEORY

An aircraft drag is divided into two main fields, the pressure drag and the viscous drag. The variable trailing edge contributes mainly to the reduction of the total pressure drag by reducing the induced, compressibility and trim drag components.

3.1 Induced Drag

The different pressure distribution over and below the wing due to airfoil geometry causes the formation of wing trailing edge vortices that induces a wind speed component called downwash which modifies the local angle of attack causing a lift force component on the direction of the aircraft drag.

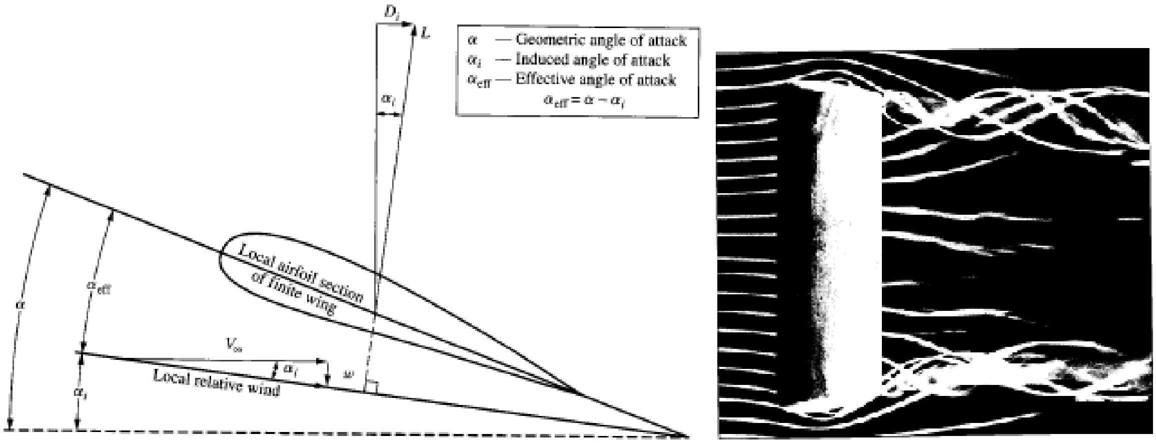

Figure 4 - Induced Drag Formation (Anderson, 2001)

The minimum induced drag occurs when the lift distribution above the wing is elliptical; the variable trailing edge contributes to guarantee an approximate elliptical distribution over the aircrafts wing at most of the flight stage.

3.2 Trim Drag

The trim drag is a special form of induced drag that appears due to the horizontal tail lift L_h necessary to compensate the aircrafts wing and fuselage pitching moment M_{wf} with the tail lever arm l_t.

$$M_{wf} = L_h \times l_t \qquad \textbf{(1)}$$

The variable trailing edge changes constantly the wing and fuselage pitching moment by deflecting aileron and flap surfaces and this may reduce the tail lift necessary to compensate the aircraft, therefore the trim drag might be reduced.

Assuming small changes on the aircrafts wing and fuselage moment due to small deflections of ailerons and flaps, the variation of induced drag may be estimated as follows:

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$$\Delta CD_{Trim} = \frac{1}{\pi A_h e_h} 2Cm_{ref} \left(\frac{c}{l_h}\right)^2 \frac{S}{S_h} \Delta Cm \quad (2)$$

On equation 2, A_h and e_h are the tail aspect ratio and Oswald efficiency respectively, c is the wing's mean aerodynamic chord, l_h is the tail arm, S and S_h are the wing and tail reference area, Cm_{ref} is the wing and body reference pitching moment coefficient and ΔCm is the pitching moment variation due to variable camber.

3.3 Compressibility Drag

The compressibility drag is caused by the formation of shock waves above the airfoil surface due to airflow speed acceleration up to supersonic speeds.

The pressure distribution over the wing affects the airflow speed distribution and consequently the shock wave intensity and location over the wing. The continuous aileron and flaps deflections on a variable camber wing change the pressure distribution on the wing's trailing edge and may reduce the compressibility drag when flying at the same Mach number.

