ESCAPE

Economic SCreening of Aircraft Preventing Emissions

Annex I: Designing aircraft for low emissions;

technical basis for the ESCAPE project

Peeters Advies

Contents

List of symbols and abbreviations

AFC	Alkaline Fuel Cell
APD	Aircraft Performance and DOC model
AR	Aspect Ratio
Aspect ratio	Slenderness of the wing: the square of the wing span divided by the wing area
BASE150	Short haul baseline aircraft with 2010 turbofan technology
BASE400	Long haul baseline aircraft with 2010 turbofan technology
Block fuel	The fuel used for a flight from an origin to a destination
Block range	The distance covered on a flight from an origin to a destination, excluding the distance flown during initial climb to 3000 ft and final approach from 3000 ft
Block time	The time needed for a flight from an origin to a destination including take off, landing and taxiing
BWB	Blended Wing Body aircraft configuration
CAS	Calibrated Airspeed (for density or altitude corrected TAS)
C_D	Drag Coefficient $\frac{Drag}{\frac{1}{2}\cdot\rho\cdot V^2\cdot S_w}$ S_w is wing area, ρ is air density and V is TAS.
Chord (wing)	The (mean) measure of the wing from leading edge to trailing edge
C_L	Lift coefficient: $\frac{Lift}{\frac{1}{2}\cdot\rho\cdot V^2\cdot S_w}$ S_w is wing area, ρ is air density and V is TAS.
count	0.0001 of drag coefficient
DOC	Direct Operating Costs
FAR-25 TO	The balanced Take-Off field length as determined by the rules of the Federal Aviation Regulations part 25 for large transport aircraft.
F-CELL150	Short haul new design with fuel cell technology
F-CELL400	Long haul new design with fuel cell technology
FLEM	FLights and Emissions Model of NLR
fuel plus carbon price	An indicator for the economic ‘weight’ of fuel consumption or CO_2 emission, expressed in terms of dollars per kg of kerosene. This fictitious fuel price could be achieved by fluctuations on the world market for kerosene, by fuel levies, by carbon emission levies or by carbon emission trading regimes
H-PROP150	New aircraft design for short haul (approx. 150 seats) with high speed PROPeller turboprop engines designed for High cruise speed
H-PROP400	New aircraft design for long haul (approx. 400 seats) with high speed PROPeller turboprop engines designed for High cruise speed
ICAO	International Civil Aviation Organisation
kCAS	Calibrated AirSpeed in knots (CAS)
kTAS	True AirSpeed in knots (TAS)
LEBU	Large Eddy Break-up Devices for reducing parasite drag
LH	Long Haul, distances over 3,000 km. In this project, a typical distance of 7,000 km is used
LH_HAR	Long Haul with High Aspect Ratio wings

LH_HSP	Long Haul with High Speed Propeller engines
LH_LFC	Long Haul with Laminar Flow Control, aerodynamic cleanup, and 2010 turbofan engines
LH_NML	Long Haul with maximum use of New Materials
LH_UHB	Long Haul with Ultra High Bypass turbofan engines
Long haul	Air transport market for distances above 3,000 km. In this project, a typical distance of 7,000 km is used
LTO	Landing and take off phase of a flight (the flight profile below 3,000 ft above the ground)
mach	Mach number: TAS/speed of sound
MCFC	Molten Carbonate Fuel Cell
M-PROP150	New aircraft design for short haul (approx. 150 seats) with high speed PROPeller turboprop engines designed for Medium cruise speed
M-PROP400	New aircraft design for long haul (approx. 400 seats) with high speed PROPeller turboprop engines designed for Medium cruise speed
M_{str}	Subsonic design parameter wing sections (see (Eq. 3-17))
MTO	Maximum Take-Off
NLR	National Aerospace Laboratory of the Netherlands
NM	Nautical Mile (1.852 km)
OEW	Operating weight empty (the weight of the aircraft without fuel and payload)
PAFC	Phosphoric Acid Fuel Cell
Payload range	The payload as a function of range, limited by maximum allowable operational weights and/or maximum fuel capacity
PEM	Proton Exchange Membrane Fuel Cell
PRESENT150	Short haul baseline aircraft 1999 (Boeing 737-400)
PRESENT400	Long haul baseline aircraft 1999 (Boeing 747-400)
ROC	Rate Of Climb
ROD	Rate Of Descent
RTK	Revenue tonne kilometre
SH	Short Haul, air transport market for distances below 3,000 km. In this project, a typical distance of 1,000 km is used.
SH_HAR	Short Haul with High Aspect Ratio wings
SH_HSP	Short Haul with High Speed Propeller engines
SH_LFC	Short haul with Laminar Flow Control, aerodynamic cleanup, and 2010 turbofan engines
SH_NML	Short Haul with maximum use of New Materials
SH_UHB	Short Haul with Ultra High Bypass turbofan engines
Short haul	Air transport market for distances below 3,000 km. In this project, a typical distance of 1,000 km is used
SOFC	Solid Oxide Fuel Cell
Sweep (wing)	The angle over which the wing points backward (positive sweep) or forward (negative sweep)
TAS	True AirSpeed (as used for lift and drag calculations and time to cover some specified distance)
TO	Take-Off
TOC	Top Of Climb
TOP	Take Off Parameter (as defined by Raymer, 1992)
U-FAN150	New aircraft design for short haul (approx. 150 seats) with Ultra high bypass turboFAN engines
U-FAN400	New aircraft design for long haul (approx. 400 seats) with Ultra high bypass turboFAN engines
WE	Empty Weight of the aircraft (the structure weight plus unusable fuel and oil)

Wrap rate	Cost for personnel per duty-hour (for example the total cost for a pilot per block hour produced by this crew member)

1 Executive Summary

1.1 Introduction

In this study, carried out in the framework of the ESCAPE[1] project, four short haul and four long haul new aircraft have been designed and evaluated. Primary focus of the study are the trade-offs between flight economics, fuel consumption, and the so-called 'fuel plus carbon price'[2], that have been assessed within boundary limits with respect to noise and NO_X, payload-range performance and field performance (runway requirements).
The main question is how trade-offs between fuel (or carbon emission) costs and fuel consumption work out in practice. Theoretically such a trade-off has been shown before (e.g. Morrison, 1984), but this theory does not give much quantitative information on the strength of the effects. To find these we have investigated the benefits and costs of eight conceptual designs meant for a hypothetical higher fuel price, or the fuel price including a levy on carbon emissions, or the price formed with tradable carbon rights.
The development and evaluation of the conceptual designs have been based on two typical representatives of the short haul and the long haul market. These so-called 'baseline aircraft' have been updated to an expected technology level of 2010 to create the BASE150 for the short haul market and the BASE400 for the long haul market. All individual technologies and new designs have been compared at the 2010 technology level.
To come to a fully optimised and balanced aircraft design will require a large working force and millions of dollars. Therefore this study does not have the intention to deliver full preliminary designs for a high fuel plus carbon price market. The 'designs' as presented here have been based on relatively simple relations between the most important parameters and characteristics of technologies. They are in the state of a first conceptual reconnaissance of possible solutions giving something like 90% of the final value of the main design parameters. The high fuel plus carbon price has been used in the design process at establishing design speeds and parameters like the wing aspect ratio.
In the following paragraphs we will first discuss the methods used for this study. Then the results for the individual technologies are presented. From this evaluation we may conclude that several technologies are too expensive on themselves to be used for reducing the environmental impact. However, when these technologies are combined into a new design the result is a much more economic aircraft as described in §1.4. Promising unconventional configurations will be described in §1.5.

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1 ESCAPE: Economic SCreening of Aircraft Preventing Emissions, a co-product of Peeters Advies, CE, the Delft University of Technology, and TRAIL, financed by the Dutch Transport Research Centre and the Ministry of Housing, Spatial Planning and the Environment.

2 Fuel plus carbon price: an indicator for the economic 'weight that fuel consumption and/or CO_2 emissions play in aviation. This weight is expressed in terms of dollars per kg of kerosene, independent of the question whether it is determined by the oil market, levies on fuel or CO_2 emissions, or CO_2 emission trading regimes.

1.2 Evaluation and models

For the short haul evaluation flight a 1,000-km block range with a 70% load factor has been chosen. For long haul these figures are 7,000 km and 75%. The evaluation flights have been computed using the APD-model (Aircraft Performance & DOC model). This calculates aircraft speed, fuel flow, weight and altitude for about 200 points of the flight path consisting of:

- 26 minutes taxiing at 7% of maximum take off (MTO) rating;
- 0.7 minutes take off at MTO;
- 2.2 minutes climb-out to 3,000 ft at 85% of MTO;
- climb at maximum climb rating;
- cruise (at one altitude);
- descent;
- 4.0 minutes approach and landing at 30% of maximum take off rating;
- Reserve fuel for flying from the destination to an alternate and keeping a hold pattern for a specified time.

The DOC module calculates the cost for oil and fuel, flight-crew, cabin-crew, landing charges, depreciation and maintenance based on the block fuel, distance and time found by the performance model. In all cases the utilisation in terms of hours per year has been kept constant to the baseline value. Therefore the direct effect of lower cruise speeds on the revenue ton kilometres is included in all DOC calculations.
For adapting the baseline aircraft to new technologies and for designing new aircraft, use has been made of tools for sizing and scaling of dimensions, weights, costs and drag. Most of these tools have been based on statistical methods from the literature and adjusted to the baseline models as far as possible.

1.3 Individual technologies

1.3.1 Description

The individual technologies are divided into three groups: propulsion, aerodynamics and materials. For propulsion three different developments have been studied. In aerodynamics we will show the effect of two technologies and in materials one. All technologies are evaluated by virtually introducing them onto the baseline aircraft as a kind of partly redesign or retrofit. Of course it is not recommended to really retrofit for example a Boeing 737-400 with propeller engines. The fuel cell technology has not been evaluated as a virtual retrofit, because it requires too many design changes. Therefore it has been evaluated only as a total new design of the aircraft (see §1.4).
A conventional way of enhancing fuel efficiency of turbofan engines is based on increasing the ‘by-pass ratio’. This bypass ratio will reduce both fuel consumption and CO_2 emissions as well as the emission of noise. However it may increase the emissions of NO_x due to the increased temperature and pressure ratio of the core engine. The development will be evaluated by the introduction of ultra high bypass engines (UHB).
In the eighties the development of ‘Propfans’ got a lot of interest due to the oil crisis and the high fuel prices of the time. Propfans are turbine engines driving a special high speed counter rotating propeller, with a high number of highly swept blades. Propfans are designed for high mach numbers up to 0.85. From the studies it turned out the engines had many problems like high vibration and noise levels. But they promised a leap down in fuel specific fuel

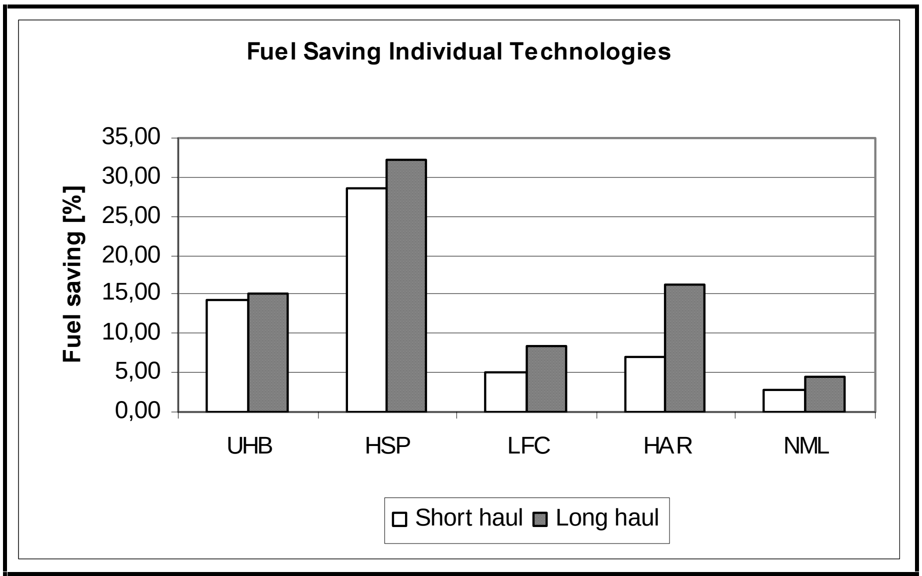
consumption. As the oil prices went down in the nineties interest in the Propfan diminished and only a few research projects survived.
From one of these, the Dutch Green Aircraft project, it turned out a High Speed Propeller with 2*6 contra-rotating swept propellers designed for mach 0.75 could decrease the mentioned problems and retain the high fuel efficiency. In our study we have based the second propulsion system on this High Speed Propeller (HSP).
The third option is a more futurist one: the use of high speed propellers driven by an electric super-conducting engine powered by fuel cells. This option requires the use of liquid hydrogen (LH_2), as fuel. Fuel cells turn hydrogen and oxygen (from the air) directly into electricity, which is used to drive the electric engines. The cryogenic cooling of the engines will be accomplished with the help of the LH_2. Fuel cells promise a high energy efficiency. However, they need a lot of space and are relatively heavy, both characteristics unwanted in fuel efficient aircraft.
The use of liquid hydrogen may enhance the environmental performance of both UHB and HSP engines. However this has not been studied in further detail in this study.
Three ways are available to the aircraft designer to reduce aerodynamic drag: reducing parasite drag, reducing induced drag and reducing mach drag. The first two have been specifically worked out in this study. In the full designs also attention has been given to mach drag.
Parasite drag can be reduced by aerodynamically ‘cleaning-up’ the aircraft (like removing protuberances and advanced design of the fairing between wings and fuselage) and by adding passive or active ‘laminar flow control’ to the wing and empennage. This last option will smoothen the flow over parts of aircraft and will thus reduce the drag. However, this requires a lot of attention on daily maintenance of the aircraft (keeping it as clean as possible, as even small disturbances will destroy the laminar flow).
‘Induced drag’ is lift-dependent: the higher the lift of the wing (per metre span), the higher the induced drag. This kind of drag originates from vortexes flowing off the wing tips and dissipating energy. The smaller the lift generated per metre wing span the smaller this tip-vortex and the induced drag will be. Therefore a way to reduce induced drag is to enlarge the wing slenderness or ‘aspect ratio’ (AR).
If the AR is infinite the induced drag becomes zero. However increasing wingspan has two disadvantages: a higher wing bending moment at the wing root and a smaller wing thickness. Both increase the wing weight and airframe cost. Optimum aspect ratios giving the lowest DOC have been found between 11 and 14, depending on the design under consideration. The fuel optimum is found to be somewhere between 15 and 20, giving the lowest fuel consumption attainable.
Reducing weight has always been an aim in aircraft design. Using strong and light-weight materials like fibre-reinforced plastics or GLARE, a fibre metal laminate developed by the Delft Technical University, will decrease the weight of the construction. In this study we will show the effect of replacing large amounts of the structure by this kind of materials.

1.3.2 Fuel consumption

Figure 1 gives the fuel saving with respect to the BASE150/BASE400 of all technologies considered. The figure shows a large difference between the technologies. The highest fuel savings may be reached with the high-speed propeller: for both short and long haul markets with fuel savings of about 30%.

With ultra high bypass engines about 15% of fuel can be saved for both markets. The high aspect ratio gives about 15% reduction for long haul, but only 7% reduction for short haul aircraft. Laminar flow and aerodynamic clean-up of the aircraft deliver between 5% and 8% decrease of fuel consumption. The introduction of new materials closes the row with less than 5% fuel saving. A general observation is further that all technologies individually have the largest potential on the long haul aircraft.

Figure 1 Fuel saving potential of the individual technologies compared to BASE150 (short haul) and BASE400 (long haul)

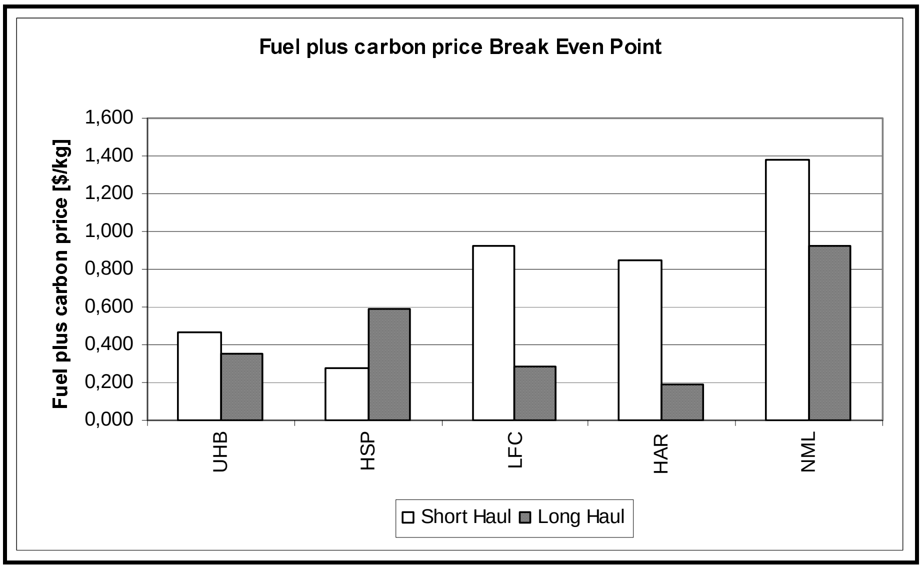


1.3.3 Economy

A way to show the economic performance of a technology is to calculate the direct operating cost of the aircraft fitted with it and to compare this to the baseline and other technologies. However, the result of this comparison depends largely on the fuel plus carbon price assumed. A better indicator is the so-called ‘break-even point’. This point gives the fuel plus carbon price at which the aircraft fitted with a certain technology will have a lower DOC than the baseline aircraft. A low break-even point indicates an economic way of reducing fuel consumption. Figure 2 gives the break-even points with the BASE150/400 for the individual technologies.

From this figure it is clear the HSP is the most economic solution for the short haul market. The high aspect ratio, LFC and UHB are cost-effective for the long haul market. The lacking behind of the HSP for the long haul market is mainly due to the high cruise mach number of the long haul baseline aircraft compared to the slower HSP fitted aircraft. The aerodynamic technologies seem less cost-effective for the short haul market. The use of new materials gives the least effective option for both markets from an economic point of view.

Figure 2 Fuel plus carbon price break even points with the BASE150/400 for the individual technologies



1.3.4 Conclusions and individual technologies

From the analysis we draw the following conclusions:

- The introduction of the high-speed propeller (HSP) gives the highest fuel savings for both short and long haul.
- For the long haul market the most *economic* ways to reduce the fuel consumption are increasing the wing aspect ratio and reducing parasite drag; for short haul this is the HSP.
- The introduction of new lightweight materials is neither an effective nor an economic way to reduce fuel consumption.

1.4 New designs

1.4.1 General description

In this paragraph we will look at eight new designs (four per market) in which several technologies are combined. Totally new aircraft configurations will be addressed in the next paragraph (§1.5). Combining technologies into a fully new design may have the following three effects:

- Lower benefits: the fuel consumption benefits of the individual technologies slowly decrease as more technologies are combined. The first 10% reduction option will give 10% fuel savings, a second will only offer (100%-10%)*10% = 9% savings.
- Higher benefits: it will be possible to use the reduction in operational weights (due to the reduction in fuel consumption) to redefine engine and wing area, which will further enhance efficiency.
- Lower costs: the cost of the technologies may be lower due to synergistic effects in engineering and production, and development costs will be written off over a larger number of aircraft built (the better a design performs, the longer it will be in production).

As the characteristics of the engines dictate large differences in operational speeds we will design the new aircraft 'around these engines'. Also we have given attention to the influence of design speed by introducing both a high speed and a medium speed design with high-speed propellers. This gives the following designs:

- **U-FAN150** and **U-FAN400**: combines the Ultra High Bypass turbofan with all other non-propulsive technologies.
- **H-PROP150** and **H-PROP400**: combines high-speed propellers at their highest possible design cruise speed with a high aspect ratio plus aerodynamic clean up.
- **M-PROP150** and **M-PROP400**: combines high speed propellers at a medium design cruise speed with a high aspect ratio and laminar flow control/aerodynamic clean-up for the long haul market only.
- **F-CELL150** and **F-CELL400**: a new design combining fuel cell power and electric/high speed propeller propulsion with all other non-propulsive technologies.

Table 1 Overview of properties of the new designs

Design	OEW	MTOW	aspect ratio	wing area	wing span	price (incl. eng.)	$W^3_{propulsion}$
	tonnes	tonnes	-	m^2	m	M$	tonnes
BASE150	34.0	61.2	7.9	105.4	28.88	43.35	5.121
H-PROP150	36.4	60.1	11.0	103.0	33.66	43.65	6.573
M-PROP150	33.8	56.2	12.0	109.5	36.25	40.81	5.053
U-FAN150	28.6	52.5	10.0	82.5	28.72	45.88	4.521
F-CELL150	46.4	64.5	12.0	144.0	41.57	N/a	14.908
BASE400	177.2	348.5	7.7	541.2	64.44	167.73	22.460
H-PROP400	167.5	290.7	14.0	460.0	80.25	152.10	24.178
M-PROP400	163.8	281.0	14.0	490.0	82.83	144.56	20.535
U-FAN400	148.1	277.3	12.0	415.0	70.57	169.43	17.784
F-CELL400	215.6	296.7	14.0	550.0	87.75	N/a	64.412

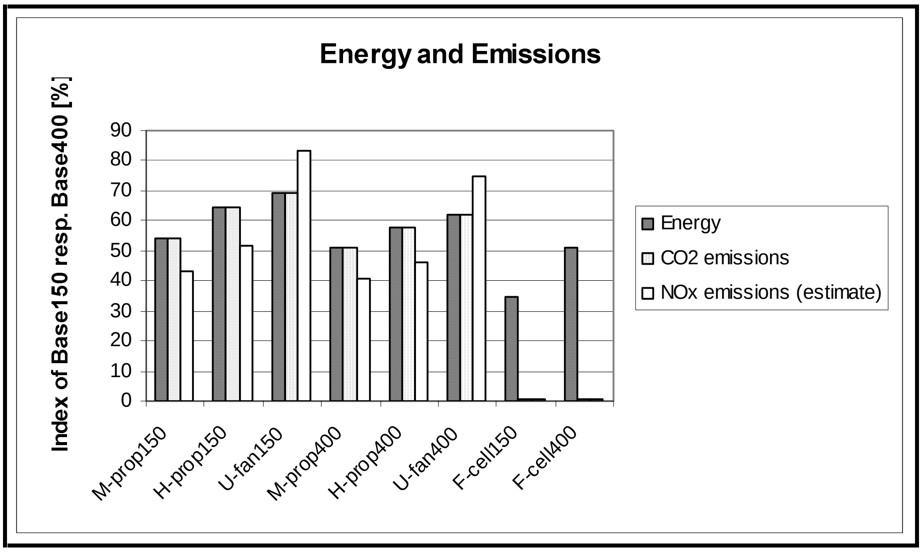
In all designs we have optimised wing and power loading. For M-PROP, H-PROP and U-FAN we have optimised the wing aspect ratio for the case of a $1.00/kg fuel plus carbon price. The aspect ratio of the M-PROP has also been used for the F-CELL designs. The main properties of the aircraft are summarised in Table 1. From this table it becomes clear the high-speed propeller (M-PROP) gives a cheap aircraft, while the ultra high bypass turbofan asks for an expensive but 'lean' aircraft. The price of the fuel cell technology aircraft has not been established due to large uncertainties in the cost of certified systems.

1.4.2 Environmental impact of the new designs

To determine the environmental impact we have concentrated on the emission of CO_2 and thus on fuel consumption. Also a first estimate of emissions of NO_X and of noise have been made. As the F-CELL designs use LH_2 and others use kerosene as fuel we will replace the fuel consumption with energy consumption to make them comparable. It must be remarked here that the results of the F-cell are tentative as many more uncertainties exist on these designs than on the other six.

[3] Propulsion weight is the sum of engine (plus propeller) weight, exhaust system weight, fuel system weight and engine installation weight.

Figure 3 Environmental impact of the new designs as index of the baseline 2010. The results for fuel cell technology are very much tentative and only added for comparison



From the figure it is clear the environmental performance of the high-speed propeller based aircraft (H-PROP and M-PROP) is better than that of the ultra high bypass (U-FAN) aircraft. Comparing the H-prop design with the M-prop design leads to the conclusion that a lower design cruise speed may lead to lower fuel consumption for this kind of high-speed propeller driven aircraft.

It will in principle be possible to introduce hydrogen as a fuel for all designs, making them probably slightly more fuel efficient (up to 10%) and reducing the in-flight emissions of carbon dioxide to zero and probably largely reducing nitrogen oxides, but increasing the emissions of water vapour.

The noise impact is influenced by two parameters: the direct emissions of noise from airframe and engines and the flight path at low altitudes during climb and approach. Both low noise emissions and a steep flight-path will reduce the noise 'footprint' (area within some pre-defined noise level) and therefore the impact of noise on the environs of the airport. The noise emissions are influenced by the power rating and the type of the engine. Due to many unknowns of the new designs and the complexity of the material we will only make some qualitative remarks on this subject (see Table 2). The final result requires extensive analysis on the subject, which is beyond the scope of this study.

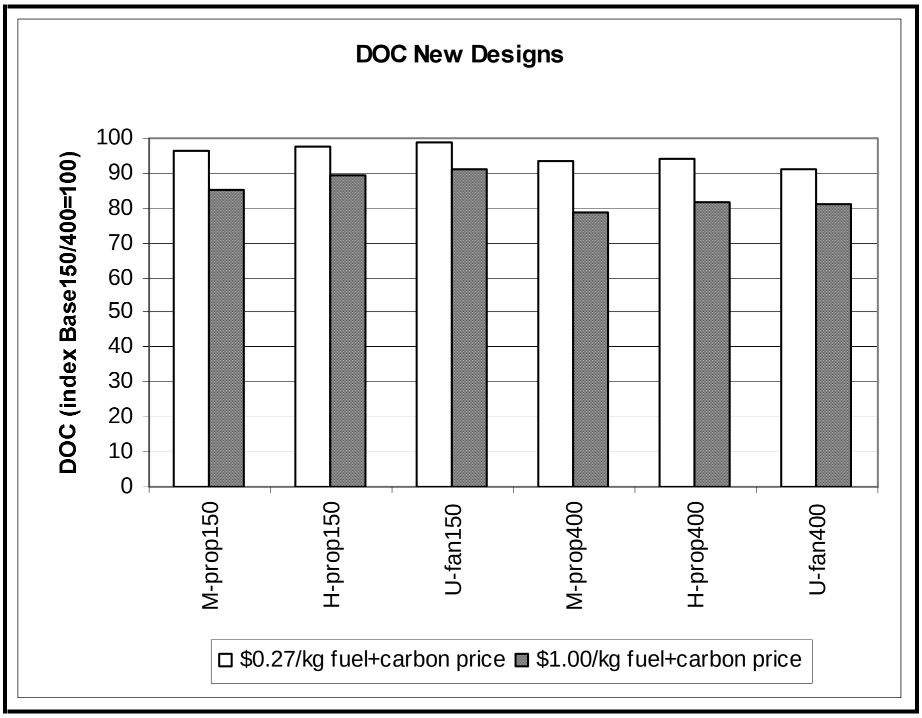
Table 2 The effect of the new designs on noise compared to the baseline 2010 (tentative estimates). The noise impact will be reduced if the engine rating is lower, the number of '–' for direct noise and installation effects increases and the climb gradient is higher

Parameter	Short haul				Long Haul			
	M-PROP	H-PROP	U-FAN	F-CELL	M-PROP	H-PROP	U-FAN	F-CELL
Engine rating [% of BASE static TO thrust]	75%	90%	80%	67%	57%	70%	67%	50%
Engine direct noise emission (relative change)	--	--	-	---	--	--	-	---
Engine installation effect on noise emission	-	-	0	-	-	-	0	-
Initial climb-out gradient [% change with respect to BASE]	-23%	+7%	+1%	-36%	-22%	-3%	-5%	-43%
Total noise effect (tentative estimate)	worse	Better	better	worse	same	better	better	worse

1.4.3 New design economics

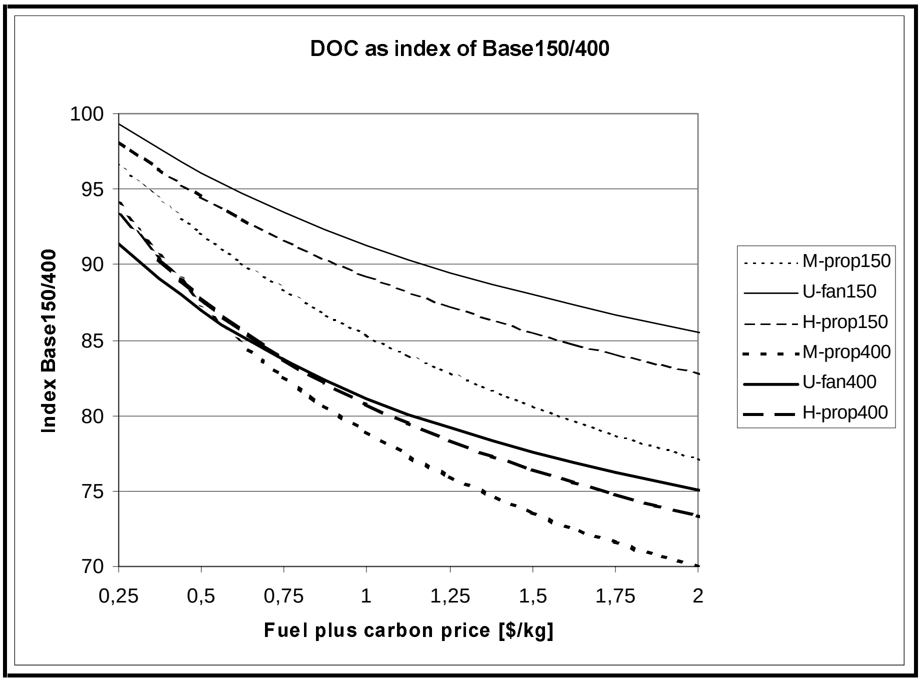
As the cost factors for the F-CELL designs are largely unknown we will only consider the economics of the six other designs. Looking at the DOC of the new designs (see Figure 4) we may observe the DOC of all designs is lower than the DOC of the baseline 2010 even at current fuel prices of $0.27/kg. At the high fuel plus carbon price of $1.-/kg M-PROP has the lowest DOC for both markets. The highest DOC have U-FAN150 and H-PROP400.

Figure 4 The DOC of the new design in indices of BASE150/400



The DOC is influenced by the assumed fuel plus carbon price. To find the cross-over points for the designs we have drawn Figure 5. This figure gives the DOC relative to the short haul and long haul baseline aircraft BASE150 respectively BASE400 as a function of the fuel plus carbon price. Now we see that for short haul the DOC of the M-PROP150 is the lowest for the whole range given and the cost of U-FAN150 the highest. H-PROP150 has intermediate costs for all fuel plus carbon prices.
For the long haul designs a different picture arises. Here U-FAN400 is the most economic option up to fuel plus carbon prices of about $0.60/kg, where the M-PROP400 becomes cheaper to operate. The H-PROP400 has always a higher DOC compared to the two other new designs. In competition with U-FAN400 the DOC of H-PROP400 becomes lower above a fuel plus carbon price of $0.75/kg.
As has been shown in Figure 5 the higher the fuel plus carbon price becomes the more advantageous the DOC of the most fuel-efficient aircraft. Also during the conceptual design it appeared optimising aspect ratio resulted into larger wing aspects ratios if the presumed fuel plus carbon price was taken higher. This also results in a more fuel-efficient aircraft to be optimal at higher fuel plus carbon costs.

Figure 5 DOC of he new designs as a function of the fuel plus carbon price



1.4.4 Performance

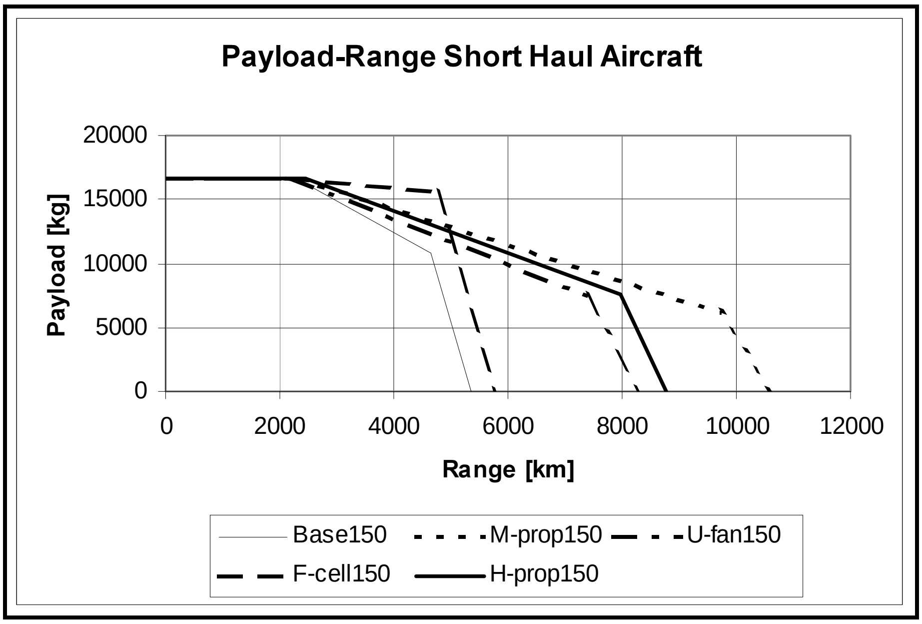
The performance of the aircraft should be within operational requirements of the airlines. Important are the evaluation flight performance, payload range performance and take off and landing performance. The operational performance in the evaluation flights is shown in Table 3. As can be seen the block time for M-PROP increases for short haul and long haul with respectively 11% and 16%. Also the fuel cell aircraft have a lower cruise speed resulting in an increase of 9% of block time for short haul and 23% for long haul.

Table 3 Performance of the new designs on the evaluation flights. Block distance for short haul is 1,000 km, for long haul 7,000 km

Design model	TO Weight	Block		Cruise	
		time	fuel	Mach	altitude
	kg	hr.min	kg	-	m
BASE150	52,160	1.52	3,591	0.745	10,000
M-PROP150	48,785	2.04	1,943	0.640	9,000
H-PROP150	52,157	1.55	2,323	0.720	10,000
U-FAN150	44,760	1.52	2,490	0.745	10,000
F-CELL150	58,825	2.02	1,246[4]	0.660	8,000
BASE400	306,376	8.30	68,513	0.840	11,000
M-PROP400	251,671	9.53	34,799	0.700	9,500
H-PROP400	261,155	9.26	39,400	0.740	10,000
U-FAN400	246,340	8.30	42,569	0.840	11,000
F-CELL400	276,822	10.28	34,818[5]	0.650	8,500

The payload-range diagram gives the maximum payload that can be transported as a function of range. The payload range capability of the short haul designs is better than it is for the baseline. However, the most important point (range with full payload) is the same for all designs (see Figure 6). The design with fuel cell technology shows a very flat rate and therefore offers twice the maximum payload range at almost full payload.

Figure 6 Payload-range performance of the short haul designs

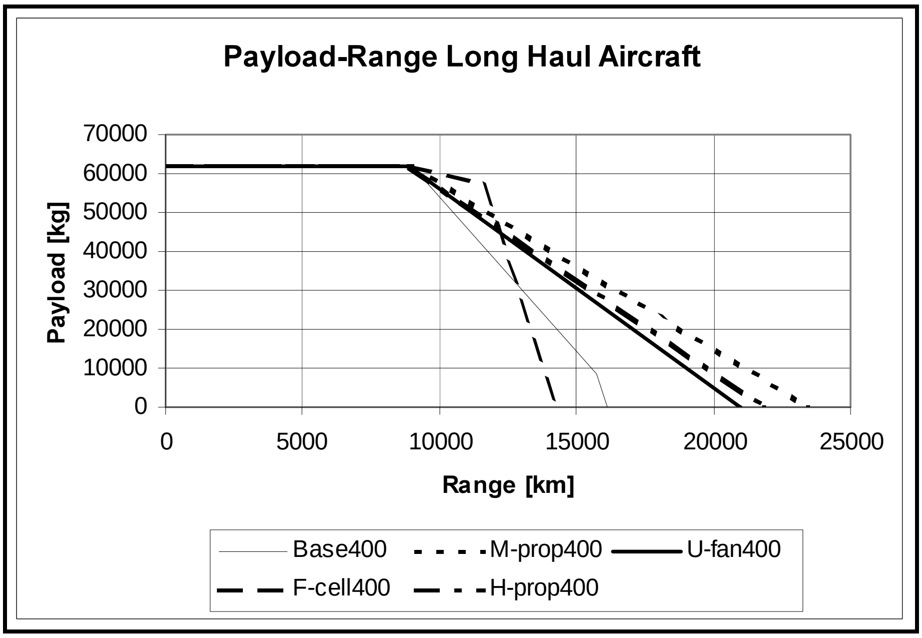


There is no fuel volume limit for the M-PROP400, H-PROP400 and U-FAN400 designs, because we did not adjust the tank volume to the lower fuel consumption (see Figure 7). Only the F-CELL400 has a volume limit, because the LH_2 storage tanks are too heavy to make them bigger than strictly necessary. The range at almost full payload is about 1.5 times the range at full payload for the F-CELL400.

4 This figure gives the mass of kerosene equivalents. The hydrogen weight is 445 kg.

5 This figure gives the mass of kerosene equivalents. The hydrogen weight is 12,435 kg.

Figure 7 Payload range performance of the long haul designs

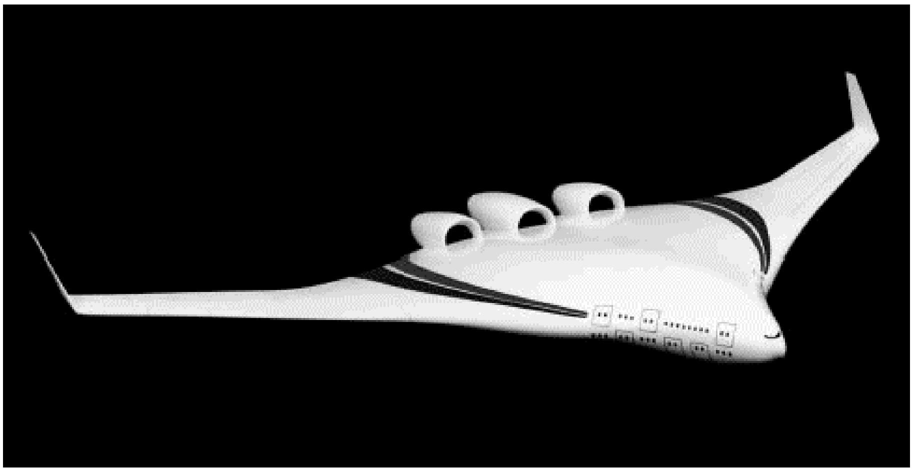


Another important performance item is field performance. As airports have runways of limited length it is important the aircraft does not need too much take off or landing field length. From a rough calculation it was found the new designs have comparable or better field performance than the baseline at the higher operational weights. This is the result of the lower fuel weight, requiring lower maximum take off and landing weights for a given mission, and the thicker wing profile on the slower aircraft (M-PROP, H-PROP and F-CELL) allowing for a higher maximum lift.

1.5 New aircraft configurations

So far we have considered only the classical layout of aircraft: non-lifting fuselage for easy storage of cargo/passengers, wings as lifting surfaces and aft tail planes for control and stability. In this paragraph we discuss other solutions. The main possibilities are: tail first, tail-less and blended wing body (BWB). The tail-first or canard and the tail-less aircraft are mainly used for transonic and supersonic aircraft. Their ability to increase fuel efficiency on a subsonic aeroplane is not considered to be spectacular. Therefore the blended wing body (see Figure 8) is at this moment the only non-classical configuration with a possibility to reduce the fuel consumption with up to 25% compared to state of the art wide body aircraft. Important is also the DOC may be reduced with up to 20%.

Figure 8 Example of a blended wing body design as given by NASA (1997)



The main problems of the configuration are controllability and layout of the cabin. Specifically the low-speed flight-envelope, like stall and spin behaviour, is largely unknown and needs investigation. To study this, NASA and Boeing recently announced flight tests on a low speed scale model to start early in 2002. The 14%-scale model will be remotely piloted and represents the latest 450-passenger second-generation BWB under study at Boeing and NASA.

Another difficulty in designing a high-speed BWB is the high mach drag arising from the relatively high wing thickness ratio required. It would be of much interest to look at the total design opportunities from an environmental point of view and including several propulsion technologies and performance specifications. Also it will be interesting to study the possibilities for aircraft with less then 450 passengers.

1.6 Conclusions

From the technical study we draw the following conclusions:

- The introduction of the high-speed propeller (HSP) gives the highest fuel savings for both short and long haul.
- For the long haul market the most *economic* ways to reduce the fuel consumption are increasing the wing aspect ratio and reducing parasite drag; for short haul this is the HSP.
- A Propfan (high speed propeller with a design speed of mach 0.8 or more) seems a more economic way to reduce fuel consumption of long haul aircraft; however such Propfans still suffer from many technological problems like high levels of vibration and noise.
- The introduction of new lightweight materials is neither an effective nor an economic way to reduce fuel consumption.
- Fuel savings of 40-45% with respect to the baseline with 2010 technology turbofans are conceivable for new designs, without sacrificing the performance of the aircraft or the economy in terms of DOC, payload-range and field-length.
- A long-term stable increase of the fuel plus carbon price may advance the introduction of more fuel-efficient new designs.
- The fuel savings of the high-speed propeller designs may be enlarged by reducing cruising speed below the design point of this propulsion system. At high fuel plus carbon prices the DOC for these lower speed aircraft may be better than for the high-speed variant.

- New aircraft configurations (especially the blended wing body) have the promise of further substantial increases of fuel efficiency.
- Fuel cell technology gives interesting opportunities for a zero CO_2/NO_X aircraft. For the short haul aircraft, the energy consumption of this concept may be lower than for the kerosene concepts studied. However, this design still requires a lot of development work. Therefore, these results are less certain than for the other designs and it is not possible at this moment to establish the DOC and other costs.
- To cut energy consumption further, the blended wing body might be an option for long haul, while the fuel cell might be promising for short haul.

1.7 Recommendations

Environment
Although fuel consumption, and thus CO_2 and H_2O emissions, is an important environmental indicator, other environmental aspects need to be further researched as they play an important role in the discussion on aviation and the environment:
- the increased engine efficiency, that may lead to an increase in contrail formation;
- the changes in cruise altitudes, that may have an impact on the formation of contrails and the lifetime of ozone.

Performance specifications
The influence of performance specifications on DOC and environmental impact needs to be studied further. Specifically the relation between design speed and environmental impact seems to present opportunities for reducing environmental impact.

High speed propellers
High-speed, probably counter rotating, propellers are one of the most promising technologies for reduced emissions because they enable aircraft transport at quite economic speeds (mach 0.72-0.75) with significantly reduced fuel burn and emissions. It is recommended to further study this technology in order to reduce the risks associated with noise, vibration and reliable high power gearboxes and propeller de-icing.
Further it is recommended to reconsider development of faster propeller engines for the long haul market (suitable for mach numbers above 0.8). Such a propulsion device may give better DOC and fuel efficiency figures than UHB engines will.

UHB engines
It is recommended to further study pros and cons of engine concepts exceeding the bypass ratios considered in this study (beyond 9:1), as it is not sure whether such an increase still is beneficial to the environment. Past studies on these types of engines suggest increasing problems in terms of a) the required heavy fan gearbox, b) ever increasing fan reverser areas, and c) increased nacelle diameter leading to increased weight and drag. On the one hand, a fan gearbox or a combination with a variable pitch fan might lead to lighter and more reliable designs, on the other hand it is also possible that the much larger nacelle will lead to ever diminishing returns due to more weight and drag.

Higher aspect ratio wings
Today's high Aspect Ratio (AR) wings on Airbus aircraft have ARs between 10 and 11. However, the report suggests an advantage for ARs in the 14-15 range. Therefore, it is recommended to further study this problem comparing

counter-rotating propeller and UHB aircraft at these high ARs[6] to obtain information on:

- Aero-elastic (flutter) limits;
- Sizing parameters.

Blended wing body

It is strongly recommended to issue a study on the possibilities and problems of the blended wing body configuration in conjunction with the other technologies presented in this study both long haul and short haul aircraft.

Hydrogen and fuel cell

Applying hydrogen as a fuel on high-speed propeller or UHB powered aircraft has not been evaluated in this study. In comparison to kerosene aircraft, these concepts lead to zero in-flight carbon dioxide and carbohydrates emissions, and lower nitrogen oxide emissions. On the other hand it will impose technological and economical problems, specifically for the fuel systems both in the aircraft and on the ground.
It is recommended to include the fuel cell technology issue into running studies on liquid hydrogen aircraft or to combine these subjects in new studies. Special attention is needed for costs, fuel system design and integration, cryogenic cooling of electrical engines, the full design integration of propulsion and airframe, and safety, including special requirements with respect of the amount of fuel cells required for the one engine out climb.

[6] This can be done by making 'point designs' (further detailing of concepts with a fixed high aspect ratio and the mentioned engine types, instead of simultaneously optimising the aspect ratio and other design parameters).

2 Introduction and assumptions

2.1 General

How will the future aircraft design be if the fuel price will rise substantially? That is the main question we try to answer in this report. Theoretically a relationship between fuel price and aircraft design has been shown for example by Morrison (1984). He shows the general relationship between time, cost and fuel price and the probable difference in a DOC or a fuel optimised design. When the designer is convinced of a high price for fuel in the future market, he will fundamentally choose for solutions different from the case a low fuel price is the prevailing forecast.
Though the theory seems sound it does not give much quantitative information on the strength of the effects. To find these we have investigated the benefits and costs of several conceptual designs meant for a hypothetical higher fuel price or the fuel price including a levy on carbon emissions or the price formed for tradable carbon rights. The effects have been evaluated by calculating block time, fuel and distance and DOC for a standard evaluation flight.
The development and evaluation of the conceptual designs have been based on two typical representatives of the short haul and the long haul market. These baseline aircraft have been updated to an expected technology level of 2010 to create the BASE150 for the short haul market and the BASE400 for the long haul market. All individual technologies and new designs have been compared at the 2010 technology level.
To come to a fully optimised and balanced aircraft design will require a large working force and millions of dollars. Therefore this study does not have the intention to deliver full preliminary designs for a high fuel plus carbon price market. The here presented 'designs' have been based on relatively simple relations between the most important parameters and characteristics of technologies. They are in the state of a first conceptual reconnaissance of possible solutions giving something like 90% of the eventual final value of the main design parameters. The high fuel plus carbon price in the design process has been used at establishing design speeds and parameters like the wing aspect ratio.

2.2 Definition of markets and baseline designs

In this study we have divided the air transport market in two: the short haul market (up to a range of 3,000 km) and the long haul market (over 3,000 km). The short haul market consists mainly of intra-continental traffic like the traffic on the intra-European market. The long haul market consists mainly of intercontinental flights.
For both markets we have defined a 'baseline aircraft'. The baseline aircraft are chosen to be a typically much used representative of the market segment in the current fleet. The baseline aircraft for short haul represents a typical aircraft in the 150 seats market section with a maximum range of approximately 3,000-4,000 km, but typically used for a range of 1,000-2,000 km. The Boeing 737-400 has been chosen for this purpose. Therefore the "PRESENT150" has been based on the dimensions, weights and aerodynamic characteristics of the Boeing 737-400.

For the long haul market the baseline aircraft must represent a typical currently much used aircraft in the 400-500 seats market section with a maximum range of approximately 13,000 km to 14,000 km, but typically used for a range of 7,000 km to 8,000 km. The Boeing 747-400 is the only suited example for this purpose. Therefore the "PRESENT400" has been based on the dimensions, weights and aerodynamic characteristics of the Boeing 747-400. Data for these two aircraft have been gathered from many sources and from data available at Peeters Advies and partners.

We are aware of the fact these aircraft are not the best technology currently available. The first flight of the Boeing 737-400 was in 1988. This aircraft has been based on the 737-100 from 1967, but the wing design and large parts of the structure as well as the engines were new design of the late eighties. The current engine has been certified in 1984. The 747-400 had its first flight also in 1988. The original 747 flew in 1966. The CF6-80C2 engines were introduced in 1985. In 2001 a growth version of it will be set into the market.

The wing design of the 737 and 747 is somewhat behind current development: both its high speed characteristics and its aspect ratio are surpassed by more modern airliners. The modern equivalent of the 747-400 is the Boeing 777 with an aspect ratio of 8.7 in stead of 7.7 or the Airbus A340 with 10.1. The 737-400 has a modern alternative in the Boeing 737-600 and higher with aspect ratio of 9.4 or the Airbus A320 with an aspect ratio of 9.5.

On the other hand newer aircraft will have to apply to more stringent safety regulations as the older derivative aircraft. This normally leads to extra cost and weight and a lower fuel efficiency.

To partly counteract the technological arrears we have updated the engine performance, price and weight with 11 years of conventional development (1999-2010). According to Van der Heijden and Wijnen (1999) the 2010 technology level turbofan engine will have had a reduction of fuel consumption with 0.85% per year, a weight reduction with 0.75% per year and a cost reduction of 1% per year. Maintenance cost will not change. For eleven years this means a reduction of fuel flows with 9%, of weight with 8% and of price with 10.5%.

See Table 4 for an overview of the characteristics of the so-called BASE150 and BASE400 baseline models defined for this study.

Table 4 Overview of basic characteristics of the two baseline aircraft BASE150 and BASE400

	BASE150	BASE400
Number of seats (typical)	146	416
Maximum payload [kg]	16,690	61,915
Wing area [m^2]	105.4	541.2
Wingspan [m]	28.88	64.44
Wing Aspect Ratio	7.9	7.7
Operating Empty Weight [kg]	34,025	177,171
Number of engines	2	4
Dry engine weight [kg]	1,795	3,967
Maximum Take off Weight [kg]	61,241	348,474

2.3 Evaluation flight

To get an idea of the economic performance of an aircraft it is practice to calculate its Direct Operating Costs. Included in these costs are all cost elements that have a direct relation to the operation of the aircraft like crew costs, fuel costs, finance and insurance, depreciation, maintenance costs and charges (e.g. landing). All these costs can be related to the fuel consumption and the flight time of the aircraft. Therefore we need to find these from a typical 'evaluation flight'.

For the short haul market the evaluation flight is defined with a 70% load factor over a block distance of 1,000 km. The long haul evaluation flight has a block distance of 7,000 km with 75% load factor. The flight profile used for calculating block-time and block fuel is a simplification of the flight profile given by Torenbeek (1982). The engine ratings and times below 3,000 ft are taken from the standard ICAO LTO-cycle[7]. The following assumptions have been made for the evaluation flight of the BASE150:

- block distance: 1,000 km;
- payload: 70% of maximum;
- 26 minutes at 7% MTO engine rating (all fuel weight for taxi is pre-TO);
- take off 0.7 minutes at 100% MTO rating and Climb-out from 35 ft to 3,000 ft in 2.2 minutes at 85% MTO rating;
- climb at 300 knots[8] constant CAS 0.745 with maximum climb thrust;
- cruise at 10,000 m altitude with mach 0.745;
- descent with constant mach 0.745/300 knots CAS;
- approach from 3,000 ft to SL at 71.4 m/s TAS; Approach time 4 minutes at 30% MTO rating;
- reserves: go around from 3,000 ft at destination, flight to alternate at 200 NM with normal cruise speed schedule, but at 8,000 m cruise altitude and 30 minutes hold as extended cruise.

For the Long haul evaluation flight the same flight profile has been used with following exceptions:

- block distance 7,000 km;
- payload: 75% of maximum;
- speed schedule for climb and descent: 320 knots CAS/mach 0.84;
- cruising speed mach 0.84 at 11,000 m altitude;
- reserves: only 120 minutes hold as extended cruise.

[7] For climb-out this standard time is compared to the real time given the aircraft and engine-parameters and the largest of the two has been chosen.

[8] Below 10,000 ft the speed is restricted to 250 kTAS (Torenbeek, 1982).