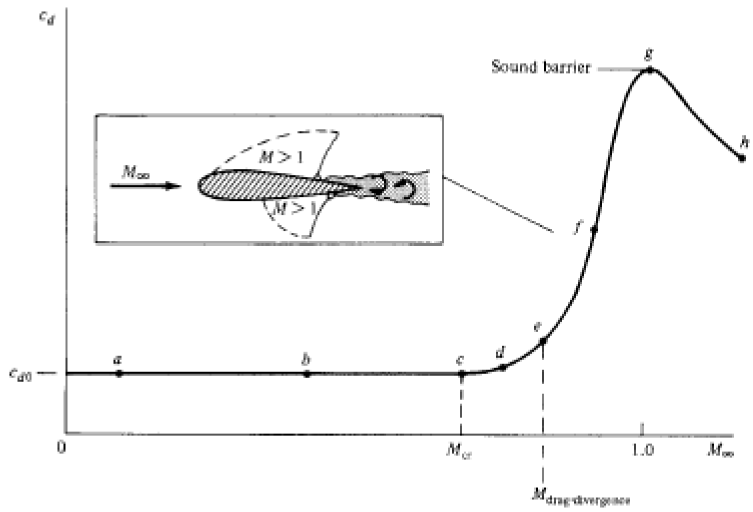

Figure 5 - Mach influence on the compressibility drag

Besides reducing the compressibility drag flying at the same Mach number, another way of taking credit of the variable camber is to fly at higher Mach numbers without a significant increase on the total drag, reducing the total flight time and consequently the direct operating costs.

4. AERODYNAMIC SIMULATION

Through the TSAGI software Boundary Layer Wing and Body (BLWF), the wing and fuselage of a commercial regional jet was simulated and the total drag and pitching moment variation due to the ailerons and flaps deflections were calculated in a factorial table considering aircrafts lift coefficient CL, free stream Mach number, aileron, inboard and outboard flap deflection.

Table 1 - Aerodynamic Simulation Table

CL	**0.3; 0.35; 0.4; 0.45; 0.5; 0.55; 0.6**
Mach	**0.3; 0.35; 0.4; 0.45; 0.5; 0.6; 0.7; 0.72; 0.74; 0.76; 0.78; 0.8**
Aileron Deflection	**-5 a 5, 0.5^o increment**
Inboard Flap Deflection	**-5 a 5, 0.5^o increment**
Outboard Flap Deflection	**-5 a 5, 0.5^o increment**

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For each pair of CL and Mach in the design table, the values of aileron and flaps deflections corresponding to the greatest reduction on total drag were organized along with the corresponding drag variation represented by drag counts, 0.0001.

Table 2 – Aircraft Configuration Corresponding to Lowest Drag (Deo, V, 2012)

Cl	Mach	Aileron	Flap Inboard	Flap Outboard
0.3	0.3	-3	-4	-2
	0.35	-3	-4	-2.5
	0.4	-2	-4	-2
	0.45	-2	-4	-2.5
	0.5	-3	-4	-2.5
	0.6	-3	-4	-2.5
	0.7	-4.5	-5	-5
	0.72	-4.25	-5	-5
	0.74	-4	-5	-5
	0.76	-4.5	-5	-5
	0.78	-4.5	-5	-5
	0.8	-3.75	-5	-5
0.4	0.3	-1	-2	0
	0.35	-1	-3	-0.5
	0.4	0	-1	1
	0.45	-1	-2.5	-0.5
	0.5	-2	-3.5	-1
	0.6	-2	-4	-2
	0.7	-3	-4	-2
	0.72	-3	-4	-3
	0.74	-3	-4	-2.5
	0.76	-3	-4	-2.5
	0.78	-3.5	-4	-2.5
	0.8	-2.5	-3.5	-2
0.5	0.3	2	1.5	3.5
	0.35	2	1	3.5
	0.4	1	1	3
	0.45	1	-0.5	1.5
	0.5	1	-0.5	1.5
	0.6	-1	-2	0
	0.7	-1.5	-3	-1
	0.72	-1.5	-2.5	-0.5
	0.74	-1.5	-2	0
	0.76	-1.5	-1.5	0
	0.78	-2.5	-2	-0.5
	0.8	-2.5	-1	0.5
0.6	0.3	3	2	4
	0.35	3	2	4
	0.4	3	2	4
	0.45	3	2	4
	0.5	2	1.5	3.5
	0.6	2	1	3.5
	0.7	0.5	0	2
	0.72	0.5	0.5	2
	0.74	0	1	2.5
	0.76	-1.5	0.5	1.5
	0.78	-3	0.5	2
	0.8	-4	1.5	1

Table 3 shows the drag reduction for each flight condition represented by the aircrafts CL and Mach number.

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Table 3 – Total Drag Reduction in Counts (Deo, V, 2012)

		Mach												
		0	**0.3**	**0.35**	**0.4**	**0.45**	**0.5**	**0.6**	**0.7**	**0.72**	**0.74**	**0.76**	**0.78**	**0.8**
Cl	**0.3**	-2.23	-2.23	-2.42	-2.30	-3.00	-3.00	-3.60	-4.90	-5.30	-5.30	-5.85	-6.10	-11.00
	0.35	-1.66	-1.66	-1.81	-1.80	-2.30	-2.30	-2.90	-3.60	-4.00	-4.30	-4.70	-4.90	-7.40
	0.4	-1.10	-1.10	-1.20	-1.30	-1.60	-1.60	-2.20	-3.00	-3.10	-3.10	-3.40	-3.80	-4.70
	0.45	-1.70	-1.70	-1.70	-1.60	-1.70	-1.45	-1.70	-2.10	-2.30	-2.20	-2.00	-2.70	-4.80
	0.5	-2.30	-2.30	-2.20	-1.90	-1.80	-1.30	-1.20	-1.30	-1.40	-1.20	-1.20	-0.20	-2.20
	0.55	-3.45	-3.45	-3.25	-2.95	-2.80	-2.15	-1.70	-1.10	-0.90	-1.00	-2.10	-3.10	-9.00
	0.6	-4.60	-4.60	-4.30	-4.00	-3.80	-3.00	-2.20	-1.40	-1.60	-2.90	-4.50	-5.40	-22.00

By analyzing table 3, the influence of variable camber on the compressibility drag becomes evident, since higher drag reduction is achieved at high lift coefficients and Mach numbers.

The performance gains may be estimated by the aerodynamic efficiency improvement represented by the lift to drag ratio L/D. On flights at Cruise Mach of 0.8, an improvement of up to 4% is achieved.

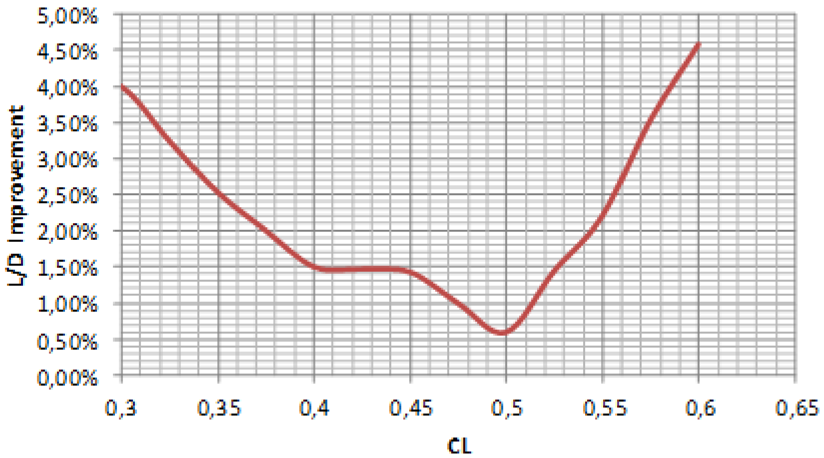

Figure 6 – L/D improvement at Mach 0.8 (Deo, V, 2012)

It is shown on figure 6 that around the aircraft operating point of CL - 0.5, the performance gains are close to 0%, this may probably be the optimized flight condition for this aircraft.

A more accurate way of analyzing the performance improvement of the variable trailing edge technology is by plotting the specific range diagram of both aircraft´s configurations.