3 Model system

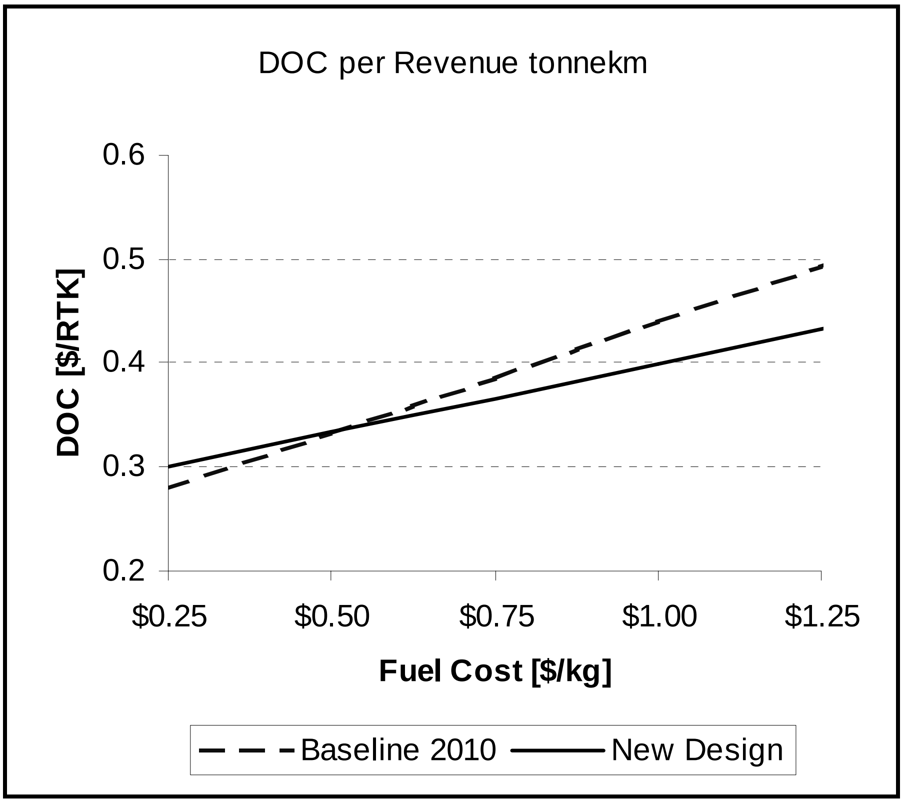
3.1 Introduction

In this chapter we give a short description of the methods and models used to find the Direct Operating Costs (DOC) for aircraft fitted with technologies for reducing fuel consumption. We do this by giving examples of the development of derivatives and new designs of aircraft for two characteristic markets: short haul and long haul. The characteristics of the designs are found by modifying the two BASE150/400 aircraft and evaluating their performance and Direct Operating Costs. These exercises are not meant to show the possibilities of for example retrofitting a Boeing 737-400 with a new type of engines, but to find the relative differences between the technologies. In the following subparagraphs we will describe the model used, as well as several design tools, the definition of the two markets and the evaluation flight. Also information is given on the validation of the models.

3.2 Method of research

Based on the survey of Van der Heijden and Wijnen (1999) new technologies or design changes in the field of propulsion, aerodynamics and materials are introduced. Technologies included in this study are ultra high bypass turbofans, High Speed Propellers, fuel cell propulsion, aerodynamic clean-up and laminar flow control, high aspect ratio wing design and the use of new light weight materials. All these technologies have been evaluated as a kind of virtual retrofit: the technology has been introduced to the baseline aircraft modifying it as few as possible. This has been done to get a consistent feeling for the change of Direct Operating Costs (DOC) for the technologies studied.
Criteria are the DOC for the current fuel price and a hypothetical high one (fuel plus carbon price) in the future and the break even fuel plus carbon price. The latter gives the fuel plus carbon price level at which the DOC of baseline aircraft with and without the new technology are exactly the same. Figure 9 gives an example. In this example the break-even fuel plus carbon price is about $0.55/kg.

Figure 9 Example of the relation between fuel plus carbon price and DOC giving the break even point for the new design



3.3 Model and tools overview

The model system used for this study consists of many tools and one model. The main tools are:

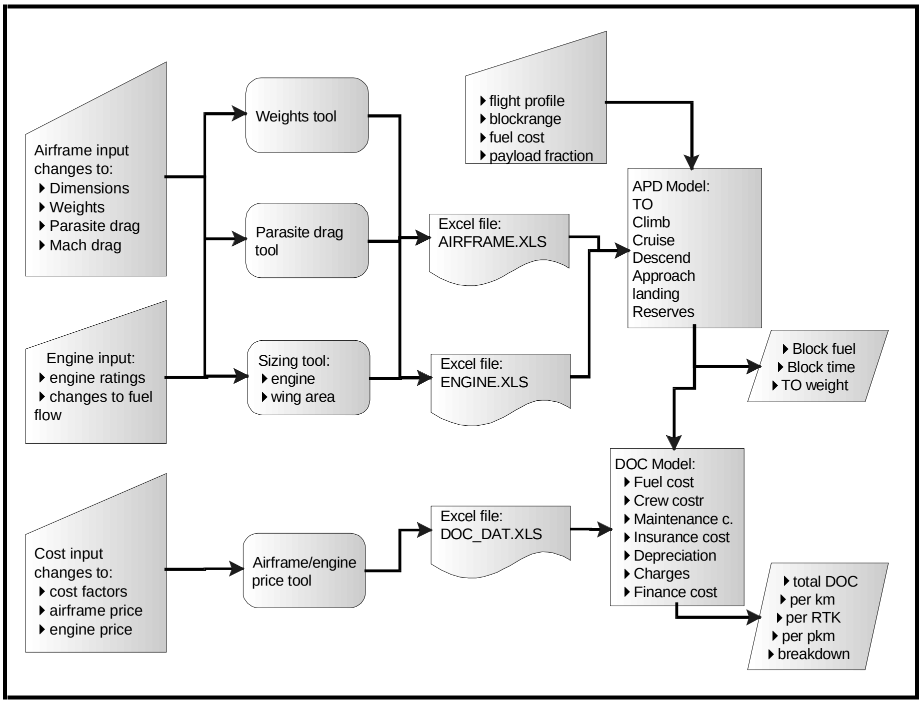
- Weight tool: a tool to determine the weight change of parts of the airframe as a function of dimension and materials of these parts as well as the maximum landing and take off weights defined.
- Drag tool: this tool uses the flat plate analogy and factors for interference, leakage and fuselage wake drag to find the parasite drag for new or modified parts of the aircraft design.
- Airframe/engine pricing tool: for finding the market price of the modified or new design this sheet calculates the total programme cost (development, material and labour cost for engineering and production) and divides it by the given number of aircraft expected to be sold within the programme.
- Sizing tool: this tool consists of several modules which help to find the right size of engines and wing area by defining power- and wing-loading and the propeller size for propeller driven aircraft (like the High Speed Propeller).

With the help of these tools several aircraft definition input files are filled with data: the airframe, engine and DOC spreadsheets. These are used by the APD model. APD stands for Aircraft Performance and DOC.
This model finds the aircraft performance for a given block range, payload, reserves strategy and speed/altitude schedule by calculating through all parts of the flight and reserves profiles. From block fuel, block time and the fuel plus carbon price per kilogram the DOC is found.

The model uses data on engine performance and airframe drag and weight characteristics for a stepwise calculation of the whole flight profile from taxi via take off, climb out, climb, cruise, descent and approach to landing. A total of about 200 points for altitude, aircraft velocity (mach number), actual weight, thrust required, distance and time are evaluated to find the total block fuel and time for a given block range.
After the aircraft performance has been found the data are transferred to the module for DOC. This module is used to find the Direct Operating Costs for a given flight as given by the output of the APD model: block time and block fuel and the given block range. The DOC is based on the method given by Roskam (1990) fitted for the current cost levels and practices in the industry. The DOC consists of the cost for crew wages, training of pilots and cabin attendants, fuel and oil, maintenance labour and material cost for airframe and engines, depreciation, insurance, finance and charges for environment, landing and air traffic control.

Figure 10 gives an overview of the tools and models. All tools and modules of the APD model are written with Mathcad 8 running on a desktop PC. The APD model is programmed in Mathconnex 8. The tools were of course used as far as appropriate for the design under development. Input changes are made within the math sheets to find weights drag, price of airframe and engines and the right size of wing area and engine thrust or power.
With the help of the output of the tools the three input spreadsheets for the models are filled. The AIRFRAME sheet contains all information on dimensions, weights and drag. ENGINE contains tables for the maximum thrust for TO, climb and cruise as a function of aircraft velocity and altitude and the fuel flow as a function of thrust, altitude and mach number.
The APD model is run with these input files and manual input on the block range, speed schedule and cruise altitude required. Block fuel, block time and TO weight as well as DOC are given as output. Not indicated in Figure 10 is the output to Excel sheets of intermediate results on all steps in the flight profile calculations and a detailed break down of DOC.

Figure 10 Overview of the design and performance toolbox used in this study



3.4 Weight prediction

The first step for creating a weight-predicting tool has been the set up of a weight breakdown for both baseline aircraft. Then the changes to weight are found using the statistical equations given by Raymer (1992). The basic form of these equations is:

(Eq. 3-1)

$$W_{partx_{new}} = W_{partx_{old}} \cdot K_{dim\_1}^{\ e1} \cdot K_{dim\_2}^{\ e2} \cdot \ldots \cdot K_{dim\_n}^{\ en}$$

where:

(Eq. 3-2)

$$K_{dim\_x} = \frac{\dim_{x\_new}}{\dim_{x\_old}}$$

A 'part' is for example a wing, undercarriage or fuselage. The dimensions $\dim_x$ may differ per aircraft part and are dimensions like wingspan, aspect ratio, fuselage wetted area, max take off weight or max landing weight. The exponents *e1*, *e2*, … *en* are given by Raymer and based on extensive statistical analysis.

As no accurate weight breakdown for both the 737-400 and 747-400 were found in the public literature it was necessary to acquire such a breakdown from an aircraft model which resembles it enough and recalculating for the differences in dimensions and weight. For both baseline aircraft a detailed breakdown has been found in Roskam (1989, Part V) for Boeing 737-200 and the Boeing 747-100.

Creating the weight break down for both baseline aircraft needs the following actions:

1 Reducing the operating weight empty (OEW) to the empty weight (W_E)
2 Recalculating the part weights using (Eq. 3-1) and differences between the two aircraft types in dimensions as given by Jane's (1999 and older versions) and summing them to the calculated empty weight W_{Ec})
3 Finding a fitting-factor between the calculated empty weight W_{Ec} and the actual empty weight W_E
4 Recalculating all partial weights using the fitting-factor from step 3.

For step 1 data have been taken from Torenbeek (1982) on the weight for passenger supplies, water and toilet chemicals, safety equipment, residual fuel and crew weight. By subtracting these weights from the OEW the W_E has been found. Table 5 gives the dimensions that has been changed between the older and the baseline aircraft (Jane's, 1998/1999 and 1995/1996).

Table 5 Dimensions changed in finding the weight breakdown for the baseline aircraft

Dimension	737-200 → 737-400	747-100 → 747-400
MTOW	+29%	+13%
MLW	+25%	+2%
Wing area	+16%	+6%
Wing span	+2%	+8%
Fuselage length	+5.96 m	N/a
Fuselage upper deck stretch	N/a	+7.11 m
Fuselage wetted area	+ 25%	+8%
Nacelles	Changed due to larger and heavier turbofan installation	N/a
Dry engine weight:	+ 38%	+11%
Fuel volume	No changes	+14%
Surface controls	1 extra function (due to spoil-ers)	N/a
Thrust	+52%	+12%
Avionics weight	+50%	+50%
Maximum number of people on board	+ 29%	+5%
Extra cabin volume	+12%	N/a
Extra maximum payload weight	+6%	-20%

All these modifications resulted into weight changes for:

- Wing;
- Fuselage;
- Nacelles;
- Undercarriage;
- Empennage;
- Thrust reverser and exhaust system;
- Fuel system;
- Avionics;
- Hydraulic and electrical systems;
- Control surfaces;
- Air-conditioning and anti-ice;
- Furnishing;
- Miscellaneous.

The fitting-factors were:

- Short haul baseline (Boeing 737-400): 1.018 (6% estimation error of the weight difference between 737-200 and 737-400);
- Long haul baseline (Boeing 747-400): 1.088 (meaning a 44% estimation error of the weight difference between 747-100 and 747-400).

The prediction error of the long haul baseline seems rather high. The cause of this prediction error will most probably not be a faulty method, but a lack of data on what Boeing has changed between the 747-100 and the 747-400. The method cannot account for unknown changes like a different interior, new balance weights, extra strengthened structures, new systems and so on. The rather small changes of wing and fuselage of course cannot account for the weight increase of over 27,000 kg between the 747-100 and the 747-400. Also the fitting factor reduces remarkably if the safety equipment, water and food allowances are enlarged from a minimum. Further it is possible the weight of the Boeing 747 has had much more “weight growth” problems during its production phase than the Boeing 737. This is a common problem due to fixes of (mostly safety related) problems turning out during the first years op production and use of the aircraft. The 747-100 was the first of its kind, while the 737-200 had already a development stage in the 737-100 version.

From a short susceptibility analysis it appeared using a fitting factor of 1.00 and a fixed weight to fit the known OEW, the largest difference in OEW calculations occurs for the U-fan (largest weight change) and is less than 1.5% overall. This seems not a very alarming result for this kind of study.

Essentially the above described procedure has been used for adjustment of the empty weight of all designs. A difficulty in using the method is that the maximum take off weight and the maximum landing weight both influence the empty weight but are not known in advance because they depend on the maximum fuel amount needed and the empty weight itself. Therefore the weight estimations have been iterated on two levels:

- An initial conservative estimation is made of the reduction in fuel consumption and with this as an assumption the empty weight and MTOW/MLW are iterated for all aircraft parts affected by the introduction of the fuel saving technology (i.e. a new engine, new wing, new materials) until the empty weight does not change more than one kg.
- The initial estimate of the reduction in fuel consumption is checked and the whole calculation is repeated until the assumed and calculated fuel consumption are the same.

With this procedure a balanced empty weight prediction has been established, retaining the original payload range performance of the aircraft.

3.5 Drag prediction

The method to find the parasite drag is based on the normal flat-plate skin friction equations and the Component Build-up Method as given by Raymer (1992). The basic equation for this method is:

(Eq. 3-3)

$$C_{D_{0_{subsonic}}} = C_{L\&P}\left[\frac{\sum (C_{f_c} \cdot FF_c \cdot Q_c \cdot S_{wet_c})}{S_{ref}} + C_{D_{misc}}\right]$$

The total parasite drag coefficient is a function of the weighted mean between the laminar and the turbulent skin friction coefficient (C_{fc}). The weighing depends on the percentage of laminar flow which differs for every component as given in Table 6.

Table 6 Percentage laminar flow per component

Component	737-400	747-400
Wing	10%	10%
Fuselage	0%	0%
Nacelles	25%	10%
Struts/pylons	0%	0%
Tail planes	10%	10%

The form factor (FF_c) is found with the equations given by Raymer and depends on dimensions like slenderness, thickness ratio and sweep angle of the components. The factor Q_c represents the interference factor per component (these are between 1.0 and 1.1), accounting for interference drag between several parts of the aircraft.

The miscellaneous drag consists mostly of the extra drag generated at the aft fuselage due to the pronounced upsweep of the fuselage. The airflow is not able to follow the form of the fuselage, which creates extra drag.
For leakage and protuberance drag ($C_{L\&P}$) a factor has been incorporated on the whole calculated drag. This factor is also used as a fitting-factor to fit the actual parasite drag coefficient to the calculated one.
With these the skin friction drag coefficients for the appropriate Reynolds number (depending on cruising altitude and speed and typical length measure of the part) are found for the changed parts of the aircraft (distinguished are fuselage, wing, empennage, nacelles and struts).
The fit for both baseline aircraft is quite good given the many uncertainties in these calculations:

- Short haul baseline (737-400): $C_{L\&P}$ = 0.901;
- Long haul baseline (747-400): $C_{L\&P}$ = 1.056.

The drag tool has been used in the way described above for the new designs. In other cases the changes to the drag were small and only the drag difference between the old and new component has been calculated.

The induced drag component has been calculated with the well known (Eq. 3-4). This equation worked very well for the short haul aircraft (see §4.2.3). for the long haul aircraft a somewhat more sophisticated equation has been used (see (Eq. 3-5)).

(Eq. 3-4)

$$C_{D_i} = \frac{C_L^{\,2}}{\pi A \mathrm{Re}}$$

The value of Oswald's induced drag factor *e* is found by fitting performance data. The aspect ratio *AR* for the baseline aircraft is known from the literature.

(Eq. 3-5)

$$C_{D_i} = C_{D_{p1}} \cdot C_L + (C_{D_{p2}} + \frac{1}{\pi A \mathrm{Re}}) \cdot C_L^{\,2}$$

$$e = 0.80$$

The values of the drag factors $C_{D_{p1}}$ and $C_{D_{p1}}$ are found by assuming Oswald's induced drag factor e to be 0.8 and fitting the values deduced from performance data (see §4.3.3).
A problem is to find the right value of Oswald's factor, as this changes with the wing aspect ratio, because not only the wing has a lift or angle of incidence part of drag, but also other parts of the aircraft. Use has been made from an equation given by Raymer (1992):

(Eq. 3-6)

$$e = K_{corr} \cdot \left[1.78 \cdot \left(1 - 0.045 \cdot AR^{0.68}\right) - 0.64\right]$$

In this form the correction factor has been introduced to flatten the influence of *AR* on *e* because the other lift dependent drag factors seem given too heavy for a modern transport aircraft with a high aspect ratio wing:

(Eq. 3-7)

$$K_{corr} = 1 + \frac{AR - 7.7}{63}$$

The mach drag table has been calculated from the baseline aircraft performance characteristics. Corrections for a lower design mach number are simply made by reducing the lift coefficient with the appropriate number.

3.6 Airframe and engine cost prediction

The method is based on the Modified DAPCA IV Cost Model method given by Raymer (1992). Raymer gives the total cost for employees (salaries, education, administration and employee benefits), the so called “wrap rates” in 1986 dollars. As a first step these figures are corrected with the Consumer Price Rates for 1986-1996 (CPR=1.49). The 1996 wrap rate are:

- Engineering: $88.06/hr;
- Tooling: $90.44/hr;
- quality control $82.55/hr;
- manufacturing $74.65/hr.

The total programme cost for a new aircraft is defined as the sum of the RDT&E cost (research and development cost) and the cost for producing and delivering a number *Q* of aircraft. The aircraft price is the programme cost plus a standard profit margin of 10% divided by the number *Q* of aircraft to be produced for the total programme. The following production numbers have been used for adjusting the method to the two current baseline aircraft (the numbers are given by Jane’s (1998/1999) for the two *models* of the 737 and 747 series of aircraft):

- 737-400 model: *Q*=485;
- 747-400 model: *Q*=450.

The general equation for the aircraft program cost is given in (Eq. 3-8).

(Eq. 3-8)

$$C_{prog} = C_{cor} \cdot C_{ICF} \cdot \left[H_E \cdot R_E + H_T \cdot R_T + H_M \cdot R_M + HQ \cdot RQ + C_{DS} + C_F + C_M + C_{avi} \right]$$

The variables *H* give the number of labour hours and the factors *R* the wrap rates. The subscript *E* stands for engineering, *T* for Tooling, *M* for Manufacturing and *Q* for quality control. Further C_{DS} stands for development support cost, C_F for Flight test cost, C_M for material cost and C_{avi} for the cost of avionics. The factor C_{ICF} stands for investment cost factor and is standardised to 1.15. The correction factor C_{corr} depends on the market (see end of this paragraph).
The final aircraft market price for *Q* aircraft produced including a profit margin C_{PROF} (standard 1.1) will be:

(Eq. 3-9)

$$P = \frac{C_{prog} \cdot C_{PROF}}{Q}$$

The labour hours for engineering, tooling and manufacturing are found with equations of the general form of (Eq. 3-10).

(Eq. 3-10)

$$H_x = C_x \cdot W_e^{e_{W_x}} \cdot V_m^{e_{V_x}} \cdot Q^{e_{Q_x}}$$

In (Eq. 3-10) C_x is a general constant, W_e the empty weight and V_m the maximum speed. The exponents are specific for engineering, tooling and manufacturing. Quality control hours are a fixed part of manufacturing hours. The equations to find development support cost, flight test cost and manufacturing cost has the same general form as (Eq. 3-10), with the exception that the exponent for Q is zero for development support and flight test cost (see Table 7 for the coefficients). Avionics cost is given by a constant cost per kilogram and the total avionics weight on board.

Table 7 Constants and exponents used in calculating program cost with (Eq. 3-10)

x	*C*	*e*	*e*	*e*
Engineering hours	4.86	0.777	0.894	0.163
Tooling hours	5.99	0.777	0.696	0.263
Manufacturing hours	7.37	0.820	0.484	0.641
Development support cost	45.42	0.630	1.300	0.000
Flight test cost	1243.03	0.325	0.822	0.000
Manufacturing materials cost	11.00	0.921	0.621	0.799

The method is validated by comparing the calculated airframe price with the figures given in literature. From this the following correction factors were found:

- short haul baseline (737-400): 0.984;
- long haul baseline (747-400): 0.947.

Before an aircraft manufacturer gives go-ahead for a major redesign of one of his models he will consider if he will be able to recover the extra cost for the modification when selling a presumed number of the modified aircraft. For major modifications we assume a total recover of the cost, including a profit, with 300 examples of the modified aircraft sold.
Therefore the new aircraft price will be based on the current price plus the total cost for developing and building 300 pieces of the new parts but minus the total building cost at constant cost of the replaced new parts. This extra cost (or sometimes savings, if the new part has a significantly lower weight!) are divided by 300 and added to the current aircraft price. (Eq. 3-11) gives the relationship for finding the price P_{new} for the modified aircraft:

(Eq. 3-11)

$$P_{new} = P_{old} - \frac{\Delta W_{\text{mod}}}{W_e} \cdot P_{old} + \frac{C_{p\_new} \cdot C_{PROF}}{Q_{new}}$$

ΔW_{mod} is the weight of the replaced aircraft structure (for example the old wing or the old nacelles). The program cost of the new parts (C_{p_new}) is based on the weight of the new parts (for example new wing or new nacelles).
With this method we neglect the learning curve of the unmodified parts. Presumed is a constant price for these because during an aircraft building programme continuously modifications are introduced due to customer wishes, safety regulations and such developments.

3.7 Sizing tools

3.7.1 High Speed Propeller scaling

Propeller sizing was necessary for the designs with High Speed Propellers. ADSE (1999) gives two scaled examples of its High Speed Propeller engine. The properties of these are given in Table 8.

Table 8 High Speed Propeller dimensions as given by ADSE (1999)

Property	Basic version (125 seater, M.72)	Scaled version (150 seater, M.74)
TOC power [SHP]	5,000	6,200
MTO power [SHP]	8,200	10,000
Propeller diameter [ft]	12.0	12.6
Core engine:		
• Length [m]	2.30	2.50
• Diameter [m]	0.80	0.85
Nacelle:		
• Length [m]	5.70	6.00
• Height [m]	1.60	1.70
• Width [m]	1.70	1.80
Weight (exc. Mounting, inc. propeller, systems and nacelle) [kg]	2,800	3,400

Raymer gives the following general scaling rule for turboprop engines:

(Eq. 3-12)

$$Dimension_{new} = Dimension_{old} \cdot \left(\frac{P_{TO_{new}}}{P_{TO_{old}}} \right)^{e}$$

Table 9 gives the exponents given by Raymer and the modified exponent to fit the two ADSE versions. The engine price is scaled with take off power using scaling rules given by Roskam (1989, part VIII).

Table 9 Exponents for (Eq. 3-12) as given by Raymer (1992) and as used in this study after fitting to the scaling of ADSE (1999)

Dimension	Exponent *e* from Raymer (1992)	Modified exponent *e* to fit ADSE scaling (1999)
Propeller diameter	0.250	0.250
Engine weight	0.803	0.903
Engine length	0.373	0.388
Engine diameter	0.120	0.282

An important consideration on propeller design is the propeller tip speed. This should be lower than mach 1.0. Chosen is to keep this value during cruise to stay below 0.95 as much as possible to avoid excessive loss in propeller efficiency, vibration and noise. Tip speed is a function of the propeller diameter, the cruise mach number and the engine rotational speed. The larger the engine the slower its rotational speed. The requirement does not give an absolute value for the maximum attainable cruising mach number. Therefore values for the tip speed, propeller rotational speed and cruise mach number are determined and evaluated based on judgement with the help of (Eq. 3-13).

(Eq. 3-13)

$$M_{tip} = \frac{\sqrt{(M_{cr} \cdot a_s)^2 + (D \cdot \pi \cdot n_p)^2}}{a_s}$$

In (Eq. 3-13) M_{tip} is the propeller tip mach number, M_{cr} the cruise mach number, as the speed of sound, D the propeller diameter and n_p the propeller rotational speed.

3.7.2 UHB Scaling

Raymer (1992) gives the following equation for scaling the dimensions of a typical jet engine:

(Eq. 3-14)

$$DIM_{new} = DIM_{old} \bullet (ESF)^{\exp}$$

ESF is the Engine Scale Factor and DIM the dimension we are trying to find. The exponent differs per dimension (length, diameter or weight). Because the UHB engine is an engine different from the jet engine for which Raymer gives his exponents and because we want to know the length and diameter of the nacelle we have redefined the exponents for the two known UHB turbofan engines of the SH_UHB and LH_UHB designs. For this (Eq. 3-14) has been rearranged to (Eq. 3-15).

(Eq. 3-15)

$$\exp = \frac{\log\left(\frac{DIM_{LH}}{DIM_{SH}}\right)}{\log\left(\frac{T_{TO\_LH}}{T_{TO\_SH}}\right)}$$

In this equation T_{TO} is the maximum take off thrust, the subscript LH denotes long haul and SH means short haul. Table 10 gives the resulting exponents.

Table 10 Exponents for (Eq. 3-14) as given by Raymer (1992) for engine length, diameter and dry weight and as found for the two UHB engines for Nacelle length and diameter and dry engine weight

Dimension	Exponent given by Raymer	Exponent for UHB
Engine/Nacelle length	0.50	0.428
Engine/Nacelle diameter	0.40	0.573
Dry engine weight	1.10	0.791

For the engine price we have used the generalised equation as given by Roskam (VIII, 1990):

(Eq. 3-16)

$$EP = 10^{(\exp 1 + \exp 2 \bullet \log(T_{TO}))}$$

EP is the engine price in \$ and T_{TO} the maximum take off thrust in [lbf]. Because we know the price for two engines (the UHB turbofan for short haul and for long haul) we have two equations with two unknown exponents. These are solved and given in Table 11.

Table 11 Exponents for calculating engine price (Eq. 3-16) as given by Roskam (VIII, 1990) and as found for the two UHB engines

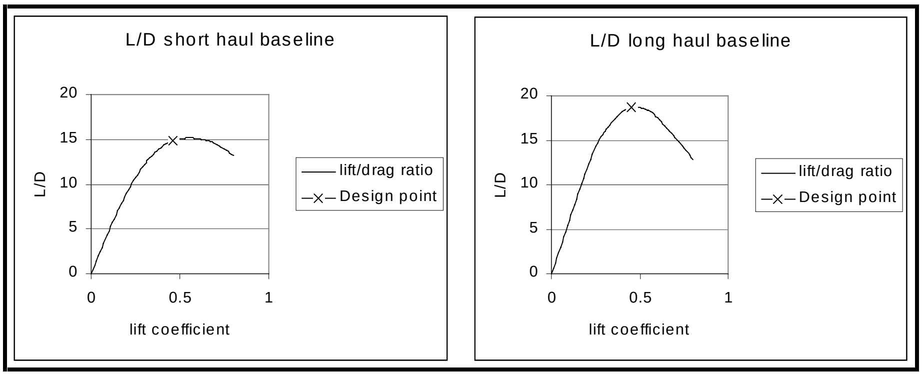
	Value given by Roskam	Value used for UHB
Exp1	2.3044	3.968
Exp2	0.8858	0.576

The new found line is slightly flatter and lower compared to the one given by Roskam. This is not unexpected as engine specific cost has been reduced during the last decades due to technological development and a strong increase in thrust levels.

3.7.3 Wing sizing

The wing sizing tool has only been used for designs with a new (higher aspect ratio) wing. The sizing is required to determine the right wing area, sweep and thickness ratio. First the design point for cruising must be established (speed and altitude). This has been done by finding the design point for the baseline aircraft for a typical cruise weight (the mean cruise weight for the evaluation flight). The design lift coefficient does not match exactly the maximum lift over drag (l/d) point as can be seen in Figure 11. This is because the aircraft apparently has been designed for a somewhat different cruising weight. To keep the results comparable the same deviation from maximum l/d has been presumed for the new design at the evaluation cruise flight.

Figure 11 Lift over drag ratios and cruising design points for short haul and long haul



The design lift coefficient of the new design is adjusted by changing the wing reference area until the l/d for the design point has the same deviation from the maximum l/d as for the baseline aircraft.
Then the wing thickness ratio is determined from equation (Eq. 3-17) given by Torenbeek (1982) that relates the maximum design mach number (MDD following the Boeing definition as the mach number with just 10 counts of mach drag rise), design lift coefficient for cruise, the quarter chord sweep back angle of the wing and a factor for the transonic quality of the wing pro-

file design. The thickness ratio must be not too small as this will increase wing weight considerable.

(Eq. 3-17)

$$tc_{cr} = \frac{0.3}{M_{DD}} \cdot \left(\frac{1}{M_{DD} \cdot \cos(\Lambda_{25})} - M_{DD} \cdot \cos(\Lambda_{25}) \right)^{\frac{1}{3}} \cdot \left[1 - \left[\frac{5 + (M_{DD} \cdot \cos(\Lambda_{25}))^2}{5 + \left(M_{str} - 0.25 \cdot \frac{C_{L\_des}}{\cos(\Lambda_{25})^2} \right)^2} \right]^{3.5} \right]^{\frac{2}{3}}$$

In (Eq. 3-17) the critical wing thickness ratio tc_{cr} is given for the maximum design mach number M_{DD}, the quarter chord wing sweep angle 7_{25} the cruise design lift coefficient C_{L_des} and the factor for the transonic quality of the wing profile design M_{str}.
As the wing thickness influence the wing weight and the wing drag the whole procedure is repeated until nothing changes anymore. This iteration is performed manually.

3.7.4 Engine sizing

The engine is sized on two criteria: top of climb (TOC) performance and take off field length. The engine size is chosen as small as possible fulfilling both requirements. The first one is found by checking the rate of climb at maximum TOC weight and desired cruising altitude and speed. This must be more than 0.5 m/s.
The second requirement is fulfilled by keeping the take off parameter (TOP) as given by Raymer (1992) constant. TOP is given by (Eq. 3.18).

(Eq. 3-18)

$$TOP = \frac{W/S}{C_{L_{TO}} \cdot T/W}$$

In (Eq. 3-18) W is weight, S is the reference wing area and T is thrust, all maximum for take off. C_{LTO} gives the maximum lift coefficient at take off. This last one depends on the wing profile, the arrangement of flaps and slats and wing sweep. As flaps and slats are kept constant in this study, and the wing profile is not specifically defined, only the effect of wing sweep has been accounted for using an equation from Torenbeek (1982). Combining both and rearranging parameters gives the following equation for the engine scaling factor:

(Eq. 3-19)

$$ESF = \frac{MTOW^2}{TOP_{baseline} \cdot S_{ref} \cdot \frac{\cos(\Lambda_{new})}{\cos(\Lambda_{baseline})} \cdot T_{TO_{new}}}$$

ESF gives the allowable reduction of the maximum take off thrust installed. The final *ESF* is chosen from the highest of the values found for the climb and take off requirements.

3.8 APD: Aircraft Performance & DOC model

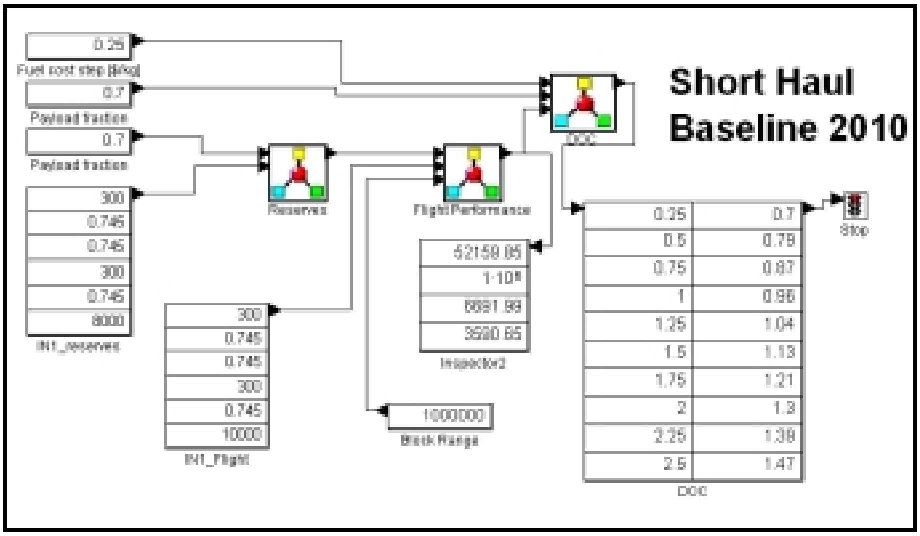
3.8.1 General overview

The Aircraft performance & DOC model has been programmed with Mathconnex, by connecting Mathcad 8 modules to each other. The Mathcad modules describe parts of the model like the calculation of DOC, the fuel for taxiing and take off and the fuel, weight and time for cruise.
APD first asks for a payload fraction of the maximum payload, a block range and the speed- and altitude-schedules for the flight and the reserves. Also the starting value for the price of fuel has to be given to the model. With all this information the following main steps are carried out:

- Find the amount of reserve fuel and the aircraft weight at the end of the flight.
- Find the required amount of block fuel and block time for the flight over the given block range
- Calculate the DOC from the given block range and payload and calculated block time and block fuel for a given set of values for fuel plus carbon price.

The general layout of the Mathconnex model for the short haul baseline 2010 aircraft is given in Figure 12. The input for the sheet is given in the tables at the left end of the diagram. The meaning of them is given by the label below each input table. The three figures give the collapsed models for Reserve fuel, Flight Performance and DOC. These will be described in more detail in §3.8.2 and §3.8.4. The table ‘inspector1’ gives the results of the DOC calculations. The first row represents the fuel plus carbon price in $/kg, the second one the DOC in $/RTK (revenue ton kilometre).

Figure 12 General lay out of the Mathconnex program APD (example for the short haul baseline aircraft)



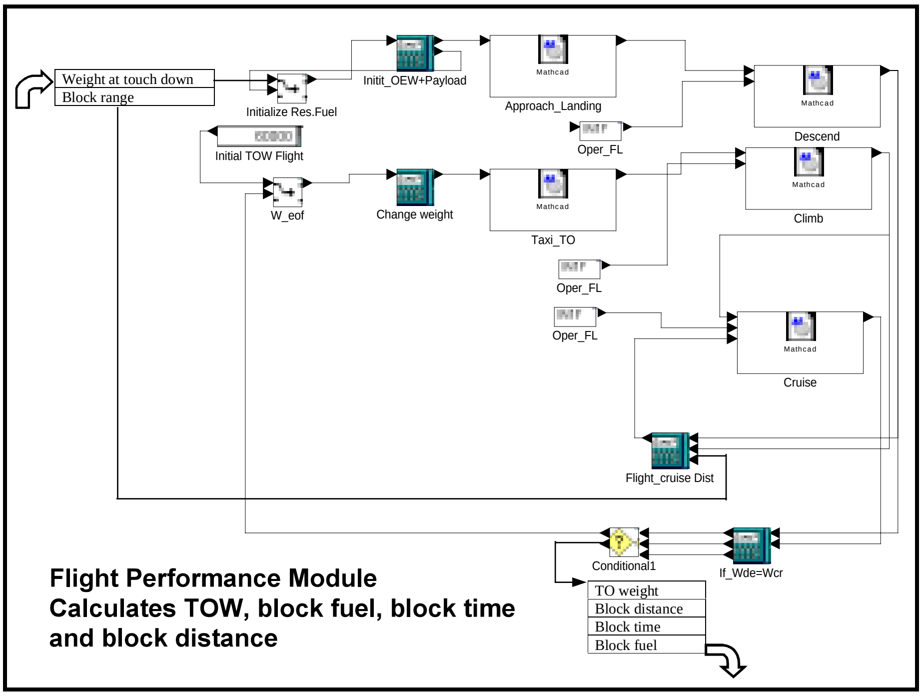
3.8.2 Aircraft performance

General set-up
To find the block performance for the evaluation flight the whole flight path is determined using normal flight mechanics and performance formulas. All stages in the flight path contribute to the block fuel and block time. Block range is found only for the flight path from above 3,000 ft: the standard ICAO LTO cycle does not count for block distance. The flight path consists of the following stages (and programme modules):

- Taxi and ground manoeuvring;
- Take off;
- Climb out to 3,000 ft;
- Climb to cruise;
- Cruise;
- Descent to 3,000 ft;
- Approach;
- Landing.

The problem with this kind of performance calculations is you need the take off weight to calculate the fuel weight, while the fuel weight is part of the take off weight. Another problem is you need the cruise distance to calculate cruise time and fuel, but this is unknown as the climb and descent distances depends on the fuel weight for the whole flight and so also on the fuel weight during cruise. These problems are solved by calculating landing and descent backwards and iterating using a temporary value of the take off weight as is shown in Figure 13.
In this figure in the high left corner the weight at touch down (that is the OEW plus the payload plus the reserve fuel) is given to an initialising routine and then to the Approach and Landing module. This directly calculates the weight and time and fuel used at the end of descent at 3,000 ft. Then the descent module backwards calculates fuel, distance, time and weight from 3,000 ft up to the cruise altitude.
At the same time the Taxi_TO module calculated the weight, fuel and time from engine start-up to 3,000 ft based on an initial TO weight (at the first loop) or as given by the result of the preceding loop, and passes these values to the climb module. This adds in a stepwise calculation the fuel, time and distance covered for the climb to cruising altitude and speed and passes the values to the cruise module. As now intermediate values for descent and climb distance are known the cruising distance is defined by subtracting them from the given block range.
With all this information the cruise fuel and time are determined resulting in an end-of-cruise-weight. Of course this weight must be the same as the start of descent weight. This is checked in the 'If_Wde=Wcr' routine. If the two weights differ more than 0.1% a new take off weight is found by adding the end-of-cruise *fuel* weight to the start-of-descent-aircraft-weight and the whole calculation is repeated. Normally three or four iterations suffice to fulfil the requirement. The final take off weight and block fuel and time are returned to the main program.

Figure 13 Mathconnex overview for the flight performance iterations



In the following subparagraphs we will give some detailed information on the modules used.

Ground manoeuvres, take off and climb to 3,000 ft
A standard time for ground manoeuvres is set at 26 minutes with 7% of MTO thrust rating (the ICAO LTO definition of idle). The fuel flow for this has been assumed to be also 7% of the MTO fuel flow.
For the takeoff run and climb-out to 35 ft an allowance of 0.7 minute at take-off power setting is taken as a standard. The corresponding fuel flow depends on the engine properties and has been selected for a mean speed of mach 0.2.
Between 35 ft and 3,000 ft the ICAO prescribes 2.2 minutes climb out at 85% MTO rating. The climb speed for this thrust setting at the mean altitude of 1500 ft is calculated to check if 2.2 minutes is not too short. The aircraft speed for this calculation is chosen 20% above the stall speed.
The time and fuel used are added to the block time and block fuel. No credit is given to the block distance up to 3,000 ft.

Climb
Climb is executed with maximum climb power as is specified for the specific engine in the engine input file. The speed schedule for climb from 3,000 ft to the specified cruising altitude depends on the following assumptions:

- Maximum of 250 knots true air speed (TAS) below 10,000 ft;
- Constant CAS climb at the specified speed until the specified climb mach number has been reached;
- Constant mach climb until the cruising altitude has been reached.

The aircraft weight starts at the weight given by the taxi, take off and climb to 3,000 ft module. Then the climb is divided into 25 altitude sectors. For every sector the rate of climb (*ROC*) is found from the known starting weight, aircraft speed, available thrust at the mean sector altitude from (Eq. 3-1).

(Eq. 3-20)

$$ROC = V \cdot \frac{T_{cl} - \frac{1}{2} \cdot C_D \cdot \rho \cdot V^2 \cdot S}{m_a \cdot g \cdot (1 + f_{acc})}$$

In (Eq. 3-1) V is the true air speed, T_{cl} the climb thrust for the speed and mean sector altitude, C_D the drag coefficient, Δ the air density at the mean sector altitude, m_a the aircraft mass, S the reference wing area and f_{acc} a factor for the acceleration needed for climb at constant CAS or constant mach (See Padilla, 1994).
From the rate of climb it is simple to find the sector time and from this and the fuel flow at the mean sector altitude and speed the total fuel weight used for the sector can be found. Subtracting this value from the starting aircraft weight gives the starting aircraft weight for the next sector. With the aircraft speed and sector time known also sector the distance can be found.
At the end all sector fuel usage, sector times and sector distances are added to the block fuel, block time and block distance and given to the next module of APD.
The rule for maximum depressurisation rate of the cabin to be lower as the equivalent of 300 ft/minute is calculated, but has no influence on the thrust setting. Normally this value is not exceeded much and therefore it has been neglected in calculations.

Cruise
The required cruise distance depends on the climb and descent distances calculated and the given block range. The module divides the cruise into 25 (short haul) or 50 (long haul) sectors with constant length for which successively the sector time and fuel consumption are calculated using standard equations for lift and drag coefficients and defining the fuel flow by interpolating into the engine table for the appropriate cruising altitude, mach number and required thrust. The cruise speed and cruise altitude have to be specified in advance. The speed is not automatically optimised for lowest fuel consumption of lowest DOC. By manual iteration an optimum altitude and cruise speed may be found (i.e. lowest fuel consumption or lowest DOC).
The thrust setting is limited by the maximum cruise thrust specified. If thrust required is higher than the thrust available this can be seen on the output files. In that case the aircraft apparently is under-powered or a too high cruising speed or altitude has been chosen. Fuel flow is read directly from engine fuel flow tables as a function of altitude, thrust and speed.
The required thrust per sector is found by first calculating the lift coefficient from aircraft weight at start of the sector and aircraft speed and altitude. The lift coefficient and the cruising mach number give the drag coefficient and with this the total drag is determined. In stationary straight flight the thrust must equal the drag, which gives the thrust required.
When this is known, the fuel flow can be interpolated from the engine table. The airspeed gives the sector flying time and then the fuel used can be found as well as the weight and the aircraft weight for the next sector is defined.
After all sectors have been run through, summing the fuel per sector, the sector time and the sector distance give the block fuel, block time and block distance for cruise.

Descent and landing
The descent is limited by the maximum cabin rate of descent of 300 ft/min. Therefore first the minimum descent time between cruising altitude and

3,000 ft is calculated from the maximum cabin pressure difference following from the cruising altitude and the maximum cabin altitude (as a measure of cabin pressure). From the minimum time the maximum aircraft rate of descent (ROD_m) is found.
The descent is divided into 25 sectors of equal altitude difference. The whole calculation is done backwards (from 3,000 ft up to the cruising altitude). For the first sector the aircraft weight is taken from the approach and landing module. For this weight and the mean sector altitude the speed is determined from the speed schedule (constant CAS until the descent mach number is reached at some altitude; below 10,000 ft the maximum aircraft speed is limited to 250 kTAS). Then the thrust required for the maximum aircraft ROD_m is calculated from (Eq. 3-21).

(Eq. 3-21)

$$T_{req} = \frac{1}{2} \cdot \frac{\left(-2 \cdot ROD_m \cdot m_a \cdot g + C_D \cdot \rho \cdot V^3 \cdot S\right)}{V}$$

In (Eq. 3-21) V is the true air speed, ROD_m the maximum rate of descent, C_D the drag coefficient, Δ the air density at the mean sector altitude, m_a the aircraft mass and S the reference wing area. If the required thrust is less then zero[9] the thrust is set to zero and the *ROD* belonging to this zero thrust is calculated. The final *ROD* is of course the minimum of ROD_m and *ROD*.
As is the case for climb, below 10,000 ft the maximum descent speed is limited to 250 kIAS. At the end all sector fuel usage, sector times and sector distances are added to the block fuel, block time and block distance and given to the next module of APD.

Approach and landing
Approach and landing time has been fixed by the ICAO LTO value of 4 minutes. The engine will be used at 30% MTO rating. The approach speed has been specified in the airframe input file (based on Jane's, 1998/1999). The fuel flow is found by interpolating into the engine tables given in the engine input file for the approach speed and the intermediate altitude (1500 ft). The amount of fuel used follows from the approach and landing time multiplied with the fuel flow.
The weight of fuel and the approach time are added to the block fuel and block time. No credit is given to the distance covered as is recommended by ICAO.

3.8.3 Reserves

To prevent accidents caused by running out of fuel during a flight, the authorities require the aircraft operator to fill the aircraft not only with the predicted amount of fuel, but also with some amount of reserves. Torenbeek (1982) gives several policies for reserves. We have chosen for two different policies for short haul and long haul.
The short haul procedure is based on the Air Transport Association recommendation ATA '67 and consists of:

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[9] Actually the minimum thrust should be the idle thrust at the specific altitude and speed, which could actually become negative as well as being positive. As idle figures are difficult to find for engines, we have simplified flight idle to be the same as zero thrust.

- Hold for 30 minutes[10] at normal cruise altitude and 99% of the maximum range cruise speed[11].
- Exercise a missed approach and climb out at the destination.
- Fly to and land at alternate airport at 200 NM distance.

For the long haul flight the ATA '67 policy without a specified alternate has been followed which is:

- Continue the basic cruise flight for two hours.

The short haul reserves mean the calculation of a whole flight for the block range of 200 NM at the end-of-flight aircraft weight. The same modules as described in §3.8.2. The reserves are calculated in advance of the flight, to find the basic end-of-flight weight (OEW plus payload plus reserve fuel). The basic reserves weight is OEW plus payload.

3.8.4 DOC

The DOC module calculates the Direct Operating Costs for a given block time, block fuel and fuel plus carbon price per kilogram. The block time and block fuel are calculated by the aircraft performance part of the APD model as has been described in the previous paragraphs. The module has been based on the method given by Roskam (1989, Part VIII). Input on the payload and the block range allows for finding the DOC per revenue ton-kilometre (RTK) or passenger-kilometre. Further input is given in the DOC input sheet (Excel) containing the following data:

- Fraction of oil in total fuel plus carbon price;
- Landing fee in $/kg MTOW;
- Labour cost for pilot, co-pilot, cabin attendant and maintenance personnel per block hour;
- Airframe market price including avionics and spares;
- Engine market price including spares;
- Fractions of total DOC for finance and insurance;
- Depreciation period and fraction for airframe and engine;
- Number of flight crew and cabin attendants;
- Annual utilisation in block hours;
- Time between overhaul for the engines;
- Airframe empty weight (excluding engines).

The total DOC is the sum of the direct flying cost (crew and fuel) and the cost for maintenance, depreciation, landing fees, insurance and finance. The values for above mentioned input file are described if they are design specific in the chapters on the designs. The general values from the literature have been adjusted to fine-tune the results (see §3.8.6). In the following subparagraphs we describe the way in which the cost items are calculated.

Direct flying cost
The cost for crew is simply the sum of the number of a specified crew type multiplied with the labour cost per block hour for it and the block time. This labour cost consists of the salary, taxes, education, training and bonuses for a mean crew member divided by the normal number of block hours produced by the crew member. Fuel cost is found by multiplying the amount of block fuel with the given price for fuel per kg and the factor for oil cost.

[10] Actually ATA '67 recommends one hour, but this seemed overdone for a 600 N.M. flight as is the evaluation flight.

[11] APD uses the given cruise mach number.

Maintenance
The maintenance costs has been calculated with the method given by Roskam (1989, part VIII), which distinguish between labour cost and material cost for both airframe and engine. The maintenance man-hour per block hour for the airframe is given by (Eq.3-22) and for the engine by (Eq.3-23).

(Eq. 3-22)

$$MHR_{af.bl} = 3.0 + 0.1467 \cdot \frac{w_{af}}{1000}$$

(Eq. 3-23)

$$MHR_{eng.bl} = \left(0.718 + \frac{0.0698}{g} \cdot \frac{T_{TO}}{1000}\right) \cdot \left(\frac{1100}{t_{BEO}} + 0.1\right)$$

In these functions w_{af} is the airframe weight in kg T_{TO} the maximum take off thrust per engine in N and t_{BEO} the time between overhaul in flight hours for the engines.
Maintenance material cost is calculated in \$/block hour for airframe (Eq. 3-24) and engine (Eq. 3-25).

(Eq. 3-24)

$$C_{mat.af.bl} = 30 + 0.79 \cdot 10^{-5} \cdot Pr_{af} \qquad \left[\frac{\$}{hr}\right]$$

(Eq. 3-25)

$$C_{mat.eng.bl} = \left(5.43 \cdot 10^{-5} \cdot Pr_{eng} \cdot ESPPF - 0.47\right) \cdot \frac{1}{0.021 \cdot \frac{t_{BEO}}{100} + 0.769}$$

$$\left[\frac{\$}{hr}\right]$$

The variables Pr_{af} and Pr_{eng} give the airframe respectively the engine market prise in \$. *ESPPF* is an engine spare part price policy factor, (usually *ESPPF* = 1.5 according to Roskam (1989, Part VIII).
The total DOC for maintenance now comes to:

(Eq. 3-26)

$$DOC_{maint} = 0.53 \cdot T_{block} \cdot \left[Pc_{maint} \cdot \left(MHR_{af.bl} + 1.3 \cdot n_{eng} \cdot MHR_{eng.bl}\right) + \left(C_{mat.af.bl} + 1.3 \cdot n_{eng} \cdot C_{mat.eng.bl}\right)\right]$$

The factor 0.53 replaces the factor 1.03 originally given by Roskam. This much lower factor has been implemented because the maintenance cost for the current fleet is largely overestimated by the original equation (see § 3.8.6). The reason for this is, among others, the strong development during the last three decades in maintenance practice in the industry. Further T_{block} gives the block time, n_{eng} the number of engines. The other variables are given in (Eq. 3-22) through (Eq. 3-25).

Depreciation
The DOC for depreciation is broken down into airframe and engine depreciation, because of variations in the depreciation period and residual value (given by a depreciation factor). The equation has been derived from Roskam (1989, Part VIII):

(Eq. 3-27)

$$DOC_{dep} = T_{block} \cdot \left(DF_{af} \cdot \frac{Pr_{af}}{DP_{af} \cdot U_{ann.bl}} + DF_{eng} \cdot \frac{Pr_{eng}}{DP_{eng} \cdot U_{ann.bl}} \right)$$

In (Eq. 3-27) T_{block} gives the block time, *DF* the depreciation factor (the fraction of the original market price that is written off), *DP* the depreciation time in years, *Pr* the market price and $U_{ann.bl}$ the annual utilisation of the aircraft in block hours.

Landing fee, charges and ground handling cost
Roskam (1989, Part VIII) identifies not only the DOC of landing fees, but also for navigation and other taxes. Jesse (2000) states the However, the AVMARK data probably includes ground handling cost, as is usual in European DOC breakdowns. As we fitted the charges to the AVMARK data we have to include following items into this part of the DOC:

- Landing fee
- Navigation charges
- Ground handling and services

For the short haul market the European rules have been followed and fitted to the AVMARK data (see § 3.8.6). The short haul equation is:

(Eq. 3-28)

$$DOC_{ch\_SH} = C_{fit_{SH}} \cdot \left(Pc_{lf} \cdot MTOW + P_{gh} + P_{nav\_EU} \right)$$

with

$$Pc_{lf\_EU} = \frac{\$0.009}{kg}$$ (European landing fee)

$$P_{gh} = \$182 + \$6.6 * n_{seat}$$ (ground handling)

$$P_{nav\_EU} = \$1.6 \cdot \frac{R_{block}}{NM} \cdot \sqrt{\frac{MTOW}{50000 \cdot kg}}$$ (European navigation)

For long haul we have assumed a mix of European and International (US) tariffs for landing fee and half the navigational cost:

(Eq. 3-29)

$$DOC_{ch\_LH} = C_{fit_{LH}} \cdot \left(Pc_{lf\_EU} \cdot \frac{MTOW}{2} + Pc_{lf\_Int} \cdot \frac{MLW}{2} + P_{gh} + P_{nav\_Int} \right)$$

with

$$Pc_{lf\_Int} = \frac{\$0.00267}{kg}$$ (International landing fee)

$$P_{gh} = \$182 + \$6.6 * n_{seat}$$ (ground handling)

$$P_{nav\_Int} = \$0.8 \cdot \frac{R_{block}}{NM} \cdot \sqrt{\frac{MTOW}{50000 \cdot kg}}$$ (International navigation)

Insurance and finance

The cost for finance and insurance is given as a fraction of the sum of fuel, crew, maintenance and depreciation cost. See § 3.8.6 for the values used in these factors.

Final DOC

Final DOC is the sum of the in the previous subparagraphs mentioned costs. The DOC is calculated as the whole cost for the evaluation flight, the cost per block hour, per block kilometre, per RTK and per passenger kilometre.

3.8.5 Landing and Take Off Distance

The PRESENT150 and PRESENT400 Far-25 take off distances has been derived for standard ISA/SL from the performance data of the 737-400 and 747-400. For all other designs, including the Base150 and Base400, the take off distance has simply been scaled with the take off parameter (TOP) as defined in §3.7.4.

For landing distance no reliable data were available. Therefore use has been made of the method given by Raymer (1992):

(Eq. 3-30)

$$S_{Landing} = F_{Far25} \cdot \left(F_{thr\_rev} \cdot 4.9942 \cdot \frac{W_{landing}}{S_{ref}} \cdot \frac{1}{C_{L_{\max}}} + 304.8 \right) \text{ [m]}$$

The factor F_{Far25} accounts for the safety margins set by the FAR25 rules (1.67). F_{thr_rev} has been taken as 0.66 to account for reverse pitch propellers or thrust reversers. The landing weight is given in [kg] and the wing reference area in [m^2]. The maximum lift coefficient depends on the wing sweep.

3.8.6 Validation

The APD model aircraft performance results have been validated with the help of performance data published by the National Aerospace Laboratory NLR for their FLEM model (Flights and Emissions Model) (Ten Have and Witte, 1997). Because FLEM gives credit to the LTO phase of the flight (of 30 km) and APD does not do so, the evaluation performance results of APD have been calculated for the given block distance less this 30 km. The DOC validation is based on the normal APD results.