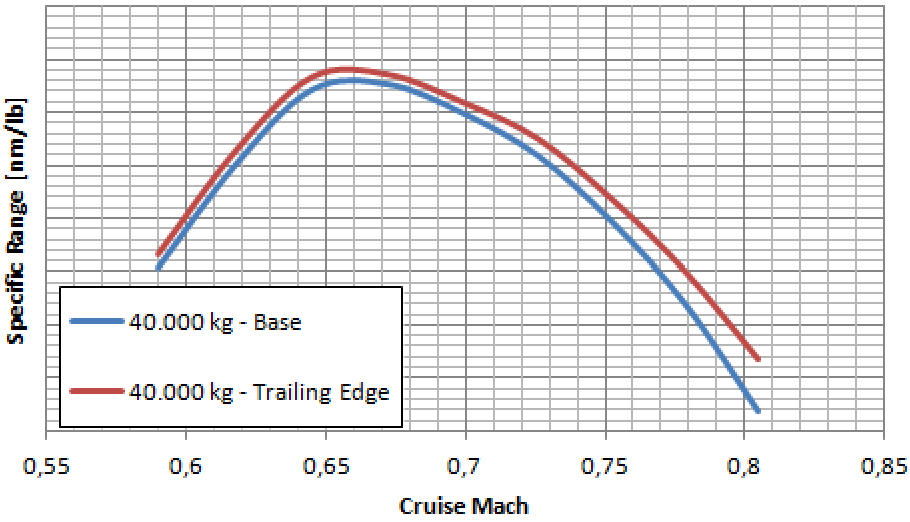

Figure 7 – Specific Range Diagram

On figure 7 the specific range was calculated for both aircrafts flying at FL 340 and at a total weight of 40.000 kg. It becomes evident the performance benefits of the variable camber technology as the cruise Mach number is increased,

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the difference between the specific ranges becomes greater allowing the aircraft to fly at higher cruise speeds without prejudice of fuel consumption.

5. CLIMB PERFORMANCE

5.1 Climb Schedule

The climb speed schedule for a typical commercial regional jet is commonly defined as a constant calibrated airspeed up until a limit Mach number is reached, when the pilot must keep this Mach number constant until cruise altitude.

The specific climb schedule chosen for a flight plan depends on the mission's main objective, reduce time to climb, reduce horizontal distance to climb, reduce total fuel burned, reduced direct operating costs etc.

The climb simulation presented in this work allows a schedule composed of two calibrated airspeeds up until the limit Mach number is reached. The graphic below shows a climb schedule example used in this simulation.

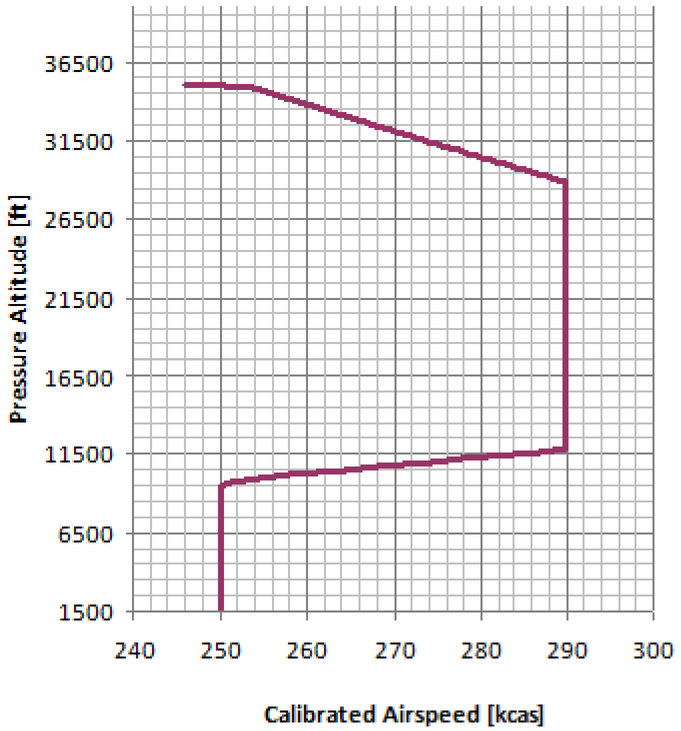

Figure 8 - Climb Schedule Example

5.2 Control Factors

The climb schedule variables were used as the control factors to optimize the flight mission performance, a total of five variables were optimized to reduce mission operating costs.

The first variable is the initial climb speed VC1, the second is the initial transition altitude H1, the third variable is the altitude necessary to accelerate from VC1 to VC2, the fourth variable is the final calibrated airspeed VC2 and the final control factor is the climb limit Mach number.

6. OPTIMIZATION METHODOLOGY

6.1 Interactive Design of Experiments

An interactive design of experiments using an orthogonal array was used to optimize the mission total cost. A total of 16 experiments were simulated at each interaction according to the matrix below for each set of control factors values. For the first iteration, the initial control factors assumed the following values:

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Table 4 - Initial Control Factors Values (Deo, V, 2012)

	Level 1	Level 2	Level 3	Level 4
VC1 [kcas]	220	230	240	250
VC2 [kcas]	250	270	290	310
H1 [ft]	10000	12000	14000	16000
Delta H1 [ft]	1000	2000	3000	4000
Mach	0.6	0.67	0.75	0.82

Since the optimization through design of experiments is limited to the control factors values, an interactive process was developed to guarantee a global minimization of the operating costs. An overall of five to six interactions was necessary until convergence is reached.

Table 5 - Orthogonal Design of Experiments

Experiments	VC1	H1	H2	VC2	Mach
1	3	4	2	1	3
2	2	2	1	4	3
3	1	1	1	1	1
4	4	1	4	2	3
5	3	1	3	4	2
6	4	4	1	3	2
7	1	2	2	2	2
8	4	3	2	4	1
9	2	4	3	2	1
10	1	4	4	4	4
11	3	2	4	3	1
12	3	3	1	2	4
13	2	3	4	1	2
14	1	3	3	3	3
15	2	1	2	3	4
16	4	2	3	1	4

6.2 Objective Function

The objective function simulates the airline direct operating cost and is composed of the mission block fuel and mission block time. The fuel related cost was estimated as U$ 0.92/kg according to the IATA Fuel Price Monitor and the total cost related to flight hour depends basically on the crew and maintenance costs which were calculated based on the work of (Liebeck, 1995) adjusted for current labor costs.

$$Obj = \sigma \cdot 0.92 \cdot Block\_Fuel + (1-\sigma) \cdot CH \cdot Block\_Time \tag{3}$$

On the above equation, CH is the total cost, considering crew and maintenance, related to one flight hour and the parameter σ is a weighing factor to simulate the influence of the variable trailing edge and the climb schedule on block fuel and block time.

7. PERFORMANCE BENEFITS

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7.1 Payload Range

With the drag reduction achieved through the variable trailing edge technology, the performance improvement is reflected on the payload range diagram.

Table 6 - Improvement on Payload Range (Deo, V, 2012)

	Range	
Payload [kg]	Ref. Aircraft	Variable Trailing Edge
11680	Ref.	+1.10%
10075	Ref.	+1.20%
0	Ref.	+1.50%