The total block time and block fuel for flights of 250, 500, 1,000, 2,000 and 3,000 km (short haul) and 1500 km, 2,000 km, 3,000 km, 6,000 km and 11,434 km (long haul) are available from the NLR FLEM reference. In Table 12 we compare these results from FLEM with the results from APD.

Table 12 Validation of the APD results with results by the FLEM model from NLR

Block Distance	Block time		Block fuel	
	Index FLEM=100		Index FLEM=100	
[km]	PRESENT150	PRESENT400	PRESENT150	PRESENT400
250	99	-	102	-
500	99	-	103	-
1,000	100	-	102	-
1,500	-	100	-	102
2,000	100	100	99	100
3,000	100	100	99	98
6,000	-	99	-	97
11,434	-	99	-	95

The block time is predicted within 1% deviation for both short haul and long haul market transports. APD over-predicts the block fuel with 2-3% for the short haul aircraft at short range and underestimates it at the medium ranges. The long haul aircraft shows deviations of up to 5% lower fuel consumption than predicted by FLEM. However the validation of the FLEM data on actual KLM flight data as shown by Ten Have and Witte (1997) shows FLEM to be about 3% too high on fuel consumption prediction for a 6,000 km block range. At this point, which is near the long range evaluation flight over 7,000 km, it seems the APD results resembles actual flight data somewhat better than FLEM does.

The DOC model has been validated against general data from AVMARK (AVMARK, 1999). The mean value of the DOC model has been weighted for the traffic volume for short and long haul. Assuming Internal European flights from all European airports to be short haul and intercontinental flights to be long haul. The long haul should be valued two times the short haul (Peeters et al., 1999).

Because the results for several of the parts of DOC did have a deviation from the figures given by AVMARK it was decided to incorporate the following modifications from the original figures given by Torenbeek (1982), Roskam (1989, part VIII) and Jesse (2000):

- Insurance cost 1% (was 2%);
- Fitting factor European (short haul) charges: $C_{fit\_EU} = 0.8115$;
- Fitting factor International (long haul) charges: $C_{fit\_Int} = 0.9625$;
- Finance cost 5% (was 7%);
- Depreciation period airframe 15 years (was 10 years);
- Flight crew 32% higher costs;
- Cabin crew 106% higher costs;
- Maintenance factored with 0.52.

The basic data are given for the late seventies/early eighties, which explains the sometimes large deviations. The crew costs are based on data given by Roskam (1990, Part VIII) for crew salaries. The main assumption is: the salaries are linearly proportional to the total cost per block hour for the airline. Roskam gives the following data (salary for the year 1989 in $):

Crew member	BAC 111	Boeing 747
Captain	$35,000	$144,000
First Officer	$24,000	$67,000
Engineer	$20,000	$62,000
Cabin attendant	approx. $30,000	approx. $30,000

The data for the Short haul market has been found by scaling the data for the BAC 111 with the number of passenger seats (rounded to thousands of dollars in the table). The long haul market (747-400) is of course kept the same. This results in:

Crew member	Boeing 737-400	Boeing 747-400
Captain	$46,000	$144,000
First Officer	$30,000	$67,000
Engineer	N/A	$62,000
Cabin attendant	approx. $30,000	approx. $30,000

From these data the ratios between these salaries have been converted to “wrap rates” by scaling them from the known 1995 figure of $750.-/hr for a 747 captain and then fitting the results to the general AVMARK data, which has given the mentioned scaling factors.
The following table gives the final data used:

Crew member	Short Haul (Boeing 737-400)	Long Haul (Boeing 747-400)
Captain	$331	$992
First Officer	$216	$467
Engineer	N/A	$428
Cabin attendant	$108	$108

After all this fine tuning of the model and parameters the final validation shows a good resemblance between AVMARK and the weighted mean (Table 13).

Table 13 Validation of the DOC model

Cost item	AVMARK (mean European market)	PRESENT150 at 1,000 km	PRESENT400 at 7,000 km	Weighted Mean for the two example planes
Flightdeck crew:	4.5	6.1	3.7	4.5
Cabin crew	4.0	6.0	3.0	4.0
Fuel&oil	5.7 (22%/17%)	6.8	5.1	5.7 (22%/17%)
Maintenance&Overhaul	5.6	7.5	4.6	5.6
Charges	6.3	13.0	2.9	6.3
Insurance	0.3	0.4	0.2	0.3
Finance	0	0 (1.9)	0 (1.0)	0 (1.3)
Depreciation (plus rentals)	(6.4)	0 (9.8)	0 (5.4)	0 (6.9)
TOTAL	26.4 (32.8)	39.8 (51.5)	19.6 (26.0)	26.3 (34.5)

4 Baseline versions

4.1 General Introduction

In this chapter we will present the baseline aircraft for the short haul and the long haul markets. First we describe the current baseline models as they are used at this moment. Then we will describe the baseline with 2010 technology level engines (i.e. with 11 years of engine development). All information has been gathered from public sources and unpublished studies of Peeters Advies and other partners in this study. Sources were for example Jane's (1998/1999 and several older copies), performance results from the NLR model FLEM (Ten Have and De Witte, 1997), data from preliminary aircraft design handbooks like Corning (1976), Torenbeek (1982, 1989), Raymer (1992), Roskam (1989 I-VII). Also handbooks on engine design has been used like Cohen and Rogers (1972) and Cumpsty (1997). Other sources were Doganis (1991), Kermode (1972) and Padilla (1996). Further information has been gathered from many Internet Sites.
All these information has been used to find the weight, low speed and high speed drag polar and the engine characteristics. These have been derived from data on performance of the two baseline aircraft (Boeing 737-400 an d747-400) using the methods mentioned in the above listed references.
As the methods used are part of the Peeters Advies company policy they are not published and cannot be published in this document. However, validation of the performance and cost models has been included (see chapter 3).

4.2 PRESENT150: Short Haul Market current engine technology level

4.2.1 Introduction

The current baseline aircraft must represent a typical currently much used aircraft in the 150 seats market section with a maximum range of approximately 3,000-4,000 km section, but typically used for a range of 1,000-2,000 km. The Boeing 737-400 seemed the best suited example for this purpose. Therefore the PRESENT150 has been based on the dimensions, weights and aerodynamic characteristics of the Boeing 737-400.

4.2.2 Definition

The aircraft has been based on the standard 146 seats Boeing 737-400 in a mixed class arrangement and fitted with two CFM56-3B-2 turbofan engines. Basic airframe dimensions used in calculating the performance and DOC are:

- Wing area: 105.4 m^2;
- Wingspan: 28.88 m;
- Wing Aspect Ratio: 7.9.

The characteristic weights are:

- Empty Weight: 31,795 kg;
- Dry engine weight: 1,951 kg/engine;
- Operating weight Empty: 34,564 kg;

- Maximum Zero Fuel weight: 51,255 kg;
- Maximum Payload (MZF-OEW): 16,690 kg (this is 146 passengers at 95 kg each plus 2,820 kg freight.

Cost figures for airframe and engine:
- Airframe market price plus avionics, spares et cetera, but excluding the engines are taken from Jane's (98/99): $37,800,000.
- Engine price including spares as given as the high price by Lloyd's Aviation (1997/1998): $3,100,000 per engine.

4.2.3 Aerodynamic properties

The aerodynamic properties are split into the low-speed drag polar and a high-speed mach drag rise. Both are derived from data on performance of the Boeing 737-400. The low-speed drag polar is modelled with the general equation as given by Torenbeek (1982):

(Eq. 4-1)

$$C_D = C_{D_0} + C_{D_i} = C_{D_0} + \frac{C_L^{\,2}}{\pi A R e}$$

The values of the zero lift or parasite drag C_{D_0} and Oswald's induced drag factor *e* are found by fitting the values taken from performance data to (Eq. 4-1). This gives the following values for the clean drag polar:

$$C_{D_0} = 0.0186$$
$$e = 0.79$$

Figure 14 Low speed drag polar as defined for the PRESENT150

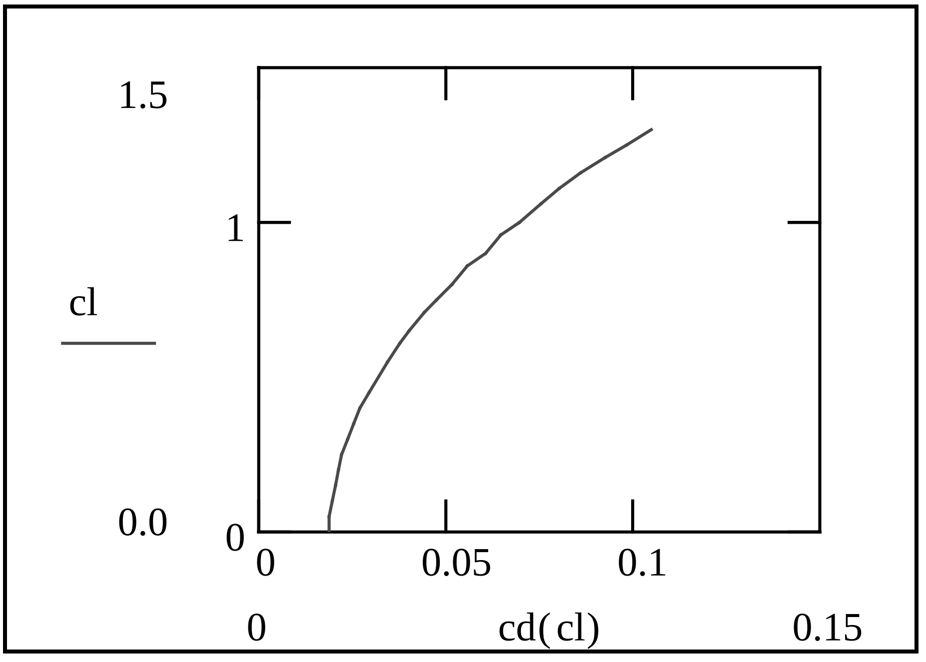
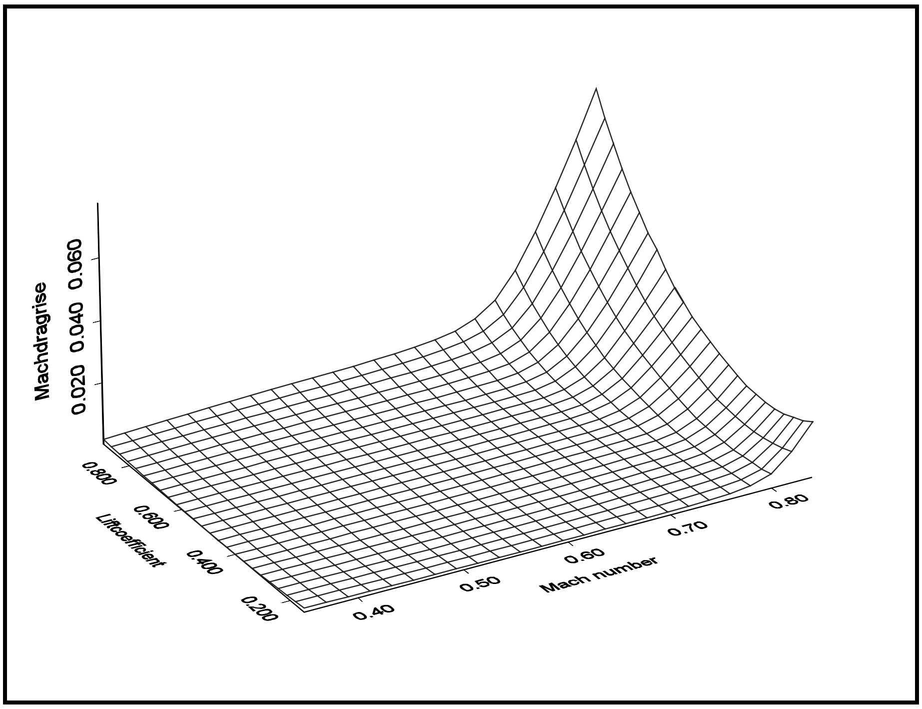


Figure 14 gives the resulting low speed clean configuration drag polar. Figure 15 gives the modelled mach drag rise as a function of mach number and lift coefficient.

Figure 15 Mach drag rise for PRESENT150



The maximum lift coefficient has been taken from data on minimum speeds for the Boeing 737-400 and calculated from its dimensions, configurations and weights. For the clean configuration the value is 1.25.

4.2.4 Performance

Flight Profile

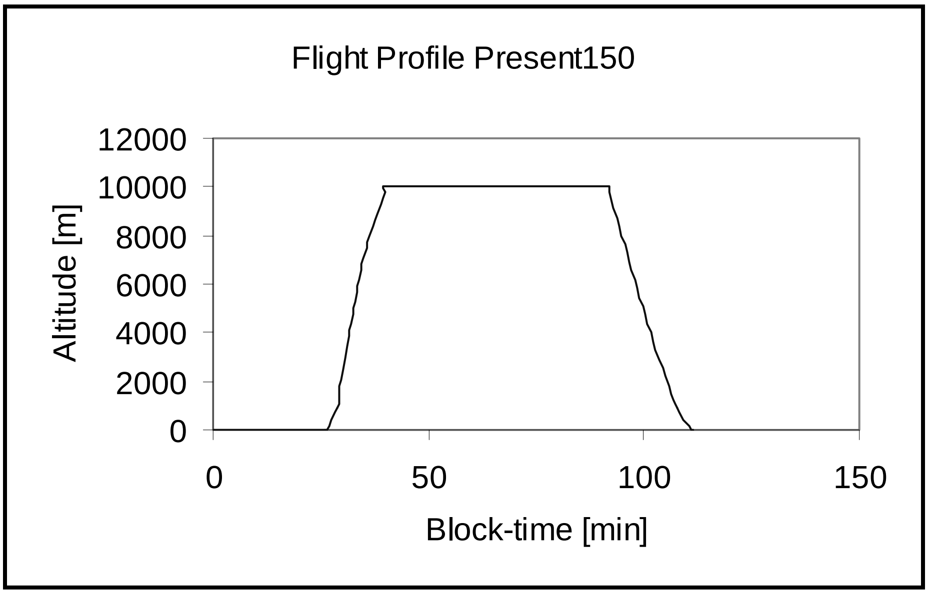
The flight profile used for calculating block-time and block fuel is a simplification of the flight profile given by Torenbeek (1982). The baseline evaluation flight has been set at 1,000 km block range with 70% load factor. The following assumptions have been made, using some performance data taken from Jane's (1998/1999) and Padilla (1996):

- Take off and Ground manoeuvring:
  - 26 minutes at 7% MTO engine rating (all fuel weight for taxi is pre-TO);
  - Take off 0.7 minutes at 100% MTO rating;
  - Climb-out from 35 ft to 3,000 ft at 85% MTO rating; climb-out time is the highest of 2.2 minutes or the real calculated time;
- Operational Climb:
  - Speed schedule 300 kCAS/0.745;
  - Max climb engine rating;
- Operational Cruise:
  - Long range speed (mach 0.745);
  - Cruise altitude 10,000 m;
- Operational descent:

    - Speed schedule: 0.745/300 kCAS;
    - Thrust set for maximum cabin rate of descent (300 ft/minute and maximum cabin altitude 6,000 ft).
- Approach and landing:
    - Approach from 3,000 ft to SL at 71.4 m/s TAS (Jane's, 1998/1999);
    - Approach time 4 minutes at 30% MTO rating;
- Reserves:
    - Go around from 3,000 ft;
    - Flight to alternate at 200 NM with flight speed schedule, but at 8,000 m cruise altitude;
    - 30 minutes hold as extended cruise.

The resulting flight profile is given in Figure 16.

Figure 16 Flight profile for the PRESENT150 in the evaluation flight over 1,000 km block distance



Results
The evaluation flight for Short Haul has been calculated with APD (see §3.8.2) for a block distance of 1,000 km. No credit has been given for the distance covered during the LTO phase. The following performance has been found for a payload at 70% load factor of 11,684 kg:
- Block time: 1 hour and 52 minutes;
- Block fuel used: 3,951 kg;
- Take off weight: 53,356 kg;
- Reserve fuel: 3,157 kg.

4.2.5 DOC

The DOC has been calculated with the DOC model (see §3.8.4) from the block time, distance and fuel. Below we give the results for the 1996 price level (fuel price of 0.27$/kg):
- Total DOC for the flight: $8,562;
- DOC per block hour: $4,604;
- DOC per block kilometre: $8.56;
- DOC per RTK: $0.733;

- DOC per passengerkm: $0.0838.

In Figure 17 a DOC breakdown has been given. Fuel comprises about 13% of the total Direct Operating Costs. Current charges (landing fee, ATC-fees, environmental fees and ground service costs) form in the short haul market the largest part and equal the total crew cost (flight deck crew and cabin crew) with 24%.

Figure 17 DOC breakdown for the PRESENT150 with 70% load factor on a 1,000 km flight

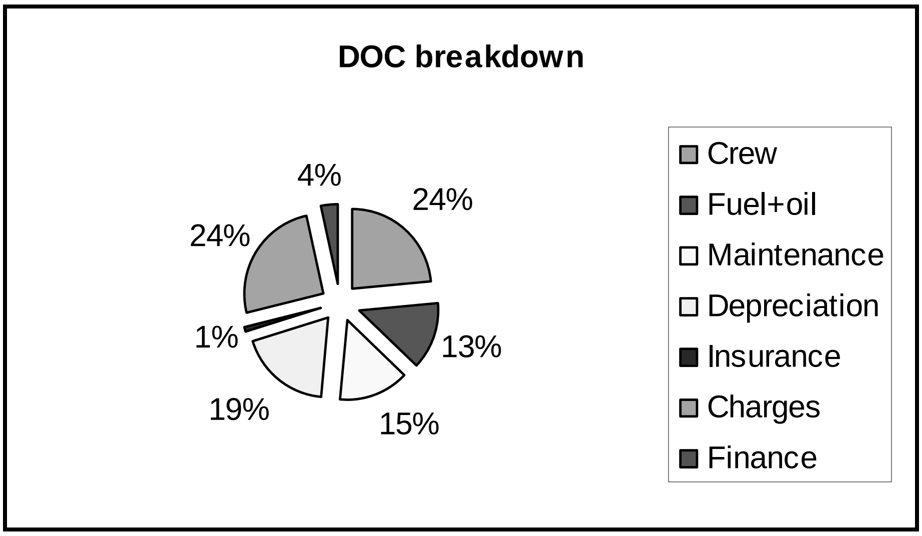
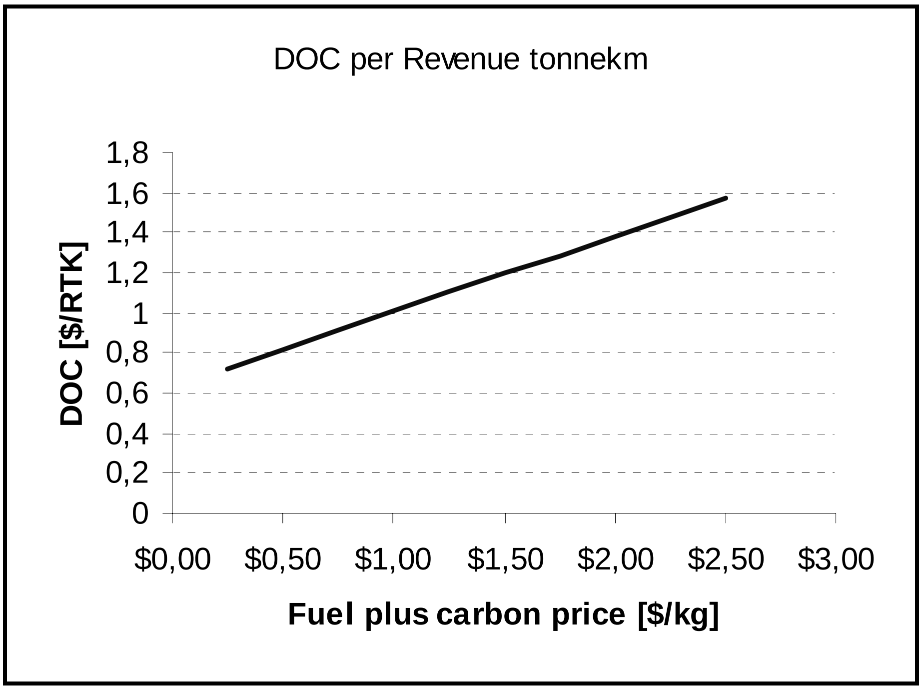


Figure 18 gives the effect of fuel plus carbon price on the DOC per RTK (Revenue Ton Kilometre). This kind of graphs will be used to find the fuel plus carbon price for which an aircraft with new technology will break even in DOC with the baseline aircraft. For this purpose, the range of fuel plus carbon price has been taken quite wide.

Figure 18 Effect of fuel plus carbon price on DOC per RTK for the baseline 1,000 km flight of the PRESENT150 at 70% load factor



4.3 PRESENT400: Long Haul Market current engine technology level

4.3.1 Introduction

The ‘current baseline aircraft’ must represent a typical currently much used aircraft in the 400-500 seats market section with a maximum range of approximately 13,000-14,000 km, but typically used for a range of 7,000-8,000 km. The Boeing 747-400 is the only suited example for this purpose. Therefore the PRESENT400 has been based on the dimensions, weights and aerodynamic characteristics of the Boeing 747-400.

4.3.2 Definition

The aircraft and engine definition is based on Jane’s (1998) and many other data available at Peeters Advies and partners in this research project. The aircraft has typically 416 seats in a mixed class arrangement and is fitted with four CF6-80C2B1F turbofan engines. Basic airframe dimensions used in calculating the performance and DOC are:

- Wing area: 541.16 m^2;
- Wingspan: 64.44 m;
- Wing Aspect Ratio: 7.7.

Weights are taken from Jane’s (1998):

- Empty Weight: 171,440 kg;
- Dry engine weight: 4,309 kg/engine;
- Operating weight Empty: 180,755 kg;
- MTOW: 362,875 kg;
- Maximum Zero Fuel weight: 242,670 kg;

- Maximum Payload (MZF-OEW): 61,915 kg (this is typically 416 passengers at 100 kg each plus 20,315 kg freight).

Cost figures for airframe and engine are:

- Airframe market price plus avionics, spares et cetera, but excluding the engines are taken from Jane's (98/99): $148,400,000.
- Engine price per engine including spares: $5,400,000, the high price given by Lloyd's Aviation (1997/1998).

4.3.3 Aerodynamic properties

The aerodynamic properties are split into the low-speed drag polar and the high-speed mach drag rise. Both are recalculated from performance data. Because (Eq. 4-1) did not give a fair fit the low-speed drag polar is modelled with the more accurate equation given by Torenbeek (1982, p370):

(Eq. 4-2)

$$C_D = C_{D_{ref}} + \beta (C_L - C_{L_{ref}})^2$$

The reference point is the point with the minimum drag. In (Eq. 4-1) this point has been assumed to be at zero lift, but in most cases this point is at a small positive value of lift coefficient. To be able to distinguish between the different contributions of drag both equations have been rearranged to:

(Eq. 4-3)

$$C_D = C_{D_0} + C_{D_{p1}} \cdot C_L + (C_{D_{p2}} + \frac{1}{\pi A R e}) \cdot C_L{}^2$$

The values of the zero lift drag C_{D_0} and the drag factors $C_{D_{p1}}$ and $C_{D_{p1}}$ are found by assuming Oswald's induced drag factor e to be 0.8 and fitting the values deduced from performance data. This gives the following values for the clean drag polar:

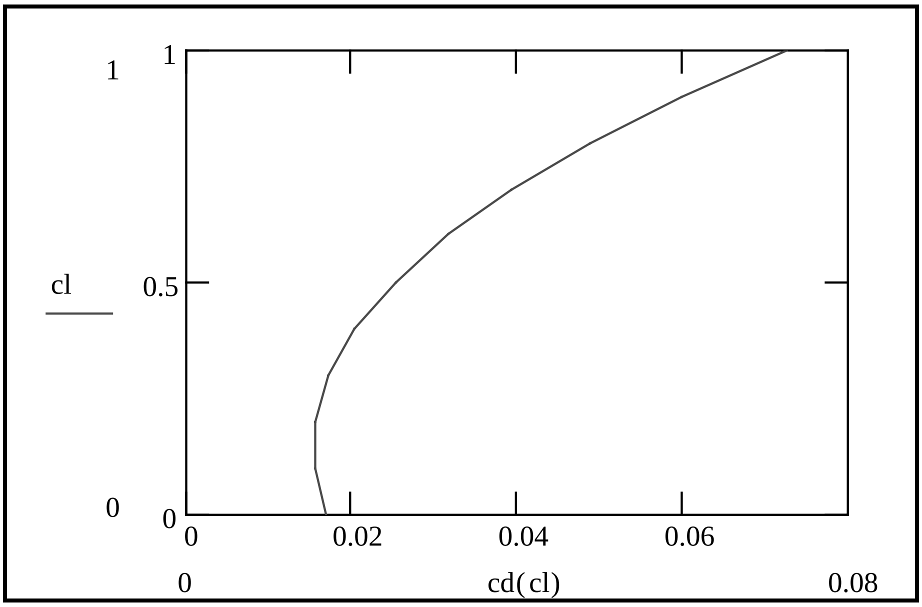
$C_{D_0} = 0.0169$
$C_{D_{p1}} = -0.0227$
$C_{D_{p2}} = 0.0265$

assuming:

$$e = 0.80$$

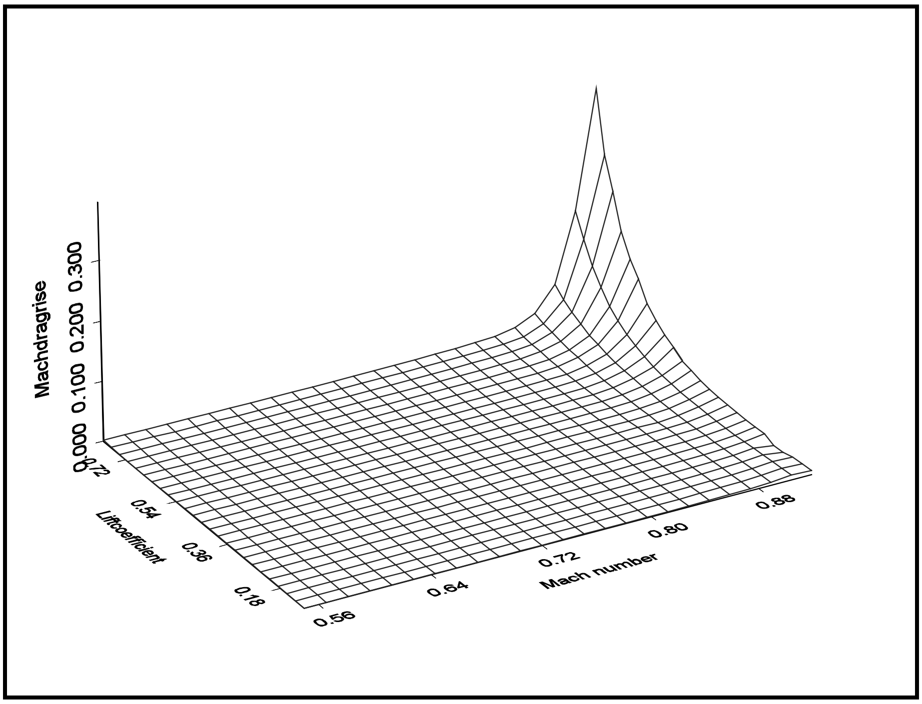
In Figure 19 the calculated drag polar with the values for the parameters mentioned.

Figure 19 Low speed clean drag polar for the long haul baseline PRESENT400



The total drag for high-speed will be calculated from the low speed drag polar plus the mach drag rise as a function of lift coefficient and mach number. Figure 20 gives the likely mach drag table as found from the analysis of performance and dimension data.

Figure 20 Mach drag rise for PRESENT400



The maximum lift coefficient has been taken from data on minimum speeds at several configurations and weights. For the clean configuration the value is only 0,90.

4.3.4 Performance

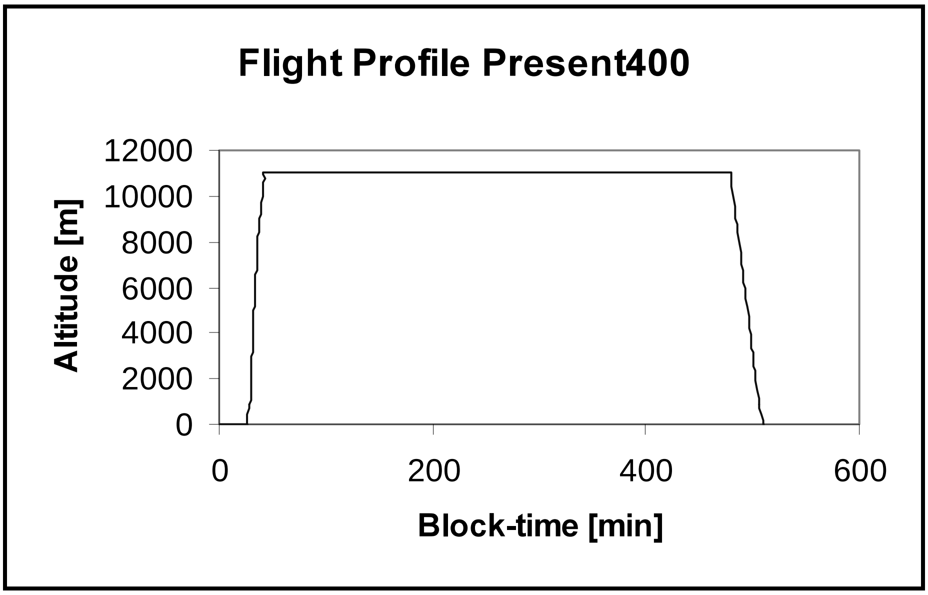
Flight Profile

The flight profile used for calculating block-time and block fuel is a simplification of the flight profile given by Torenbeek (1982). The following assumptions have been made, based on performance information taken from Jane's (1998/1999) and Padilla (1996):

- Take off and Ground manoeuvring:
  - 26 minutes at 7% MTO engine rating (all fuel weight for taxi is pre-TO);
  - Take off 0.7 minutes at 100% MTO rating;
  - Climb-out from 35 ft to 3,000 ft at 85% MTO rating; climb-out time is 2.2 minutes, being the highest of 2.2 minutes or the real calculated time;
- Operational Climb:
  - Speed schedule 320 kCAS/0.84;
  - Max climb engine rating;
- Operational Cruise:
  - Long range speed (mach 0.84);
  - Cruise altitude 11,000 m;
- Operational descent:
  - Speed schedule: 0.84/320 kCAS;
  - Thrust set for maximum cabin rate of descent (300 ft/minute and maximum cabin altitude 6,000 ft);
- Approach and landing:
  - Approach from 3,000 ft to SL at 75 m/s TAS (Jane's, 1998);
  - Approach time 4 minutes at 30% MTO rating;
- Reserves:
  - 120 minutes hold as extended cruise.

The resulting flight profile is given in Figure 21.

Figure 21 Flight profile for the PRESENT400 in the evaluation flight with current engine technology over 7,000 km block distance



Performance results

The evaluation flight for Long Haul has been calculated with APD (see §3.8.2) for a block distance of 7,000 km. The distance covered is measured without the distance for the LTO phase below 3,000 ft. The block time and fuel are including the LTO phase. The following performance has been calculated for a Payload at 75% load factor of 46,436 kg:

- Block time: 8 hour and 30 minutes;
- Block fuel used: 77,268 kg;
- Take off weight: 320,224 kg;
- Reserve fuel: 15,765 kg.

4.3.5 DOC

The DOC has been calculated with the DOC model (see §2.6) from the block time, distance and fuel. Below we give the results for the 1996 price level (fuel price of 0.27$/kg):

- Total DOC for the flight: $112,702;
- DOC per block hour: $13,26;
- DOC per block kilometre: $16.10;
- DOC per RTK: $0.347;
- DOC per passenger km: $0.0516.

In Figure 22 a DOC breakdown has been given. Fuel comprises about 19% of the total Direct Operating Costs. Crew cost is now the largest part with 26%. Current charges (landing fee, ATC-fees, environmental fees and ground service costs) form only 11% of the total.

Figure 22 DOC breakdown for the PRESENT400 with 75% load factor on a 7,000 km flight

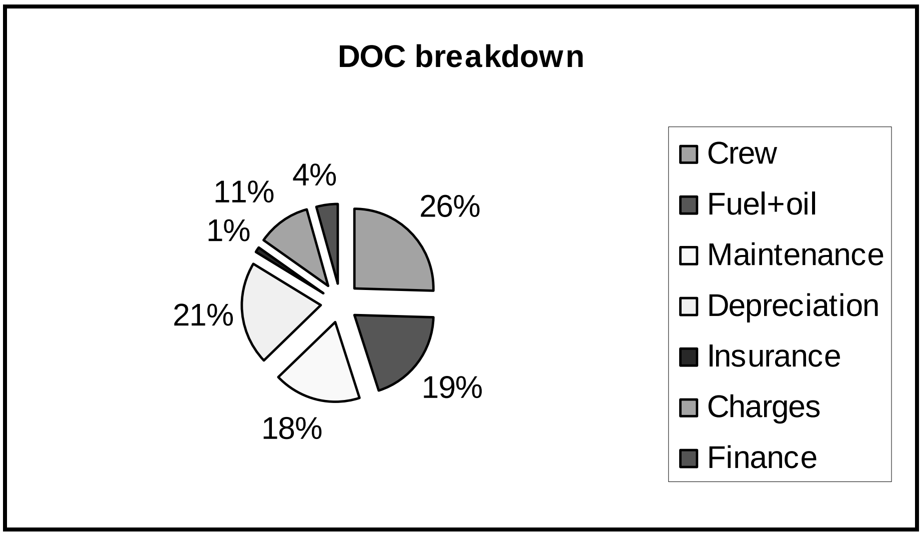
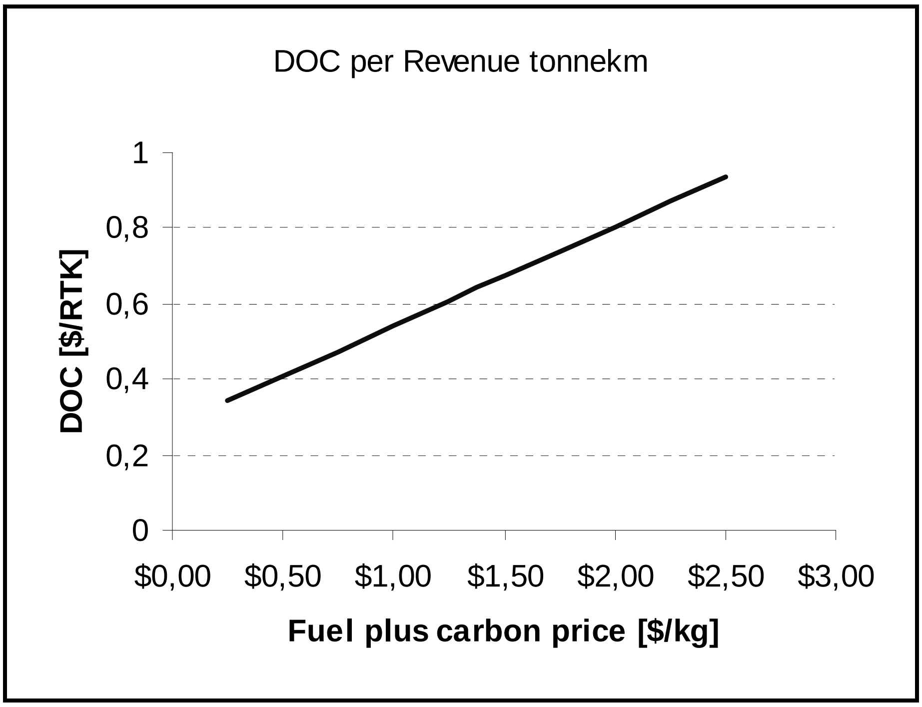


Figure 23 gives the effect of fuel plus carbon price on DOC per RTK. This kind of graphs will be used to find the fuel plus carbon price at which the DOC for a design with a given technology breaks even with the DOC of the baseline aircraft. The range of fuel plus carbon price has therefore been taken quite wide.

Figure 23 Effect of fuel plus carbon price on DOC per RTK for the baseline 7,000 km flight of the PRESENT400 at 75% load factor



4.4 BASE150: short haul market, 2010 engine technology level

4.4.1 Definition

The BASE150 aircraft has been derived from the baseline aircraft PRESENT150 with current engine by retrofitting it with 2010 engine technology. The following changes are due to this engine retrofit:

- Lower fuel consumption;
- Lower engine weight;
- Lower engine price.

The primary assumptions are taken from Van der Heijden and Wijnen (1999). He gives the changes as a percentage per year. Because the current fleet is built up by aircraft of several ages we assume the fleet technology level in the 2010 to be developed over 11 years from current technology. The following alterations result:

- 0.85%/year lower fuel consumption over 11 years gives 9% reduction;
- 0.75%/year lower engine weight over 11 years gives 8% reduction;
- 1.0% lower engine price over 11 years gives 10.5% reduction.

OEW and EW will reduce when the MTOW and MLW reduces if some redesign is done. We assume this redesigning will take place and have some second order influence on OEW. The mentioned changes will therefore influence the following weights of the aircraft:

- The Empty Weight (EW) and the Operating Weight Empty (OEW);
- The Maximum Landing Weight MLW;
- The Maximum Take off Weight (MTOW).

Now following weights result from the iterative weight calculations:

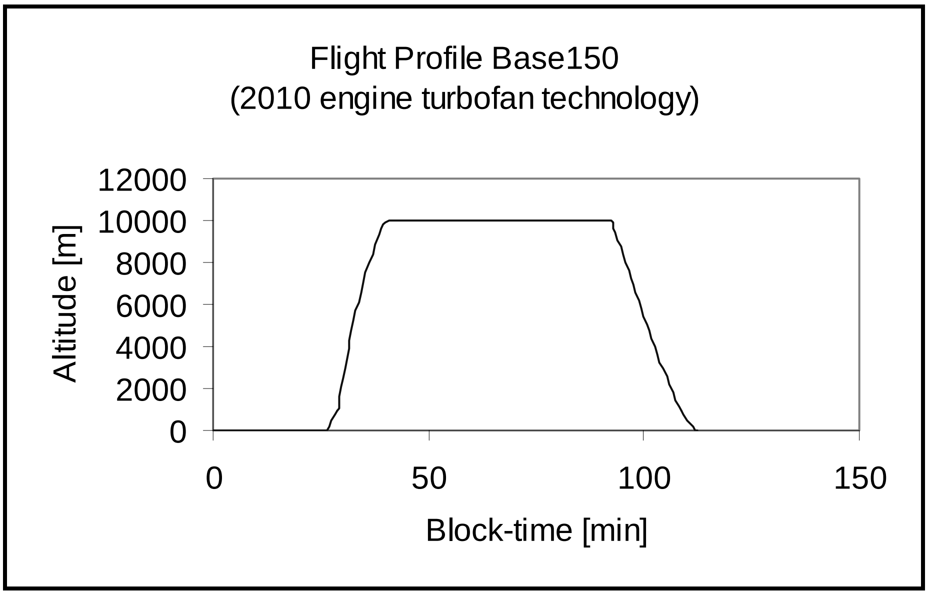
- The reduction in empty weight totals to: 539 kg
- MRW: 61,471 kg;
- MTOW: 61,241 kg;
- MLW: 54,346 kg;
- MZFW: 50,716 kg;
- OEW: 34,025 kg.

All other dimensions are kept the same as for the PRESENT150/400 with current engine technology.

4.4.2 Performance

Flight Profile
The flight profile used is the same as for the PRESENT150 aircraft (see §4.2.4). The resulting flight profile for the BASE150 with 2010 technology turbofans is given in Figure 24.

Figure 24 Flight profile for the BASE150 evaluation flight over 1,000 km block distance



Performance results
The evaluation flight for Short Haul has been calculated with APD (see §2.5) for a block distance of 1,000 km (excluding the distance covered during the LTO phase). The following performance has been calculated for a payload at 70% load factor of 11,684 kg:

- Block time: 1 hour and 52 minutes;
- Block fuel used: 3,591 kg;
- Take off weight: 52,160 kg;
- Reserve fuel: 2,860 kg.

The fuel consumption for the evaluation flight of BASE150 has been reduced with 9%. Block time has not changed.
The payload range capability of the BASE150 is given in Figure 25. Due to the lower fuel consumption the range at lower load factors has become somewhat larger than for the current aircraft.

The field performance for take off and landing has also been calculated on a rough scale. This has been done for comparison of the new designs with the baseline and to prevent deterioration of field performance while enhancing fuel economy. Figure 26 gives the resulting baseline performance on a standard day, ISA, with no wind and no runway gradient.

Figure 25 The payload range capability of the short haul BASE150 for a standard atmosphere and the standard speed schedule and cruise altitude

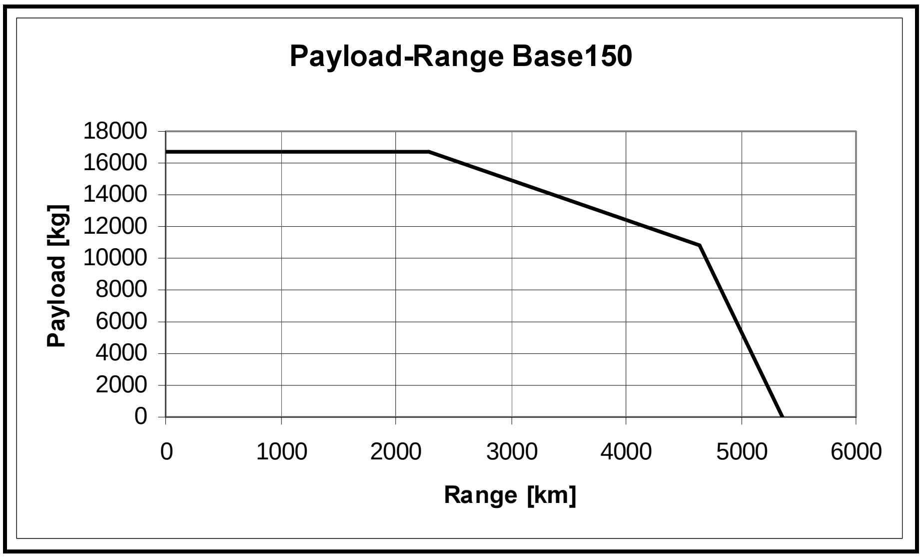
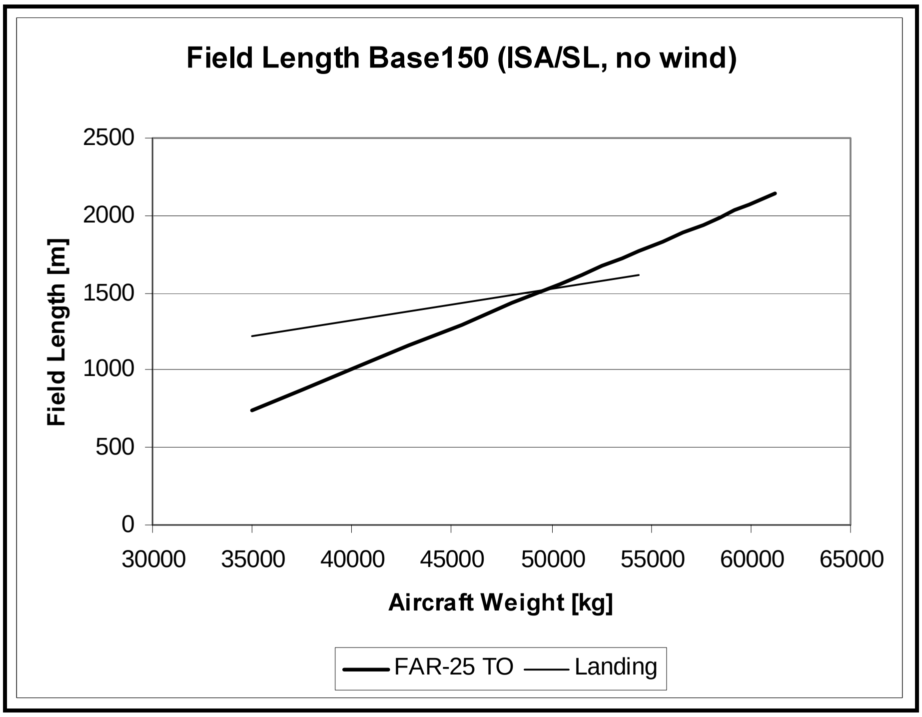


Figure 26 Field length performance of the BASE150 for a standard day, ISA, no wind and no runway gradient. The lines are drawn up to MTOW respectively MLW



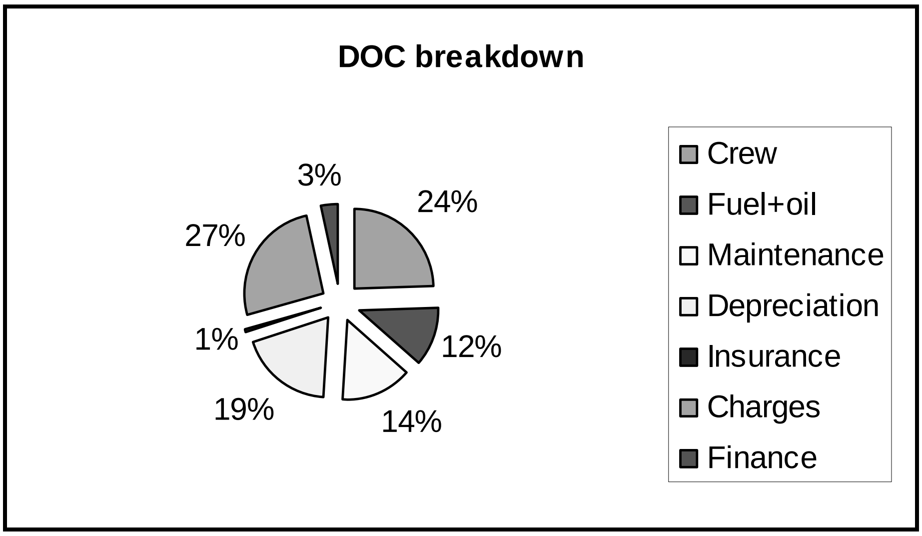
4.4.3 DOC

The DOC has been calculated with the DOC model (see §2.6) from the block time, distance and fuel. Below we give the results for the 1995 price level (fuel price of 0.27$/kg):

- Total DOC for the flight: $8,311;
- DOC per block hour: $4,471;
- DOC per block kilometre: $8.311;
- DOC per RTK: $0.711;
- DOC per passenger-km: $0.0813.

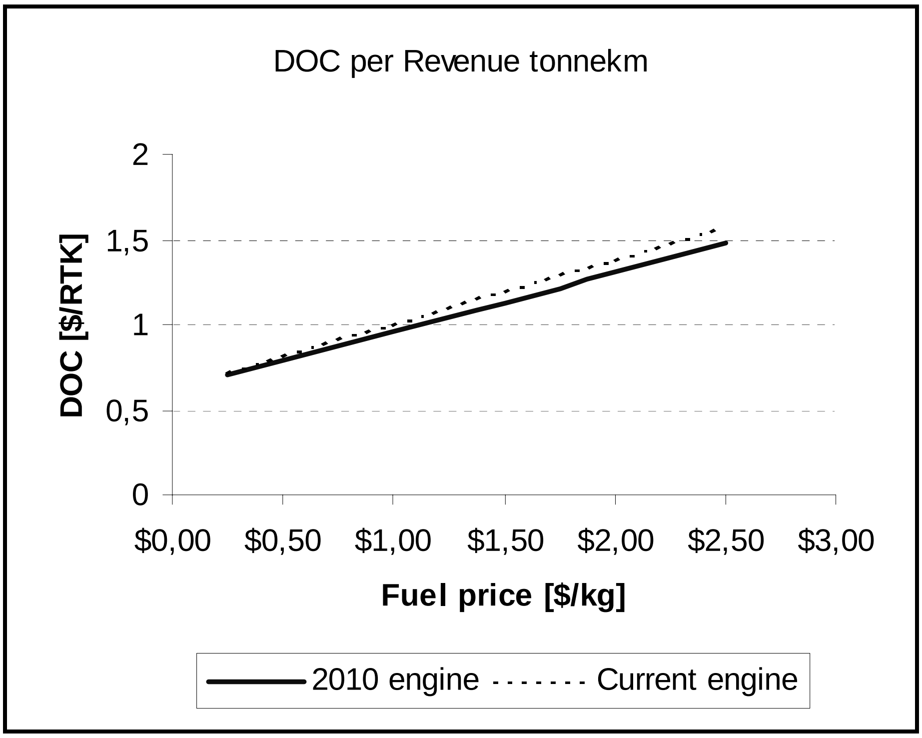
In Figure 27 a DOC breakdown has been given. Fuel and oil accounts for about 12% of the total Direct Operating Costs. Current charges (landing fee, ATC-fees, environmental fees and ground service costs) form also in the short haul market of 2010 the largest part and surpass the total crew cost (flight deck crew and cabin crew).

Figure 27 DOC breakdown for the BASE150 with 2010 technology level turbofan engines at 70% load factor on a 1,000 km block distance flight



The relation between fuel plus carbon price and DOC per RTK is given in Figure 28. The figure shows clearly the new Turbofan is a good proposition at any fuel plus carbon price level. This makes the changes high the development will carry on.

Figure 28 Effect of fuel plus carbon price on DOC per RTK for the 1,000 km flight of BASE150 at 70% load factor



4.5 BASE400: long haul market, 2010 engine technology level

4.5.1 Definition

The long haul BASE400 baseline aircraft has been derived from the PRESENT400 aircraft with current engine technology by initially changing the following for the engine characteristics:

- Lower fuel consumption;
- Lower engine weight;
- Lower engine price.

These initial changes for fuel consumption, engine weight and engine price are taken from Van der Heijden and Wijnen (1999). He gives the development as a percentage per year. Because the current fleet is built up by aircraft of several ages we assume the fleet technology level in 2010 to be developed over 11 years (1999-2010) from current technology. The following changes now result:

- 0.85%/year lower fuel consumption over 11 years gives 9% reduction;
- 0.75%/year lower engine weight over 11 years gives 8% reduction;
- 1.0% lower engine price over 11 years gives 10.5% reduction.

These changes will have some second order effects on the following weights of the aircraft:

- The Empty Weight (EW) and the Operating Weight Empty (OEW);
- The Maximum Landing Weight MLW;
- The Maximum Take off Weight (MTOW).

OEW and EW will reduce when the MTOW and MLW reduces and if some redesign is done. We assume this redesigning will take place and the second order effects influence the OEW. Following weights result from the iterative calculations:

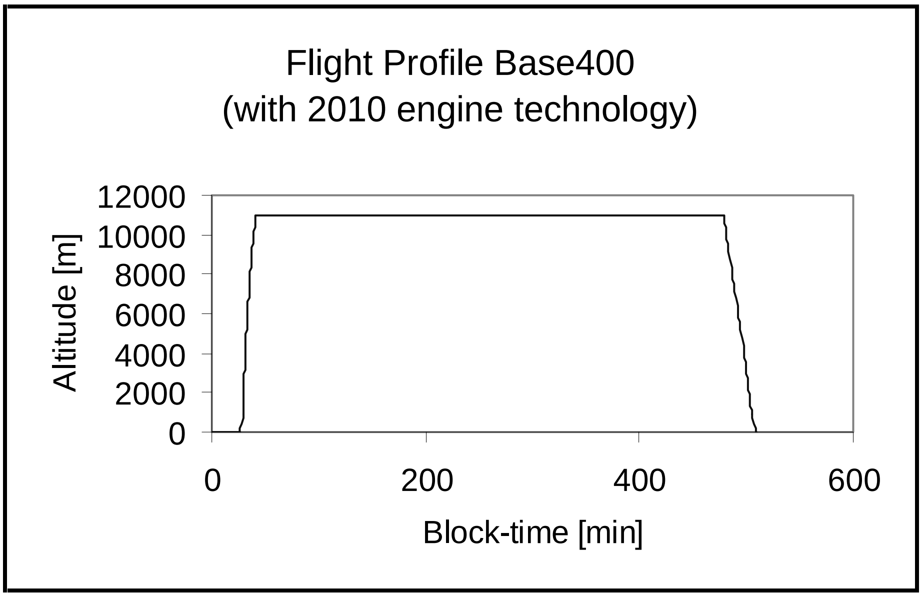
- The reduction in empty weight totals to: 3,583 kg
- MRW: 349,834 kg;
- MTOW: 348,474 kg;
- MLW: 256,777 kg;
- MZFW: 239,087 kg;
- OEW: 177,171 kg.

All other dimensions are kept the same as for the PRESENT400.

4.5.2 Performance

Flight Profile
The flight profile used for calculating block-time and block fuel is the same as for the PRESENT400 aircraft (see §4.3.4). The resulting flight profile for the BASE400 is given in Figure 29.

Figure 29 Flight profile for the BASE400 evaluation flight over 7,000 km block distance



Performance results
The evaluation flight for Long Haul has been calculated with APD (see §2.5) for a block distance of 7,000 km (excluding the distance covered during the LTO-phase). The following performance has been found for a payload at 75% load factor of 46,436 kg

- Block time: 8 hour and 30 minutes;
- Block fuel used: 68,513 kg;
- Take off weight: 306,376 kg;
- Reserve fuel: 14,255 kg.