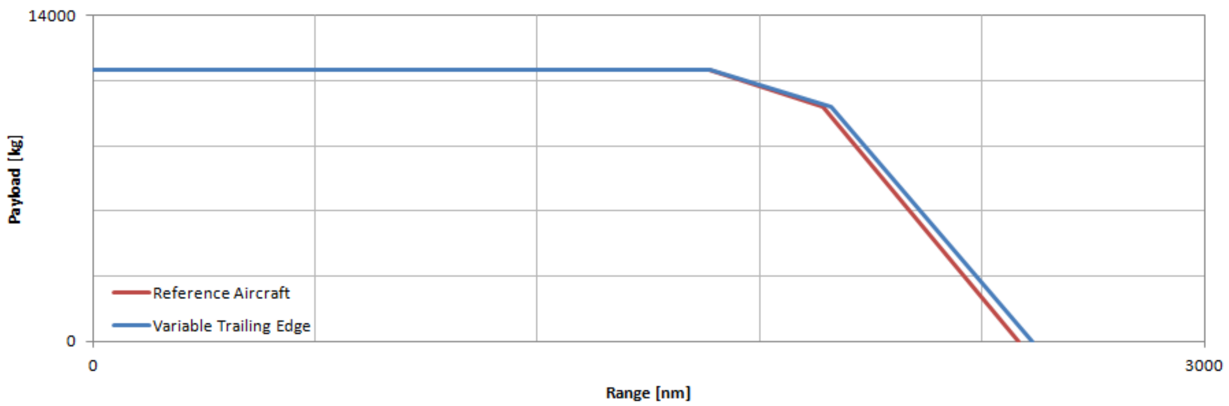

Figure 9 - Payload Range (Deo, V, 2012)

7.2 Typical Missions

A total of three missions were analyzed, a short missions of 500 nm flying at Mach 0.8, a medium range mission of 1500 nm also flying at Mach 0.8 and a long range mission of 2200 nm flying at long range speed.

Table 7 - Benefits on Short Mission (Deo, V, 2012)

Short Mission	Block Time	Block Fuel
Reference Aircraft	REF.	REF.
Variable Trailing Edge	REF.	– 20 kg

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Table 8 – Benefits on Short Mission of Variable Trailing Edge with Climb Optimization (Deo, V, 2012)

σ	VC_1	VC_2	H_1	H_2	Mach	Block Time	Block Fuel
0	250	310	10000	11000	0.82	- 1min39seg	+ 69.8 kg
0.25	250	284	10000	13000	0.82	- 45 seg	+ 27 kg
0.5	250	271	10000	11000	0.73	+ 45 seg	- 35 kg
0.75	250	267	10000	11000	0.68	+ 1 min	- 42 kg
1	250	267	10000	11000	0.67	+ 1 min	- 42 kg

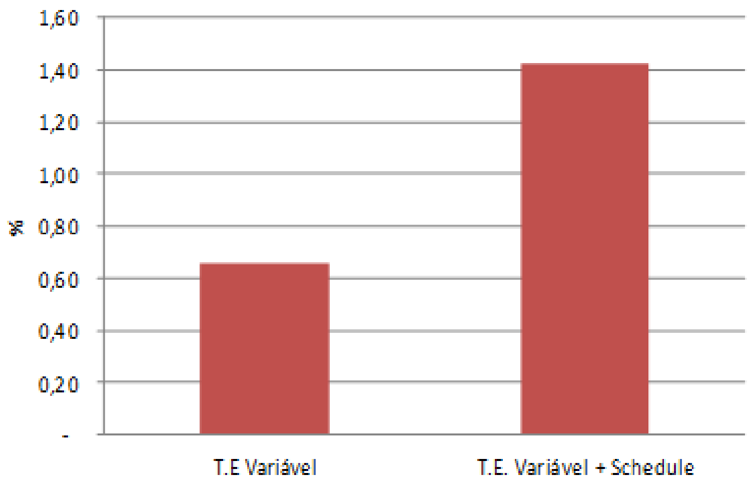

Figure 10 – Block Fuel Reduction Comparative on Short Mission (Deo, V, 2012)

It becomes clear by analyzing the results above, that for a short haul mission the climb segment optimization is responsible for most of the fuel economy. This is justified by the contribution of the climb segment on total block fuel on which the climb fuel corresponds to almost 50% of the mission total fuel burn.

Table 9 - Benefits on Medium Mission (Deo, V, 2012)

Medium Mission	Block Time	Block Fuel
Reference Aircraft	REF.	REF.
Variable Trailing Edge	REF.	- 76.5 kg

Table 10 - Benefits on Medium Mission of Variable Trailing Edge with Climb Optimization (Deo, V, 2012)

σ	VC_1	VC_2	H_1	H_2	Mach	Block Time	Block Fuel
0	250	310	10	11	0.82	-2min54seg	+63.7 kg
0.25	250	308	10	11	0.795	-2min30seg	+ 36.1 kg
0.5	250	289	10	11	0.71	=	- 88.6 kg
0.75	250	279	11	12	0.68	+50seg	- 96.0 kg
1	250	271	10	11	0.68	+50seg	- 96.0 kg