The above results mean a reduction of the fuel consumption with respect to the current engine technology with 11.3%. The extra effect of 2.3% above the engine fuel consumption reduction is caused by the lower structural

weight and the lower weight of the fuel carried during climb and cruise. This effect is typical for the long haul market.
The payload range capability of the BASE150 is given in Figure 30. Due to the better fuel economy and the fact the fuel capacity has not been reduced accordingly, the payload has no fuel capacity limit. Reducing fuel capacity with about 15% would result in an empty weight reduction of only about 180 kg.
The field performance for take off and landing has also been calculated on a rough scale. This has been done for comparison of the new designs with the baseline and to prevent deterioration of field performance while enhancing fuel economy. Figure 31 gives the resulting baseline performance on a standard day, ISA, with no wind and no runway gradient.

Figure 30 The payload-range capability of the long haul BASE400 for a standard atmosphere and the standard speed schedule and cruise altitude

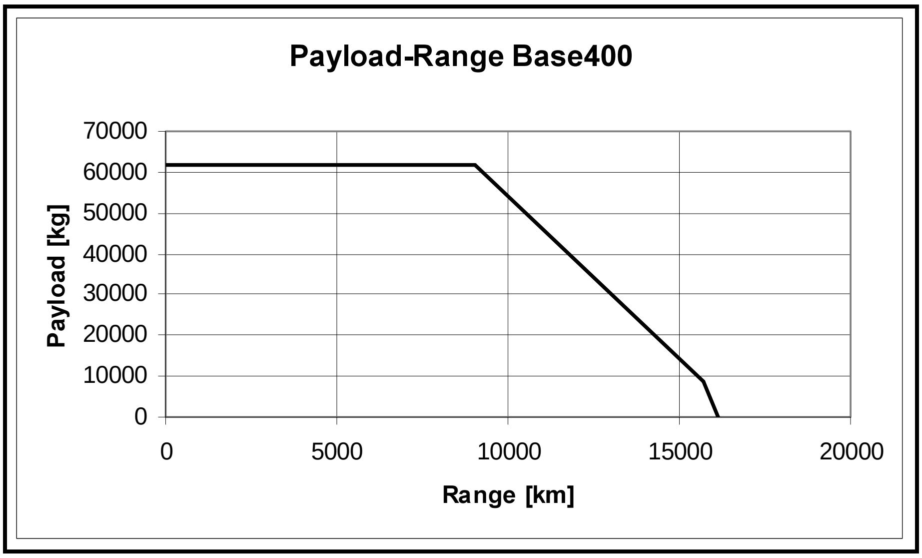
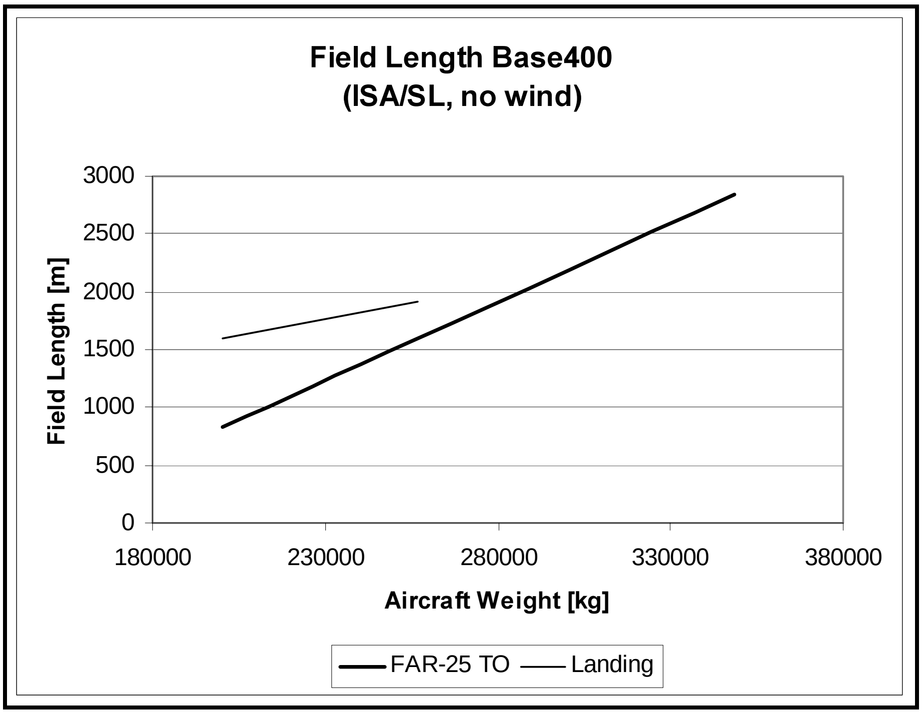


Figure 31 Field length performance of the BASE400 for a standard day, ISA, no wind and no runway gradient. The lines are drawn up to MTOW respectively MLW



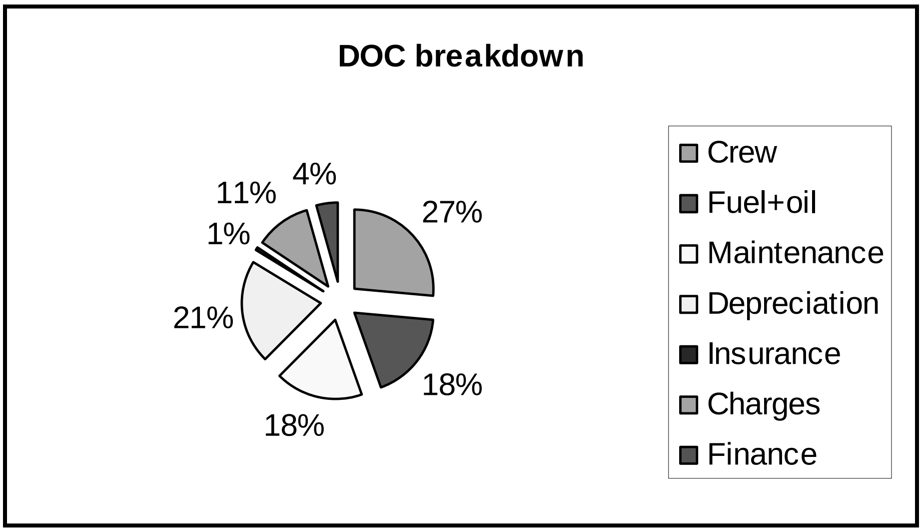
4.5.3 DOC

The DOC has been calculated with the DOC model (see §2.6) from the block time, distance and fuel. Below we give the results for the 1995 price level (fuel price of 0.27$/kg):

- Total DOC for the flight: $ 108,262;
- DOC per block hour: $12,74;
- DOC per block kilometre: $15.47;
- DOC per RTK: $0.333;
- DOC per passenger-km: $ 0.0496.

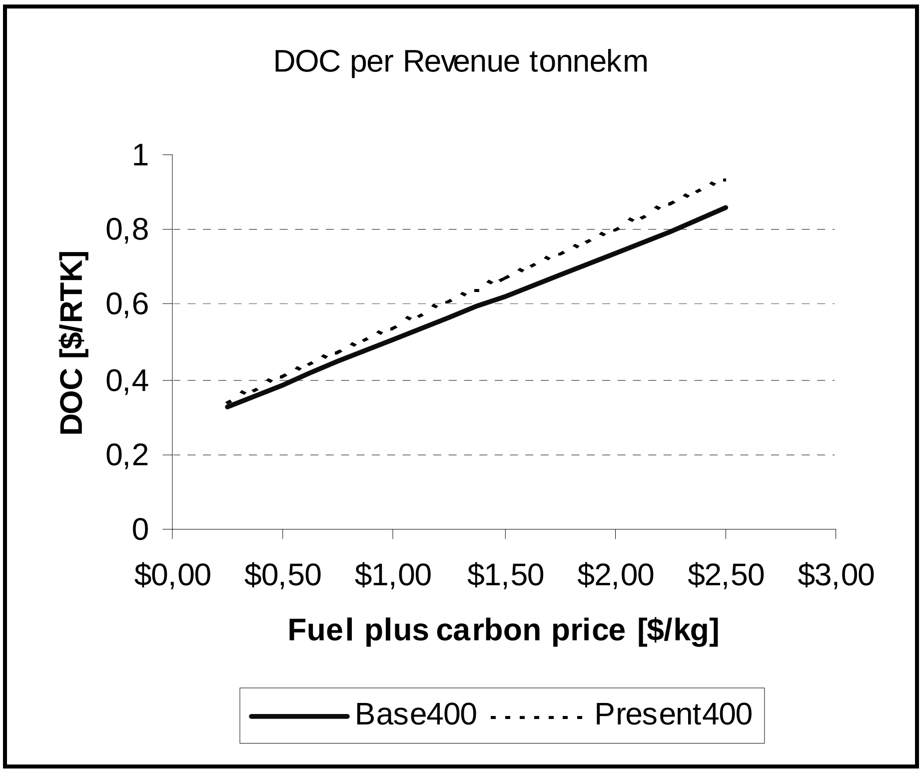
The DOC has been reduced with almost 4% with respect to the current engine technology PRESENT400. In Figure 32 a DOC breakdown has been given. Fuel comprises about 18% of the total Direct Operating Costs. Crew cost form in the long haul market the largest part (27%) of total DOC.

Figure 32 DOC breakdown for the long haul BASE400 at 75% load factor on a 7,000 km flight



The relationship between fuel plus carbon price and the DOC per RTK is given in Figure 33. The dotted line gives the relationship for the PRESENT400 with engine technology. Again the new engines make the aircraft economically a better proposition and the presumed engine development seems likely.

Figure 33 Effect of fuel plus carbon price on DOC per RTK for the 7,000 km flight of long haul BASE400 at 75% load factor



5 New engine technologies

5.1 Introduction

A wide range of propulsion options exist. The most conventional technologies are those aimed at improving current turbofan engines. An example is the ultra high bypass turbofan engine (UHB). Another possibility is to improve the technology of normal turboprop engines. However this still means a notable reduction of the flying speed and increase of DOC. A nice compromise may be found in the development of high speed propeller technology (HSP). These latter are a hybrid between so-called Propfan engines with a high number of highly swept propeller blades and normal turboprops. The HSP is able to fly economically at mach numbers up to 0.75[12].
A more or less exotic solution may be found in a combination of electrical engines, HSP and fuel cells. Fuel cells emit only water vapour if liquid hydrogen (LH_2) is used as fuel. Their energy efficiency is very high as up to 75% of the energy content of the fuel is outputted to the propeller. Disadvantages of fuel cell systems are their high specific weight and volume and the need to store liquid hydrogen fuel.
The only engine fit for a real retrofit may be the UHB engine. The High Speed Propellers will never be used directly on an existing aircraft like PRESENT150 and PRESENT400. Therefore the effects of the High Speed Propellers are in this chapter evaluated by presuming them on the existing airframes, not as an example of a really to expect development. Fuel cells basically require a total new design and are described in a full new design in Chapter 8.

Summarising, the following new engine technology has been studied in detail and will be described in this chapter:

- UHB Turbofans;
- High Speed Propellers (for medium flight speeds up to mach 0.75);
- Fuel cells (for flight speeds up to mach 0.70).

The proposed effects of the new engines (UHB and High Speed Propeller) are assumed to have benefited from the technological development of conventional turbofan technology (see §4.4 and §4.5).
The fuel cell option will have a long development path and is still far from introduction in aerospace. In this chapter we give a first estimate of its characteristics in §5.6.

5.2 Short haul market, UHB engines

5.2.1 Introduction

The engines of the PRESENT150 have a bypass ratio of around 5.5. UHB engines will increase this to a value around 9-10. The object of this is increasing the fuel efficiency and reducing noise emissions. However, if at the

[12] Th high speed propeller differs with the Propfan, which has been designed for mach numbers up to 0.84. The Propfan will face many more problems on noise and vibrations than the HSP.

same time the turbine inlet temperature is raised the emissions of NO_x might be higher, which must be seen as a disadvantage. Also engine dimensions and weight will be larger as well as the engine price.

5.2.2 Aircraft Definition

The UHB engines have been based on the 2010 technology level turbofans by changing the following (according to Van der Heijden and Wijnen, 1999):

- Lower fuel consumption (-15%);
- Higher engine weight (+10%);
- Higher engine price (+10%);
- Higher engine maintenance cost (+10%);
- Larger engine diameter (+25%).

These changes induce following second order effects calculated with the APD toolbox:

- Enlarged undercarriage due to larger engines, requiring a larger ground clearance;
- Higher weight and parasite drag due to larger nacelles;
- New weight definitions due to weight changes of engines, nacelles, undercarriage and fuel consumption for the maximum range flight;
- Higher airframe price due to redesigning the new parts of the airframe.

Based on the above assumptions following weights have been found from the iterative calculations:

- The BASE150 empty weight increases with 19 kg;
- MRW: 60,756 kg;
- MTOW: 60,526 kg;
- MLW: 54,904 kg;
- MZFW: 51,274 kg;
- OEW: 34,583 kg.

The parasite drag increases due to the larger nacelles with 0.0004 to a total clean configuration parasite drag of $C_{D_0} = 0.0190$.

Van der Heijden and Wijnen (1999) gives a general engine cost reduction for conventional turbofans with 1% per annum. Including this cost reduction for the UHB turbofan this means a total engine price reduction between 1999 and 2010 with $100 \bullet (1-0.01)^{11} - 100 = -10.5\%$. Relative to this reduction the price will increase due to the introduction of the UHB technology with 10%. The net engine price decrease becomes now 1.5%: from \$3,100,000 to \$3,053,100.

The need for redesigning the undercarriage (enlarging to prevent the larger nacelles scraping the ground during take off or landing) and the nacelles result into an increase of the airframe purchase price. The following has been assumed:

- The investment is written of over 300 new aircraft;
- 100% of the nacelles is new;
- 50% of the undercarriage is new.

These assumptions lead to an airframe price increase of \$2,465,000 making the new aircraft price \$40,599,000.

5.2.3 Performance

The flight profile used for calculating block-time and block fuel is the same as used for the baseline aircraft PRESENT150 (see §4.2.4). The evaluation flight for Short Haul for a block distance of 1,000 km resulted in following performance for a payload at 70% load factor of 11,684 kg:

- Block time: 1 hour and 52 minutes;
- Block fuel used: 3,077 kg;
- Take off weight: 51,807 kg;
- Reserve fuel: 2,463 kg.

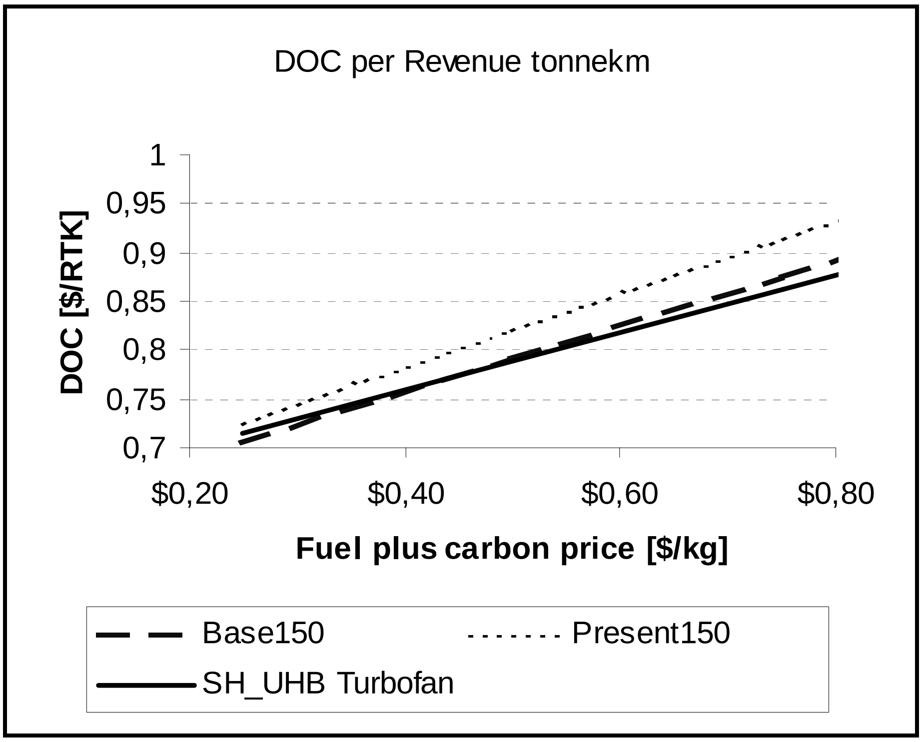
The fuel consumption has been reduced with respect to the PRESENT150 with current technology engines with 874 kg or 22%. With respect to the 2010 technology turbofans the reduction is 514 kg or 14%.

5.2.4 DOC

The DOC has been calculated from the block time, block distance and block fuel. From the intersection of the DOC lines as a function of fuel plus carbon price the following two DOC break points are found (see Figure 34):

- With respect to the current engine technology: $0.128/kg;
- With respect to the 2010 engine technology: $0.467/kg.

Figure 34 Effect of fuel plus carbon price on DOC per RTK for the 1,000 km flight of the SH_UHB Short Haul aircraft fitted with Ultra High Bypass Turbofans at 70% load factor compared with current and 2010 technology turbofan aircraft



For the latter fuel plus carbon price ($0.467/kg) following DOC has been found:

- Total DOC for the flight: $9,098;
- DOC per block hour: $4,895;
- DOC per block kilometre: $9.098;
- DOC per RTK: $0.779;
- DOC per passenger-km: $0.0890.

The Ultra High Bypass Turbofan turns out to be economically not too effective a way to reduce fuel consumption: its DOC remains higher than for the baseline 2010 at fuel plus carbon price below $0.467/kg, which is quite high compared to the value of $0.27/kg of 1996.

5.3 Long Haul Market, UHB engines

5.3.1 Introduction

The current engines of the PRESENT400 have a bypass ratio of around 5.5. UHB engines will increase this to a value around 9-10. UHB engines will be developed for the long haul market in the first place. The object for this is reducing the fuel consumption and noise emissions. If at the same time the turbine inlet temperature is raised the emissions of NO_x might be higher. Which must be seen as an disadvantage. Also engine dimensions and weight will be larger as well as the engine price.

5.3.2 Aircraft Definition

The UHB turbofan engine performance has been derived from the current Turbofan definition including eleven years of conventional Turbofan development by reducing fuel consumption with 15%. The BASE400 airframe is retrofitted with the UHB Turbofans by changing the following with respect to the 2010 technology level turbofan (according to Van der Heijden and Wijnen, 1999):

- Lower fuel consumption (-15%);
- Higher engine weight (+10%);
- Higher engine price (+10%);
- Higher engine maintenance cost (+10%);
- Larger engine diameter (+25%).

These changes induce the following second order effects:

- Enlarged undercarriage due to larger engines, requiring a larger ground clearance;
- Higher airframe price due to redesigning of some parts of it;
- Higher weight and parasite drag due to larger nacelles;
- New weight definitions due to weight changes of engines, nacelles, undercarriage and fuel consumption for the maximum range flight.

Following weights result from the iterative calculations:

- The empty weight decreases with: 3,059 kg;
- MRW: 334,731 kg;
- MTOW: 333,371 kg;
- MLW: 257,301 kg;
- MZFW: 239,611 kg;
- OEW: 177,696 kg.

The parasite drag increases due to the larger nacelles with 0.000408 to a total clean configuration parasite drag of $C_{D_0} = 0.0173$.

Van der Heijden and Wijnen (1999) gives a general engine cost reduction for conventional turbofans with 1% per annum. Accounting for half of this cost reduction for the UHB turbofan this means a total engine price reduction between 1999 and 2010 with $100 \bullet (1-0.01)^{11} - 100 = -10.5\%$. Relative to this reduction the price will increase due to the introduction of the UHB technology with 10%. The net engine price decrease becomes now 1.5%. The engine price will rise from $5,400,000 to $5,319,000. This figure has been inserted into the DOC_data sheet.

The retrofit with UHB engines not only asks for redesigning the undercarriage and the nacelles results into an increase of the airframe price, but also for a higher engine maintenance cost. The following has been assumed:

- Engine Maintenance cost +10% (Van der Heijden and Wijnen, 1999);
- The investment is written of over 300 aircraft;
- 100% of the nacelles is new;
- 50% of the undercarriage is new.

These assumptions lead to an airframe price increase from $148,400,000 to a price of $159,524,000 (which is 7.5% increase).

5.3.3 Performance

The flight profile used for calculating block-time and block fuel is the same as used for the PRESENT400 (see §4.3.4). The evaluation flight for Long Haul LH_UHB has been calculated with APD (see §2.5) for a block distance of 7,000 km for a payload at 75% load factor of 46,436 kg

- Block time: 8 hour and 30 minutes;
- Block fuel used: 58,181 kg;
- Take off weight: 294,690 kg;
- Reserve fuel: 12,377 kg.

The fuel consumption has been reduced compared to PRESENT400 with 19,081 kg or 24.7%. With respect to the BASE400 the reduction is 10,327 kg or 15.1%.

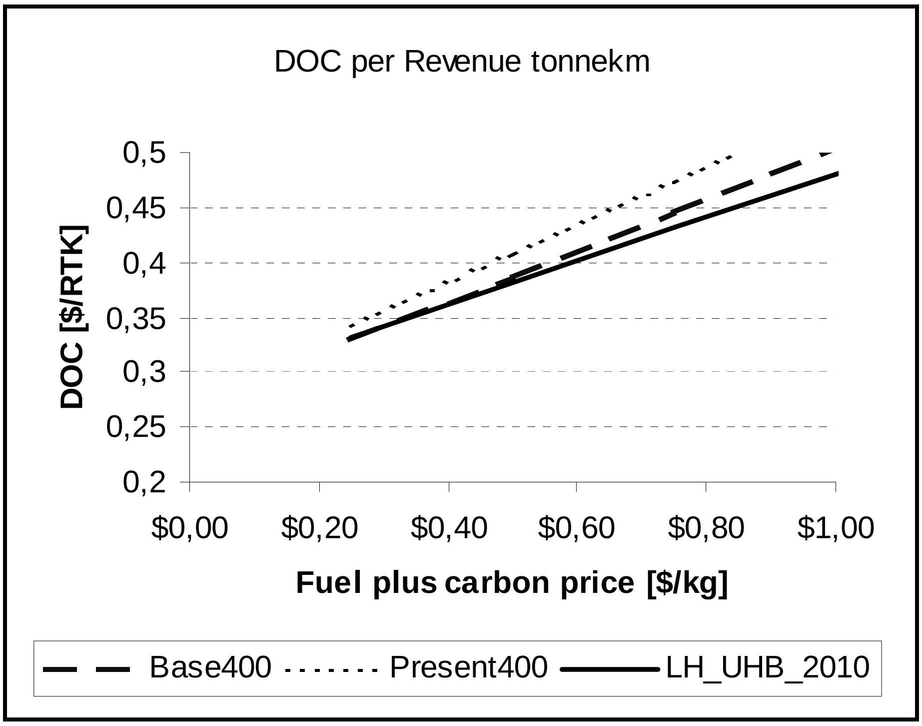
5.3.4 DOC

The DOC has been calculated with the DOC model (see §2.6) from the block time, block distance and block fuel. In Figure 35 the relation between DOC and fuel plus carbon price has been given for the baseline with current engine technology, with 2010 engine technology and with UHB Turbofans. From the intersection of the DOC lines as a function of fuel plus carbon price the following two DOC break points are found:

- With respect to the current engine technology: $0.103/kg;
- With respect to the 2010 engine technology: $0.348/kg.

It appears retrofitting a Long Range aircraft with UHB Turbofans will be profitable to airlines already at current fuel prices. Compared with the BASE400 the UHB is already economically a viable option with a rise of fuel plus carbon price with 29%.

Figure 35 Effect of fuel plus carbon price on DOC per RTK for the 7,000 km flight of the LH_UHB Long Haul aircraft fitted with Ultra High Bypass Turbofans at 75% load factor compared with aircraft fitted with current and 2010 technology turbofans



For the latter fuel plus carbon price ($0.348/kg) the results are:

- Total DOC for the flight: $114,208;
- DOC per block hour: $13,444;
- DOC per block kilometre: $16.315;
- DOC per RTK: $0.3514;
- DOC per passenger-km: $0.0523.

5.4 Short Haul Market, High Speed Propeller

5.4.1 Introduction

For the High Speed Propeller engine definition use has been made of the information of ADSE (1999). ADSE has defined an engine table meant for use in a 125 seats aircraft (cruising at mach 0.72). Further they have given the external dimensions and cost for an up-scaled version meant for a 150 seats aircraft (mach 0.74). These figures have been used for the two High Speed Propeller aircraft. For the short haul market the larger ADSE engine was nearly strong enough. For the long haul market it has been scaled up with a factor three. Included has been a scaling effect on all engine parameters as well as the fuel consumption (lower). Further 11 years of normal engine development has been incorporated on fuel consumption only.

5.4.2 Aircraft Definition

The SH_HSP aircraft is fitted with two High Speed Propellers for use at mach 0.74. First the engine size has to be found. The engine is sized to two requirements: the thrust/weight ratio for MTOW at 70 m/s TAS, SL/ISA and the Top of Climb (TOC) capabilities. The first is kept the same as for the PRESENT150 to ensure appliance to FAR-25 TO and climb out requirements and a maximum take off run approximately the same as for the baseline. The second requirement is not used as a hard requirement, but as a way to define the speed-altitude capabilities of the aircraft and to find the design cruise mach number and altitude.
For the PRESENT150 the take off thrust is (both engines) 156,000 N giving a thrust/weight ratio of 2.48 N/kg. With a first guess for MTOW for the SH_SP1 model of 58,750 kg and a thrust of 118,900 N at SL/ISA and TAS 70 m/s the Engine Size Factor (ESF) becomes ESF=1.225.

The maximum service ceiling, defined as the altitude where the climb speed is just over 0.5 m/s with both engines running at Maximum Climb Thrust, for the baseline aircraft at maximum TOC weight and a normal cruising speed of 0.745 turns out to be 11,100 m. For a first guess of the SH_SP1 characters some figures are tabulated in Table 14.

Table 14 The service ceilings for the first guess SH_HSP with several scaling factors for the engines

TOC Mach	Service ceiling [m]		
	ESF=1.225	ESF=1.25	ESF=1.3
0.66	10,500	10,600	10,900
0.68	10,500	10,600	10,900
0.70	10,400	10,600	10,900
0.72	10,200	10,400	10,800
0.73	9,900	10,200	10,600
0.74	9,600	9,900	10,400
0.75	9,100	9,400	10,100
0.76	8,400	8,800	9,500
0.77	7,100	8,000	8,900

Due to refining the design we expect some weight reduction will be possible, so we choose for an ESF of 1.25. This means the following dimensions of the engine apply according to ADSE (1999) and scaled with 1.25 for TOC SHP:

- Prop diameter: 12.5 ft;
- Number of blades: 2*6;
- Activity factor: 120;
- Core engine length: 2.5 m;
- Engine diameter: 0.85 m;
- Nacelle length: 6.0 m;
- Nacelle diameter: 1.7 m;
- Weight including system, nacelle and propeller: 3,400 kg;
- Removal of Thrust Reversers.

Evaluating the effect of High Speed Propellers is done by changing the following to the aircraft design:

- Lower fuel consumption (engine table produced by ADSE (1999) plus 11 years of conventional turbofan development on s.f.c. being 0.85%/year (or 8.9% overall);
- Higher airframe price due to redesigning of some parts of it;
- Higher parasite drag due to larger nacelles;

- New weight definitions due to weight changes of engines, nacelles and fuel used.

Following weights result from the iterative calculations:
The empty weight increases with: 672 kg;

- MRW: 59,675 kg;
- MTOW: 59,445 kg;
- MLW: 55,557 kg;
- MZFW: 51,927 kg;
- OEW: 35,236 kg.

The parasite drag increases due to the larger nacelles with 0.0007 to a total clean configuration parasite drag of $C_{D_0} = 0.0193$.

Van der Heijden and Wijnen (1999) gives an increase of 20% of the engine price and also an increase of 20% of the engine maintenance cost. ADSE more or less agrees on this price, but states the nacelle will be cheaper, because of the removal of the thrust reverser. The net price (engine plus airframe) would be in the same order of magnitude. Therefore prices of engines and airframe are initially kept unchanged.
But the need for redesigning half of the wing and the nacelles results into an increase of the airframe price. The following assumptions apply:

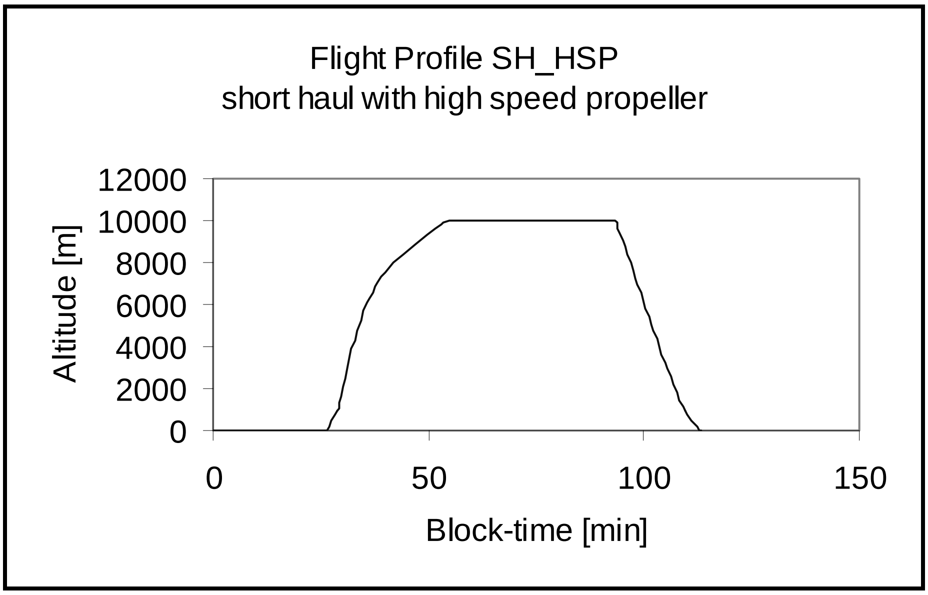
- The investment is written of over 300 aircraft;
- 100% of the nacelles is new;
- 50% of the wing structure weight is new;
- Engine maintenance cost is increased with 20% with respect to the baseline.

These assumptions lead to an airframe price increase of $2,876,600 making the new aircraft price $40,676,600.

5.4.3 Performance

The flight profile used for calculating block-time and block fuel is the same as for PRESENT150 (see §4.2.4). The resulting flight profile for the SH_HSP aircraft is given in Figure 36. From the figure it is clear the SH_HSP is slightly under-powered.

Figure 36 Flight profile for the SH_HSP short haul High Speed Propeller aircraft for the evaluation flight over 1,000 km block distance



The evaluation flight for Short Haul has been calculated with APD (see §2.5) for a block distance of 1,000 km. The following performance has been calculated for a payload at 70% load factor of 11,684 kg:

- Block time: 1 hour and 52 minutes;
- Block fuel used: 2,568 kg;
- Take off weight: 51,443 kg;
- Reserve fuel: 1,955 kg.

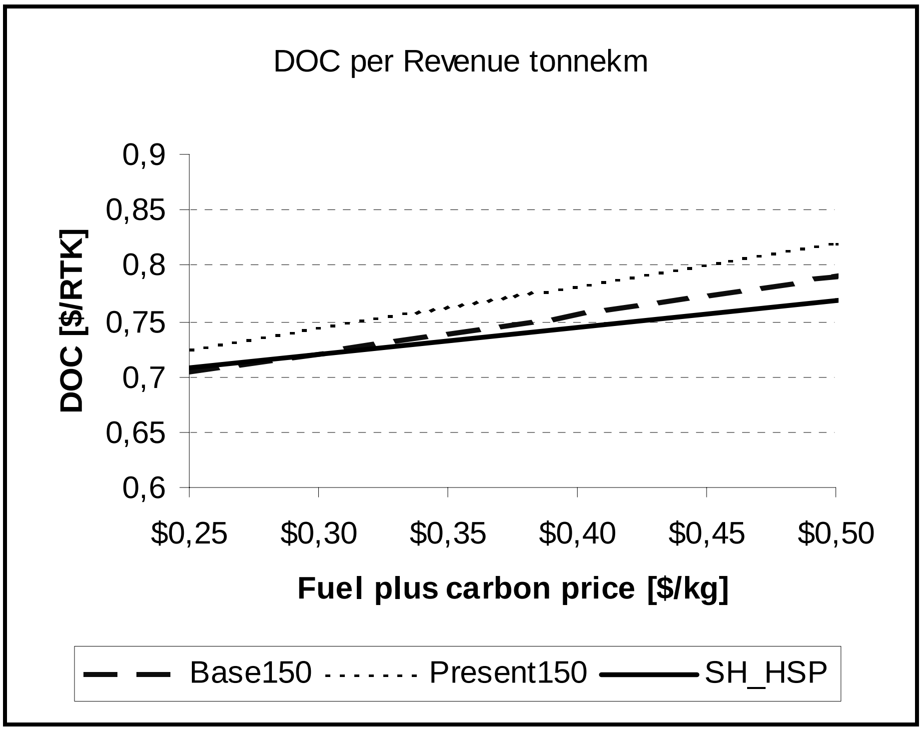
The fuel consumption has been reduced with respect to the PRESENT150 with 1,383 kg or 35.0%. With respect to the 2010 technology turbofans the reduction is 1,023 kg or 28.5%.

5.4.4 DOC

The DOC has been calculated with the DOC model (see §2.6) from the block time, block distance and block fuel. From the intersection of the DOC lines as a function of fuel plus carbon price the following two DOC break even points are found (see Figure 34):

- With respect to the current engine technology: $0.112/kg;
- With respect to the 2010 engine technology: $0.276/kg.

Figure 37 Effect of fuel plus carbon price on DOC per RTK for the 1,000 km flight of the Short Haul aircraft fitted with High Speed Propellers at 70% load factor compared with current and 2010 technology turbofans



For the latter fuel plus carbon price ($0.276/kg) the results are:

- Total DOC for the flight: $8,341;
- DOC per block hour: $4,474;
- DOC per block kilometre: $8.341;
- DOC per RTK: $0.714;
- DOC per passenger-km: $0.0816.

The High Speed Propeller seems an economically viable proposition for the short haul market.

5.5 Long Haul market, High Speed Propeller

5.5.1 Introduction

As for the short haul case the High Speed Propeller engine definition has been taken from information of ADSE (1999). For the long haul market the basic engine has been scaled up with a factor three. Further 11 years of normal engine development has been assumed on specific fuel consumption.

5.5.2 Aircraft Definition

The LH_HSP is fitted with four High Speed Propeller turboprop engines. Since the ADSE definition is too small for use on the long haul aircraft the engines have been scaled up. The engine has been sized to two requirements: the thrust/weight ratio for MTOW at 70 m/s TAS, SL/ISA and the Top

of Climb (TOC) capabilities. The first is kept the same as for the PRESENT400 to ensure appliance to FAR-25 TO and climb out requirements and a maximum take off run approximately the same as for the baseline. The second requirement is not used as a hard requirement, but as a way to define the speed-altitude capabilities of the aircraft and to find the normal cruise mach number and altitude.
For the PRESENT400 the all engine take off thrust is 827,200 N giving a thrust/weight ratio of 2.28 N/kg. With a first guess for MTOW for the SH_SP1 model of 315,000 kg and a thrust of 237,800 N (4 engines) at SL/ISA and TAS 70 m/s the Engine Size Factor (ESF) becomes ESF=3.02.
The maximum service ceiling for the PRESENT400 at maximum TOC weight and a normal cruising speed of 0.85 turns out to be 11,200 m. Figure 38 gives the altitude capability of the LH_HSP aircraft. Of course the altitude performance will be better with lower take off weights, when not flying at maximum range (MTOW). The design cruise altitude/speed will be reduced to 10,000m/0.74.

Figure 38 The service ceilings for the first guess LH_HSP

TOC Mach	Service ceiling [m]
	ESF=3.0
0.77	10,370
0.76	10,430
0.75	10,470
0.74	10,500
0.73	10,510
0.72	10,510
0.71	10,500
0.70	10,470

To scale the fuel flow we have assumed the difference between the short haul UHB and the short haul High Speed Propeller is valid also for the long range case, because in both cases the same core engine will be used. As the BPR for both UHB engines is assumed to be equal, the difference in s.f.c. is a result of scale differences in the core engines. These considerations resulted into a scale factor of (rounded conservatively) 0.60 on fuel flow.
A point of concern is further the propeller tip speed. This will go up from mach 0.95 to about 0.98 in cruise flight, even when the propeller rpm is reduced with 13% with respect to the basic ADSE engine propeller combination. At the same time the maximum cruise mach number also will have to be limited from 0.74 to 0.72.
For scaling the engine from 8,200 shp TO power to 24,000 shp scaling equations of Raymer (1992) have been used, slightly adjusted to fit the two ADSE engines (see also §3.7.1). The resulting engine parameters are:

- TO rating: 24,000 SHP;
- TOC rating: 15,000 SHP;
- Core engine length: 3.5 m;
- Engine diameter: 1.1 m;
- Nacelle length: 7.4 m;
- Nacelle diameter: 2.2 m;
- Weight including system, nacelle and propeller: 7,551 kg.

The High Speed Propeller engine including contra rotating propellers will have a weight of 5,836 kg. Following aircraft weights result now from the iterative calculations:
The empty weight decreases with: 5,438 kg

- MRW: 313,120 kg;

- MTOW: 311,760 kg;
- MLW: 254,923 kg;
- MZFW: 237,233 kg;
- OEW: 175,318 kg.

The parasite drag is not changed: initially it will decrease very slightly because of the smaller nacelles, but some extra drag will arise from interference, assumed to cancel the decrease.

As for the short haul High Speed Propeller aircraft (SH_HSP) we decided the engine price will not change with respect to the PRESENT400 engine. The price of one engine will therefore be unchanged: $5,400,000. Engine maintenance cost is increased with 20% with respect to the baseline.
For calculating the new airframe price following has been assumed:

- The investment is written of over 300 new re-engined aircraft;
- 100% of the nacelles is new;
- 50% of the wing structure weight is new.

These assumptions lead to an airframe price increase of $9,655,500 making the new airframe price $158,055,500. Because the reduction in speed is large (from 0.84 to 0.71), slightly lower wrap rates for flight deck crew are assumed (calculated with a method by Raymer (1992) to be 7.8% lower).

5.5.3 Performance

Because many parameters are changed a new speed schedule and cruising altitude, best fitted for a low fuel plus carbon price break even point has been defined. The combination of cruising altitude of 10,000 m and mach 0.71 turned out to be the most profitable. So the resulting flight profile used for calculating block-time and block fuel is:

- Take off and Ground manoeuvring:
  - 26 minutes at 7% MTO engine rating (all fuel weight for taxi is pre-TO);
  - Take off 0.7 minutes at 100% MTO rating;
  - Climb-out from 35 ft to 3,000 ft at 85% MTO rating; climb-out time is 2.2 minutes;
- Operational Climb:
  - Speed schedule 270 kCAS/0.71;
  - Max climb engine rating;
- Operational Cruise:
  - Long range speed (mach 0.71);
  - Cruise altitude 10,000 m;
- Operational descent:
  - Speed schedule: 0.71/270 kCAS;
  - Thrust set for maximum cabin rate of descent (300 ft/minute and maximum cabin altitude 6,000 ft);
- Approach and landing:
  - Approach from 3,000 ft to SL at 71.4 m/s TAS (Jane's, 1998);
  - Approach time 4 minutes at 30% MTO rating;
- Reserves:
  - Go around from 3,000 ft;
  - Holding as extended cruise for two hours with mach 0.71 at 10,000 m altitude.

The evaluation flight has been calculated with APD (see §2.5) for a block distance of 7,000 km. The following performance has been found for a payload at 75% load factor of 46,436 kg:

- Block time: 9 hour and 48 minutes;
- Block fuel used: 46,428 kg;
- Take off weight: 276,635 kg;
- Reserve fuel: 8,453kg.

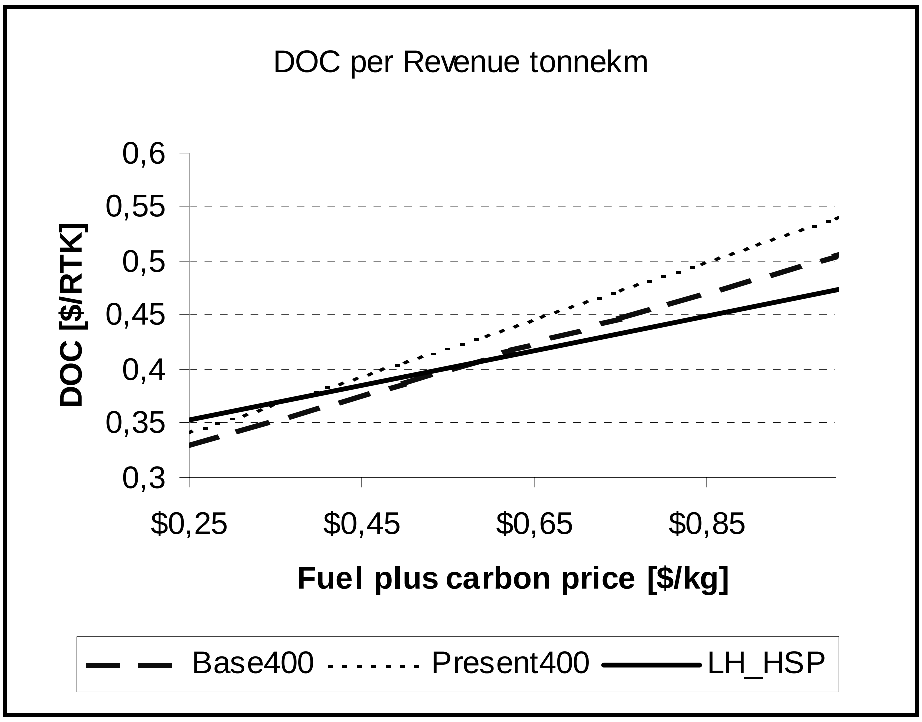
The block time has been increased with 15% compared to the long haul baseline version. The fuel consumption has been reduced with respect to the PRESENT150 with 30,840 kg or 39.9%. Compared to BASE150 the reduction is 22,085 kg or 32.2%.

5.5.4 DOC

The DOC has been calculated with the DOC model (see §2.6) from the block time, block distance and block fuel. From the intersection of the DOC lines as a function of fuel plus carbon price the following two DOC break even points are found (see Figure 39):

- With respect to the current engine technology: $0.369/kg;
- With respect to the 2010 engine technology: $0.589/kg.

Figure 39 Effect of fuel plus carbon price on DOC per RTK for the 7,000 km flight of the Long Haul aircraft fitted with High Speed Propellers (LH_HSP) at 75% load factor compared with current and 2010 technology turbofans



For the latter fuel plus carbon price ($0.589/kg) the results are:

- Total DOC for the flight: $132,579;
- DOC per block hour: $13,538;
- DOC per block kilometre: $18.94;
- DOC per RTK: $0.408;
- DOC per passenger-km: $0.0607.

The High Speed Propeller seems at first sight a rather expensive solution mainly due to the low cruise speed. However the reduction in fuel consumption compared to the 2010 technology turbofan is more than 30% making it two times more effective from a fuel efficiency point of view than the UHB Turbofan engine.

5.6 Fuel Cells

5.6.1 Introduction

At the NASA Environmental Compatibility Research Workshop III Chris Snyder of NASA presented a paper on the possibilities of a zero-Emissions Aircraft (Snyder, 1998). He distinguished the following technologies to achieve this:

- Liquid hydrogen fuelled aircraft (giving water and nitrogen oxide as emissions);
- Nuclear aircraft (but conventional power for takeoff/climb and approach/landing);
- Fuel cell/liquid hydrogen powered electric aircraft (emission of water only).

From these three options the nuclear aircraft seems to have severe safety and public acceptance problems and is not considered further. The liquid hydrogen aircraft seems to give good opportunities to eliminate the emissions of CO_2, but the emissions of NO_x stays to be a problem, though probably less. As liquid hydrogen can be used in modified turbofan engines it is a good proposition in reducing the amount of carbon dioxide emissions. A lot of information on this subject is given by Brewer (1991).
The fuel cell is the only way to reduce the in-flight emissions to water vapour only. The negative effects on the environment will be reduced if the aircraft flies at the right altitudes (see Sauser, 2000). For both options applies the total environmental effect depends on the way of production of the liquefied hydrogen. We will discuss this in §5.6.5.

Kalhammer et al. (1998) define fuel cells as follows; “Fuel cells are electrochemical devices that enable the chemical energy of fuels to be converted directly into electricity, thereby avoiding the fundamental loss of efficiency and emission of air pollutants associated with combustion-based engines.” The principle is simple: feed an anode with gaseous hydrogen and a cathode with oxygen and electricity will be the result, while the two gases unite to water. The efficiency of this process is high compared to the overall energy efficiency of combustion-based engines. Summarised the advantages are:

- High energy efficiency;
- No emissions;
- No noise;
- Modular built-up of the system.

The disadvantages may be:

- Low power/weight ratio;
- Low power/volume ratio;
- High specific cost;
- Safety hazards.

5.6.2 Technical information on fuel cells

Figure 40 gives an overview of several types of fuel cells as given by the European Fuel Cell Group (EFCG, 1999). The following abbreviations are used:

- AFC Alkaline Fuel Cell;
- PEMFC Proton Exchange Membrane Fuel Cell;
- PAFC Phosphoric Acid Fuel Cell;
- MCFC Molten Carbonate Fuel Cell;
- SOFC Solid Oxide Fuel Cell.

As can be seen from the figure, most systems require very high operating temperatures. All fuel cells require gaseous hydrogen as a fuel and oxygen as oxidant. Several of the systems are not able to handle carbon dioxide or nitrogen gas, because they become poisoned with a detrimental effect on efficiency. In that case stored liquefied oxygen will be required, making these systems more complicated and heavy. In other cases air may be used to supply the oxygen.
As is shown in Figure 41 (EFCG, 1999) the total power system as designed for use in cars and busses consists of four subsystems: the fuel pre-processor to generate hydrogen from a more common fuel, the fuel cell itself, a power conditioner (for example from DC to AC) and a fuel and air controller. For the full aircraft power system we have to add the electric engine driving a propeller or fan.

Figure 40 Fuel cell systems (figure from EFCG, 1999)

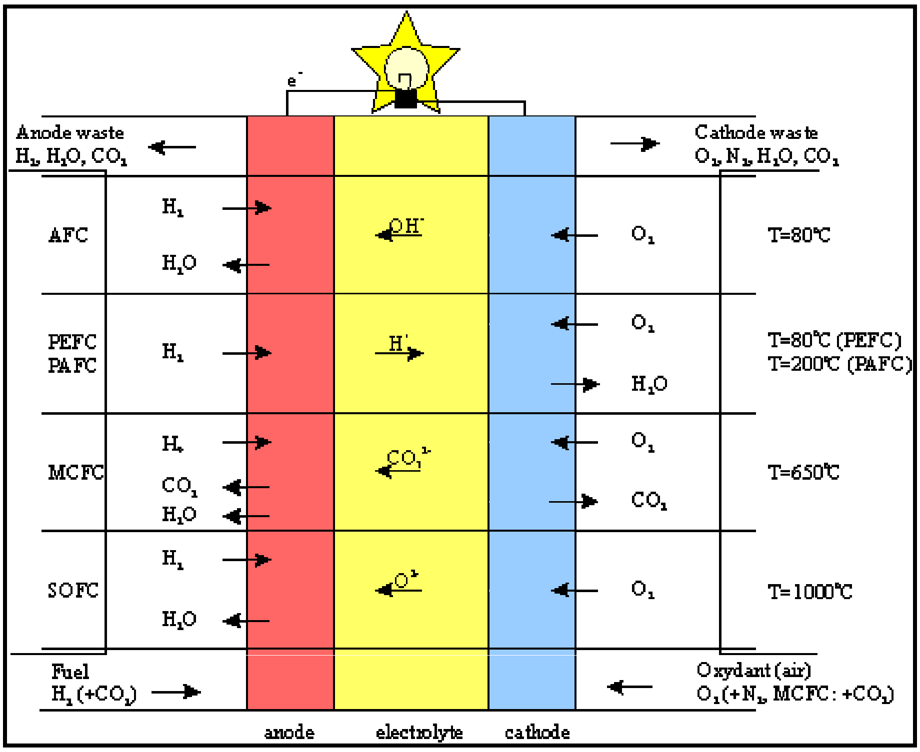
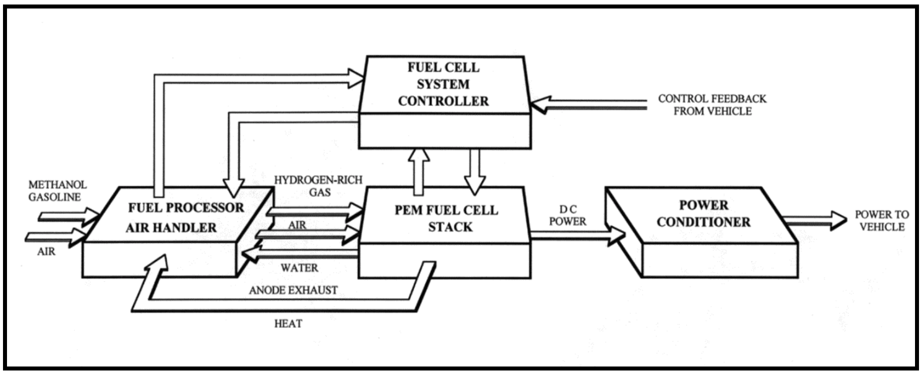


Figure 41 General layout of fuel cell system (figure from Kalhammer et al., 1998)



At this moment no large-scale commercial use of fuel cells is known. However, many experiments, most with cars and busses, have been implemented with success.

5.6.3 System for aircraft

Definition

For use of fuel cells in aircraft we have to consider the following main system choices:

- Fuel cell type;
- Power system set-up;
- Electric engine type;
- Propulsion type.

In general the following considerations will be kept in mind by choosing for the systems:

- Weight;
- Volume;
- Cost;
- Efficiency;
- Reliability.

In general a fuel cell system will cause high weight and volume penalties but will largely increase fuel efficiency.

Fuel cell type

From a short preview on these systems Kalhammer et al. (1998) conclude the PEMFC has the best opportunities for transport applications as its power density is relatively high, combined with a high efficiency and relatively low cost. All other systems seem to give penalties on the power density, cost or handling (mainly because of the high temperature required for the fuel cell stacks). As almost the same requirements as given by Kalhammer et al. for automotive vehicles are true for aircraft we will also choose for the PEM fuel cell based system.

For automotive vehicles the requirement for a system based on the use of conventional liquid fuels is strong because of cost and safety considerations. But this means the necessity of an onboard fuel processor. For an aircraft we will choose another solution as described in the next subparagraph.

Power system set-up
Weight and volume are both scarce in an aeroplane. The weight of the fuel cell stacks will be relatively high. We can therefore better save the extra weight of the fuel pre-processor. The pre-processor adds about 60-70% to the weight of the stack alone for a given power. A second reason to leave the pre-processor out is the weight saving of the fuel: for a given energy content hydrogen weighs only 36% of kerosene (Brewer, 1991). On the other hand: liquefied hydrogen requires 4.02 times the space as kerosene. Further it will be necessary to built fuel tanks into the fuselage, requiring an extension of the fuselage, which of course will add to weight, drag and cost. Still, this seems to be favourable to the option with a fuel pre-processor, as this will almost double the weight and volume of the fuel cell system. Further these pre-processors will emit carbon dioxide at almost the same rate as if the fuel used is burnt also other waste will be created. Only the emission of NO_x will be avoided. Production of hydrogen in land based factories gives the possibility to reduce or eliminate these carbon dioxide emissions.

Electric engine and propulsion type
The choice of engine type is also important. Conventional electric engines are not optimised very much to low weight. In Table 15 some examples from literature are given.

Table 15 Some examples of engines and their main properties as given in literature

Type	Source	Power rating	Specific weight
		kW	kg/kW
Standard Range Engines	Ivanov-Smolensky, 1982	200	6.85
1,000 rpm machine	Wildi, 1991	100	5.00
2,000 rpm machine	Wildi, 1991	100	3.00
Samarium Cobalt Electric Engine	Colozza, 1994	5-10	5.50
Brushless PM Motor	Unique Mobility, 1999	100	0.86-1.02
Super-conducting electric motor	Snyder, 1998	Large	0.14[13]

The electric engine efficiency comes in the range of 90-95%. The Super-conducting engine has an efficiency of almost 100%. Super-conducting can be reached at cryogenic temperatures. This idea seems attractive as the required cold is onboard through the liquid hydrogen.
The low specific power of the fuel cell makes it unfavourable to submit high power. Therefore it is not very useful to design for high subsonic speeds at cruise. This makes a choice for the high speed propeller the most logical.

Characteristics of the system

Full system built-up
The total propulsion system consists globally of a fuel system (tank, pumps, vaporiser), the air system (giving the right air flow, temperature and pressure at the stack), the fuel cell stacks, the electric engine and the propulsive unit (ducted fan or propeller). In the following paragraphs we will discuss the volume, weight and cost parameters of the systems. Also the placement in the aircraft will be given.

[13] The reference states the advanced super-conducting engine will weigh about half of an advanced turbofan at the same thrust. Here we have taken half of the weight of the long haul High Speed Propeller engine divided by its maximum take off power.