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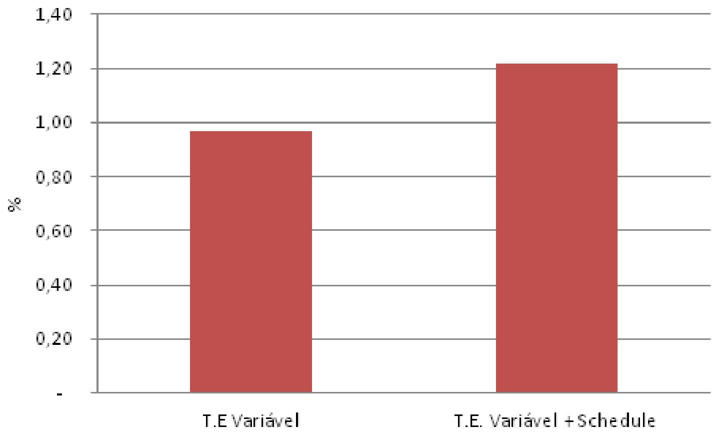

Figure 11 - Block Fuel Reduction Comparative on Medium Mission (Deo, V, 2012)

On medium range missions, the cruise segment corresponds to almost 80% of the mission's total block fuel, therefore the climb optimization loses its importance and most of the fuel economy is achieved by the variable trailing edge technology. On a 1500 nm mission at cruise Mach 0.8, the cruise compressibility optimization is the responsible for most of the fuel burn reduction.

Table 11 - Benefits on Long Mission (Deo, V, 2012)

Long Mission	Block Time	Block Fuel
Reference Aircraft	REF.	REF.
Variable Trailing Edge	REF.	- 48 kg

Table 12 - Benefits on Long Mission of Variable Trailing Edge with Climb Optimization (Deo, V, 2012)

σ	VC_1	VC_2	H_1	H_2	Mach	Block Time	Block Fuel
0	250	290	10	12	0.76	=	- 37 kg
0.25	250	279	10	12	0.79	=	- 39 kg
0.5	250	278	10	11	0.71	+ 1min	- 62 kg
0.75	250	267	10	11	0.68	+1min30seg	- 66 kg
1	250	261	10	11	0.65	+5min40seg	- 84 kg

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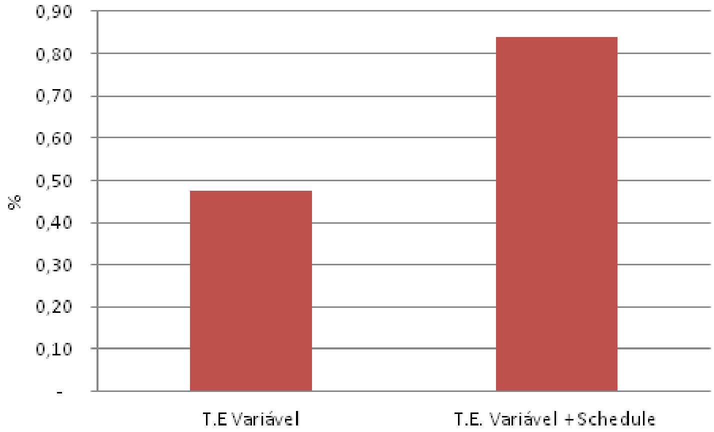

Figure 12 - Block Fuel Reduction Comparative on Long Mission (Deo, V, 2012)

On this flight at the long range cruise regime, the performance gains due to drag reduction is reduced because the cruise Mach number is lower when flying at the long range speed. The wave drag reduction when compared to a flight at Mach 0.8 is lower; therefore the performance improvement at this flight regime is not as big as the performance gains expected at higher cruise speeds.

8. CONCLUSION

By the careful analysis of the previous results, it becomes evident the importance of the climb schedule on short haul missions, the block fuel reduction on the optimized climb schedule is 110% greater when compared to the fuel economy using only the variable trailing edge. On longer flights, the performance gains of the variable trailing edge technology due to the reduced wave drag at the cruise segment is responsible for the majority of the block fuel reduction and the climb optimization loses its importance due to the lower contribution of the climb flight phase on the mission's total fuel.

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