Stack

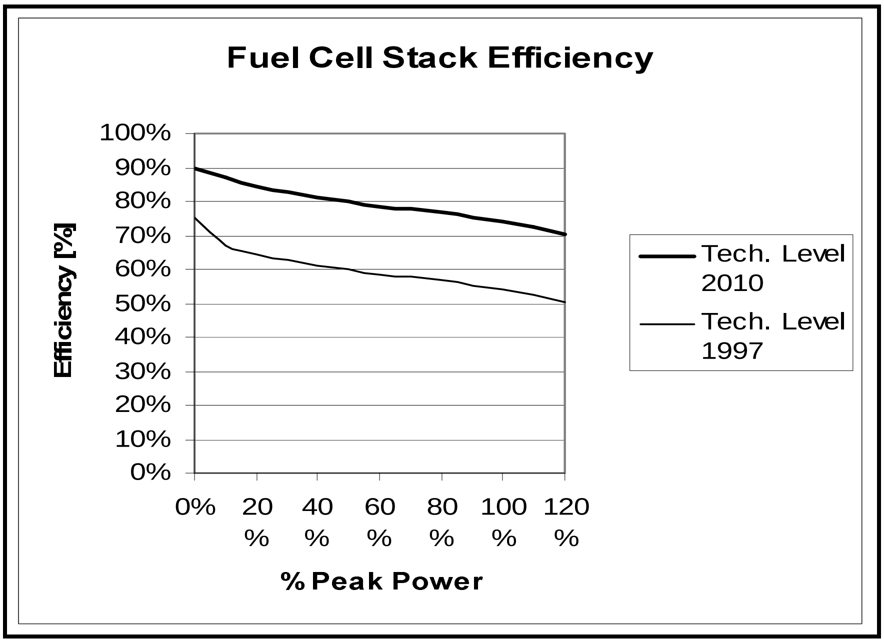
Snyder gives 0.5 kW/kg as the specific power of a fuel cell system. Kalhammer (1998) gives an overview of properties of current stacks and near future projections. He comes at the same figure for the specific power in the near future. However, the next generation of Ballard's PEM fuel cells is intended to reach a power density of 1.4 kW/l. As power density and specific power almost in all examples are about the same (meaning the system weighs one kilogram per litre) we may deduce that the Ballard system of the near future will get at a specific power of 1.4 kW/kg. The latest information on this subject is the Mark 900 fuel cell stack, the latest model of Ballard) has a power density of 1.31 kW/litre (Hydrogen&Fuel Cell Letter, February 2000). This stack is planned to be in large scale production by 2004.

The cost of stacks is currently over $100/kW but is believed by several commercial developers to settle down to $20-35/kW at mass production.

Stack efficiency is a function of the power loading. Figure 42 gives the Stack efficiency as a function of power rating (Moore, 1997). This 1997 technology level is likely to be improved to the suggested 2010 technology level line (approximated by adding 20 percent points to the 1997 level). The efficiency may be improved by:

- Increasing fuel utilisation by re-circulation (now 15% of the hydrogen seems to be lost as stated by Kumar et al., 1998).
- Increasing air and fuel system components efficiencies (18% of the energy output is lost to the compressor, Kumar et al., 1998).
- Oei et al. (1997) give an overall system efficiency (for a direct hydrogen system) to be 57%, which is 5% better than the stack efficiency given by Moore (1997).
- In an aircraft compressed air is more efficiently to get due to the ram-pressure at the air-inlet during cruise flight.

Figure 42 Fuel Cell Stack efficiency as a function of the power rating (technology level 1997 from Moore, 1997)



The fuel cell stacks contain the anode and cathode material and are of electrically coupled relatively small units. They lent themselves best to be built into the wing in stead of the fuel tanks. This will give some static relaxation of wing loads, but now at every stage of the flight and not only with tanks full as in a normal plane. This will allow for a lighter wing weight. Based on the two new designs with High Speed Propellers the following power, volume and available space in the wing gives a first idea of the possibility for this. Only 20-40% of the available space will be required.

Model	Power M-PROP	Stack volume	Current tank volume	Ratio stack/current tank
	kW	l	l	-
Short haul	11,010	7,862	20,104	0.39
Long haul	51,330	36,670	203,500	0.18

Summarised the following stack properties will be adopted:

- Stacks built into the wing;
- Specific stack density: 1.4 kW/l;
- Specific stack power: 1.4 kW/kg;
- Efficiency as given by Figure 40;
- Cost: up to $100.00/kW.

Electric engine

As can be seen from Table 15 the only suitable engine seems to be the advanced super-conducting electric motor as proposed by Snyder (1998). Conservatively we will set the engine specific power to 0.2 kg/kW. The efficiency will be 99% as no losses are assumed due to the cryogenic cooling of the engine. The cost of such an engine is difficult to estimate. The outer dimensions for the nacelle of the engine including the cryogenic cooling system has been set at a lower level than for the High Speed Propeller designs. They will be mounted on top of the wings with pulling contra-rotating propellers.

Summarised:

- Engine specific power: 0.2 kg/kW;
- Engine cost: unknown;
- Efficiency: 99%;
- Nacelle dimensions: $\frac{HSP\ dimension}{1.6}$

Propulsive unit

Snyder (1999) suggests to simply replace the turbine section of a high bypass turbofan engine with an electrical (super-conducting) engine to drive the fan for propulsion. However, this type of solution works best for higher mach numbers, requiring large powers, giving a large weight and drag penalty. Therefore we have chosen to use the High Speed Propeller as defined earlier, for propulsion, flying at moderate mach numbers between 0.6 and 0.7.

The properties and efficiency of the High Speed Propeller has been used to create the engine table. As a first assumption the dimensions have been scaled with the same rules as for the High Speed Propeller. The propeller weight will be calculated using an equation given by Torenbeek (1982):

(Eq. 5-1)

$$W_{prop} = 0.124 \cdot N_p \cdot \left(N_{disc} \cdot D_p \cdot P_{TO} \cdot \sqrt{B_p}\right)^{0.78174}$$

In (Eq. 5-1) N_p gives the number of propellers, N_{disc} the number of propeller discs (two in case of contra-rotating propellers) D_p the propeller diameter in [m] and B_p the number of blades per propeller. The weight is given in [kg].

Propeller cost is given by an equation from Roskam (1989), adjusted for 1997 cost level:

(Eq. 5-2)

$$P_{prop} = 2.59 \cdot 10^{0.7746 + 1.1432 \cdot \log(P_{TO})}$$

The first numerical factor in (Eq. 5-2) accounts for adjusting from 1989 dollars to 1997 dollars and a factor two as we use contra-rotating propellers with six blades each. Further the coefficients for composite propellers have been chosen, adding some 30% to the cost of the propeller.

Fuel system

Table 16 we summarise properties for LH_2 as well as Jet fuel. From this table it becomes clear that liquid hydrogen needs almost four times the space per unit of energy as kerosene. On the other hand, hydrogen has a 2.8 times better heat of combustion per kg.

Table 16 Properties of hydrogen and two common jet fuels (Brewer, 1991)

Property	Unit	LH_2	Jet A	JP-4
Heat of combustion (low)	kJ/g	120	42.8	42.8
Liquid density (at 283 K)	g/cm^3	0.071[14]	0.811	0.774
Boiling point (at 1 atmosphere)	K	20.27	440-539	333-519
Specific Heat	J/gK	9.69	1.98	2.04
Heat of vaporisation (at 1 atm.)	J/g	446	360	344
Specific density	kJ/l	8.52	34.71	33.13

The fuel system requires a lot of changes because of the change to liquid hydrogen fuel. Much detailed information on this can be found in Brewers extensive study on hydrogen aircraft (Brewer, 1991). However, as the designs described by Brewer are based on conventional engines some of his systems cannot be used directly. The main set-up of a fuel system will be the fuel tanks containing the very cold liquid hydrogen, several boosters and pumps to bring the hydrogen to the engines and cool them to cryogenic temperatures (for super-conducting) and further bring the gas to the working temperature of the fuel cells (from 14 K to about 360 K (80-90° C) and pressure (2-3 atmosphere).

The largest weight penalty comes from the fuel tanks, which will be placed in a stretched part of the fuselage. Brewer gives an estimated tank weight of at least 0.343 kg/kg LH_2. The fuel system adds some 10% to this, so for the full fuel system including tanks (but excluding the fuselage extension) the weight will be 0.38 kg/kg LH_2. From this weight we will have to subtract the weight of the conventional baseline fuel system:

- Short haul: 265 kg;
- Long haul: 1239 kg.

The cost for the fuel system has been estimated with the aircraft cost method given in the aircraft calculation sheet (see §3.6). The relatively large weight of the fuel system will account for the higher cost for it compared to conventional systems.

Summarised:

- Fuel system direct weight penalty: $0.38 \cdot W_{\max\_fuel\_capacity} - W_{fs\_old}$ (weights in [kg]);
- Fuel tank indirect effect on weight by increasing fuselage length;

14 This figure has been given for liquid hydrogen at its boiling point.

- Fuel tank effect on parasite drag by increasing fuselage length;
- Cost is unknown.

Engine table

To find the aircraft designs for short and long haul we will first have to define a scalable engine table. Then with this we will have to establish power and wing loading and optimum cruising speed. The propeller thrust and power required has been based on the basic table produced by ADSE (1999). This table contains values of power and propeller efficiency, which are used to recalculate the fuel consumption. The fuel consumption now will be given by (Eq. 5-3).

(Eq. 5-3)

$$Fuelflow = \frac{P_r + \Delta P_{off}}{\eta_p(rating) \cdot \eta_{fs} \cdot \eta_{eng} \cdot \eta_{misc} \cdot Hc_{LH_2}}$$

In this equation the variables are defined as follows:

- P_r is the required power for the given (propeller) thrust in the engine table [N].
- ΔP_{off} are the off-takes per engine [W]:
- $\eta_p(rating)$ gives the fuel cell stack efficiency as taken from Figure 42
- η_{fs} accounts for losses due to fuel conditioning from liquid to gaseous at the appropriate temperature and pressure.
- η_{eng} efficiency of the super-conducting engine.
- η_{misc} efficiency accounting for miscellaneous system losses.
- Hc_{LH_2} heat content of hydrogen [J/kg].

Following assumptions have been set:

- Maximum power 8200 hp (before scaling, taken from the ADSE table) used for calculating the power rating to find the stack efficiency.
- ISA temperature.
- $\Delta P_{off} = 100\ hp$ before scaling.
- $\eta_{fs} = 0.97$
- $\eta_{eng} = 0.99$
- $\eta_{misc} = 0.98$

The fuel cell propulsive system efficiency in terms of mach number times s.f.c. are given in Figure 43 as a function of mach number and in Figure 44 as a function of thrust, both at an altitude of 28,000 ft. The best efficiency can be reached at mach numbers between 0.6 and 0.75 and at large thrust ratings.

Figure 43 Fuel Cell Propulsion efficiency (mach number times s.f.c.) as a function of mach number

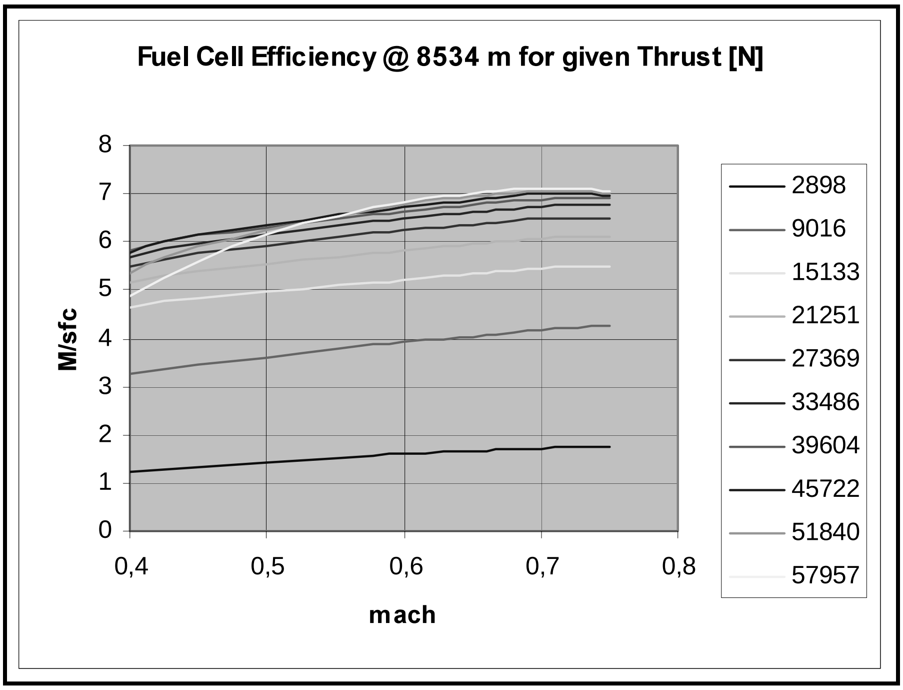
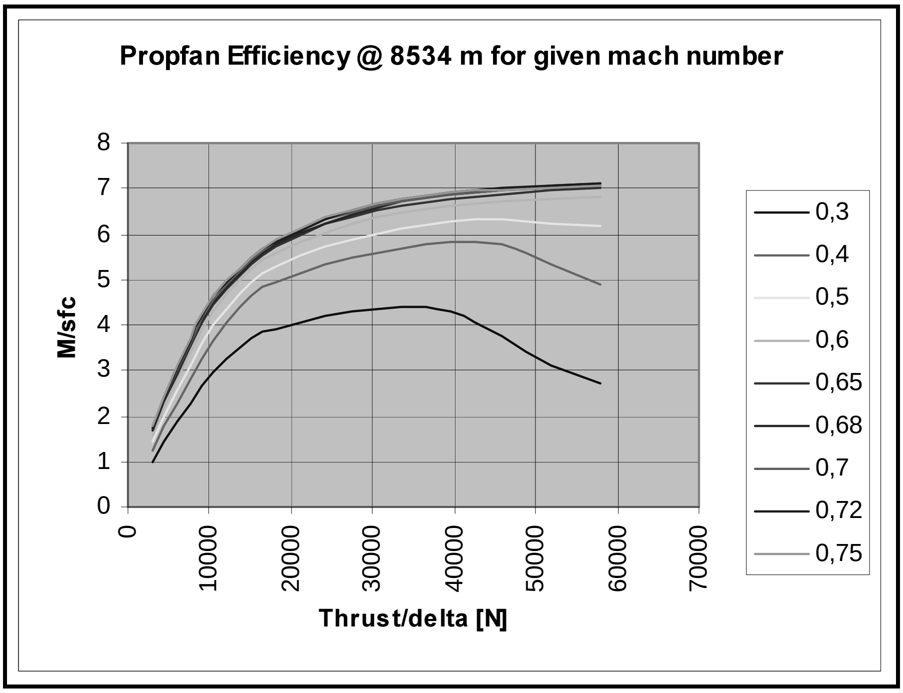


Figure 44 Fuel Cell Propulsion efficiency (mach number times s.f.c.) as a function of mach number



5.6.4 Other design aspects of fuel cells

Safety and reliability

The propulsion system will have to comply to normal aviation safety standards and operational requirements. For safety the following items will probably need special attention:

- The use of liquid hydrogen and the crash fire hazards of the aircraft.
- The reliability of all propulsion system components.

Lets first look at the crash-fire hazard. Every fuel forms a hazard in case of a crash of the aircraft. The properties of the fuel will be reflected in the number of casualties at a survivable crash. Brewer (1991) has studied the safety of an LH_2 aircraft and comes to the following conclusions:

> *"On the basis of the analyses performed, LH_2 was found to be a safer fuel than any of the other candidates."*

This conclusion is valid for both the occupants of the crashing aircraft and for the people and property in the surroundings of the crash. Brewer explains his conclusion with the following fundamental considerations:

- LH_2 tanks are less susceptible to damage because:
  - They are mounted in the fuselage where they present a far smaller dimension in frontal impact.
  - They are protected by a significant amount of structure.
  - They are designed for higher pressure than the rest of the fuselage and therefore are less apt to be the point of failure in event of a survivable crash.
- In the event of a large fuel spill, LH_2 will not spread as far as other fuels because it evaporates in a much shorter time, it becomes buoyant immediately and dissipates strongly upwards into the air.
- In case of ignition of the large spill, the fire will be very brief in the order of 10-20 seconds. This will normally not be enough to destroy the fuselage as in the case of a kerosene fire.

The second point of consideration is system reliability as the whole system contains many new unproven parts. These are specifically:

- The fuel stack;
- The super conducting engine;
- The fuel conditioning system.

The fuel stack reliability is currently very high according to Barbir (n.y.). The reliability of the super-conducting engine will pose a challenge on the technical development of the system. In case this problem cannot be solved, choosing for a normal electric engine will raise the specific weight by probably a factor four or more. Also the efficiency will deteriorate from 99% to about 90-95%. The reliability of the fuel system may be better, because there is much experience with handling LH_2 at the commercial suppliers of it. These have proved to be workable and remarkably safe (Brewer, 1991).

Of course more aspects will have to be discussed with respect to safety in general. If the chance on a crash is larger than for current aircraft the total safety effect will be negative. As the fuel cell requires a lot of new systems that are not proven in *combination* with each other and also not proven in the conditions occurring in flight much work has to be done. Before conclusions may be drawn.

Operational requirements

Operational requirements are at first the response of the propulsion system to power demands given by the pilot. Specially at take off and landing it is important the system has a high power acceleration between idle and maximum take off power. It seems this can be accomplished by fuel cell systems if the supply of the hydrogen gas to the stacks is sufficiently fast. An electric engine reacts almost immediately to power demands. Current fuel cell stacks have demonstrated a power transient of 100% within one second (Meyer et al., 1999). This seems much better than for current large turbofan engines.

Other requirements are the need for a short fuel fill time to get a short turn-around time. This depends on the fuelling system. Brewer (1991) concludes from his study the refuelling time for LH_2 need not take longer than for kerosene and the safety hazards may be even lower.

Airport requirements

Brewer has studied the possibilities of a LH_2 fuel system for San Francisco International Airport (SFO) and concludes that modification of SFO to incorporate the capability of servicing long-range transport aircraft fuelled with LH_2 was entirely practicable. The airport system consists of a liquefaction facility, storage tanks and a distribution system. For this system about 14%-23% of the energy content of the primary hydrogen will be needed.

Total cost of the delivered LH_2 will be in the order of \$0.88 per kg (or almost \$0.32 in kerosene equivalents). These figures were found by Brewer (1991) for 1975. The consumer index for 1975-1998 is about three and with this factor the LH_2 fuel cost will stay below \$1.00/kg in kerosene equivalents and 1996 dollars.

5.6.5 Environmental hazards of hydrogen production

Though the environmental impact of the end-use of hydrogen may be low for both the hydrogen fuelled turbofan and the fuel cell craft, the environmental effect of producing hydrogen may be large, compared to production of jet fuel. Brewer (1991) gives an overview, comparing hydrogen production with *synthetic* jet fuel. His conclusion on the whole fuel-cycle (production and use) is:

"This brief review of environmental considerations of aircraft operations and manufacture of potential fuels has shown that hydrogen will be far less harmful to the environment than hydrocarbon fuels."

On the environmental effects of hydrogen production he states many methods are available, with widely different effects on emissions. Coal gasification (or steam reforming) produces a lot of emissions and costs a large part of the energy content of the coal. But many other processes exist like electrolysis and thermochemical with renewable energy as electricity source, photolysis and recovery from industrial waste gases. All these processes have low or no emissions to the atmosphere, but most are costly and need a lot of energy with a low energy efficiency.

More recently the following possibilities get more attention as has been published on by the U.S. Department of Energy (DOE, 1995):

- Photobiological production: using sunlight on bacteria, algae or enzymes to split water into oxygen and hydrogen.
- Photo-electrochemical (PEC) technology: a semiconductor uses light to split water directly into oxygen and hydrogen.
- Thermochemical production: the gasification and pyrolysis methods of hydrogen production use heat to produce a vapour from biomass from which hydrogen can be derived using a conventional steam reforming

process. The resulting hydrogen weight is about 15% of the original biomass weight. The biomass is used for the energy required. Carbon dioxide is one of the emissions, but this carbon has been removed from the atmosphere by the plants used as biomass.

All these methods use renewable energy (sun-light) for the production of the hydrogen based on natural sources (water or biomass) and their environmental hazards seem low. The direct processes (without the use of biomass) seem the best option for large scale production. Using biomass from waste will largely enhance the cycle efficiency of the production chains producing the waste biomass. So it seems useful for all processes to become commercially available.
Impacts may be: large land-use or low energy conversion rates. In most cases the hydrogen may be expensive compared to jet fuel. For land use an approximation for all current aviation energy needs may be covered with a Photo-electrochemical (PEC) system at 10% efficiency (see for example A. Bansal et al., 1999 and Miller and Rocheleau, 1999) requires 1.7 million hectares or 0.004% of the earth's total surface (which is about 0.012% of the land surface). This seems not a very large amount.
Not much information is available on the cost of production of hydrogen. Only Czernik et al. (1999) give some estimate for a combined system creating hydrogen from biomass. This is about $1.-/kg hydrogen, which is the energy equivalent of $0.35/kg for kerosene.

5.6.6 Conclusions Fuel Cell

In §8.8 and §8.9 we describe the results of a design for short haul respectively long haul fitted with fuel cell technology and electrically driven propellers. The following conclusions can be drawn now:

- Energy consumption may be equal (long haul) or even lower (short haul) than for the high speed propeller designs on the condition all technologies to reduce fuel consumption and power requirements are used in these designs.
- The operational environmental performance of the fuel cell designs is good: no harmful in-flight emissions exist apart from water. This is an advantage above the use of hydrogen in normal turbofan engines where NO_x emissions still exist though less than for kerosene fuelled turbofan engines.
- The environmental impact including the production of liquid hydrogen depends largely on the production method used. With the current processes (like steam reforming from coal) many of the in-flight advantages are offset by the production emissions and environmental impacts. However, large efforts are made to develop new methods based on the use of the energy from the sun. These processes will be really durable.
- The fuel cell technology designs are packed with new technology (at least new in aeronautical applications). This will make them a long term development requiring a lot of technology development and experimenting.

It is recommended to start a development trajectory for fuel cell technology on transport aircraft along with the development of hydrogen aircraft as currently financed by the EU. This because many of the technological problems arise from the use of hydrogen.

Trying to introduce a fuel converter to be able to use normal kerosene will result in a much higher weight of the aircraft, much lower energy savings and the introduction of CO_2 emissions and the problem of other wastes from the kerosene, after the hydrogen has been drawn from it. This seems not a very desirable way to go, though it is the current development in car industry.

6 Aerodynamic improvements

6.1 Introduction

Aerodynamically two ways to improve the aircraft performance have been studied: reducing parasite drag and reducing the 'induced' or lift-related drag. The first one can be reduced by aerodynamically cleaning up the aircraft and by using passive or active laminar flow control (LFC). With these devices one tries to retain a laminar flow over parts of the airframe as long as possible before changing to a turbulent state. Reason for this is the much lower resistance force of a laminar flow compared to turbulent one. A clean and smooth airframe surface is a method to enhance laminar flow. Normally with this method not more than 5-10% of the airframe will have laminar flow. Passively the transition point from laminar to turbulent can be postponed by using specially designed laminar airfoils for wings and tail surfaces. An active way of retaining laminar flow is by 'boundary layer suction'. Via small holes in the airframe surface the air flowing along it is sucked away partly, preventing the built up of a turbulent boundary layer. Van der Heijden and Wijnen (1999) expects an overall reduction of 12.5% of the parasite drag. This at the expense of extra weight, airframe acquisition and maintenance cost. Two aircraft have been developed: the SH_LFC and the LH_LFC.
To reduce the induced drag a common method is increasing the wing aspect ratio by increasing its span and reducing its mean chord. The two baseline aircraft have an aspect ratio of 7.7-7.9. The latest models of Boeing and Airbus have aspect ratios between 8 and 10. For this study we will introduce an DOC optimised aspect ratio for both markets.

6.2 SH_LFC: Short Haul: parasite drag reduction plus 2010 Turbofans

6.2.1 Aircraft Definition

The aircraft has been cleaned-up aerodynamically and is fitted with (active) laminar flow control techniques as proposed by Van der Heijden and Wijnen (1999)[15]. This has the following effect with respect to the baseline short haul aircraft with 2010 technology level Turbofans (see §4.4):

- Net effect on parasite drag: -12.5%;
- Aircraft empty weight: +1%;
- Airframe price effect: +7.5%;
- Airframe maintenance hours: +20%.

Due to the effect on airframe weight the following aircraft weights have been calculated with APD (see §2.5) assuming an initial fuel saving of 15% with respect to the PRESENT150 (so including the effect of the 2010 technology level Turbofans):
The empty weight decreases with: 164 kg

- MRW: 61382 kg;
- MTOW: 61152 kg;
- MLW: 54721 kg;

[15] For an aircraft with a high subsonic wing only active laminar flow may be effective, as the transonic capabilities of the wing section prevent the use of passive laminar wing section.

- MZFW: 51091 kg;
- OEW: 34400 kg;
- EW: 31566 kg.

The parasite drag reduces due to the LFC with 12.5% to $C_{D_0} = 0.0163$.

Following cost changes are introduced due to the engine development and the introduction of Laminar flow Control:

- The engine price goes down from $3,100,000 tot $2,774,500;
- The airframe price increases with 7.5% from $37,800,000 to $40,635,000.

6.2.2 Performance

The flight profile has been calculated with APD (see §2.5) using the speed schedules, reserve fuel strategy, allowances and cruising altitude as used for the PRESENT150 (see §4.2.4). The evaluation flight for short haul has been calculated with APD (see §2.5) for a block distance of 1,000 km. The following performance has been calculated for a payload at 70% load factor of 11,684 kg:

- Block time: 1 hour and 52 minutes;
- Block fuel used: 3,410 kg;
- Take off weight: 52,191 kg;
- Reserve fuel: 2,596 kg.

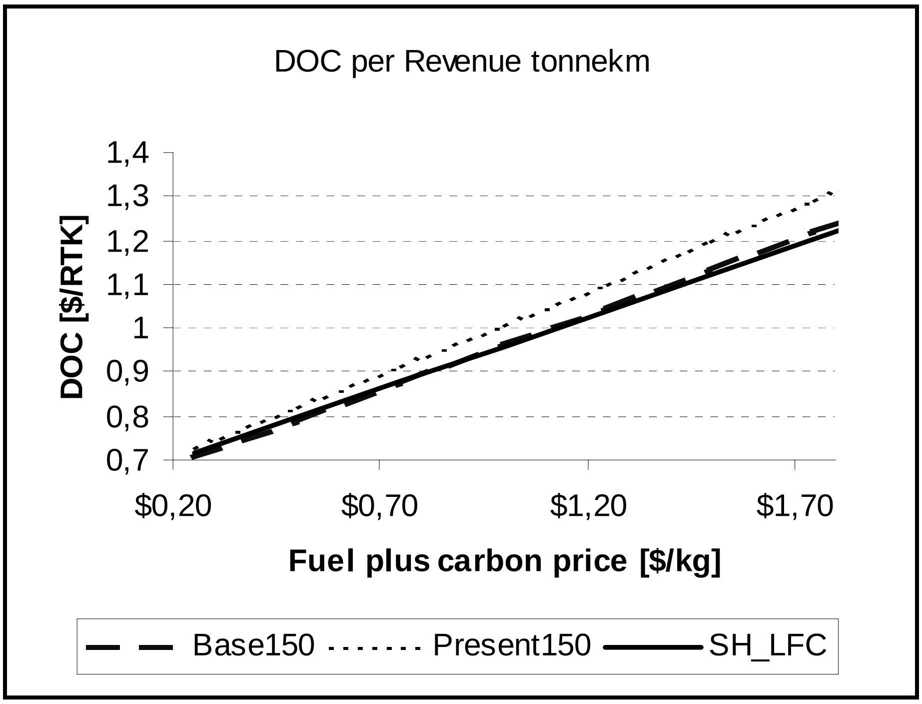
The fuel consumption has been reduced compared to the PRESENT150 with 541 kg or 13.7%. With respect to the 2010 technology turbofans the reduction is 181 kg or 5.0%.

6.2.3 DOC

The DOC has been calculated with the DOC model (see §2.6) from the block time, block distance and block fuel. From the intersection of the DOC lines as a function of fuel plus carbon price the following two DOC break even points are found (see Figure 45):

- With respect to the current engine technology: $0.012/kg;
- With respect to the 2010 engine technology: $0.922/kg.

Figure 45 Effect of fuel plus carbon price on DOC per RTK for the 1,000 km flight of the SH_LFC Short Haul aircraft fitted with Laminar Flow Control and 2010 Turbofans at 70% load factor compared with current and 2010 technology turbofans



For the latter fuel plus carbon price ($0.922/kg) the results are:

- Total DOC for the flight: $10,916;
- DOC per block hour: $5,867;
- DOC per block kilometre: $10.92;
- DOC per RTK: $0.934;
- DOC per passenger-km: $0.1068.

It seems clear laminar flow control is not a very economic solution for reducing fuel consumption in the short haul market given the assumptions on cost of the technique.

6.3 LH_LFC: Long Haul Laminar Flow Control plus 2010 Turbofans

6.3.1 Aircraft Definition

The aircraft has been cleaned-up aerodynamically and is fitted with active laminar flow control techniques as proposed by Van der Heijden and Wijnen (1999)[16]. This has the following effect with respect to the baseline long haul aircraft with 2010 technology level Turbofans (see §4.4):

- Net effect on parasite drag: -12.5%;
- Aircraft empty weight: +0.5%;
- Aircraft price effect: +2.5%;
- Airframe maintenance hours: +20%.

[16] For an aircraft with a high subsonic wing only active laminar flow may be effective, as the transonic capabilities of the wing section prevent the use of passive laminar wing section.

From the above assumption, the introduction of the 2010 Turbofans and an assumed initial fuel saving of 15% the following weights have been calculated:
The empty weight decreases with 1,470 kg, giving:

- MRW: 356,755 kg;
- MTOW: 355,395 kg;
- MLW: 258,890 kg;
- MZFW: 241,200 kg;
- OEW: 179,285 kg;
- EW: 169,966 kg.

The parasite drag reduces due to the LFC with 12.5% to $C_{D_0} = 0.0148$.

Following cost changes are introduced due to the engine development and the introduction of Laminar flow Control:

- The engine price goes down from $5,400,000 tot $4,833,000;
- The airframe price increases with 2.5% from $148,400,000 to $152,110,000;
- Airframe maintenance hours increase with 20%.

6.3.2 Performance

The flight profile has been calculated with APD (see §2.5) using the speed schedules, reserve fuel strategy, allowances and cruising altitude as used for the PRESENT400 (see §4.3.4). The evaluation flight for Long Haul has been calculated with APD (see §2.5) for a block distance of 7,000 km. The following performance has been found for a payload at 75% load factor of 46,436 kg:

- Block time: 8 hour and 30 minutes;
- Block fuel used: 62,848 kg;
- Take off weight: 301,637 kg;
- Reserve fuel: 12,983 kg.

The fuel consumption has been reduced compared to PRESENT400 with 14,420 kg or 18.7%. With respect to BASE400 the reduction is 5,665 kg or 8.3%.

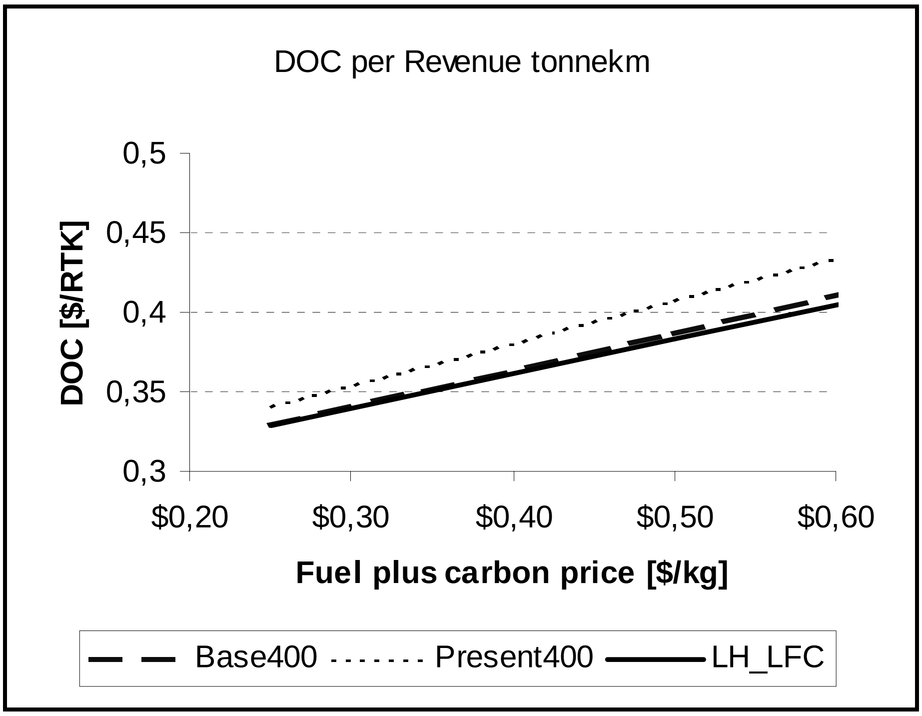
6.3.3 DOC

The DOC has been calculated with the DOC model (see §2.6) from the block time, block distance and block fuel. From the intersection of the DOC lines as a function of fuel plus carbon price the following two DOC break even points are found (see Figure 46):

- With respect to the current engine technology: $0.000/kg;
- With respect to the 2010 engine technology: $0.282/kg.

It is clear from these figures that laminar flow control is cost effective in the long haul market from fuel plus carbon prices 4% above the current value, with respect to the BASE400.

Figure 46 Effect of fuel plus carbon price on DOC per RTK for the 7,000 km flight of the LH_LFC Long Haul aircraft fitted with Laminar Flow Control and 2010 Turbofans at 75% load factor compared with current and 2010 technology turbofans



For the latter fuel plus carbon price ($0.282/kg) the results are:

- Total DOC for the flight: $109,175;
- DOC per block hour: $12,846;
- DOC per block kilometre: $15.60;
- DOC per RTK: $0.336;
- DOC per passenger-km: $0.0500.

6.4 SH_HAR: Short Haul High Aspect Ratio Wing

6.4.1 Introduction

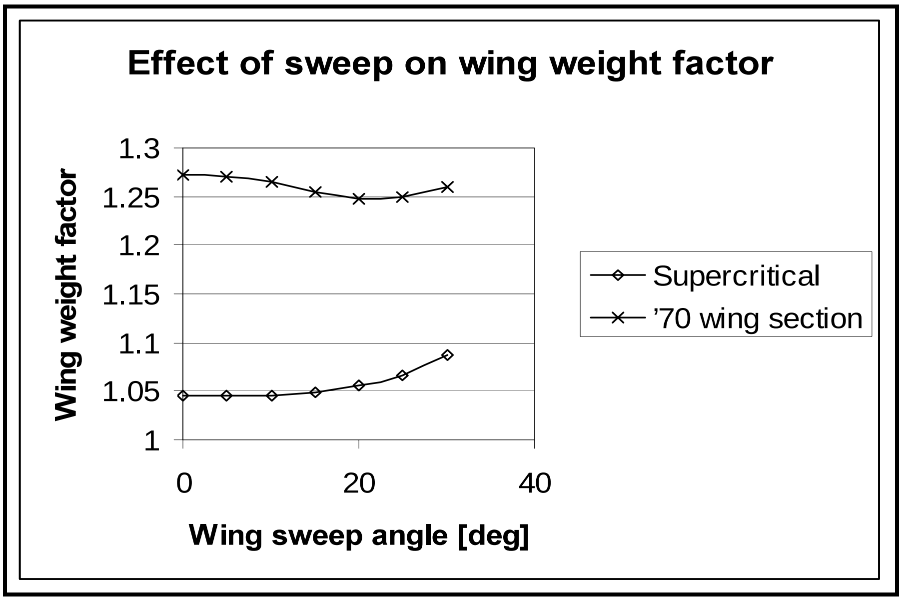
The SH_HAR model is aimed at the short haul market and consists of the baseline airframe fitted with the 2010 turbofans plus a new high aspect ratio wing. A high aspect ratio wing has many consequences for the aircraft design. In this study we have considered the following:

- Higher aircraft cost;
- Lower maximum cruise mach number;
- Higher mach drag;
- Lower wing area;
- Higher wing weight.

6.4.2 Aircraft Definition

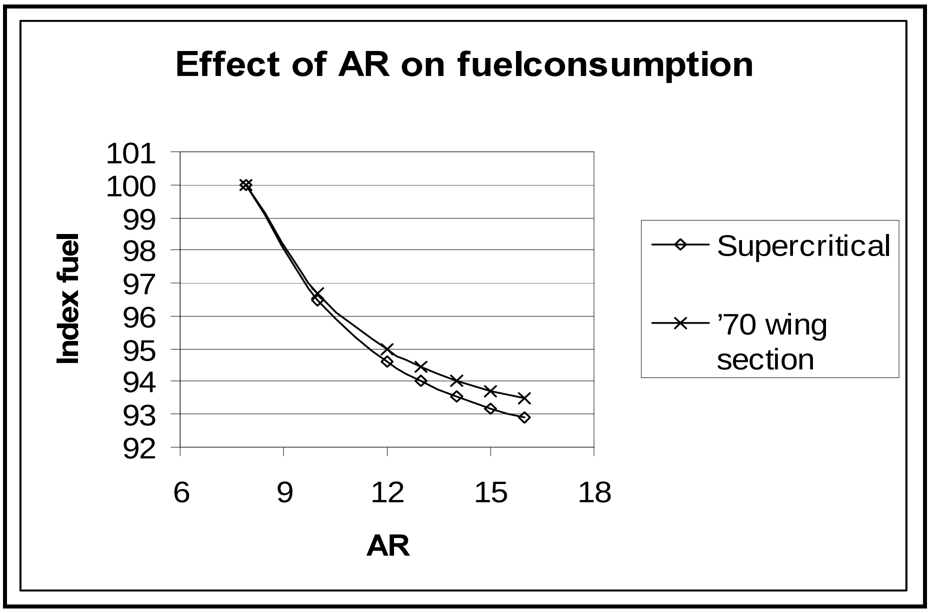
The aircraft is fitted with high aspect ratio wings and the 2010 technology level Turbofan engines (see §4.4). The wing aspect ratio influences the induced drag and the wing weight. Increasing the wing aspect ratio means decreasing this induced drag, but also increasing the wing weight. This extra weight will increase fuel consumption.
The wing weight does also depend on the wing thickness ratio: the weight will reduce with increasing thickness ratio. However: the mach drag will increase with increasing thickness ratio. This latter effect is influenced by two parameters: type of wing section and wing sweep angle.
Some types of wing sections (commonly called the 'supercritical' wing sections) have favourable high speed transonic capabilities, reducing the mach drag rise at a given mach number. Again, wing sweep also has influence on the wing weight.
For every wing design with a wing section we can find the optimum sweep angle, defined as the angle with which the wing weight increase has a minimum. Figure 47 gives an example for this effect for two wing sections. M_{DD} is the maximum mach number above which the mach drag rise will be 10 counts or more (the Boeing definition for Drag Divergent Mach number).

Figure 47 Effect of wing sweep on wing weight for a given maximum M_{DD} (mach 0.80)



Of course a detailed study on the effect of AR on the aircraft performance and DOC is the way to establish the economical optimum wing design. In this study we have simplified this analysis to get a first idea. Not included in the analysis so far is the effect on optimum wing area and on mach drag.
First we have to find the direct effect of the AR on the fuel consumption by just changing AR, assuming two types of wing sections. Figure 48 gives the results for this effect. Also included in this figure is a correction for the effect of empty weight on fuel consumption for the effect of wing weight on fuel consumption.

Figure 48 The effect of AR (including Oswald's factor e) on the fuel consumption with two wing section types and for a given M_{DD}=0.80



From Figure 48 it is clear the fuel optimum aspect ratio is more than 16. Also a supercritical wing section has a better performance in terms of fuel consumption and emissions. The DOC optimum aspect ratio depends on the fuel plus carbon price and is lower as can be seen in Figure 49 for the current fuel plus carbon price and Figure 50 for a hypothetical high fuel plus carbon price.

Figure 49 Effect of AR on DOC for a fuel price of $0.27/kg

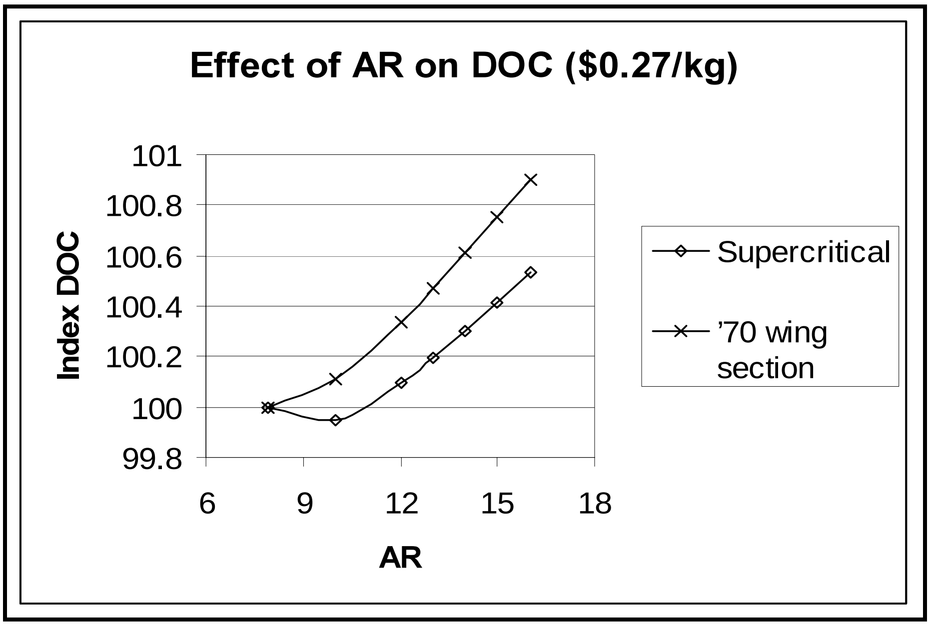
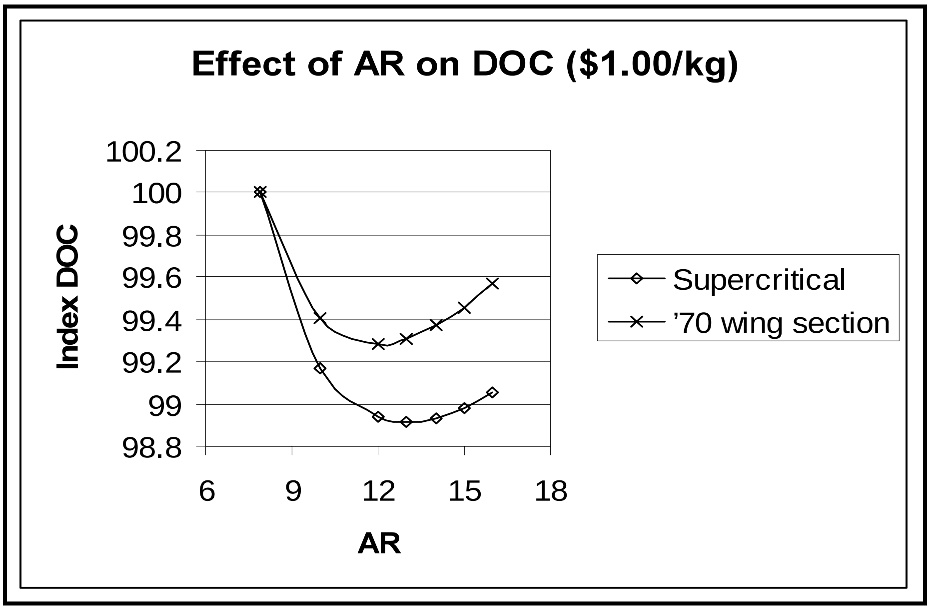


Figure 50 Effect of AR on DOC for a fuel plus carbon price of \$1.00/kg



From these figures it is clear the current baseline aircraft has a wing design optimised for a low fuel price. With a supercritical wing section this optimum may be shifted up to 10, saving about 5% fuel. However for the hypothetical high fuel plus carbon price of \$1.0/kg we should go to higher aspect ratio wings. With a normal wing section (as common practice in the seventies) this is 12; using a supercritical wing section may save 0.4% DOC by shifting optimum AR to 13.
As we are looking at the best option for environment we assume the following wing design:

- Sweep back angle reduced from 26° to 0°;
- M_{DD} reduced from 0.82 of the baseline to 0.80;
- The use of a supercritical wing profile (M_{str}=1.15).

This resulted into a thickness ratio of 12% for SH_HAR, where the baseline aircraft has 9%.
The reduction in M_{DD} will result in a slightly higher mach drag rise for a given mach number. This has been incorporated by reducing all values of the mach number in the mach drag table by 0.02.
With increasing AR the lift coefficient for best L/D will increase. This means the optimum wing area for a given cruise mach number may be reduced. To find the new wing area S_{ref} following assumptions apply for both the baseline and the SH_HAR:

- Cruising mach number is 0.745;
- Cruising weight is the mean weight for the evaluation flight of 1,000 km at 70% load factor (49700 kg);
- Cruising altitude is 10,000 m.

It appeared the PRESENT150 cruises in the evaluation flight slightly under the lift coefficient for highest L/D (2%). For SH_HAR the same deviation has been employed. From the calculations it appeared the wing area has to be reduced from 105.4 m^2 to 103.0 m^2. Summarising the following wing dimensions apply (between parenthesis the baseline value);

- Wing area: 103.0 m^2 (105.4 m^2);
- Wing aspect ratio: 13 (7.9);
- Wing sweep back angle: 0° (26°);
- Wing thickness ratio: 0.12 (0.09);
- Wing Span: 36.59 m (28.88 m);
- Thickness of mean chord: 0.340 m (0.333 m);
- Taper ratio is 0.25 (0.239).

Other influences like those on tail planes, fuselage, nacelles et cetera are neglected.

The empty weight is calculated starting with a factor for the wing weight and an initial reduction of the fuel consumption of 10%. Further the lower engine weight of the 2010 technology level turbofan is accounted for. The initial change of the empty weight and guessed reduction of fuel consumption induce a chain reaction in the empty weight. This has been iteratively calculated, giving a total empty weight decrease of 483 kg. The following weights now result:

- MRW: 61,410 kg;
- MTOW: 61,180 kg;
- MLW: 54,402 kg;
- MZFW: 50,772 kg;
- OEW: 34,081 kg;
- EW: 31,247 kg.

The dimensions and weights mentioned above are used in the airframe input sheet.
To find the cost of the aircraft with the new wing the aircraft price worksheet has been used with the following assumptions:

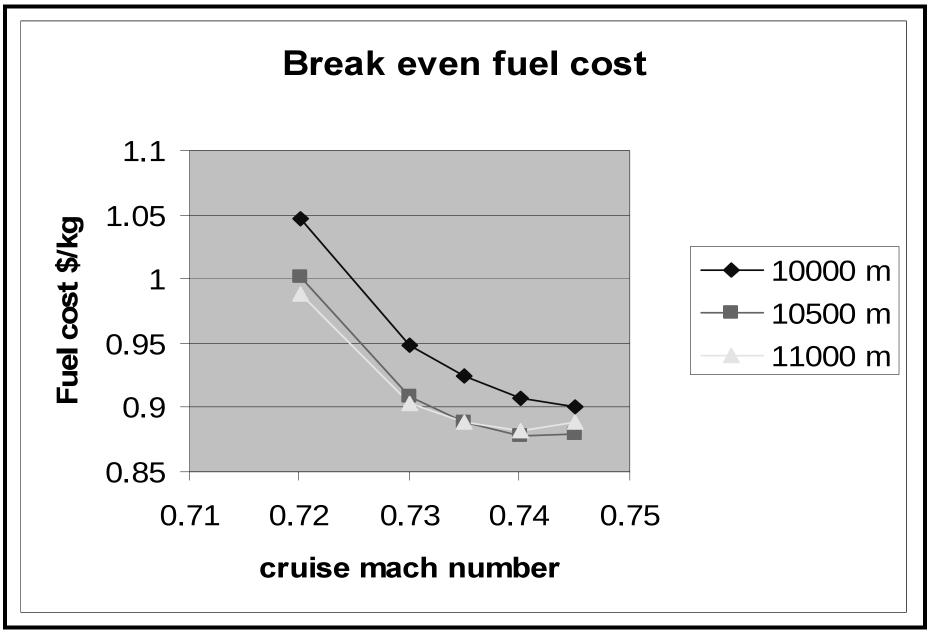
- The replaced wing weight is 6,221 kg;
- The new wing weight is 6,191 kg;
- 300 new aircraft will be build for break even (including 10% profit).

Now the airframe price increases with $3.5624 million to $41.3624 million. Because of the use of the 2010 engine technology Turbofan the engine price goes down from $3,100,000 tot $2,774,500.

6.4.3 Performance

As many parameters have been changed it is necessary to find a new speed schedule and cruising altitude, to attain the lowest fuel plus carbon price break even point. From a short range of calculations it turned out the cruising speed should be slightly reduced from mach 0.745 to mach 0.74 and the cruising altitude increased from 10,000 m to 10,500 m (see Figure 51). This is within the mach range defined for the new wing (M_{DD}=0.8).

Figure 51 Finding the optimum cruising mach number and altitude combination for the lowest fuel plus carbon price break even point for the SH_HAR



Summarising the following flight profile has been used:

- Take off and Ground manoeuvring:
  - 26 minutes at 7% MTO engine rating (all fuel weight for taxi is pre-TO);
  - Take off 0.7 minutes at 100% MTO rating;
  - Climb-out from 35 ft to 3,000 ft at 85% MTO rating; climb-out time is 2.2 minutes;
- Operational Climb:
  - Speed schedule 280 kCAS/0.74;
  - Max climb engine rating;
- Operational Cruise:
  - Long range speed (mach 0.74);
  - Cruise altitude 10,500 m;
- Operational descent:
  - Speed schedule: 0.74/280 kCAS;
  - Thrust set for maximum cabin rate of descent (300 ft/minute and maximum cabin altitude 6,000 ft);
- Approach and landing:
  - Approach from 3,000 ft to SL at 71.4 m/s TAS (Jane's, 1998);
  - Approach time 4 minutes at 30% MTO rating;
- Reserves:
  - Go around from 3,000 ft;
  - Flight to alternate at 200 NM with flight speed schedule, but at 8,000 m cruise altitude;
  - 30 minutes hold as extended cruise.

The evaluation flight for Short Haul has been calculated with APD (see §2.5) for a block distance of 1,000 km. The following performance has been calculated for a payload at 70% load factor of 11,684 kg:

- Block time: 1 hour and 54 minutes;
- Block fuel used: 3,335 kg;
- Take off weight: 51,802 kg;
- Reserve fuel: 2,702 kg.

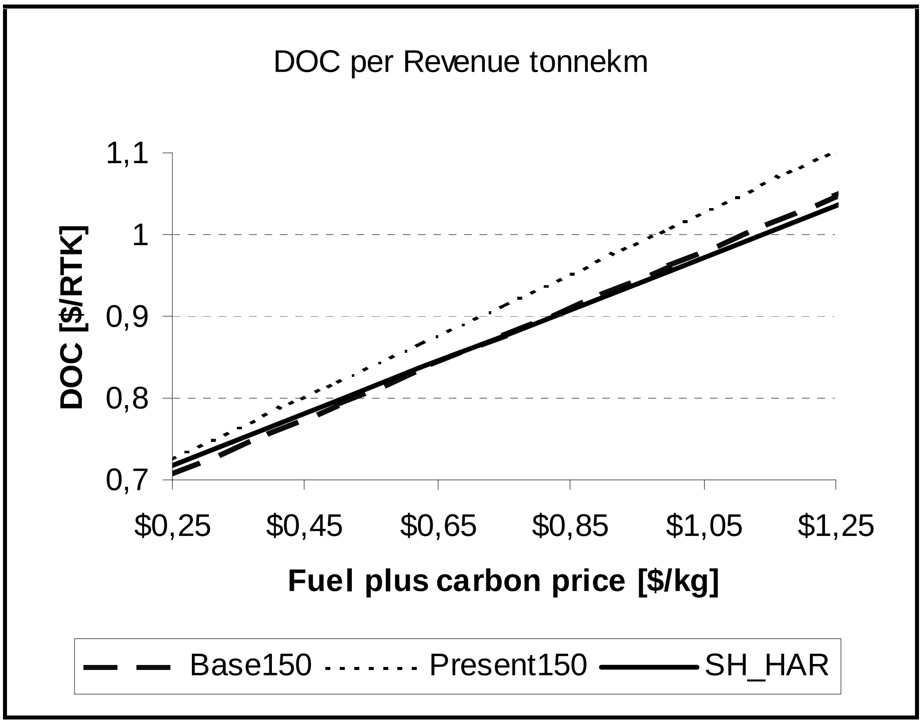
The fuel consumption has been reduced compared to the PRESENT150 with 616 kg or 15.6%. With respect to the 2010 technology turbofans the reduction is 256 kg or 7.1%.

6.4.4 DOC

The DOC has been calculated with the DOC model (see §2.6) from the block time, block distance and block fuel. From the intersection of the DOC lines as a function of fuel plus carbon price the following two DOC break even points are found (see Figure 52):

- With respect to the current engine technology: $0.145/kg;
- With respect to the 2010 engine technology: $0.849/kg.

Figure 52 Effect of fuel plus carbon price on DOC per RTK for the 1,000 km flight of the SH_HAR short haul aircraft fitted high aspect ratio wings and 2010 Turbofans at 70% load factor compared with both baseline aircraft



For the latter fuel plus carbon price ($0.849/kg) the results are:

- Total DOC for the flight: $10,625;
- DOC per block hour: $5,617;
- DOC per block kilometre: $10.63;
- DOC per RTK: $0.909;
- DOC per passenger-km: $0.1040.

6.5 LH_HAR: Long Haul High Aspect Ratio Wing

6.5.1 Introduction

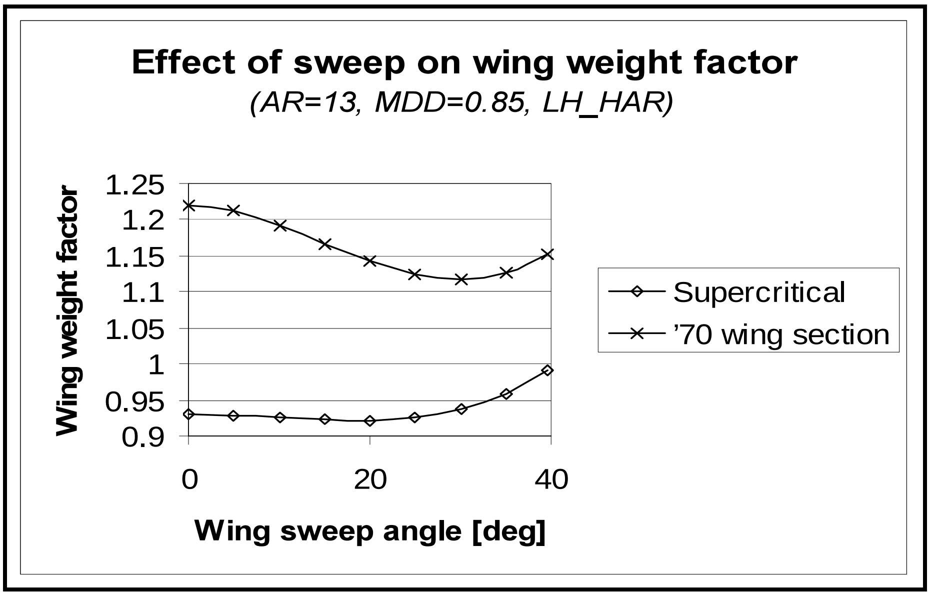
The LH_HAR model is aimed at the long haul market and consists of the baseline airframe fitted with the 2010 turbofans plus a new high aspect ratio wing. Chosen is for a DOC optimised aspect ratio. A new wing has many consequences for the aircraft design. In this study we have considered the following:

- Higher aircraft cost;
- Lower maximum cruise mach number;
- Higher mach drag;
- New wing area;
- New wing weight.

6.5.2 Aircraft Definition

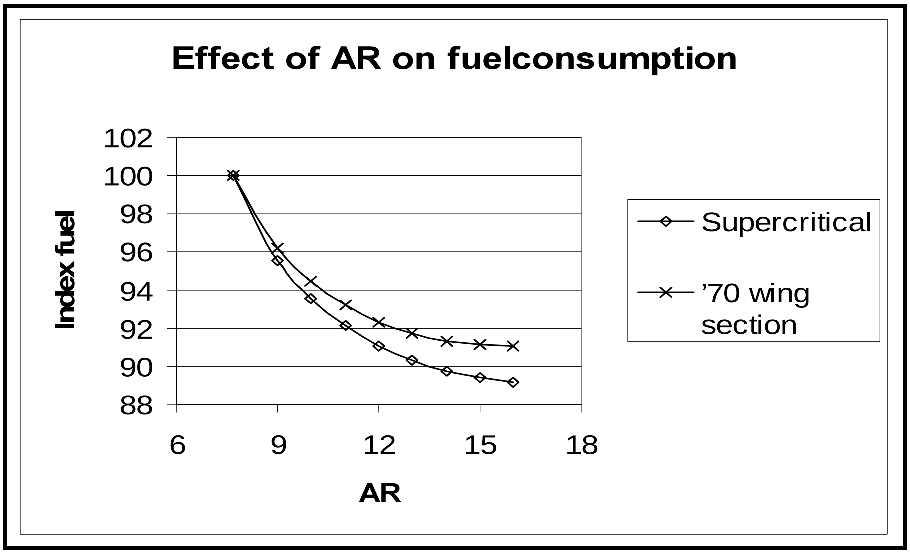
The aircraft is fitted with high aspect ratio wings. Also LH_HAR is fitted with 2010 technology level Turbofan engines (see §4.5). The wing aspect ratio influences the induced drag and the wing weight. Increasing the wing aspect ratio means decreasing this induced drag, but increasing the wing weight. This extra weight will increase fuel consumption.
The wing weight does also depend on the wing thickness ratio: the weight will reduce with increasing thickness ratio. However, the mach drag will increase with increasing thickness ratio. This latter effect is influenced by two parameters type of wing section and wing sweep angle. Supercritical wing sections have high speed transonic capabilities, reducing the mach drag rise at a given mach number. Increasing the sweep angle reduces mach drag, but increases wing weight. For every wing design with a wing section we can find an optimum sweep angle, defined as the angle with the lowest wing weight. Figure 53 gives an example for this effect for two wing sections. M_{DD} is the maximum mach number above which the mach drag rise will be 10 counts or more (the Boeing definition for Drag Divergent Mach number).

Figure 53 Example of the effect of wing sweep on wing weight for a given maximum M_{DD} (mach 0.85) for the long haul high aspect ratio design



Of course a detailed study on the effect of AR on the aircraft performance and DOC is the way to establish the economical optimum wing design. In this study we have simplified this analysis to get a first idea. Not included in the analysis so far is the effect on optimum wing area and on mach drag.
First we have to find the direct effect of the AR on the fuel consumption by just changing AR. Figure 54 gives the results for the net effects of AR and e. Also included in this figure is a correction based on a trend number for the effect of empty weight on fuel consumption caused by the changes in wing weight.

Figure 54 The effect of AR on the fuel consumption with two wing section types and for a given M_{DD}=0.85



From Figure 54 it is clear a supercritical wing section has a better performance in terms of fuel consumption. Also it becomes clear increasing the aspect ratio with a '70 wing section beyond 16 may even increase fuel consumption due to the wing weight growth. For the supercritical wing this optimum will be near an aspect ratio of 17 or 18. Of more interest is DOC optimum. To find this we use trend numbers for the influence of weight on aircraft price and DOC and created Figure 55 for the current fuel plus carbon price and Figure 56 for a hypothetical high fuel plus carbon price of $1.00/kg.

Figure 55 Effect of AR on DOC for a fuel price of $0.27/kg

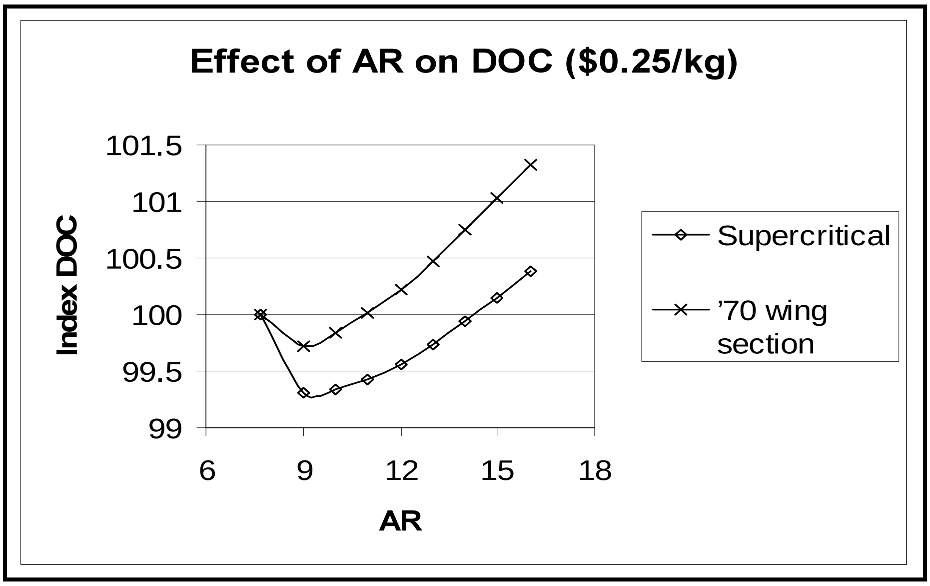
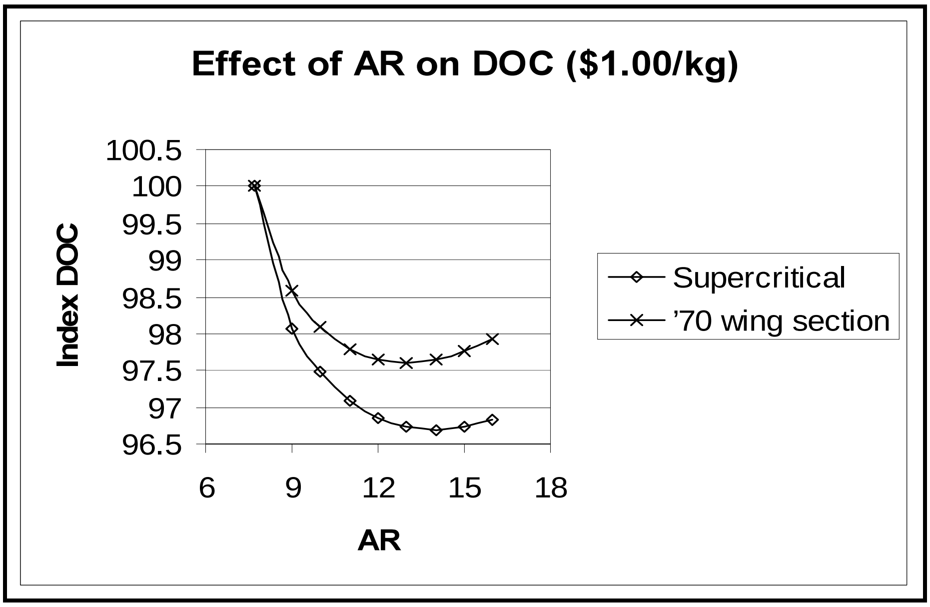


Figure 56 Effect of AR on DOC for a fuel plus carbon price of $1.00/kg



From these figures it seems the PRESENT400 aircraft has a wing design optimised for a low fuel price, though the aspect ratio could have been a bit higher. However for the high fuel plus carbon price of $1.00/kg case we should go to higher aspect ratio wings. With a normal wing section (as common practice in the seventies) this is 13; using a supercritical wing section may save 0.9% DOC and shifts the optimum AR to 14.

As we are looking for the best option for environment we assume the following wing design:

- Wing aspect ratio from 7.7 to 14;
- Sweep back angle reduced from 26° to 19°;
- M_{DD} reduced from 0.88 of the baseline to 0.85;
- The use of a supercritical wing profile (M_{str}=1.15).

This resulted into a thickness ratio of 12.4% for LH_HAR, where PRESENT400 has 9%. The reduction in M_{DD} will result in a slightly higher mach drag rise for a given mach number. This has been incorporated by reducing all values of the mach number in the mach drag table by 0.03.
With increasing AR the lift coefficient for best L/D will increase. This means the optimum wing area for a given cruise mach number may be reduced. To find the new wing area S_{ref} following assumptions apply for both the baseline and the LH_HAR:

- Cruising mach number is 0.82;
- Cruising weight is the mean weight for the evaluation flight of 7,000 km at 75% load factor (for the PRESENT400 this is 278,200 kg, for the LH_HAR it is guessed at 252,000 kg);
- Cruising altitude is 11,000 m.

It appeared the PRESENT400 cruises slightly under the lift coefficient for highest L/D (0.3%) at the evaluation flight. For LH_HAR the same deviation has been employed. From the calculations it appeared the wing area may be reduced from 541.2 m^2 to 452.0 m^2. As this is a large reduction in wing area, the TO requirement has been checked. Because the smaller wing sweep gives a higher maximum lift coefficient and the aircraft weight is lower, the TO runway length still may be smaller compared to the PRESENT400. Summarising the following wing dimensions apply (between parenthesis the baseline value):

- Wing area: 452 m^2 (541.16 m^2);
- Wing aspect ratio: 14 (7.7);
- Wing sweep back angle: 19° (39.5°);
- Wing thickness ratio: 0.1237 (0.08);
- Wing Span: 79.55[17] m (64.66 m);
- Thickness of mean chord: 0.703 m (0.671 m);
- Taper ratio is 0.25 (0.269).

The empty weight is calculated starting with a factor for the wing weight and an initial reduction of the fuel consumption of 25%. Further the lower engine weight of the 2010 technology level turbofan is accounted for. The initial change of the empty weight and guessed reduction of fuel consumption induce a chain reaction for wing weight. This has been iteratively calculated, giving a total empty weight decrease of 13,085 kg, largely due to the much smaller wing and the lower wing sweep and the larger wing thickness ratio. The following weights now result:

- MRW: 321,099 kg;
- MTOW: 319,739 kg;
- MLW: 247,275 kg;
- MZFW: 229,585 kg;
- OEW: 167,670 kg;
- EW: 158,351 kg.

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17 The wingspan is just inside the current airport maximum 80*80 m box.

When a wing structure changes dramatically, it will be necessary to change also the wing-fuselage mount and probably the undercarriage. To find the cost of the aircraft with the new wing the aircraft price worksheet has been used with the following assumptions:

- The replaced wing plus 20% structure weight is 62,801 kg;
- The new wing with 20% structure weight is 51,086 kg;
- 300 new aircraft will be build for break even (including 10% profit).

Now the airframe price increases with $8,211,000 to $156,611,000. Because of the use of the 2010 engine technology Turbofan the engine price goes down from $5,400,000 tot $4,833,000.

6.5.3 Performance

Much has been changed with the new wing. A short survey on the effect of the speed-schedule revealed a high speed to be the most profitable, but also destroying much of the gain in fuel consumption. Therefore we chose here for a cruise at 11,000 m and mach 0.82, as these were the design values. This is the PRESENT400 flight speed schedule (see §4.3.4). The evaluation flight for Long Haul has been calculated with the APD model (see §2.5) for a block distance of 7,000 km. The following performance has been found for a payload at 75% load factor of 46,436 kg:

- Block time: 8 hour and 41 minutes;
- Block fuel used: 57,411 kg;
- Take off weight: 283,037 kg;
- Reserve fuel: 11,520 kg.

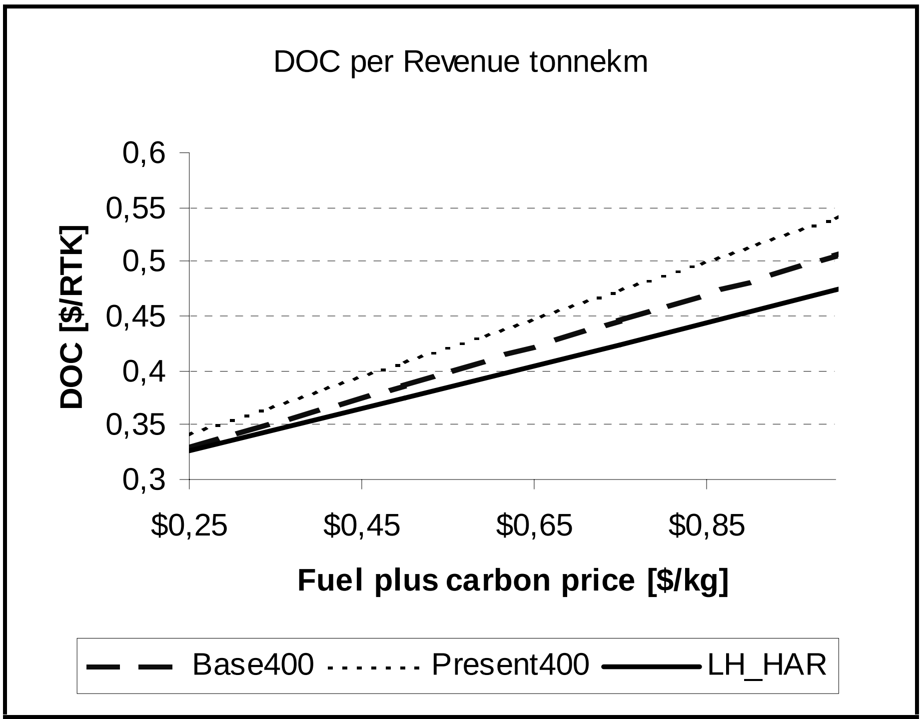
The fuel consumption has been reduced compared to the PRESENT400 with 19,851 kg or 25.7%. With respect to BASE400 the reduction is 11,102 kg or 16.2%.

6.5.4 DOC

The DOC has been calculated with the DOC model (see §2.6) from the block time, block distance and block fuel. From the intersection of the DOC lines as a function of fuel plus carbon price the following two DOC break even points are found (see Figure 57):

- With respect to the current engine technology: $0.022/kg;
- With respect to the 2010 engine technology: $0.186/kg.

Figure 57 Effect of fuel plus carbon price on DOC per RTK for the 7,000 km flight of the Long Haul aircraft with high aspect ratio wings and 2010 Turbofans at 75% load factor compared with current and 2010 technology turbofans



For the latter fuel plus carbon price ($0.186/kg) the results are:

- Total DOC for the flight: $101,855;
- DOC per block hour: $11,732;
- DOC per block kilometre: $14.55;
- DOC per RTK: $0.313;
- DOC per passenger-km: $0.0466.

Economically a high aspect ratio wing for the long haul aircraft is a profitable solution even at current or lower fuel prices.

7 New materials and weight reduction

7.1 Introduction

The application of new materials has the purpose to reduce the airframe weight. As a rule of thumb, every 3% reduction in empty weight will directly reduce the fuel consumption by 1%. A lower weight may Allow for reduction of the engine power and thus reduce the empty weight further. However this iteration has not been included into this evaluation of the effects of new materials.
Considered are new metal alloys and composites materials. New metal alloys like aluminium-lithium give a moderate reduction of weight in the order of 7% but are very expensive (two to four times the conventionally used aluminium alloys).
The most likely materials for reducing weight are composites like fibre reinforced plastics, fibre metal laminates and metal matrix composites. All these materials have their own specific characteristics and fields of application. The two NML designs (New Materials Large application) are based on the use of a mix of composites materials in as much of the airframe structure as physically possible.

7.2 SH_NML: short haul medium scale introduction of new materials

7.2.1 Aircraft Definition

Van der Heijden and Wijnen (1999) gives a maximum replacement of 70.2% of the weight of all structural parts achieving an empty weight reduction of 8%. Further it is assumed the aircraft will be fitted with 2010 technology level turbofan engines. The application of the new materials is assumed to have no influence on the drag of the aircraft. The airframe price will increase as well as the airframe maintenance cost.
Iterating the weight effect based on an initial assumption of fuel savings of 15% and with a 8% lower overall empty weight the following weights were found:

- The empty weight decreases with: 3,453 kg.
- MRW: 57,862 kg;
- MTOW: 57,632 kg;
- MLW: 51,432 kg;
- MZFW: 47,802 kg;
- OEW: 31,111 kg;
- EW: 28,277 kg.

Van der Heijden and Wijnen (1999) gives an increase of $340 per replaced kg of structural parts. This is the extra manufacturing cost for a major design. As large parts of the aircraft will have to be redesigned, we assume a long production line to get return on the investment. Therefore no extra cost is added for the development of the new parts. The increase of the airframe price with $340/kg replaced material gives the following airframe price increase: 0.702 * 18078 * $340 = $4,314,000. Also according to Van der Heijden and Wijnen, the airframe maintenance hours are increased with

17.6%[18]. The engine price will reduce from $3,100,000 to $2,774,500, due to the 2010 engine technology level.

7.2.2 Performance

Flight Profile

The flight profile used for calculating the evaluation flight is the same as used for the PRESENT150 (see §4.2.4). The evaluation flight for Short Haul has been calculated with APD (see §2.5) for a block distance of 1,000 km. The following performance has been found for a payload at 70% load factor of 11,684 kg:

- Block time: 1 hour and 51 minutes;
- Block fuel used: 3,488 kg;
- Take off weight: 49,087 kg;
- Reserve fuel: 2,804 kg.

The fuel consumption has been reduced compared to the PRESENT150 with 463 kg or 11.7%. With respect to the BASE150 the reduction is only 103 kg or 2.9%.

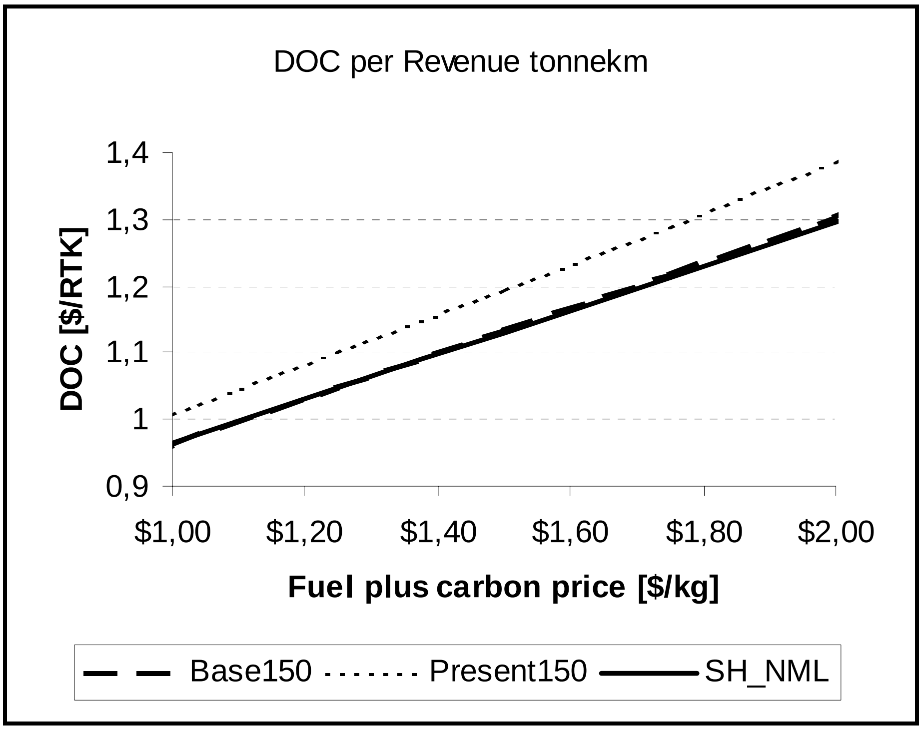
7.2.3 DOC

The DOC has been calculated with the DOC model (see §2.6) from the block time, block distance and block fuel. From the intersection of the DOC lines as a function of fuel plus carbon price the following two DOC break even points are found (see Figure 58):

- With respect to the current engine technology: less than $0.030/kg;
- With respect to the 2010 engine technology: $1.377/kg.

[18] This figure has been derived from a 50% increase on airframe maintenace hours for 70.2% of the airframe weight and assuming a 50/50 division between airframe and system maintenance hours (excluding engines).

Figure 58 Effect of fuel plus carbon price on DOC per RTK for the 1,000 km flight of the Short Haul aircraft with large use of new materials (SH_NML) and 2010 Turbofans at 70% load factor compared with current and 2010 technology turbofans



For the latter fuel plus carbon price ($1.377/kg) the DOC is:

- Total for the flight: $12,736;
- per block hour: $6,857;
- per block kilometre: $12.736;
- per RTK: $1.090;
- per passenger-km: $0.125.

For the short haul market and with the assumptions made in this study, the use of new materials with the purpose to save fuel seems not an economically sensible solution.

7.3 LH_NML: long haul medium scale introduction of new materials

7.3.1 Aircraft Definition

A maximum of sixty percent of the aircraft structure of BASE400 may be redesigned with the use of new materials (Van der Heijden and Wijnen, 1999), leading to a reduction of the empty weight with 8% for LH_NML. Further it is assumed the aircraft will be fitted with 2010 technology level turbofan engines. The new materials are assumed to have no influence on the drag of the aircraft. The airframe price will increase as well as the airframe maintenance cost. Iterating the effects of the lower structure weight and an initial assumption for fuel saving (15%) results in the following weights:

- The empty weight decreases with: 20,253 kg;
- MRW: 325,952 kg;

- MTOW: 324,592 kg;
- MLW: 240,107 kg;
- MZFW: 222,417 kg;
- OEW: 160,502 kg;
- EW: 151,183 kg.

The increase of the airframe price with $300/kg replaced material as given by Van der Heijden and Wijnen (1999) gives the following airframe price: 0.60 * 115105 * $300 = $20,719,000. Thus the airframe price will increase from $148.4 million to $169.119 million. Also the airframe maintenance hours is increased with 15%[19] (Van der Heijden and Wijnen, 1999). The engine price will reduce from $5,400,000 to $4,833,000, due to the 2010 technology level.

7.3.2 Performance

The flight profile used for calculating the evaluation flight is the same as used for the PRESENT150 (see §4.3.4). The Evaluation flight for Short Haul has been calculated with APD (see §2.5) for a block distance of 7,000 km. The following performance has been calculated for a payload at 75% load factor of 46,436 kg:
- Block time: 8 hour and 30 minutes;
- Block fuel used: 65,403 kg;
- Take off weight: 286,083 kg;
- Reserve fuel: 13,742 kg.

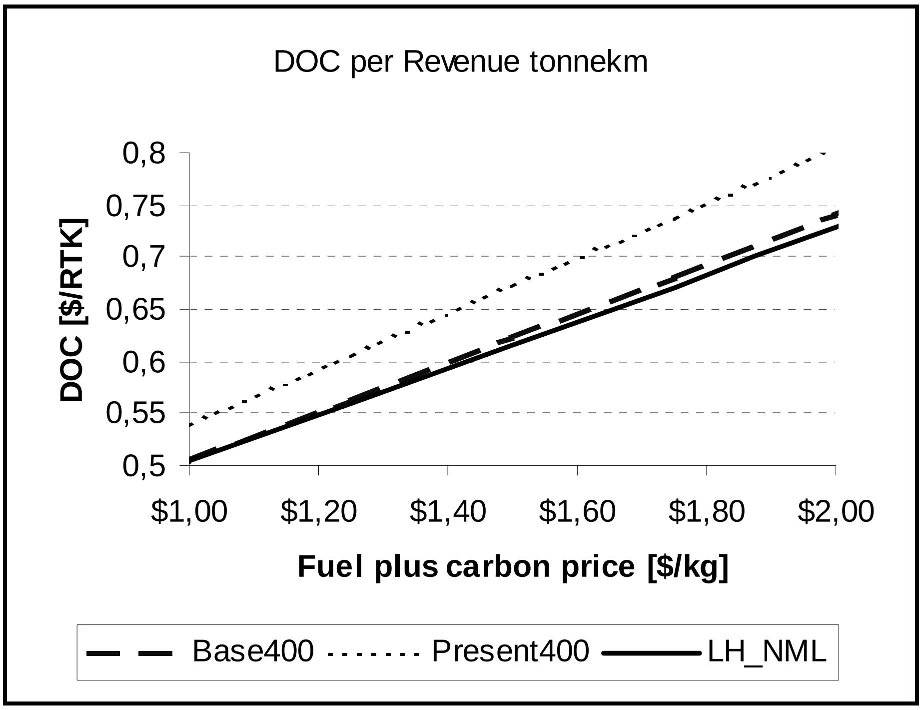
The fuel consumption has been reduced to the PRESENT400 with 11,859 kg or 15.4%. With respect to the BASE400 the reduction is 3,110 kg or 4.5%.

7.3.3 DOC

The DOC has been calculated with the DOC model (see §2.6) from the block time, block distance and block fuel. From the intersection of the DOC lines as a function of fuel plus carbon price the following two DOC break even points are found (see Figure 59):
- With respect to the current engine technology: $0.106/kg;
- With respect to the 2010 engine technology: $0.926/kg.

[19] This figure has been derived from a 50% increase on airframe maintenace hours for 60.0% of the airframe weight and assuming a 50/50 division between airframe and system maintenance hours (excluding engines).

Figure 59 Effect of fuel plus carbon price on DOC per RTK for the 7,000 km flight of the Long Haul aircraft with Large use of New materials (LH_NML) and 2010 Turbofans at 75% load factor compared with both baseline aircraft



For the latter fuel plus carbon price ($0.926/kg) the DOC is:

- Total for the flight: $158,284;
- per block hour: $18,633;
- per block kilometre: $22.61;
- per RTK: $0.487;
- per passenger-km: $0.0725.

Economically the use of new materials seems not a very profitable option in the long haul market, mainly because the effect on fuel is small, giving a high break-even point. Nevertheless the DOC is very near the BASE400.

8 New designs: integrating new technologies

8.1 Introduction

The ultimate new design would include the consideration of the aircraft configuration and a full sizing and trade-off study. The configuration study would give clues to choose between design and position of wings (high, middle or low), stabiliser (aft or front), tail set-up (normal, T- or V-tail) and position (wing, tail, mixed) and number of engines. Even a blended wing-body or other novel concept may be considered. Unfortunately these considerations fall beyond the scope of this study. Such a study will probably shift the attainable economic reduction of fuel consumption further up, however it will not fundamentally change the conclusions of this study. Nevertheless for the future a configuration study for a high fuel plus carbon price environment is strongly recommended as is substantiated in §8.10.
Combining technologies into a fully new design may have three effects:

- The reduction in fuel consumption of the individual technologies will generally add to each other.
- The cost of the new technologies will be written off over a larger number of aircraft built (as the new aircraft performs better it will be longer in production).
- It will be possible to use the reduction in operational weights (due to the reduction in fuel consumption) to redefine engine and wing area, which will further enhance efficiency.

For the individual technologies we described two different engine options: ultra high bypass and high speed propeller engines. The third propulsion system considered is the fuel cell. We will show designs around all three propulsion options for both short and long haul markets. Also two designs will be displayed for the high speed propeller option: one with a low and one with a high design cruise speed. The low speed variant will give a hint to the effects of design speed on both fuel economy, DOC and environmental impact.

Table 17 Overview of the technologies used in the new designs

	H-PROP150	H-PROP400	M-PROP150	M-PROP400	U-FAN150	U-FAN400	F-CELL150	F-CELL400
High speed propeller	+	+	+	+			+	+
Turbine engine (kerosene as fuel)	+	+	+	+				
Ultra high bypass engine (kerosene as fuel)					+	+		
Super-conducting electrical engine							+	+
Fuel cell technology (liquid hydrogen as fuel)							+	+
High aspect ratio	+	+	+	+	+	+	+	+
Aerodynamic clean-up	+	+	+	+	+	+	+	+
Laminar wing section			+	+			+	+
Active laminar flow control					+	+		
New materials					+	+	+	+

In choosing technologies for the designs we have looked at the cost-effectiveness and the general use of the aircraft. Table 17 gives the resulting new design definitions. As the M-PROP will be a slower aircraft we have decided to save as much as possible on the fixed costs by choosing only the most cost-effective technologies. The H-PROP designs will both be fitted with aerodynamic improvements, where this has only been done for the long haul version of the M-PROP design. The U-FAN aircraft has a high cruising speed, but has a less fuel efficient engine as M-PROP. As the importance of fixed cost will now diminish and fuel saving has to be increased more, we have combined the UHB engine with all other non-propulsive fuel-saving technologies. For the fuel cell technology design we again use high speed propellers and reduce the cruising speed of the aircraft. In this case we nevertheless have chosen to combine with all non-propulsive technologies, because of the need to reduce power and fuel volume requirements due to the high weight and drag penalties of the fuel cells and the LH_2 storage tanks.

8.2 H-PROP150: High speed new design with HSP

8.2.1 Combining technologies

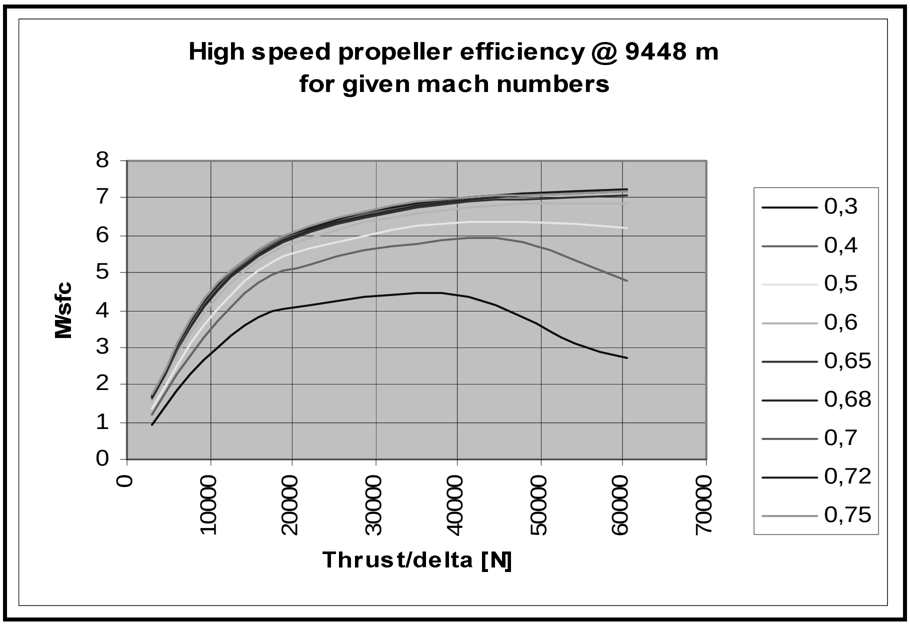
The high speed propeller allows almost the same cruise speed as for the BASE150, as the High Speed Propellers are designed for up to mach 0.75. Further the take-off performance may not deteriorate with respect to BASE150. These requirements determine the engine power, when flying at the highest top of climb weight. The highest mach number for the airframe (M_{DD}) has been reduced from mach 0.82 to mach 0.80 to allow for a slightly thicker wing section. Also a moderately supercritical wing section has been chosen to further increase the wing thickness ratio. This also means no laminar wing section can be used. As active laminar flow control is considered too expensive for this design, no LFC will be implemented into the design, but only a 5% reduction of parasite drag due to aerodynamically clean-up of the design has been included. The wing aspect ratio has been optimised for a $1.00/kg fuel plus carbon price. Wing loading has been optimised for the design cruise condition.
Altogether the H-PROP150 design comes close to the usual operational design specifications of the BASE150. It includes the high aspect ratio wing and part of the reduction of the parasite drag, making it a comparable design around the same engine as the Dutch Green Aircraft proposed by ADSE (Anon., 1997).

8.2.2 Sizing the aircraft

Design mach number and altitude

The engine overall efficiency has been defined as the ratio of speed (mach number) and specific fuel consumption (s.f.c.) as given by Cumpsty (1997). Figure 60 shows clearly the overall efficiency of the High Speed Propeller engine increases with the available thrust for a given mach number above 0.6. This means we will have to choose an engine as small as possible to get the lowest overall fuel consumption. This effect is exaggerated by the fact, a small engine will have a lower weight and drag penalty. By analysing the engine tables it was found altitude does not have much influence on the overall efficiency.

Figure 60 Engine efficiency as a function of thrust and mach number



As a design requirement we have chosen for the following cruise conditions, which are close to the economy cruise of the PRESENT150:

- Mach 0.74 design cruise speed;
- 10,000 m design cruise altitude.

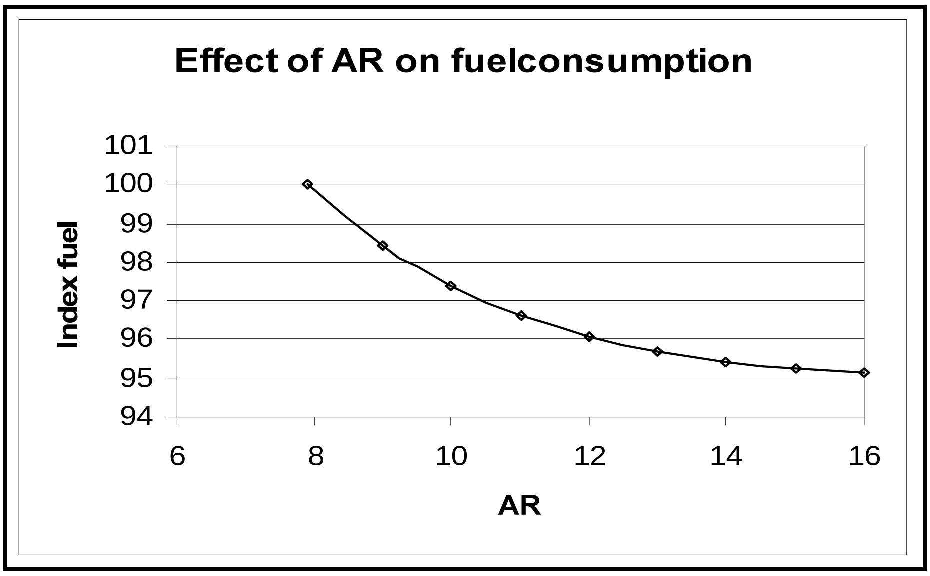
Wing Aspect ratio

The wing aspect ratio influences the induced drag and the wing weight. Increasing the wing aspect ratio means decreasing this induced drag, but also increasing the wing weight. This extra weight will increase fuel consumption.
The wing weight does also depend on the wing thickness ratio: the weight will reduce with increasing thickness ratio. However: the mach drag will also increase (much) with increasing thickness ratio. This latter effect is influenced by two parameters:

- Type of wing section;
- Wing sweep angle.

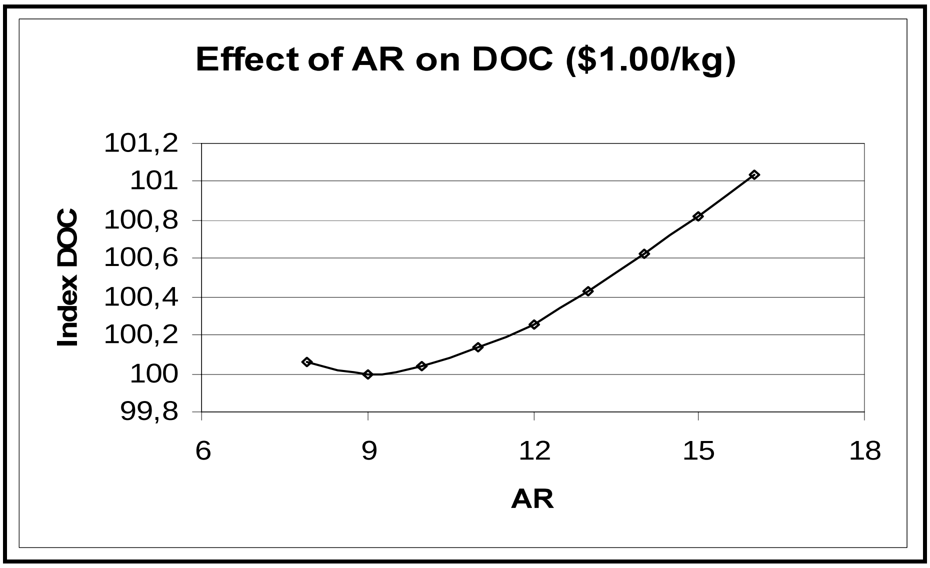
The type of wing section for a high subsonic aircraft will have been optimised for the lowest mach drag or the highest attainable M_{DD}. The problem is a high subsonic airfoil has a flat and even distributed pressure distribution. This makes the wing section less suitable for low drag at medium speeds: a laminar flow wing section for lower subsonic speeds has a continuously decreasing pressure at its upper surface. This means we have to choose between the way we optimise the airfoil design. As we have retained the speed for the H-PROP150 we will emphasise the high subsonic characteristics and consider the laminar characteristics less important. This means reduced mach drag for a given mach number but at the cost of a higher parasite drag as possible with better laminar flow characteristics of the wing section.
First we have calculated the direct effect of the AR on the fuel consumption by just changing AR. The figures calculated directly with APD are corrected for the effect of wing aspect ratio on wing weight (30 kg extra fuel for every 1,000 kg increase in basic wing weight). Figure 61 gives the results on fuel consumption.

Figure 61 The effect of AR on fuel consumption for a given M_{DD}=0.80



From Figure 61 it is clear the fuel optimised aspect ratio is about 16. The DOC optimum for a given fuel plus carbon price will be different. To find this we used trends for the influence of weight on aircraft price and DOC and created Figure 62 for a fuel plus carbon price of $1.00/kg.

Figure 62 Effect of AR on DOC for a fuel plus carbon price of $1.00/kg



From this figure it is clear an AR of 9 gives the DOC optimum. However, the effect on DOC is very small (some tenths of percents), while the effect on fuel consumption is about five times as large. Further it has been found the engine power may be reduced with a higher aspect ratio if the power is limited by the top-of-climb-condition, which may be the case for this design. This will reduce the empty weight at higher aspect ratios which will shift the optimum also towards higher aspect ratios. Therefore we have chosen for AR=11 on the sacrifice of just 0,2% of DOC, but gaining 1.8% on fuel consumption.

What maximum speed (M_{DD}) will we have to choose for a design speed of mach 0.74? The M_{DD} for the BASE150 is 0.82 and has a design cruise speed of mach 0.745. So the same M_{DD} seems appropriate. On the other hand this figure seems rather high for an airframe fitted with engines that are not meant to deliver thrust at a high efficiency at speeds above mach 0.75. Therefore, somewhat arbitrarily we have chosen mach 0.8 as M_{DD}.
With these figures the sweep angle has been optimised for lowest wing weight. Now we can define the wing design as follows:

- Sweep back angle reduced from 26° to 17°;
- M_{DD} reduced from 0.82 of the PRESENT150 to 0.80;
- The use of a moderately supercritical wing section (M_{str}=1.10).

This resulted into a thickness ratio of 10.2% for H-PROP150, where the PRESENT150 has 9%.

Wing area
With an iteration we have determined wing area. The wing area is sized for optimum cruise performance, but with TO performance as a constraint. For the iteration following assumptions apply to the H-PROP150:

- Design cruising mach number: 0.74;
- Cruising altitude: 10,000 m;
- Cruising weight is the mean weight found iteratively for the evaluation flight of 1,000 km at 70% load factor: 50,694 kg.

From the calculations it appeared the wing area must be decreased a little. Summarising the following wing dimensions apply (between parenthesis the baseline value):

- Wing area: 103.0 m^2 (105.4 m^2);
- Wing aspect ratio: 11 (7.9);
- Wing sweep back angle (quarter chord): 17° (26°);
- Wing thickness ratio: 0.102 (0.09);
- Wing Span: 33.66 m (28.88 m);
- Thickness of mean chord: 0.313 m (0.329 m);
- Taper ratio is 0.25 (0.239).

Aerodynamics
With the help of the Mathcad sheet for parasite drag calculation the influence of a change of dimensions for the empennage, fuselage, struts, nacelles and wing area have been determined. A factor has been used (0.95) to account for the effect of aerodynamic clean-up. This is a rather moderate factor because the design mach number is too high to use a laminar wing section. Active laminar flow control is considered too expensive for this kind of aircraft. The final result is an increase of the parasite drag coefficient for clean cruising configuration with 1.1%, but a decrease of the total drag area with 1.2%) .

Engine
It appeared the engine has to be scaled up to 125% of the original small engine defined by ADSE (ADSE, 1999) giving 10,250 shp TO power. This value has been used to scale the engine parameters with the method given by Raymer (1992), but with the scaling coefficients fitted for the two engines given by ADSE (1999):

- TO rating: 10,250 SHP;
- TOC rating: 6,250 SHP;
- Prop diameter: 12.69 ft;
- Number of blades: 2*6;
- Activity factor: 120;

- Core engine length: 2.508 m;
- Engine diameter: 0.852 m;
- Nacelle length: 6.195 m;
- Nacelle diameter: 1.755 m;
- Weight including system, nacelle and propeller: 3,425 kg;
- Removal of thrust reversers.

From a short analysis it was found the propeller tip speed is of no concern at a design cruise mach number of 0.74. It will stay below mach 0.95 at 900 rpm propeller speed.

8.2.3 Weights

The empty weight as well as the operational weights (MTOW, MLW) have been calculated with a reduction of the fuel consumption of 39.6%. This reduction is the result of the High Speed Propeller, the high aspect ratio wing and the changed drag and weight. To find this value the calculation has been iterated because a lower weight gives a larger reduction of fuel consumption, which in itself will reduce the weight. Further the higher engine weight of the High Speed Propeller is accounted for as well as the new dimensions for nacelles, wings and the removal of thrust reversers. The final result of this iteration is a total empty weight increase of 1821 kg with respect to the PRESENT150 aircraft. The following weights now result:
- MRW: 60,291 kg;
- MTOW: 60,061 kg;
- MLW: 56,706 kg;
- MZFW: 53,076 kg;
- OEW: 36,385 kg;
- EW: 33,551 kg.

8.2.4 Airframe and engine price

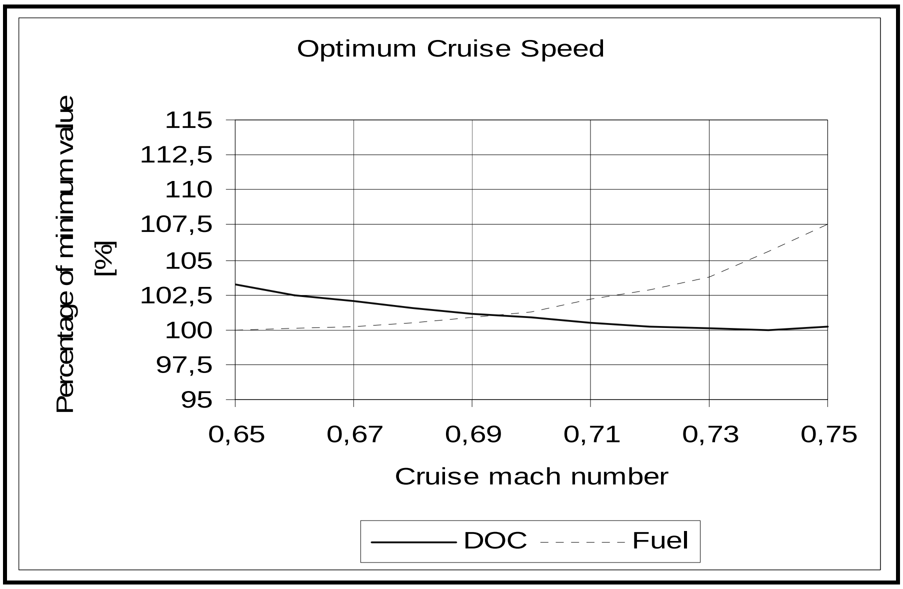
The engine price has been scaled with the help of the method of Roskam (Part VIII, 1990). From this calculation the engine price increases from $3,100,000 for the PRESENT150 to $3,109,000.
The airframe price has been calculated using the aircraft price Mathcad sheet with the following assumptions:
- The investment is written off over 485 aircraft;
- The replaced structure weight (empty weight minus the engines) is 27,758 kg;
- The new structure weight is 26,701 kg;
- Engine maintenance hours increase with 10% due to the new type of engines;
- Airframe maintenance hours increase with 10% due to retain the lower parasite drag due to the aerodynamic cleanup of the design;
- The maximum speed M_{DD} has been reduced from mach 0.82 to mach 0.80.

These assumptions give a final airframe price decrease of $368,000 to a price of $37,430,000. The engine maintenance cost has been kept the same as for the baseline, because the High Speed Propeller is used now at lower speeds as in the example given by ADSE (1999).
The flight crew wages depend on cruising speed and MTOW (Raymer, 1992). As the cruising speed reduces from 0.745 to 0.740 and the MTOW from 62,820 kg to 60,061 kg the wages will be 1.5% lower.

8.2.5 Performance

Before calculating the performance the DOC- and fuel-optimum flight profiles have been redefined. It turned out from calculations the cruising altitude of 10,000 m is practically the limit for the optimum cruising mach number. From Figure 63[20] we find the fuel optimum speed is mach 0.65 while the DOC optimum comes to 0.74. As this value is very near to the limit for the current size of the engine a slightly lower speed schedule will be used (mach 0.72), loosing 0.25% on DOC but saving 1.8% on fuel compared with mach 0.74.

Figure 63 Optimising the speed schedule (cruise mach number) for the H-PROP150 aircraft for the $1.00/kg fuel plus carbon price market



The following assumptions have been made:

- Take off and Ground manoeuvring:
  - 26 minutes at 7% MTO engine rating (all fuel weight for taxi is pre-TO);
  - Take off 0.7 minutes at 100% MTO rating;
  - Climb-out from 35 ft to 3,000 ft at 85% MTO rating; climb-out time is 2.2 minutes;
- Operational Climb:
  - Speed schedule 280 kCAS/0.72;
  - Max climb engine rating;
- Operational Cruise:
  - Long range speed (mach 0.72);
  - Cruise altitude 10,000 m;
- Operational descent:
  - Speed schedule: 0.72/280 kCAS;
  - Thrust set for maximum cabin rate of descent (300 ft/minute and maximum cabin altitude 6,000 ft);
- Approach and landing:
  - Approach from 3,000 ft to SL at 71.4 m/s TAS (Jane's, 1998);
  - Approach time 4 minutes at 30% MTO rating;
- Reserves:

[20] The irregular shape of this figure is caused by the step-wise increase of the climb CAS speed schedule.

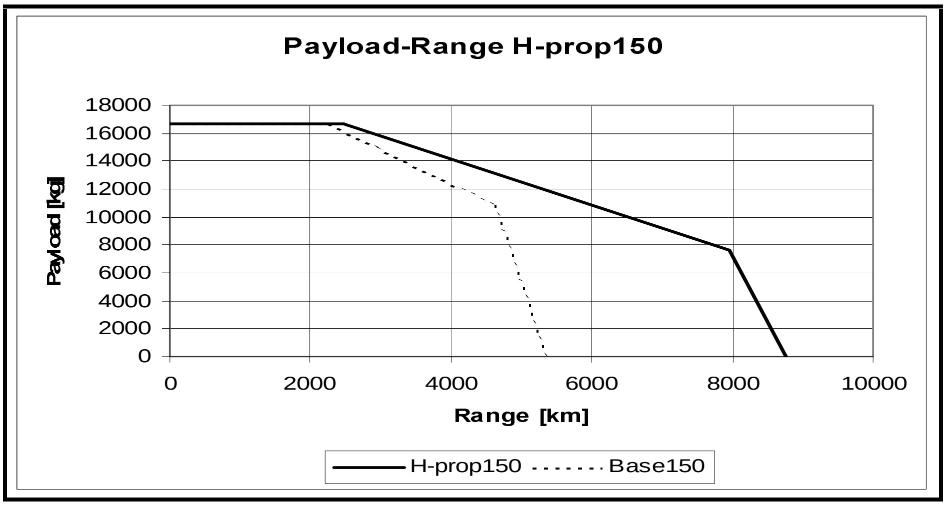
- Go around from 3,000 ft at destination;
- Flight to alternate at 200 NM with flight speed schedule, but at 8,000 m cruising altitude;
- 30 minutes hold as extended cruise.

The Evaluation flight for Short Haul has been calculated with APD (see §3.8) for a block distance of 1,000 km. The following performance has been calculated for a payload at 70% load factor of 11,684 kg:

- Block time: 1 hour and 55 minutes;
- Block fuel used: 2,323 kg;
- Take off weight: 52,157 kg;
- Reserve fuel: 1,765 kg.

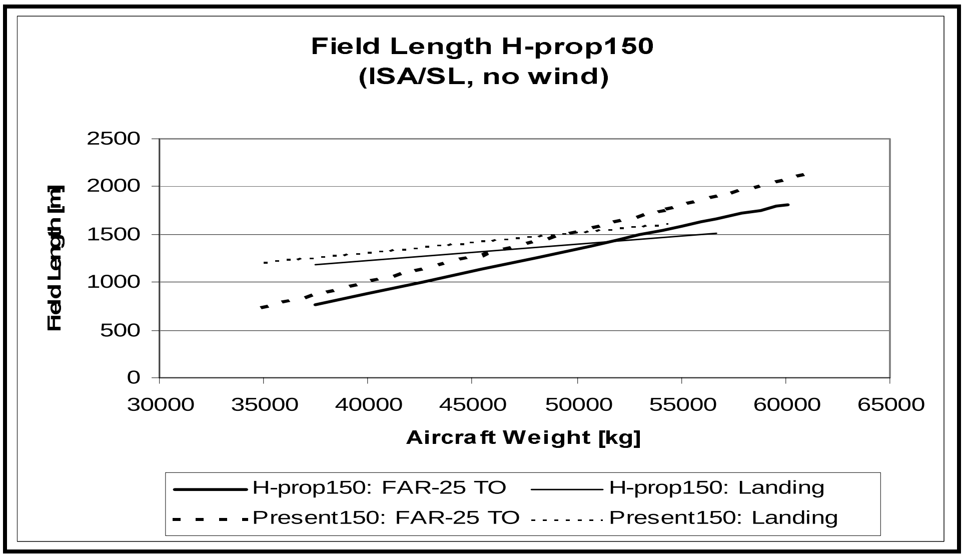
The fuel consumption has been reduced compared to the PRESENT150 with 1,628 kg or 41.2%. With respect to the BASE400 the reduction is 1,268 kg or 35.3%. The aircraft is slower with a 2.6% higher block time. The lowest attainable fuel consumption (for mach 0.65/10,000 m) is almost 43% below PRESENT150.
The payload range capability of the H-PROP150 is given in Figure 64. From this figure it is clear the high fuel economy results in a large range extension at partly loaded payloads. This may enhance flexibility of the aircraft. Due to the same fuel economy it is possible to extend range for full payload substantially at much less extra cost as will be the case for the Base150.

Figure 64 The payload range capability of the short haul H-PROP150 aircraft with high speed propeller engines for a standard atmosphere and the standard speed schedule and cruise altitude



The field performance for take off and landing has also been given a rough estimate. Figure 65 gives the resulting performance on a standard day, ISA, with no wind and no runway gradient and compares it with the PRESENT150. From this figure it is clear the take off and landing performance is better at all weights.

Figure 65 Field length performance of the H-PROP150 with high speed propeller engines for a standard day, ISA, no wind and no runway gradient. The lines are drawn up to the actual MTOW and MLW



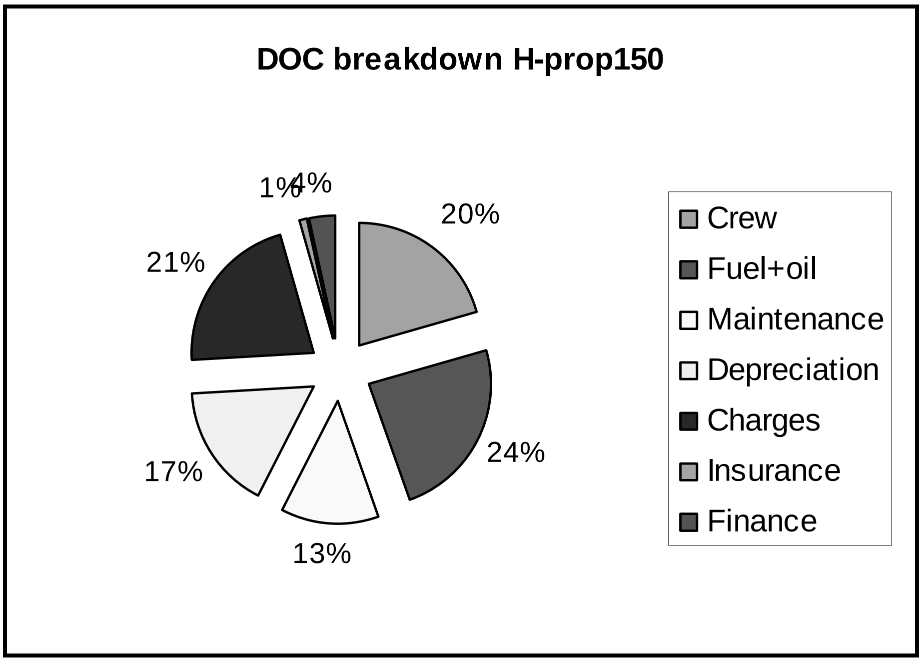
8.2.6 DOC

As we designed for a \$1.00/kg fuel plus carbon price environment we give the DOC for this situation:

- Total for the flight: \$10,022;
- per block hour: \$5,229;
- per block kilometre: \$10.022;
- per RTK: \$0.858;
- per passenger-km: \$0.0981.

The DOC breakdown for \$1.00/kg fuel plus carbon price can be found in Figure 66. The DOC (at \$1.00/kg fuel plus carbon price) is 15.1% lower compared to the PRESENT150 and 10.8% lower compared to BASE150. At \$0.27/kg fuel price the DOC will decrease with 5.0% compared to the PRESENT150 and with 2.2% compared to the BASE150.

Figure 66 DOC breakdown for the H-PROP150 New design aircraft at $1.00/kg fuel plus carbon price



Conclusion is the total DOC for the new design will be substantially lower than for the BASE150, mainly due to a saving of over 35% on fuel.

8.2.7 Environment

The environmental impact of H-PROP150 in terms of emissions is 35% less than for the baseline. All emissions will be reduced by about the same factor as the reduction in fuel consumption. The emissions of NO_x may even be reduced further for this type of engine. Anon. (1997) gives a difference of specific NO_x emissions per kg fuel of about 1 to 1.8 for Propfan to UHB.
The noise impact of the aircraft will be influenced by the following characteristics:

- The propulsion system has been de-rated with about 10% (in terms of static thrust). This will reduce the take off noise emissions.
- Sideline noise of the High Speed Propeller Aircraft may be lower compared to the baseline.
- Fly-over noise will be lower, due to the high position of the engines and the lower noise emission of a propeller engine.
- Fly-over noise will decrease mainly due to 7% larger initial rate of climb.

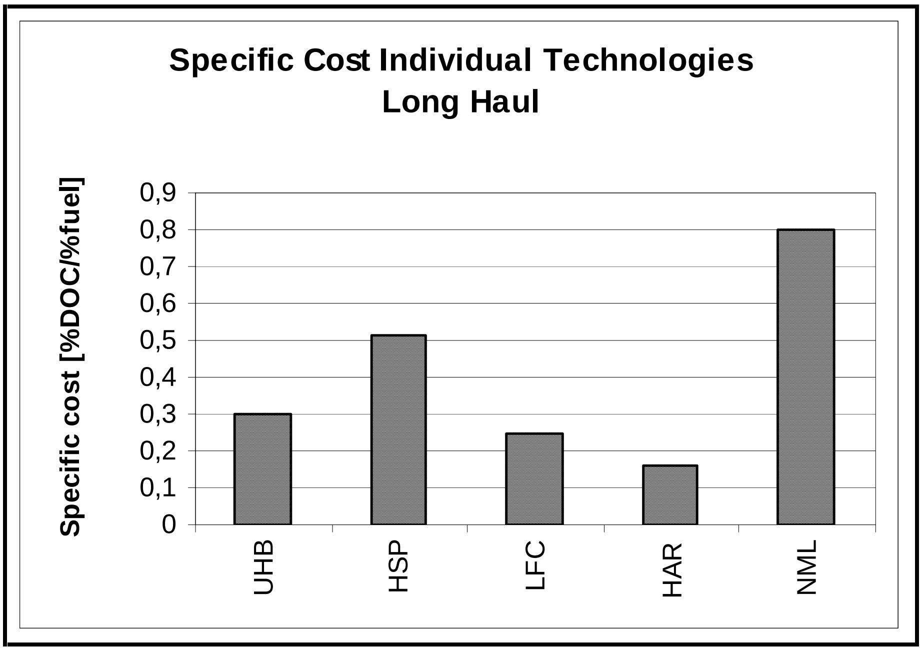
The net effect of these is probably a decrease in noise impact of H-PROP150. How much this decrease will be and if the aircraft will apply to current noise regulations can be determined only with further study.

8.3 H-PROP400: High speed new design with HSP engines

8.3.1 Combining technologies

The baseline long haul aircraft cruises at mach 0.82. This is too fast for the high speed propeller as used in this study[21] and the new design H-PROP400 will be designed around a lower cruising speed (0.74). Also we will include the most cost-effective technologies into the design. From Figure 67 it can be seen both a high aspect ratio wing and laminar flow control may be cost effective. However, the figure gives the specific cost of active LFC for a high cruising speed (mach 0.84). Therefore active LFC is considered too expensive for this rather slow aircraft, while laminar wing sections will have a conflict with the moderately transonic capabilities of the wing. Therefore we have only introduced an aerodynamic clean-up of the design and focussed on transonic quality of the wing design. The aspect ratio will be optimised for a $1.00/kg fuel plus carbon price.

Figure 67 The specific cost (% non-fuel DOC rise per % fuel saving) for the long haul aircraft technologies



Wing and power loading have initially been optimised for cruise and then for TO distance and second segment climb capabilities. In a full-scale design sizing study we would try to fit many more parameters of the aircraft design to the presumed high fuel plus carbon price of $1.00/kg as we are able to do within the scope of this study.
First we have to decide to which design speed and cruising altitude we will optimise the aircraft. As the DOC of a long haul aircraft suffers much from a low speed we have chosen for the highest possible cruising speed, allowed

[21] The socalled Propfan are designed for mach numbers around 0.8 and may be more suitable for long haul aircraft. however, the technical problems associated with Propfans are more abundant as with the high speed propellers as defined in this study.

by the technical specification of the HSP. Therefore the design point for cruise will be:

- mach number: 0.74;
- altitude: 10,000 m.

8.3.2 Sizing the aircraft

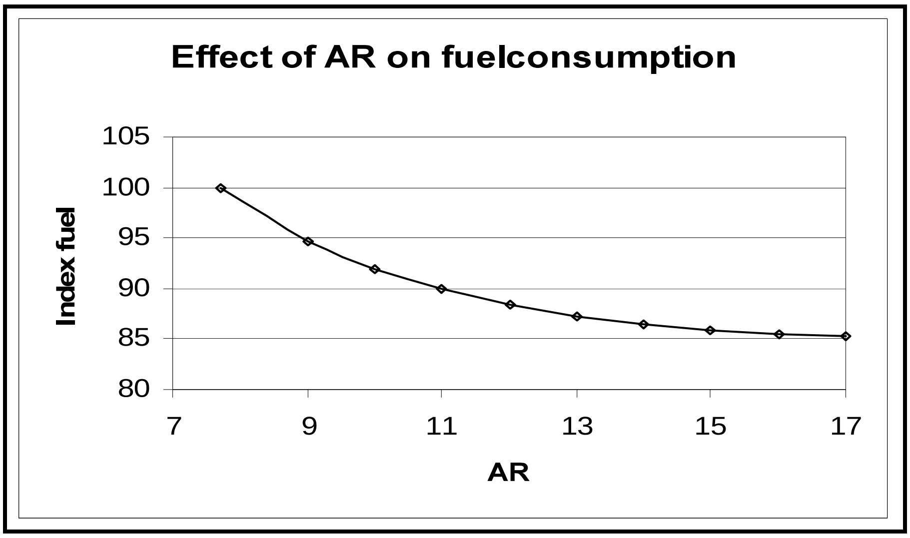
Wing Aspect ratio

The wing aspect ratio influences the induced drag and the wing weight. Increasing the wing aspect ratio means decreasing this induced drag, but also increasing the wing weight. This extra weight will increase fuel consumption. The wing weight does also depend on the wing thickness ratio: the weight will reduce with increasing thickness ratio. However: the mach drag will also increase (much) with increasing thickness ratio. This latter effect is influenced by two other parameters:

- Type of wing section;
- Wing sweep angle.

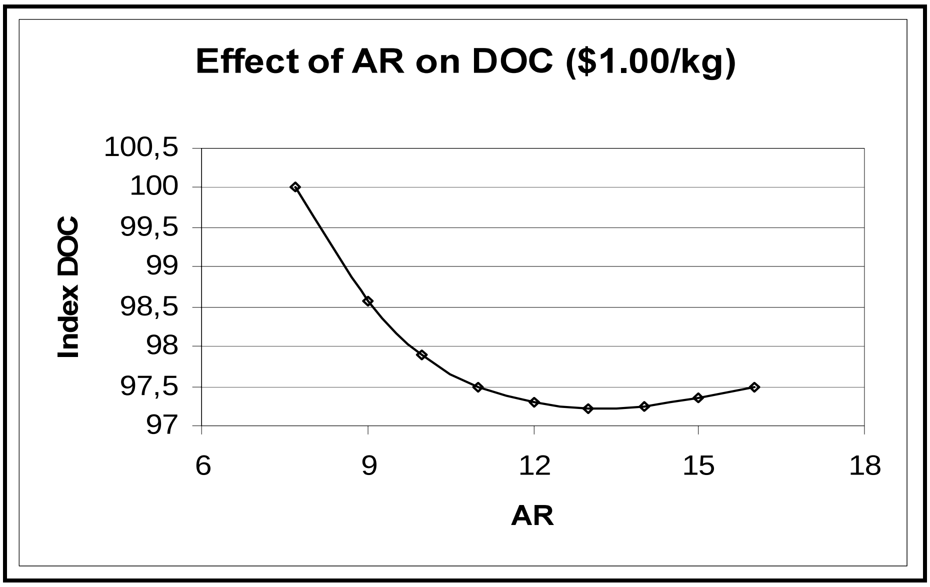
The type of wing section for a high subsonic aircraft will have been optimised for the lowest mach drag or the highest attainable M_{DD}. The problem is a high subsonic airfoil has a flat and even distributed pressure distribution. This makes the wing section less suitable for low drag at medium speeds: a laminar flow wing section has a continuously decreasing pressure at its upper surface. This means we have to choose between the way we optimise the airfoil design. Though we have reduced the cruising speed for the H-PROP400 we will emphasise on subsonic characteristics as these play still an important role in the fuel efficiency at mach 0.74. The M_{DD} has been reduced (somewhat arbitrarily) from mach 0.88 to mach 0.80.
First we have calculated the direct effect of the AR on the fuel consumption by just changing the AR. These figures calculated with APD are corrected for the effect of wing aspect ratio on wing weight (152 kg extra fuel for every 1,000 kg increase in wing weight). Figure 68 gives the results on fuel consumption.

Figure 68 The effect of AR on fuel consumption for a M_{DD}=0.80



From Figure 68 it is clear the fuel optimised aspect ratio is 17. The DOC optimum has been determined by incorporating the influence on DOC of the extra wing weight on airframe cost and the above mentioned correction on fuel consumption. The result is shown by Figure 69 for the high fuel plus carbon price of $1.00/kg.

Figure 69 Effect of AR on DOC for a fuel plus carbon price of $1.00/kg



From this figure it is clear an AR of between 13 and 14 has a DOC optimum. We have chosen for AR=14.
The sweep back angle of the wing has been chosen for minimum wing weight and is 17°.

Now we can define the wing design as follows:

- Sweep back angle reduced from 39.5° to 17°;
- M_{DD} reduced from 0.88 of the baseline to 0.80;
- The use of a moderately super-critical wing section (M_{str}=1.10);
- A mean thickness ratio of 10.0% for H-PROP400, where the PRESENT400 has 8%.

Engine
From the calculations it appeared the engine could be scaled down from 3.0 times the original value (as for the LH-HSP) to 2.6 (so with 13%). To scale the fuel flow we have assumed the difference between the short haul UHB and the short haul High Speed Propeller engine is valid also for the long range case, because in both cases the same core engine may be used. As the BPR for both UHB engines is assumed to be equal, the resulting difference in s.f.c. must be a result of scale effects and general design differences in the core engines. These considerations resulted into a scale factor of (rounded conservatively) 0.60 on fuel flow.
Scaling the engine with a factor 2.6 using a method given by Raymer (1992), but with the scaling coefficients fitted for the two engines given by ADSE (1999) resulted into the following engine parameters:

- TO rating: 21,307 SHP;
- TOC rating: 13,000 SHP;
- Propeller diameter: 15.238 ft;
- Cruise propeller rotational speed: 800 rpm;

- Number of blades: 2*6;
- Activity factor: 120;
- Core engine length: 3.332 m;
- Engine diameter: 1.047 m;
- Nacelle length: 8.231 m;
- Nacelle diameter: 2.158 m;
- Weight including system, nacelle and propeller: 6,636 kg.

From a short analysis it was found the propeller tip speed is of no concern at a design mach number of 0.74. It will be below mach 0.98 at 800 rpm.

Wing area
With an iteration we have determined wing area and aerodynamics: after estimating the aerodynamic effects (see the next paragraph titled 'Aerodynamics') we had to resize wing area and power loading and so on. The wing area is sized for optimum cruise performance. To find the new wing area S_{ref} following assumptions apply for the H-PROP400:

- Design cruising mach number: 0.74;
- Design cruising altitude: 10,000 m;
- Cruising weight is the mean weight found iteratively for the evaluation flight of 7,000 km at 75% load factor: 240,000 kg.

The final wing area has not been fully determined by the optimum cruising condition. The low speed take off and second segment climb gave a lower limit to the wing area. Summarising the following wing dimensions apply (between parenthesis the baseline value):

- Wing area: 460.0 m^2 (541.16 m^2);
- Wing aspect ratio: 14 (7.7);
- Wing sweep back angle (quarter chord): 17° (39.5°);
- Wing thickness ratio: 0.100 (0.08);
- Wing Span[22]: 80.25 m (64.44 m);
- Thickness of mean chord: 0572 m (0.671 m);
- Taper ratio is 0.25 (0.239).

Aerodynamics
With the help of the Mathcad sheet for parasite drag calculation the influence of a change of dimensions for the empennage, fuselage, struts, nacelles and wing area have been determined. The parasite drag coefficient has been factored with 0.95 due to aerodynamic clean-up. No active or passive laminar flow has been assumed. The final result is an increase of the parasite drag coefficient for clean cruising configuration with 5.6% (and a decrease of the total drag area with 10.2%) .

8.3.3 Weights

The empty weight as well as the operational weights (MTOW, MLW) have been calculated with an initial reduction of the fuel consumption of 49%. This reduction is the result of the High Speed Propeller and the changed drag and weight due to the smaller engine and the new wing design. To find this value the calculation has been iterated because a lower weight gives a larger reduction of fuel consumption, which in itself will reduce the weight. Further the new engine weight of the High Speed Propeller is accounted for as well as the new dimensions for nacelles, wings and the removal of thrust

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22 This wingspan is larger as the ICAO 80*80 m^2 maximum box for airports and will require special measures to receive this aircraft on many airports.

reversers. The final result of this iteration is an empty weight decrease of 13,234 kg with respect to the PRESENT400. The following weights now result:

- MRW: 292,092 kg;
- MTOW: 290,732 kg;
- MLW: 247,117 kg;
- MZFW: 229,427 kg;
- OEW: 167,512 kg;
- EW: 158,193 kg.

8.3.4 Airframe and engine price and other cost factors

The engine price has been scaled down with the help of the method of Roskam (Part VIII, 1990). From this calculation the engine price goes down from $5,400,000 to $5,134,000.
The airframe price has been calculated using the aircraft price Mathcad sheet with the following assumptions:

- The investment is written off over 450 aircraft (it is a totally new design);
- The replaced structure weight (empty weight minus the engines) is 154,200 kg;
- The new structure weight is 136,404 kg;
- The maximum speed M_{DD} has been reduced from mach 0.88 to mach 0.80.

These assumptions give a final airframe price decrease of $17,044,000 to a price of $131,356,000. Airframe maintenance hours have been increased with 10% due to extra maintenance to retain the effect of the aerodynamic cleanup of the airframe during normal operations. The engine maintenance hours have been increased with 20% with respect to the baseline case.
The flight crew wages depend on cruising speed and MTOW (Raymer, 1992). As the cruising speed reduces from 0.84 to 0.80 and the MTOW from 362,875 kg to 290,732 kg the wages will be 9.9% lower.

8.3.5 Performance

Before calculating the performance the DOC-and fuel-optimum flight profiles have been redefined primarily to check if the design cruise mach number really turns out to be the optimum value. From Figure 70[23] we find the fuel optimum speed is mach 0.66 while the DOC optimum for a fuel plus carbon price of $1.00/kg comes to 0.74. This value is the same as the design value of mach 0.74.

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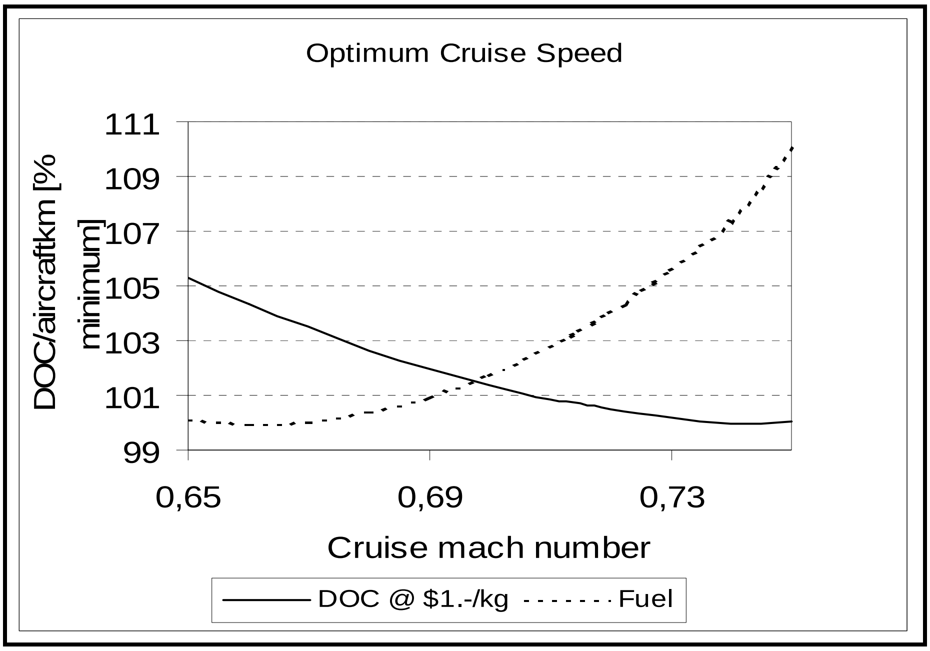
[23] The irregular shape of this figure is caused by the step-wise increase of the climb CAS speed schedule.

Figure 70 Optimising the speed schedule (cruise mach number) for the H-PROP400 aircraft for the $1.00/kg fuel plus carbon price market



The following assumptions have been made, based on the DOC optimum:

- Take off and Ground manoeuvring:
  - 26 minutes at 7% MTO engine rating (all fuel weight for taxi is pre-TO);
  - Take off 0.7 minutes at 100% MTO rating;
  - Climb-out from 35 ft to 3,000 ft at 85% MTO rating; climb-out time is 2.2 minutes;
- Operational Climb:
  - Speed schedule 280 kCAS/0.74;
  - Max climb engine rating;
- Operational Cruise:
  - Long range speed (mach 0.74);
  - Cruise altitude 10,000 m;
- Operational descent:
  - Speed schedule: 0.74/280 kCAS;
  - Thrust set for maximum cabin rate of descent (300 ft/minute and maximum cabin altitude 6,000 ft);
- Approach and landing:
  - Approach from 3,000 ft to SL at 71.4 m/s TAS (Jane's, 1998);
  - Approach time 4 minutes at 30% MTO rating;
- Reserves:
  - 120 minutes hold as extended cruise.

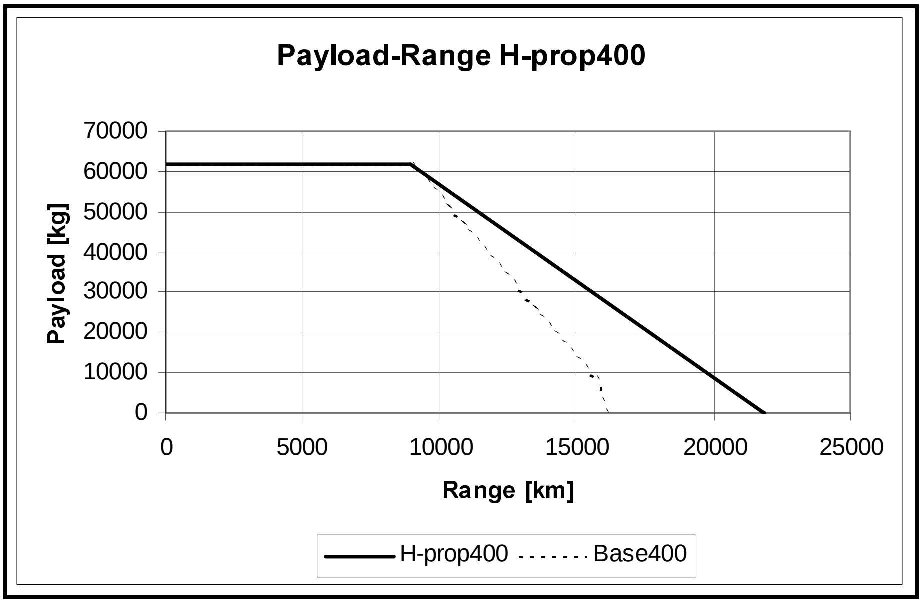
The Evaluation flight for Long Haul has been calculated with APD (see §2.5) for a block distance of 7,000 km. The following performance has been calculated for a payload at 75% load factor of 46,436 kg:

- Block time: 9 hour and 26 minutes;
- Block fuel used: 39,400 kg;
- Take off weight: 261,155 kg;
- Reserve fuel: 7,807 kg.

The fuel consumption has been reduced compared to the PRESENT400 with 37,886 kg or 49.0%. With respect to the BASE400 the reduction is 29,113 kg

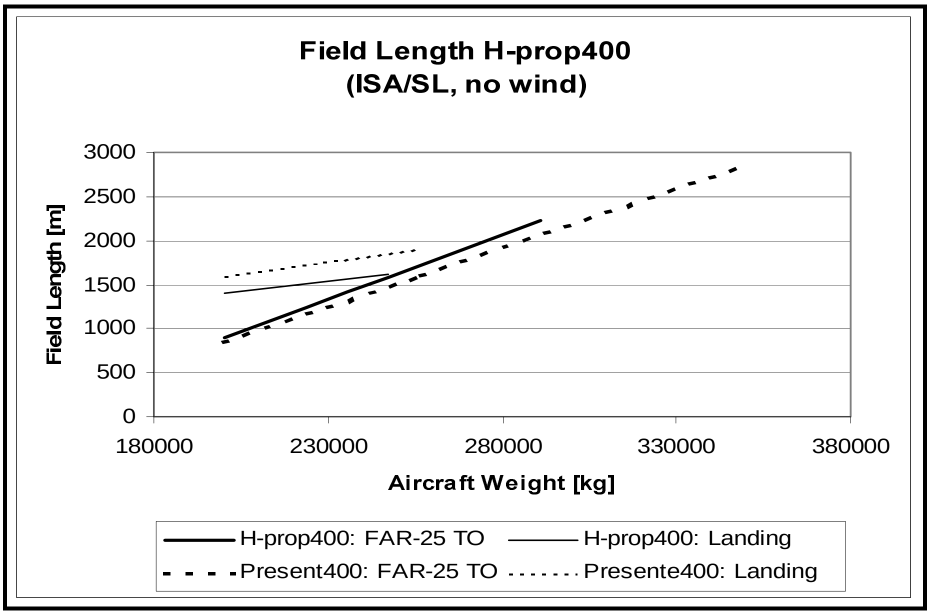
or 42.5%. The aircraft is slower with a 9.9% higher block time. The lowest attainable fuel consumption (at mach 0.66/10,000 m) is almost 53% below the PRESENT400 aircraft.
The payload range capability of the H-PROP400 is given in Figure 71. From this figure it is clear the high fuel economy results in a large range at partial payload. This may slightly enhance operational flexibility of the aircraft. Due to the same fuel economy it is possible to substantially extend the range for full payload at much less cost as will be the case for the PRESENT400 and BASE400. The aircraft is not fuel capacity limited at any point, meaning the fuel capacity might be reduced. This may result in a further empty weight saving of several hundreds of kilograms.

Figure 71 The payload range capability of the long haul H-PROP400 for a standard atmosphere and the standard speed schedule and cruise altitude



The field performance for take off and landing has also been calculated roughly. Figure 72 gives the resulting performance on a standard day, ISA, with no wind and no runway gradient and compares it with the PRESENT400. From this figure it is clear the take off performance is much better at MTOW. For low weights the performance is slightly worse, but in most cases this will not be limiting. The landing performance is remarkably better for all operational weights up to the MLW.

Figure 72 Field length performance of the H-PROP400 for a standard day, ISA, no wind and no runway gradient. The lines are drawn up to MTOW respectively MLW



8.3.6 DOC

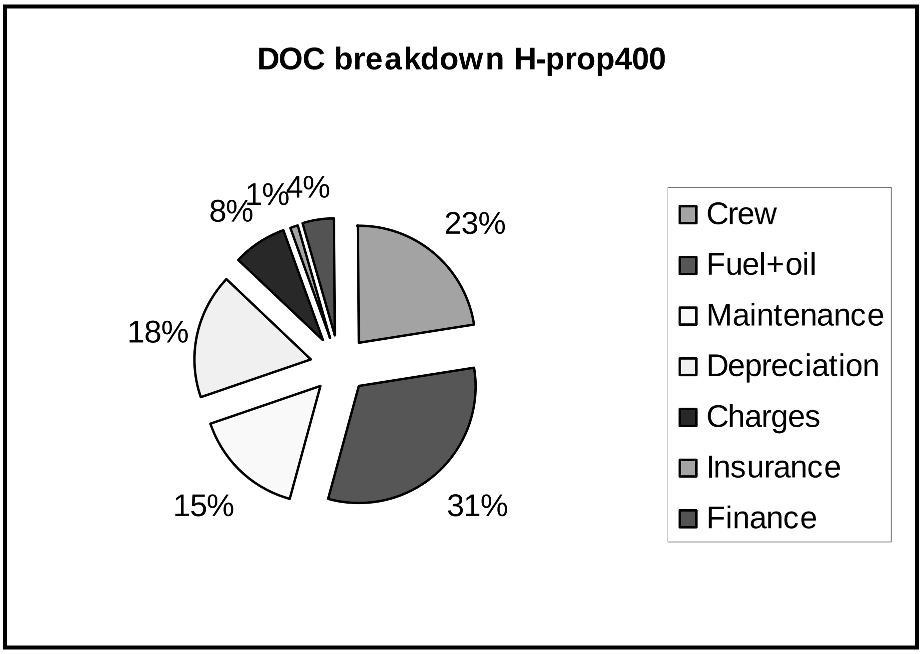
As we designed for a $1.00/kg fuel plus carbon price environment we give the DOC for this situation:

- Total for the flight: $134,237;
- per block hour: $14,225;
- per block kilometre: $19.18;
- per RTK: $0.4130;
- per passenger-km: $0.0615.

The DOC breakdown for $1.00/kg fuel plus carbon price can be found in Figure 73. For the BASE400 the breakdown has a much larger fuel part as is shown in Figure 32.

The DOC (at $1.00/kg fuel plus carbon price) is 23.5% lower compared to for the current aircraft and 18.1% lower compared to the BASE400. At $0.27/kg fuel price the DOC will decrease with 9.3% compared to the PRESENT400, but increase with 5.6% compared to BASE400.

Figure 73 DOC breakdown for the H-PROP400 New design aircraft at $1.00/kg fuel plus carbon price



Conclusion is the total DOC for the new design is at current fuel prices much lower than for the BASE400, mainly due to a saving of over 40% on fuel and a lower cost structure due to the lower weight and lower cruising speed.

8.3.7 Environment

The environmental impact of H-PROP400 in terms of emissions is much less than for the BASE400. All emissions will be reduced by about the same factor as the reduction in fuel consumption.
The noise impact of the aircraft will be influenced by the following:

- The propulsion system has been de-rated with 30% (in terms of static thrust). This will reduce the total noise emissions.
- Sideline noise of the High Speed Propeller Aircraft will be lower compared to the baseline.
- Fly-over noise will be lower, due to the high position of the engines and the lower noise emission of a propeller engine.
- Fly-over noise will increase due to the lower rate of climb: almost 3% lower.

The net effect of these influences will have to be subject of further study, but noise seems to be a moderate point of concern for this design.

8.4 M-PROP150: Medium speed new design with HSP

8.4.1 Combining technologies

To study the influence of design cruise speed on the use of high speed propellers we introduce the M-PROP150. This aircraft will be based on a lower design cruise speed (mach 0.64). This will make the fixed cost part of DOC

more important as well as the cost for crew. Therefore we will try to reduce the airframe and engine cost as much as possible. We assume a high aspect ratio and an aerodynamic clean-up and passive laminar flow control as defined in §6.2 are included into the design. The aspect ratio will be optimised for a $1.00/kg fuel plus carbon price.
Other benefits of a lower speed included are:

- A higher wing thickness ratio for a lower wing weight.
- A lower technology level of the High Speed Propeller as it is used at a lower speed resulting in no engine maintenance cost rise.
- Reduction of airframe price.
- Lower airframe weight and take off weight.
- Lower crew wages (for a slower, lighter aircraft).

All these effects will tend to reduce the non-fuel parts of DOC, bringing the DOC-optimum cruising mach number down to the value better suited for the high speed propeller engine and for use of the high aspect ratio wing.

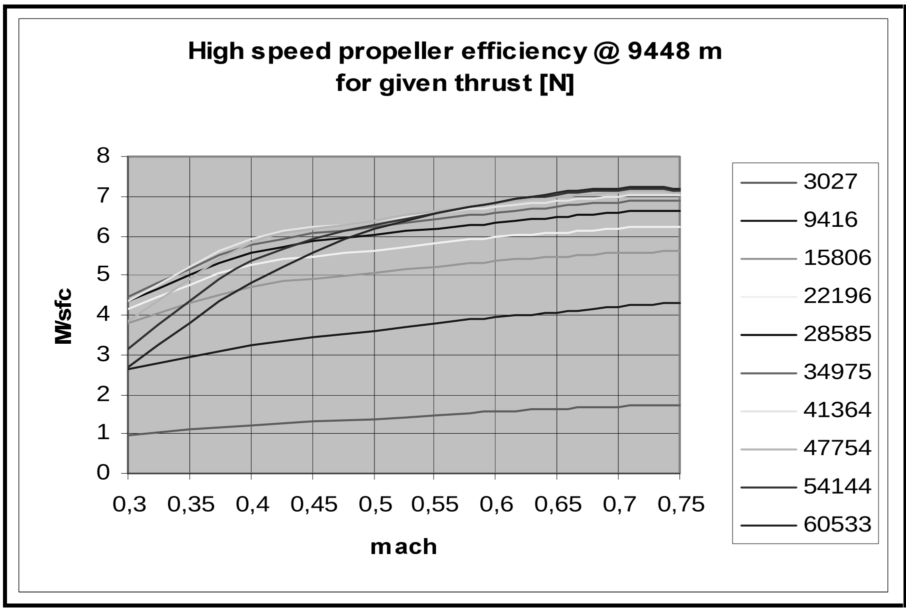
8.4.2 Sizing the aircraft

Design mach number and altitude
First we have to decide to which design speed and cruising altitude we will optimise the aircraft. Two considerations give us some clue for this:

- The design point for the engine
- The effect of wing design on the overall efficiency of the aircraft

The engine overall efficiency has been defined as the ratio of speed (mach number) and specific fuel consumption (s.f.c.) as given by Cumpsty (1997). Figure 60 (see §8.2.2) shows clearly the overall efficiency of the High Speed Propeller engine increases with the available thrust for a given mach number above 0.6. This means we will have to choose an engine as small as possible to get the lowest overall fuel consumption. This effect is exaggerated by the fact, a small engine will have a lower weight and drag penalty. The mach number has not a very large effect on the efficiency, with an optimum between mach 0.65 and mach 0.7 (see Figure 74). This optimum will shift to lower mach numbers if we include the effect of engine weight. By analysing the engine tables it was found altitude does not have much influence on the overall efficiency.

Figure 74 High Speed Propeller overall efficiency as a function of mach number and thrust



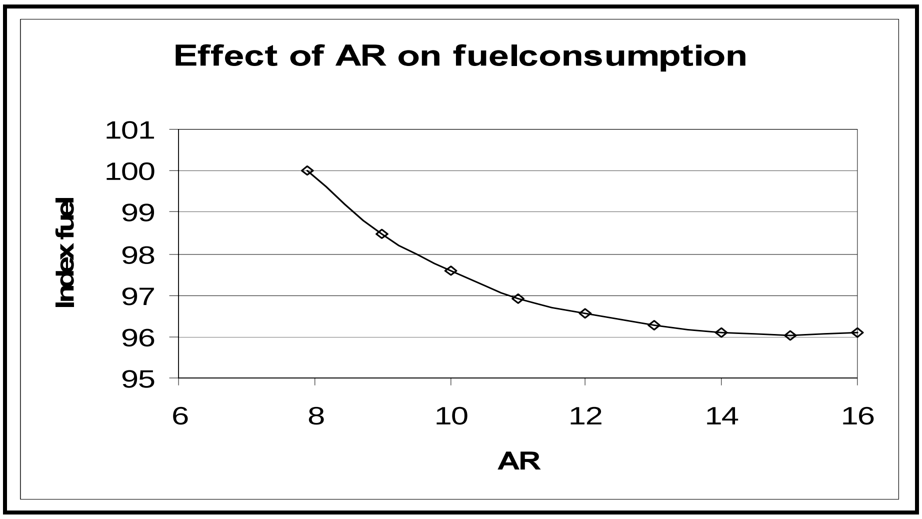
The wing design has many effects on aircraft efficiency. First we have optimised the aspect ratio with respect to the SH_HAR variant. We have optimised power loading and wing area for cruise with the TO distance as a lower limit (TO distance may not grow above the value of the PRESENT150). The decrease in MTOW and increase in maximum lift coefficient (due to reduction of the sweep angle and increase of the airfoil thickness ratio) did allow for a 10% down sized engine. However, this engine limits the aircraft altitude and speed capability: maximum practical cruising mach number and altitude with this engine size is 0.65/9,000 m. The design point has therefore been chosen at mach 0.64/9,000 m. A trade-off between engine size, engine cost, parasite drag and propulsion group weight might result in a solution different from the one chosen here. To check for this also a design has been worked out for mach 0.6, but this turned out to be slightly less fuel efficient. As the DOC is also higher for this latter case, mach 0.64, seems to be some kind of optimum.

Wing Aspect ratio
The wing aspect ratio influences the induced drag and the wing weight. Increasing the wing aspect ratio means decreasing this induced drag, but also increasing the wing weight. This extra weight will increase fuel consumption.
The wing weight does also depend on the wing thickness ratio: the weight will reduce with increasing thickness ratio. However: the mach drag will also increase (much) with increasing thickness ratio. This latter effect is influenced by two parameters:
- Type of wing section;
- Wing sweep angle.

The type of wing section for a high subsonic aircraft will have been optimised for the lowest mach drag or the highest attainable M_{DD}. The problem is a high subsonic airfoil is generally less suitable for laminar flow. As we have reduced the speed for the M-PROP150 we will emphasise the laminar characteristics and consider the high subsonic characteristics less important. This means increased mach drag for a given mach number but lower parasite drag because of a longer sustained laminar flow on the wing. For a rela-

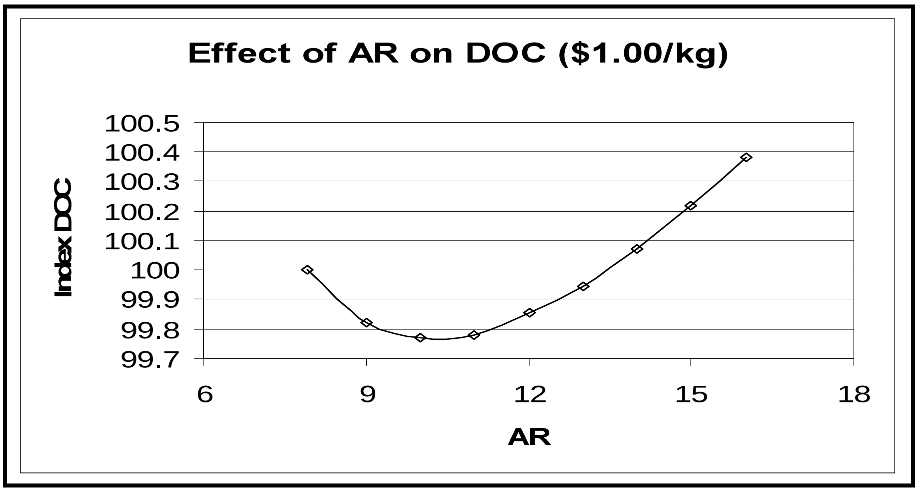
tively low cruising speed it is expected this will result in the lowest cruise drag.
First we have calculated the direct effect of the AR on the fuel consumption by just changing AR. The figures calculated directly with APD are corrected for the effect of wing aspect ratio on wing weight (55 kg extra fuel for every 1,000 kg increase in empty weight). Figure 75 gives the results on fuel consumption.

Figure 75 The effect of AR on fuel consumption for an initial version of M-PROP150



From Figure 75 it is clear the fuel optimum aspect ratio is 15. To find the DOC optimum we used trends for the influence of weight on aircraft price and DOC and created Figure 76 for the high fuel plus carbon price of $1.00/kg.

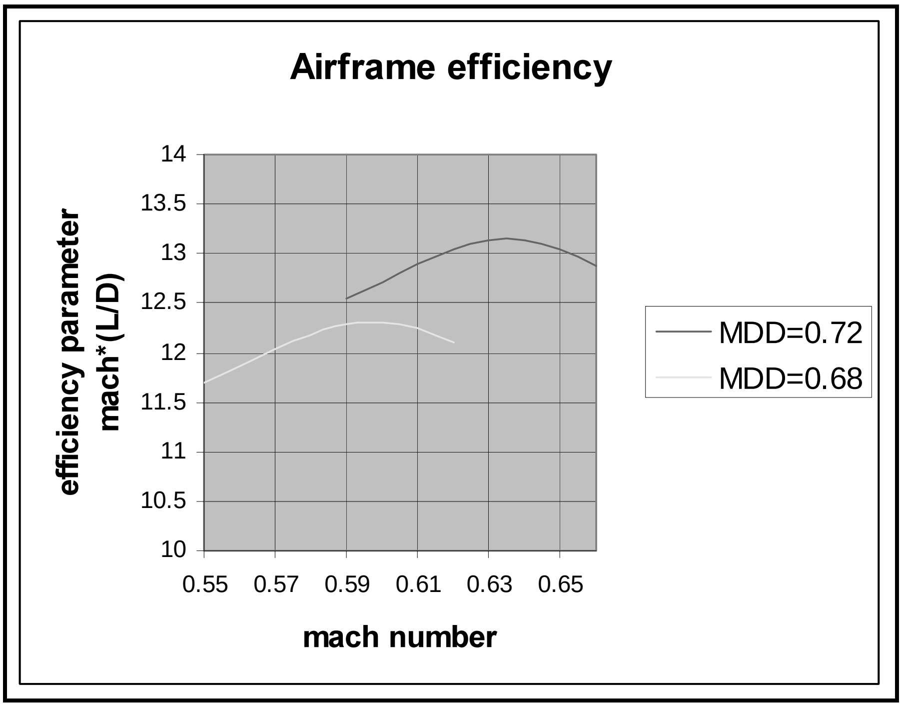
Figure 76 Effect of AR on DOC for a fuel plus carbon price of $1.00/kg



From this figure it is clear an AR of between 10 and 11 has a DOC optimum. However, the effect on DOC is small (some tenths of percents). The effect on fuel consumption is about five times as large. Therefore we have chosen for AR=12.

What maximum speed (M_{DD}) will we have to choose for a design speed of mach 0.64? A first indication for this can be found from the airframe efficiency parameter {mach*(L/D)}. As Figure 77 shows the highest airframe efficiency is reached at mach 0.08 below the M_{DD}. With a design mach number of 0.64 this means a M_{DD} of 0.72. However, the optimum speed for lowest DOC is always somewhat higher than for lowest fuel consumption. To save on aircraft cost and weight and to allow for a smaller wing and better laminar flow performance of the wing section it may be desirable to define a lower M_{DD}. First we have chosen a wing thickness ratio of 0.12 to be optimum as it gives the best possibilities for a laminar, high maximum lift airfoil section. Therefore the combination of the wing sweep and M_{DD} has been chosen such that the wing thickness ratio becomes 0.12. The optimum was found at a M_{DD} /sweep combination of 0.71/18°. A lower M_{DD} increases the mach drag at the design cruise-speed and requires a larger wing. A higher MDD asks for a large sweep angle, causing the take off parameter to decrease and thus also requiring a larger wing area.

Figure 77 Airframe efficiency parameter as a function of mach number and M_{DD} (excluding the effect of the possibilities of laminar flow with a lower M_{DD})



Now we can define the wing as follows:

- Sweep back angle reduced from 26° to 18°;
- M_{DD} reduced from 0.82 of the PRESENT150 to 0.71;
- The use of a conventional (partly laminar) wing section (M_{str}=1.00).

This resulted into a thickness ratio of 12.0% for M-PROP150, where the PRESENT150 has 9%.

Wing area
With an iteration we have determined wing area. The wing area is sized for optimum cruise performance, but with TO performance as a constraint. For the iteration following assumptions apply to the M-PROP150:

- Design cruising mach number is 0.64;

- Reduce cruising altitude from 10,000 m to 9,000 m;
- Cruising weight is the mean weight found iteratively for the evaluation flight of 1,000 km at 70% load factor (47,510 kg).

The final wing area has been determined by the optimum cruising condition. From the calculations it appeared the wing area must be increased for optimum cruise performance. Further the use of a conventional airfoil with emphasis on natural laminar flow has been assumed. Summarising the following wing dimensions apply (between parenthesis the baseline value):

- Wing area: 109.5 m^2 (105.4 m^2);
- Wing aspect ratio: 12 (7.9);
- Wing sweep back angle (quarter chord): 18° (26°);
- Wing thickness ratio: 0.12 (0.09);
- Wing Span: 36.25 m (28.88 m);
- Thickness of mean chord: 0.361 m (0.329 m);
- Taper ratio is 0.25 (0.239).

Aerodynamics

With the help of the Mathcad sheet for parasite drag calculation based on the flat plate analogy and corrected for the baseline drag polar the influence of a change of dimensions for the empennage, fuselage, struts, nacelles and wing area have been determined. A factor has been used (0.9) to account for effect of aerodynamic clean-up and passive laminar flow control. The final result is a reduction of the parasite drag coefficient for clean cruising configuration with 13% (and a decrease of the total drag area with 9%) .

Engine

It appeared the engine could be scaled down to 90% of the original small engine defined by ADSE (ADSE, 1999) with 8,200 shp TO power. This value has been used to scale the engine parameters with a method given by Raymer (1992), but with the scaling coefficients fitted for the two engines given by ADSE (1999):

- TO rating: 7,380 SHP;
- TOC rating: 4,500 SHP;
- Prop diameter: 11.69 ft;
- Number of blades: 2*6;
- Activity factor: 120;
- Core engine length: 2.208 m;
- Engine diameter: 0.777 m;
- Nacelle length: 5.47 m;
- Nacelle diameter: 1.55 m;
- Weight including system, nacelle and propeller: 2,546 kg;
- Removal of thrust reversers.

From a short analysis it was found the propeller tip speed is of no concern at a design mach number of only 0.64. It will stay far below mach 0.95.

8.4.3 Weights

The empty weight as well as the operational weights (MTOW, MLW) have been calculated with a reduction of the fuel consumption of 50.5%. This reduction is the result of the High Speed Propeller, the high aspect ratio wing and the lower drag and weight due to the smaller engine. To find this value the calculation has been iterated because a lower weight gives a larger reduction of fuel consumption, which in itself may reduce the weight. Further the higher engine weight of the High Speed Propeller is accounted for as well as the new dimensions for nacelles, wings and the removal of thrust reversers. The final result of this iteration is a total empty weight decrease of 779 kg with respect to the PRESENT150 aircraft. The following weights now result:

- MRW: 56,431 kg;
- MTOW: 56,201 kg;
- MLW: 54,106 kg;
- MZFW: 50,476 kg;
- OEW: 33,785 kg;
- EW: 30,951 kg.

8.4.4 Airframe and engine price

The engine price has been scaled down with the help of the method of Roskam (Part VIII, 1990). From this calculation the engine price goes down from $3,100,000 to $2,792,000.
The airframe price has been calculated using the aircraft price Mathcad sheet with the following assumptions:

- The investment is written off over 485 aircraft;
- The replaced structure weight (empty weight minus the engines) is 27,758 kg;
- The new structure weight is 26,533 kg;
- Airframe maintenance hours increase with 10% due to retaining the lower parasite drag during normal day-to-day operation;
- The maximum speed M_{DD} has been reduced from mach 0.82 to mach 0.71.

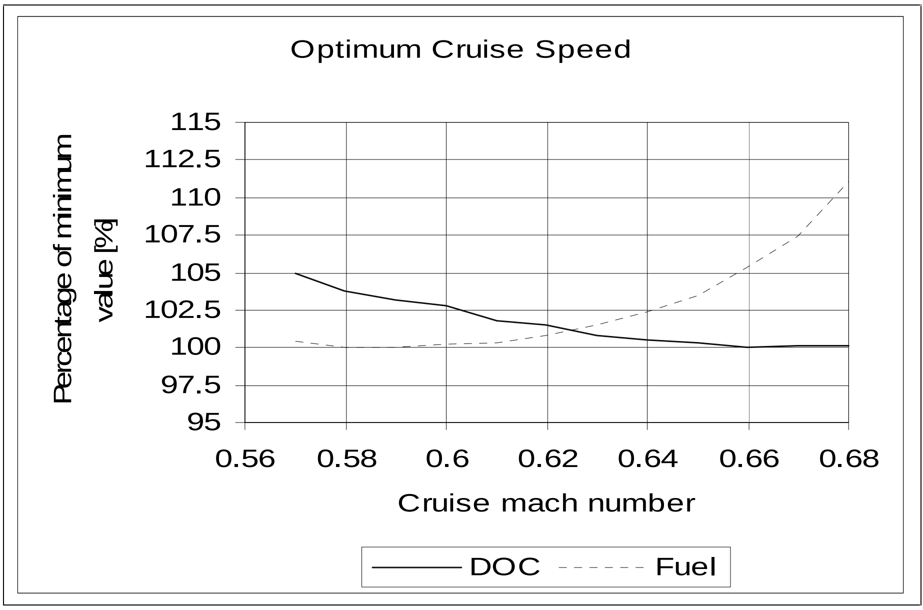
These assumptions give a final airframe price decrease of $2,570,000 to a price of $35,230,000. The engine maintenance cost has been kept the same as for the baseline, because the High Speed Propeller is used now at lower speeds than in the example given by ADSE (1999).
The airframe maintenance hours have been increased with 10% due to the introduction of the laminar wing section. Further the flight crew wages depend on cruising speed and MTOW (Raymer, 1992). As the cruising speed reduces from 0.745 to 0.64 and the MTOW from 62,820 kg to 56,201 kg the wages will be 7.6% lower.

8.4.5 Performance

Before calculating the performance the DOC-and fuel-optimum flight profiles have been redefined. It turned out from calculations the cruising altitude of 9,000 m is practically the limit for the optimum cruising mach number. From Figure 78[24] we find the fuel optimum speed is mach 0.58 while the DOC optimum comes to 0.66. This value is also near to the limit for the current size of the engine. Therefore the design point will be used (mach 0.64), loosing 0.5% on DOC but saving 3% on fuel compared with mach 0.66.

[24] The irregular shape of this figure is caused by the step-wise increase of the climb CAS speed schedule.

Figure 78 Optimising the speed schedule (cruise mach number) for the M-PROP150 aircraft for the $1.00/kg fuel plus carbon price market



The following assumptions have been made, based on a performance slightly below the DOC optimum:

- Take off and Ground manoeuvring:
  - 26 minutes at 7% MTO engine rating (all fuel weight for taxi is pre-TO);
  - Take off 0.7 minutes at 100% MTO rating;
  - Climb-out from 35 ft to 3,000 ft at 85% MTO rating; climb-out time is 2.2 minutes;
- Operational Climb:
  - Speed schedule 250 kCAS/0.64;
  - Max climb engine rating;
- Operational Cruise:
  - Long range speed (mach 0.64);
  - Cruise altitude 9,000 m;
- Operational descent:
  - Speed schedule: 0.64/250 kCAS;
  - Thrust set for maximum cabin rate of descent (300 ft/minute and maximum cabin altitude 6,000 ft);
- Approach and landing:
  - Approach from 3,000 ft to SL at 71.4 m/s TAS (Jane's, 1998);
  - Approach time 4 minutes at 30% MTO rating;
- Reserves:
  - Go around from 3,000 ft at destination;
  - Flight to alternate at 200 NM with flight speed schedule, but at 8,000 m cruising altitude;
  - 30 minutes hold as extended cruise.

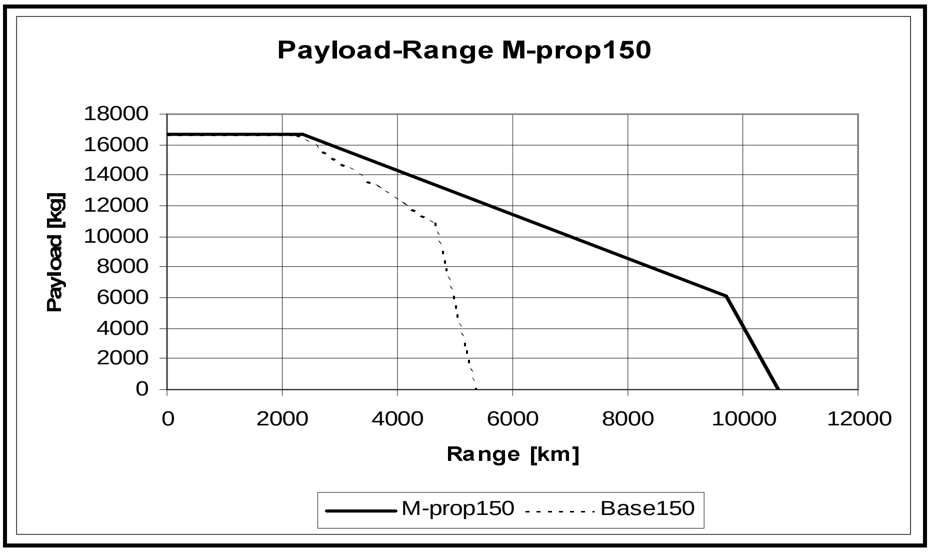
The Evaluation flight for Short Haul has been calculated with APD (see §3.8) for a block distance of 1,000 km. The following performance has been calculated for a payload at 70% load factor of 11,684 kg:

- Block time: 2 hours and 4 minutes;
- Block fuel used: 1,943 kg;
- Take off weight: 48,785 kg;

- Reserve fuel: 1,373 kg.

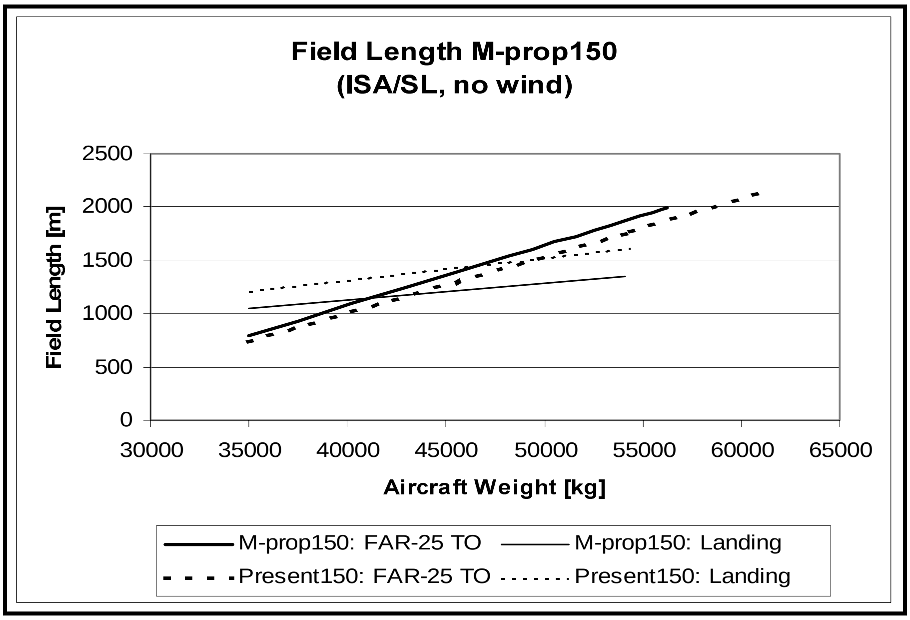
The fuel consumption has been reduced to the PRESENT150 with 2,008 kg or 50.8%. With respect to the BASE400 the reduction is 1,648 kg or 45.9%. The aircraft is slower with a 10.1% higher block time. The lowest attainable fuel consumption (for mach 0.58/9,000 m) is almost 52% below PRESENT150.
The payload range capability of the M-PROP150 is given in Figure 79. From this figure it is clear the high fuel economy results in a large range extension at partly loaded payloads. This may enhance flexibility of the aircraft. Due to the same fuel economy it is possible to extend range for full payload substantially at much less extra cost as will be the case for the Base150.

Figure 79 The payload range capability of the short haul M-PROP150 aircraft with high speed propeller engines for a standard atmosphere and the standard speed schedule and cruise altitude



The field performance for take off and landing has also been calculated roughly. Figure 80 gives the resulting performance on a standard day, ISA, with no wind and no runway gradient and compares it with the PRESENT150. From this figure it is clear the take off performance is slightly better at MTOW. For low weights the difference is negligible. The landing performance seems better for all operational weights up to the MLW.

Figure 80 Field length performance of the M-PROP150 with high speed propeller engines for a standard day, ISA, no wind and no runway gradient. The lines are drawn up to the actual MTOW and MLW



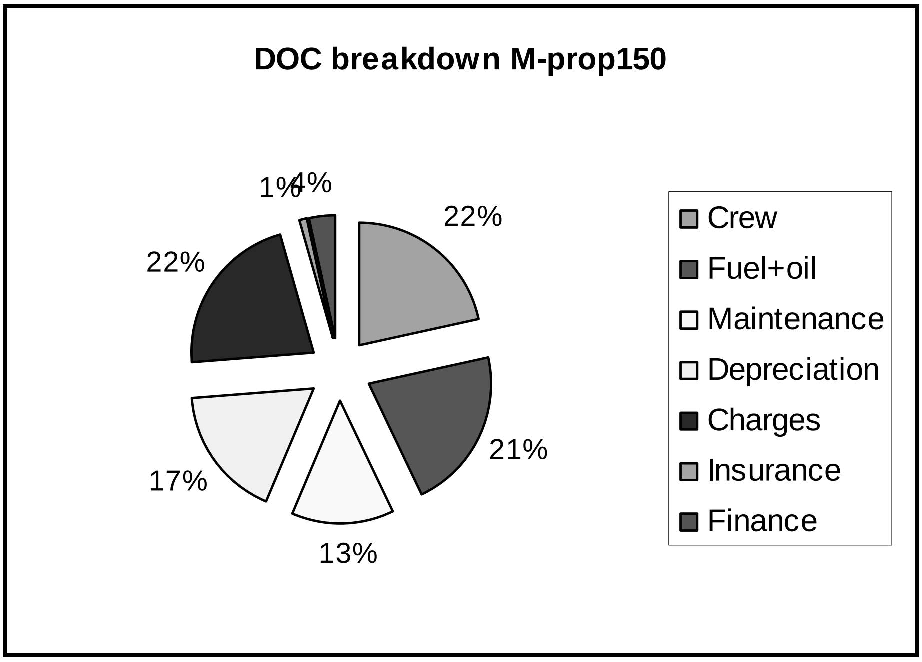
8.4.6 DOC

The break-even fuel plus carbon price is remarkably much lower than the current fuel plus carbon price: $0.103/kg (with respect to the BASE150). As we designed for a $1.00/kg fuel plus carbon price environment we give the DOC for this situation:

- Total for the flight: $9,584;
- per block hour: $4,634;
- per block kilometre: $9.584;
- per RTK: $0.820;
- per passenger-km: $0.0938.

The DOC breakdown for $1.00/kg fuel plus carbon price can be found in Figure 81. The DOC (at $1.00/kg fuel plus carbon price) is 18.8% lower compared to the PRESENT150 and 14.7% lower compared to BASE150. At $0.27/kg fuel price the DOC will decrease with 6.4% compared to the PRESENT150 and with 3.6% compared to the BASE150.

Figure 81 DOC breakdown for the M-PROP150 New design aircraft at $1.00/kg fuel plus carbon price



Conclusion is the total DOC for the new design might be much lower than for the BASE150, mainly due to a saving of over 45% on fuel and lower cost structure due to the lower weight, relatively small engine and lower cruising speed.

8.4.7 Environment

The environmental impact of M-PROP150 in terms of emissions is much less than for the baseline. All emissions will be reduced at least by about the same factor as the reduction in fuel consumption. The emissions of NOx may even be reduced more, as the pressure ratio and the turbine temperatures in the HSP engine will be somewhat lower than for an ultra-high bypass engine. Anon. (1997) gives a difference of specific NO_x emissions per kg fuel of about 1 to 1.8 for Propfan to UHB. The noise impact of the aircraft will be influenced by the following:

- The propulsion system has been derated with about 25% (in terms of static thrust). This will reduce the noise emissions.
- Sideline noise of the High Speed Propeller Aircraft may be lower compared to the baseline
- Fly-over noise will be lower, due to the high position of the engines and the lower noise emission of a propeller engine.
- Fly-over noise will increase due to the 23% lower initial rate of climb.

The net effect of these is probably an increase in noise impact of M-PROP150. How much this increase will be and if the aircraft will apply to current noise regulations can be determined only with further study.

8.5 M-PROP400: Medium speed new design with HSP engines

8.5.1 Combining technologies

Also in this case we will try to reduce the design cruise speed further to enhance the fuel efficiency, without sacrificing DOC. Benefits of a lower speed are:

- General reduction of airframe price.
- A higher wing thickness ratio for a lower wing weight.
- A lower technology level of the High Speed Propeller as it is used at a lower speed resulting in no engine maintenance cost rise.
- Lower airframe weight and take off weight.
- Lower crew wages (for a slower, lighter aircraft).

All these effects will tend to reduce the non-fuel parts of DOC, bringing the DOC-optimum cruising mach number down to the value better suited for the High Speed Propeller engine and for use of the High Aspect ratio wing, which must be thicker and have less wing sweep.
The cost-effectiveness of a technology will in general be higher on fast aircraft than on slower examples. As the Mprop400 is rather slow we have decided not to use active LFC or the extensive use of new materials, because these will probably not be cost-effective. The parasite drag is reduced by introducing laminar wing profiles.
Wing loading is optimised for cruise and then power loading has been optimised for cruise without letting the TO distance grow over the current value: the decrease in MTOW and increase in maximum lift coefficient due to the high aspect wing allow for a lower maximum TO power rating.

8.5.2 Sizing the aircraft

Design mach number and altitude
In a full-scale design sizing study we would try to fit many more parameters of the aircraft design to the presumed high fuel plus carbon price of $1.00/kg as we are able to do within the scope of this study. First we have to decide to which design speed and cruising altitude we will optimise the aircraft. Two considerations give us some clue for this:

- The design point for the engine;
- The effect of wing design on the overall efficiency of the aircraft.

The engine overall efficiency has been defined as the ratio of speed (mach) and specific fuel consumption (s.f.c.) as given by Cumpsty (1997). Figure 60 in §8.2.2 shows clearly the overall efficiency of the High Speed Propeller engine increases over the full range with the available thrust for mach numbers above 0.6. This means we will have to choose an engine as small as possible to get the lowest overall fuel consumption. This effect is exaggerated by the fact, a small engine will have a lower aircraft weight and drag penalty[25].
The mach number has not a very large effect on the efficiency, with an optimum between mach 0.65 and mach 0.7 (see Figure 74 in §8.4.2). Again, this optimum will shift to lower mach numbers if we include the effect of engine weight. By analysing the engine tables it was found altitude does not have

[25] But the scale effect on s.f.c. makes the optimal engine size larger, see subparagraph Engine.

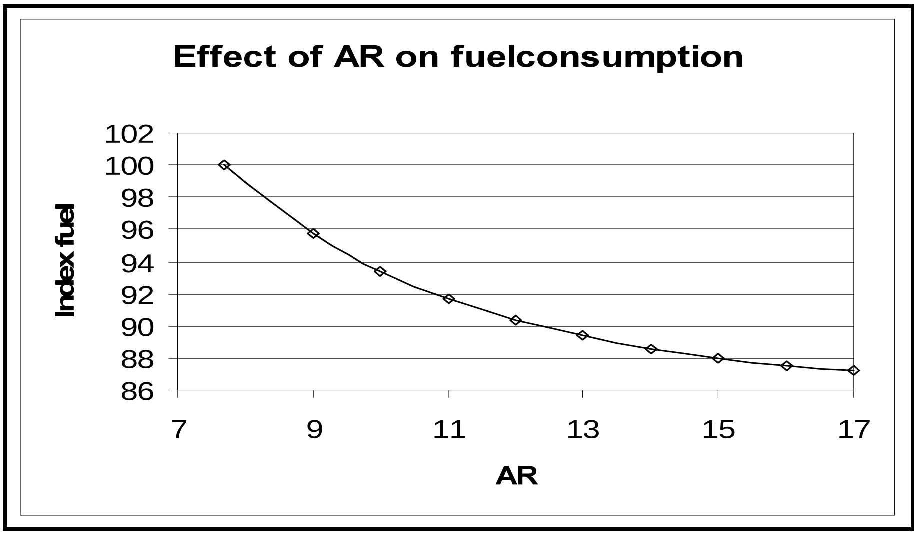
much influence on the overall efficiency. As speed has a major influence on final DOC for the long haul market, we will choose a value at the high end: mach is 0.70 at an altitude of 9500 m.

Wing Aspect ratio
The wing design has many effects on aircraft efficiency. First we have optimised the aspect ratio with respect to the LH_HAR variant. We have optimised power loading and wing area for cruise with the TO distance as a lower limit (TO distance may not grow above the value of the BASE150).
The design point has been chosen at mach 0.70 and 9500 m. A trade-off between engine size, engine cost, parasite drag for nacelles and propulsion group weight might result in a solution different from the one chosen here.
The wing aspect ratio influences the induced drag and the wing weight. Increasing the wing aspect ratio means decreasing this induced drag, but also increasing the wing weight. This extra weight will increase fuel consumption. The wing weight does also depend on the wing thickness ratio: the weight will reduce with increasing thickness ratio. However: the mach drag will also increase (much) with increasing thickness ratio. This latter effect is influenced by two other parameters:

- Type of wing section;
- Wing sweep angle.

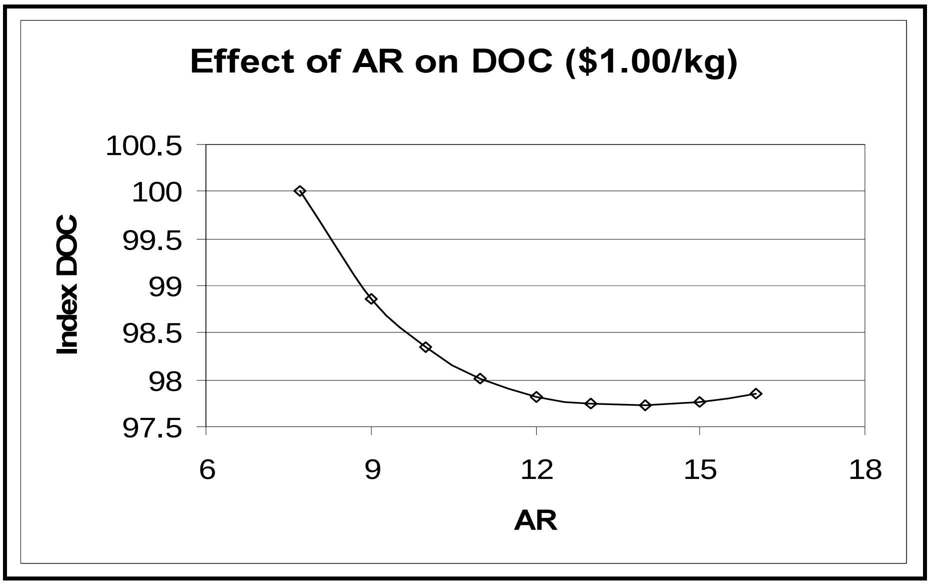
The type of wing section for a high subsonic aircraft will have been optimised for the lowest mach drag or the highest attainable M_{DD}. As a high subsonic airfoil is less suitable for laminar flow and we have reduced the speed for the M-PROP400 we will emphasise on the laminar characteristics and consider the high subsonic characteristics less important. This means increased mach drag for a given mach number but lower parasite drag because of a longer sustained laminar flow on the wing. For a relatively low cruising speed it is expected this will result in the lowest cruise drag.
First we have calculated the direct effect of the AR on the fuel consumption by just changing the AR. The figures calculated with APD are corrected for the effect of wing aspect ratio on wing weight (118,5 kg extra fuel for every 1,000 kg increase in empty weight). Figure 82 gives the results on fuel consumption.

Figure 82 The effect of AR (including the effect on Oswald's factor e) on fuel consumption for a given M_{DD}=0.72



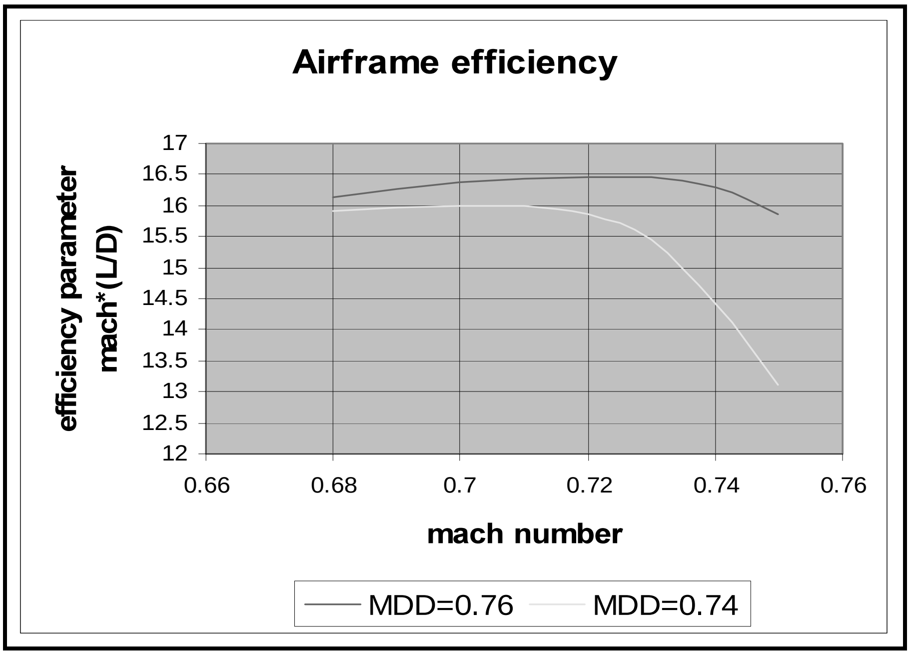
From Figure 82 it is clear the fuel optimised aspect ratio is even larger than 17. But the higher the aspect ratio the more expensive the wing will become. The airframe cost effect on DOC is stronger than the wing weight effect on fuel consumption so the DOC optimum AR is lower as can be seen from Figure 83 for the high fuel plus carbon price of $1.00/kg.

Figure 83 Effect of AR on DOC for a fuel plus carbon price of $1.00/kg



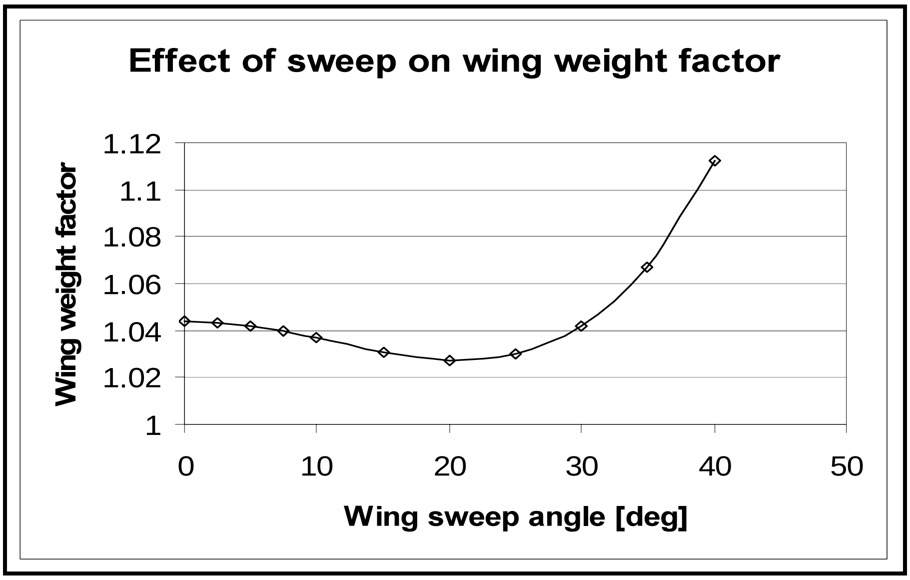
From this figure it is clear an AR of between 13 and 15 has a DOC optimum. We have chosen for AR=14.
What maximum speed (M_{DD}) will we have to choose for a design speed of mach 0.70? This can be found from the airframe efficiency parameter {mach*(L/D)}. As Figure 84 shows the highest airframe efficiency is reached at mach 0.04 below the M_{DD}. With a design mach number of 0.70 this means a M_{DD} of 0.74.

Figure 84 Airframe efficiency parameter as a function of mach number and M_{DD}



The sweep back angle of the wing will be chosen for minimum wing weight. The optimum sweep angle is 21□ as can be seen in Figure 85.

Figure 85 Effect of wing sweep on wing weight factor for the M-PROP400 (AR=13, M_{DD}=0.76)



Now we can define the wing design as follows:

- Sweep back angle reduced from 39.5° to 21°;
- M_{DD} reduced from 0.88 of the baseline to 0.74;
- The use of a conventional (partly laminar) wing section (M_{str}=1.00);
- A thickness ratio of 10.6% for M-PROP400, where the PRESENT400 has 8%.

Engine
It appeared the engine could be scaled down from 3.0 times the original value (as for the LH-HSP) to 2.1 times (so with 30%). To scale the fuel flow we have assumed the difference between the short haul UHB and the short haul High Speed Propeller engine is valid also for the long range case, because in both cases the same core engine may be used. As the BPR for both UHB engines is assumed to be equal, the resulting difference in s.f.c. must be a result of scale effects and general design differences in the core engines. These considerations resulted into a scale factor of (rounded conservatively) 0.60 on fuel flow.
Scaling the engine with a factor 2.1 using a method given by Raymer (1992), but with the scaling coefficients fitted for the two engines given by ADSE (1999) resulted into the following engine parameters:

- TO rating: 17,210 SHP;
- TOC rating: 10,500 SHP;
- Propeller diameter: 14.446 ft;
- Cruise propeller rotational speed: 850 rpm;
- Number of blades: 2*6;
- Activity factor: 120;
- Core engine length: 3.067 m;
- Engine diameter: 0.986 m;
- Nacelle length: 7.576 m;
- Nacelle diameter: 2.032 m;
- Weight including system, nacelle and propeller: 5,472 kg.

From a short analysis it was found the propeller tip speed is of no concern at a design mach number of 0.70. It will stay below mach 0.95.

Wing area
With an iteration we have determined wing area and aerodynamics. After estimating the aerodynamic effects (see the next paragraph titled 'Aerodynamics') we will have to resize wing area and power loading. The wing area is sized for optimum cruise performance. To find the new wing area S_{ref} following assumptions apply for the M-PROP400:

- Design cruising mach number is 0.70;
- Reduce cruising altitude from 11,000 m to 9,500 m;
- Cruising weight is the mean weight found iteratively for the evaluation flight of 7,000 km at 75% load factor (232,903 kg).

The final wing area has been determined by the optimum cruising condition. From the calculations it appeared the wing area may be decreased for optimum cruise performance. Further the use of a conventional airfoil with emphasis on natural laminar flow has been assumed. Summarising the following wing dimensions apply (between parenthesis the baseline value):

- Wing area: 490.0 m^2 (541.16 m^2);
- Wing aspect ratio: 14 (7.7);
- Wing sweep back angle (quarter chord): 21° (39.5°);
- Wing thickness ratio: 0.106 (0.08);
- Wing Span[26]: 82.83 m (64.44 m);
- Thickness of mean chord: 0.627 m (0.671 m);
- Taper ratio is 0.25 (0.239).

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26 This wingspan is larger as the ICAO 80*80 m^2 maximum box for airports and will require special measures to recieve this aircraft on many airports.

Aerodynamics
With the help of the Mathcad sheet for parasite drag calculation based on the flat plate analogy and corrected for the drag polar of the PRESENT400 the influence of a change of dimensions for the empennage, fuselage, struts, nacelles and wing area have been determined. Further the laminar flow on wings and empennage has been increased, due to the introduction of airfoil sections better suited for medium cruising speeds. The final result is a reduction of the parasite drag coefficient for clean cruising configuration with 3% (and a decrease of the total drag area with 12%) .

8.5.3 Weights

The empty weight as well as the operational weights (MTOW, MLW) have been calculated with a reduction of the fuel consumption of 54%. This reduction is the result of the High Speed Propeller, the high aspect ratio wing and the lower drag and weight due to the smaller engine and the new airfoil. To find this value the calculation has been iterated because a lower weight gives a larger reduction of fuel consumption, which in itself will reduce the weight. Further the new engine weight of the High Speed Propeller is accounted for as well as the new dimensions for nacelles, wings and the removal of thrust reversers. The final result of this iteration is a total empty weight decrease of 16973 kg with respect to the PRESENT400. The following weights now result:

- MRW: 282,351 kg;
- MTOW: 280,991 kg;
- MLW: 243,387 kg;
- MZFW: 225,697 kg;
- OEW: 163,782 kg;
- EW: 154,463 kg.

8.5.4 Airframe and engine price and other cost factors

The engine price has been scaled down with the help of the method of Roskam (Part VIII, 1990). From this calculation the engine price goes down from $5,400,000 to $4,624,000.
The airframe price has been calculated using the aircraft price Mathcad sheet with the following assumptions:

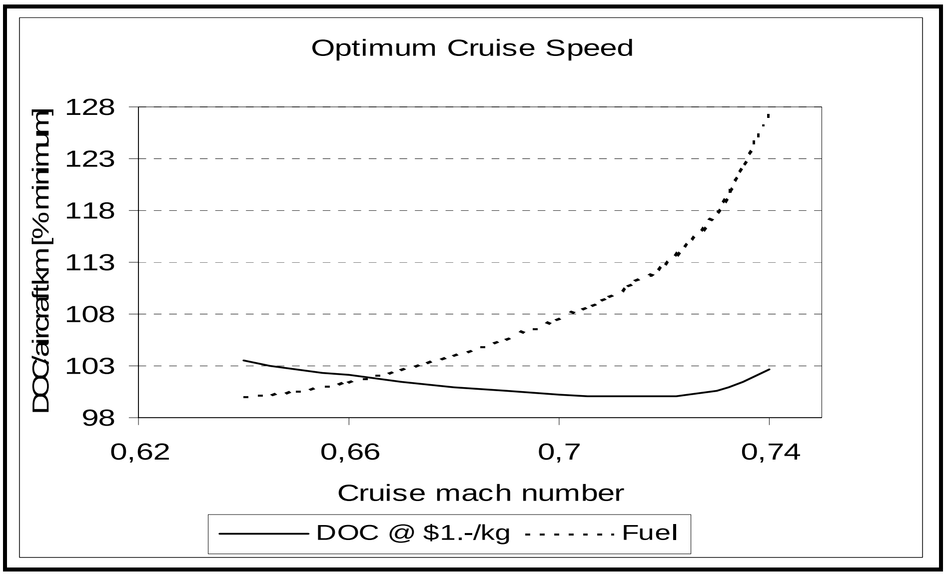
- The investment is written off over 450 aircraft (it is a totally new design)
- The replaced structure weight (empty weight minus the engines) is 154,200 kg
- The new structure weight is 136,316 kg
- The maximum speed M_{DD} has been reduced from mach 0.88 to mach 0.74.

These assumptions give a final airframe price decrease of $22,336,000 to a price of $126,064,000. The engine maintenance cost parameters have been kept the same as for the baseline, because the High Speed Propeller is used now at lower speeds than the example given by ADSE (1999) and the engine is smaller.
The airframe maintenance hours have been increased with 10% due to the introduction of the laminar flow control.
The flight crew wages depend on cruising speed and MTOW (Raymer, 1992). As the cruising speed reduces from 0.84 to 0.70 and the MTOW from 362,875 kg to 280,991 kg the wages will be 12.3% lower.

8.5.5 Performance

Before calculating the performance the DOC-and fuel-optimum flight profiles have been redefined primarily to check if the design cruise mach number really turns out to be the optimum value. From Figure 86[27] we find the fuel optimum speed is below mach 0.64 while the DOC optimum for a fuel plus carbon price of $1.00/kg comes to 0.71. This value is quite near to the design value of mach 0.70. With higher mach numbers the fuel consumption will rise considerably.

Figure 86 Optimising the speed schedule (cruise mach number) for the M-PROP400 aircraft for the $1.00/kg fuel plus carbon price market



The following assumptions have been made, based on a performance slightly below the DOC optimum:

- Take off and Ground manoeuvring:
  - 26 minutes at 7% MTO engine rating (all fuel weight for taxi is pre-TO);
  - Take off 0.7 minutes at 100% MTO rating;
  - Climb-out from 35 ft to 3,000 ft at 85% MTO rating; climb-out time is 2.2 minutes;
- Operational Climb:
  - Speed schedule 270 kCAS/0.70;
  - Max climb engine rating;
- Operational Cruise:
  - Long range speed (mach 0.70);
  - Cruise altitude 9,500 m;
- Operational descent:
  - Speed schedule: 0.70/270 kCAS;
  - Thrust set for maximum cabin rate of descent (300 ft/minute and maximum cabin altitude 6,000 ft);
- Approach and landing:
  - Approach from 3,000 ft to SL at 71.4 m/s TAS (Jane's, 1998);
  - Approach time 4 minutes at 30% MTO rating;

[27] The irregular shape of this figure is caused by the step-wise increase of the climb CAS speed schedule.

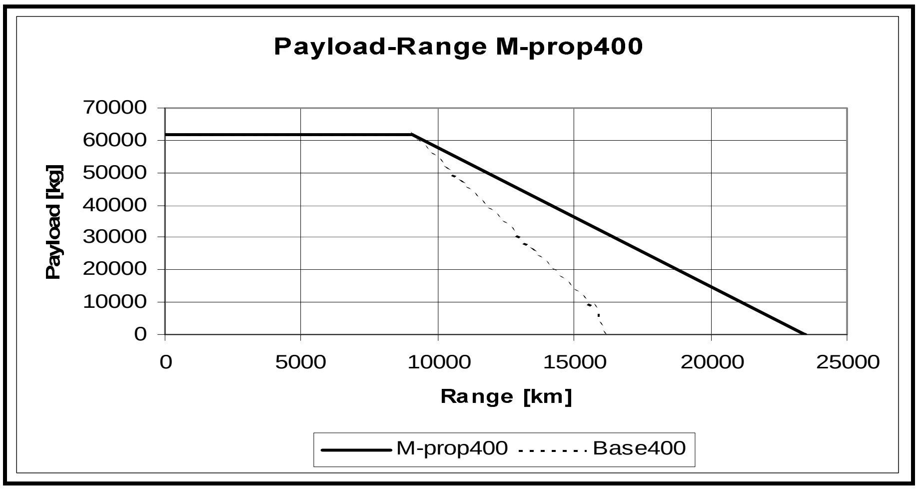
- Reserves:
    - 120 minutes hold as extended cruise.

The evaluation flight for Long Haul has been calculated with APD (see §2.5) for a block distance of 7,000 km. The following performance has been calculated for a payload at 75% load factor of 46,436 kg:

- Block time: 9 hour and 53 minutes;
- Block fuel used: 34,779 kg;
- Take off weight: 251,671 kg;
- Reserve fuel: 6,654 kg.

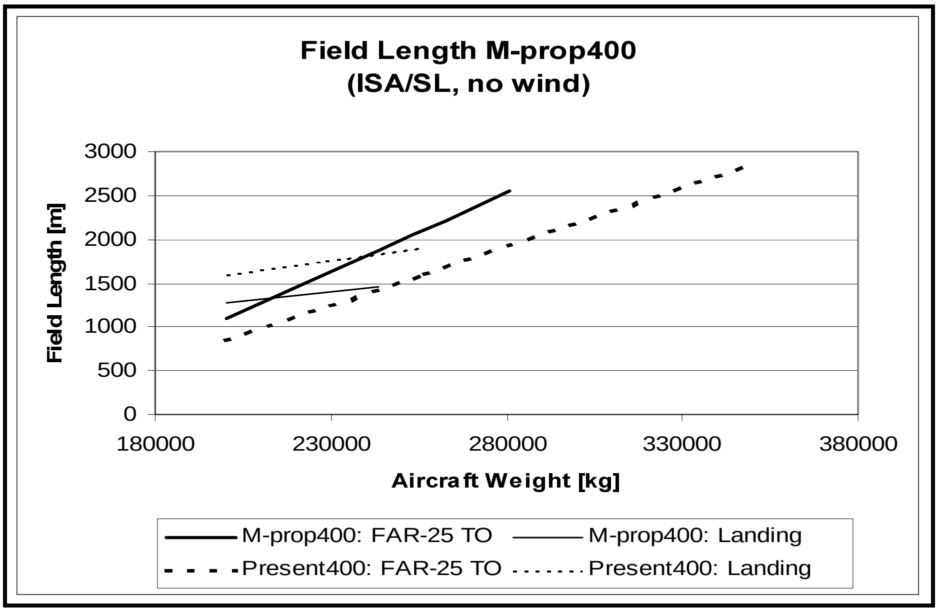
The fuel consumption has been reduced compared to the PRESENT400 with 42,469 kg or 55.0%. With respect to the BASE400 the reduction is 33,741 kg or 49.2%. The aircraft is slower with a 16.1% higher block time. The lowest attainable fuel consumption (at mach 0.63/9500 m) is almost 60% below the PRESENT400 aircraft.
The payload range capability of the M-PROP400 is given in Figure 87. From this figure it is clear the high fuel economy results in a large range at partial payload. This may slightly enhance operational flexibility of the aircraft. Due to the same fuel economy it is possible to substantially extend the range for full payload at much less cost than will be the case for the PRESENT400 and BASE400 The aircraft is not fuel capacity limited at any point, meaning the fuel capacity might be reduced. This would result in an empty weight saving of several hundreds of kilograms.

Figure 87 The payload range capability of the long haul M-PROP400 for a standard atmosphere and the standard speed schedule and cruise altitude



The field performance for take off and landing has also been calculated roughly. Figure 88 gives the resulting performance on a standard day, ISA, with no wind and no runway gradient and compares it with the PRESENT400. From this figure it is clear the take off performance is much better at MTOW. For low weights the performance is worse, but in most cases this will not be limiting. The landing performance is remarkably better for all operational weights up to the MLW.

Figure 88 Field length performance of the M-PROP400 for a standard day, ISA, no wind and no runway gradient. The lines are drawn up to MTOW respectively MLW



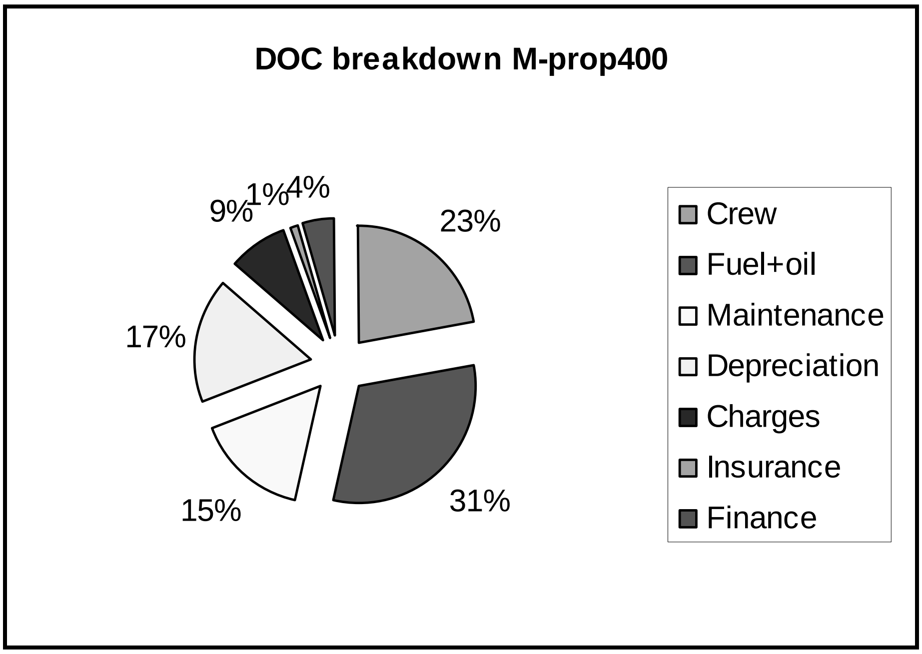
8.5.6 DOC

As we designed for a $1.00/kg fuel plus carbon price environment we give the DOC for this situation:

- Total for the flight: $129,299;
- per block hour: $13,092;
- per block kilometre: $18.471;
- per RTK: $0.3978;
- per passenger-km: $0.0592.

The DOC breakdown for $1.00/kg fuel plus carbon price can be found in Figure 89. The DOC (at $1.00/kg fuel plus carbon price) is 26.3% lower compared to for the current aircraft and 21.1% lower compared to the BASE400. At $0.27/kg fuel price the DOC will decrease with 10.4% compared to the PRESENT400, but increase with 6.7% compared to BASE400.

Figure 89 DOC breakdown for the M-PROP400 New design aircraft at $1.00/kg fuel plus carbon price



The conclusion is that the total DOC for the new design at current fuel prices is much lower than for the BASE400, mainly due to a saving of almost 50% on fuel and a lower cost structure due to the lower weight, relatively small engine and lower cruising speed.

8.5.7 Environment

The environmental impact of M-PROP400 in terms of emissions is much less than for the BASE400. All emissions will be reduced by about the same factor as the reduction in fuel consumption.
The noise impact of the aircraft will be influenced by the following:

- The propulsion system has been de-rated with 43% (in terms of static thrust). This will reduce the noise emissions.
- Sideline noise of the High Speed Propeller Aircraft will be lower compared to the baseline.
- Fly-over noise will be lower, due to the high position of the engines and the lower noise emission of a propeller engine.
- Fly-over noise will increase due to the 22% lower rate of climb: this may increase the noise footprint with a factor 2.31.

The net effect of these influences will have to be subject of further study, but noise seems to be a point of concern.

8.6 U-FAN150: New design for $1.00/kg with UHB engines

8.6.1 Combining technologies

The characteristics of the UHB engines are a high mach cruise number but also a higher fuel consumption than for the high speed propeller. The cost-effectiveness of a technology will in general be higher on fast aircraft than on slower examples. Therefore we have decided to include all available technologies to reduce fuel consumption, regardless there specific cost. Further we will try to reduce fuel consumption by optimising wing area and power loading. Summarised the aircraft will be equipped as follows:

- Two UHB engines;
- Optimum high aspect ratio;
- Large use of new materials (NML);
- Introduction of aerodynamic clean-up/active laminar flow control (LFC).

8.6.2 Initial changes

Initial weights

The introduction of the UHB engine increases the net weight of the dry engine with 1.25% compared to the current turbofan engine. This is the result of a 8% decrease of the weight due to the expected development of the conventional engines, and an increase of this weight with 10% due to the change to an UHB engine. Further the undercarriage will have to be enlarged (with 25%) as well as the diameter of the nacelles (also with 25%). The introduction of LFC increases the empty weight with 1%, but the use of new materials decreases it with 8%, making a net decrease of 7%.
With these initial changes introduced to the weight design tool and assuming initially 40% fuel saving the following initial weights have been calculated:

- MRW: 53,952 kg;
- MTOW: 53,722 kg;
- MLW: 50,413 kg;
- MZFW: 46,783 kg;
- OEW: 30,092 kg;
- EW: 27,258 kg.

Initial drag

The drag will initially decrease due to the introduction of active laminar flow control and aerodynamic cleanup, but increase due to the larger nacelle diameter. The parasite drag will initially be reduced with 12.5% due to both effects. The mach-drag has initially been kept the same as for the baseline aircraft.

Initial cost

The airframe price will change due to the new empty weight and the replacement of conventional materials with new materials like carbon fibre reinforced resins. Following assumptions now apply:

- The material to be replaced is 70.2% of the structural weight before replacing
- structural weight before replacing of 17,243 kg;
- cost penalty for new materials of $340.- per kilogram replaced material (Van der Heijden and Wijnen, 1999);
- 485 new aircraft are produced with a 10% profit on the program;
- 7.5% extra cost due to active LFC.

The net airframe price increase is $3,870,600.-, giving $41,670,600.- as the initial price for the U-FAN150. Van der Heijden and Wijnen (1999) give a general engine cost reduction for conventional turbofans with 1% per annum. Accounting for half of this cost reduction for the UHB turbofan this means a total engine price reduction between 1999 and 2010 with $100 \bullet (1-0.01)^{11} - 100 = -10.5\%$. Relative to this reduction the price will

increase due to the introduction of the UHB technology with 10%. The net engine price decrease becomes now with 1.5%. The engine price will decrease from $3,100,000 to $3,053,100. This figure has been inserted into the DOC_data sheet.
Other cost factors changing are the following:

- Engine maintenance cost +10%;
- Airframe maintenance hours +20% due to LFC;
- Airframe maintenance hours +17.6% due to NML[28].

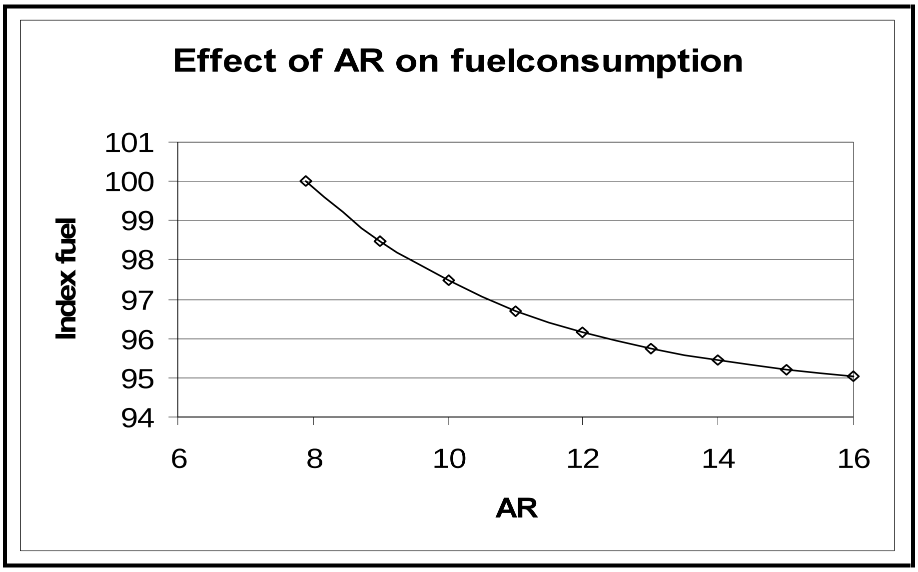
8.6.3 Sizing

Aspect ratio
Based on the initial costs and airframe definition given in §8.6.2 the effect of wing aspect ratio on fuel consumption and DOC for a fuel plus carbon price of $1.00/kg has been derived using following factors for empty weight changes on fuel consumption and DOC:

- 1.15% increase of DOC per 1,000 kg increase of Empty weight
- 0.97% increase of fuel consumption per 1,000 kg increase of Empty weight

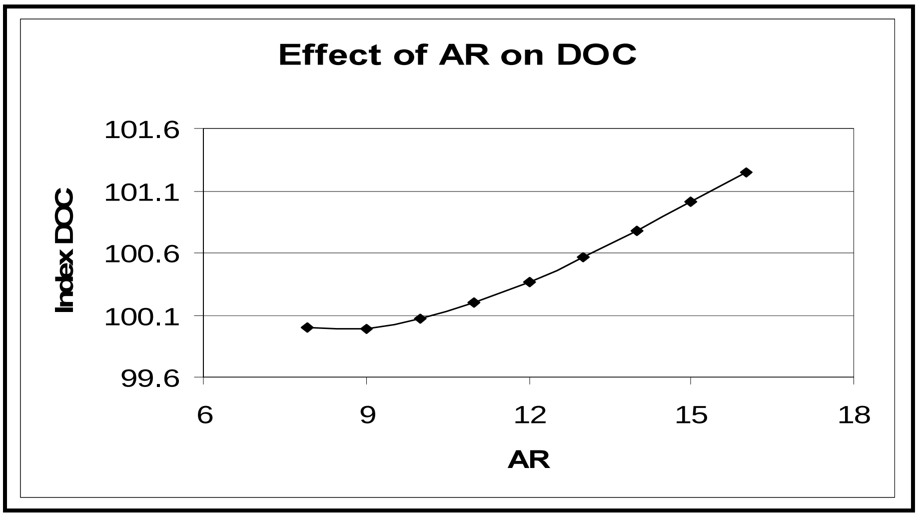
In Figure 90 the effect on fuel consumption has been given. It seems the lowest fuel consumption will be reached at an aspect ration of a little more than 16. However the cost for this in terms of DOC is quite large as is shown by Figure 91: the optimum aspect ratio is 9.

Figure 90 Effect of wing aspect ratio on fuel consumption, corrected for wing weight (U-FAN150, initial aircraft set-up)



[28] This figure has been derived from a 50% increase on airframe maintenace hours for 70.2% of the airframe weight and assuming a 50/50 division between airframe and system maintenance hours (excluding engines).

Figure 91 Effect of wing aspect ratio on DOC for the initial U-FAN150 assuming a fuel plus carbon price of $1.-/kg



Because the increase of DOC between an aspect ratio of 9 and 10 is only 0.1%, while the effect on fuel consumption is for the same range 1.0% we have chosen for an aspect ratio of 10. Above 10 the effect on DOC increases more rapidly while the effect on fuel consumption decreases.

Engine
Scaling the engine has been based on the performance of the PRESENT150. The engine scale factor has been chosen such that:

- TOP (Take off parameter) does not increase;
- The engine rating for top of climb does not increase above the value for the PRESENT150 at a MTOW minus 1,000 kg on 10,000 m with mach 0.745).

The top of climb condition turns out to be limiting the engine scaling factor to 0.8 (so a reduction in engine size of 20%). Following engine dimensions have now been found:

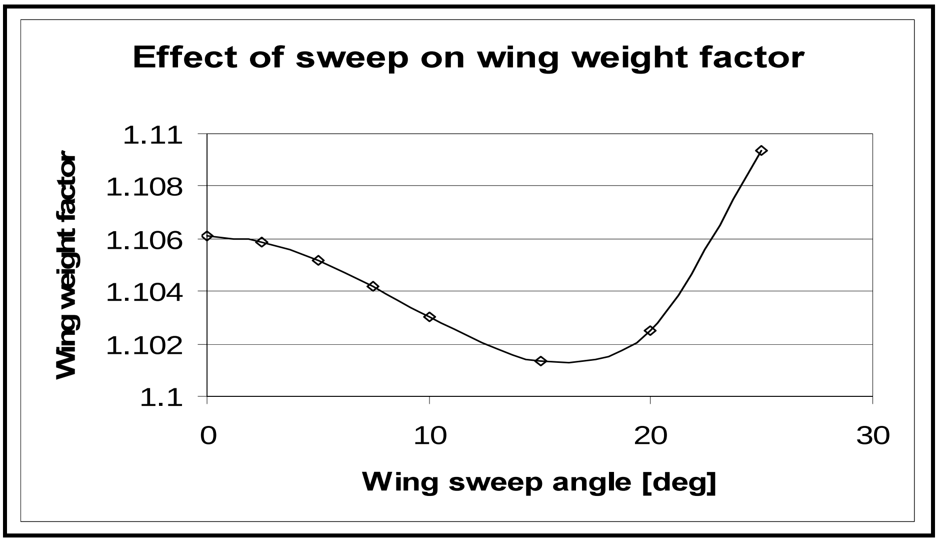
- MTO thrust: 83,600 N;
- Nacelle length: 3.399 m;
- Nacelle diameter: 1.76 m;
- Dry engine weight: 1,686 kg.

Wing design
The wing area is sized for optimum cruise performance. To find the new wing area S_{ref} following assumptions apply for the U-FAN150:

- Design cruising mach number is 0.745;
- Cruising altitude is 10,000 m;
- Cruising weight is the mean weight found iteratively for the evaluation flight of 1,000 km at 70% load factor (43,207 kg).

From the calculations it appeared the wing area must be decreased for optimum cruise performance. Further the use of a supercritical airfoil (M_{str}=1.15) with emphasis high subsonic capabilities and a larger wing section thickness ratio to reduce wing weight and increase wing maximum lift coefficient has been assumed. For this wing the wing sweep angle has been optimised for lowest wing weight. This turned out to be 16° (see Figure 9).

Figure 92 Effect of wing sweep angle on the wing weight factor for the short haul U-FAN150 wing with a supercritical wing section



Summarising the following wing dimensions have been chosen (between parenthesis the baseline value):

- Wing area: 82.5 m^2 (105.4 m^2);
- Wing aspect ratio: 10 (7.9);
- Wing sweep back angle (quarter chord): 16° (26°);
- Wing thickness ratio: 0.104 (0.09);
- Wing Span: 28.723 m (28.88 m);
- Thickness of mean chord: 0.297 m (0.329 m);
- Taper ratio is 0.25 (0.239).

Interesting is that the total wing span becomes lower than for BASE150, due to the decreased wing area.

Aerodynamics

With the help of the Mathcad sheet for parasite drag calculation (see §3.5) based on the flat plate analogy and corrected for the baseline drag polar the influence of a change of dimensions for the empennage, fuselage, struts, nacelles and wing area have been determined. The parasite drag has been reduced with 12.5% due to aerodynamic cleaning-up the introduction of active LFC. The final result is a reduction of the parasite drag area with 16.2% (the parasite drag coefficient has been increased with 7.0% due to the much smaller wing area).

8.6.4 Weights

The empty weight as well as the operational weights (MTOW, MLW) have been calculated with a reduction of the fuel consumption of 37%. This reduction is the result of the down scaled UHB Turbofan engine, the high aspect ratio wing and the lower drag and weight due LFC and new materials. The final result of the iteration is a total empty weight decrease of 5,986 kg with respect to the PRESENT150 aircraft. The following weights now result:

- MRW: 52,762 kg;
- MTOW: 52,532 kg;
- MLW: 48,899 kg;
- MZFW: 45,269 kg;

- OEW: 28,578 kg;
- EW: 25,744 kg.

8.6.5 Airframe and engine price

The engine price has been scaled down with the help of the method of Roskam (Part VIII, 1990) from \$3,053,000 to \$2,685,000.
The airframe price has been calculated using the aircraft price Mathcad sheet with the following assumptions:

- The investment is written off over 485 aircraft (it is a totally new design);
- The replaced weight (empty weight minus the engines) is 27,758 kg;
- The weight of the new structure is 22,372 kg;
- The weight of by new materials replaced structure of the new aircraft is 15,792 kg, costing \$340.- per kg (Van der Heijden and Wijnen, 1999).

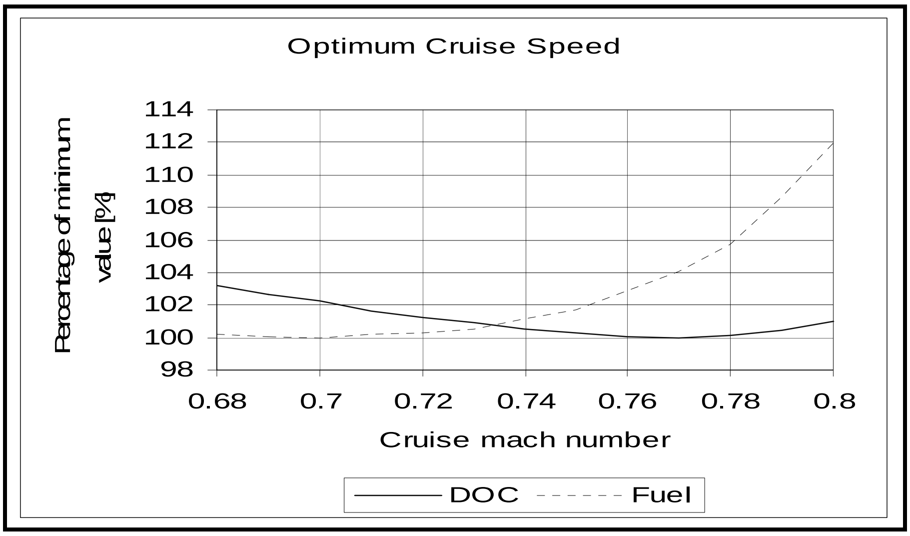
These assumptions give a final airframe price increase of \$2,709 to a price of \$40,509,000. The engine maintenance cost has been increased with 10 % as given by Van der Heijden and Wijnen (1999). The airframe maintenance hours have been increased with 20% due to the introduction of LFC and with another 17.6%[29] due to the introduction of the new materials (a total increase with 41.1%). The flight crew wages depend on cruising speed and MTOW (Raymer, 1992). As the MTOW has been reduced from 62,820 kg to 52,532 kg the wages will be 5.2% lower.

8.6.6 Performance

Before calculating the performance the DOC-and fuel-optimum flight profiles have been redefined. It turned out from calculations the cruising altitude of 10,000 m is practically the optimum cruising mach number (at 10,500 m a decrease of 0.1% on DOC might be reached). From Figure 93 we find the fuel optimum speed is mach 0.70 while the DOC optimum comes to 0.77. As this is close to the initial speed schedule of mach 0.745 at 10,000 m cruising altitude we will retain these for reasons of comparability (the PRESENT150 cruises also slightly below the DOC optimum speed).

[29] This figure has been derived from a 50% increase on airframe maintenace hours for 70.2% of the airframe weight and assuming a 50/50 division between airframe and system maintenance hours (excluding engines).

Figure 93 Optimum speed schedule (cruise mach number) for the U-FAN150 aircraft for the $1.00/kg fuel plus carbon price market at cruising altitude of 10,000 m

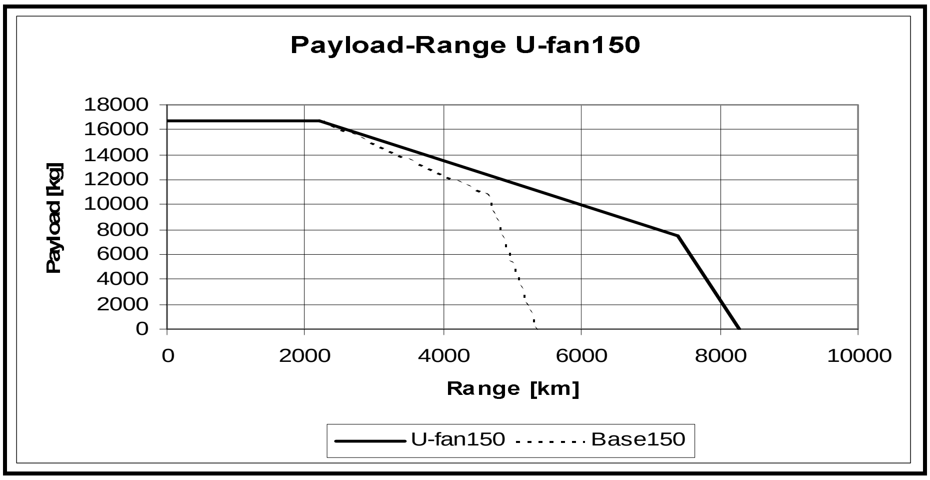


Resuming, the same flight profile as for the PRESENT150 has been used (see §4.2.4). The Evaluation flight for Short Haul has been calculated with APD (see §3.8) for a block distance of 1,000 km. The following performance has been calculated for a payload at 70% load factor of 11,684 kg:

- Block time: 1 hour and 52 minutes
- Block fuel used: 2,490 kg
- Take off weight: 44,760 kg
- Reserve fuel: 2,008 kg

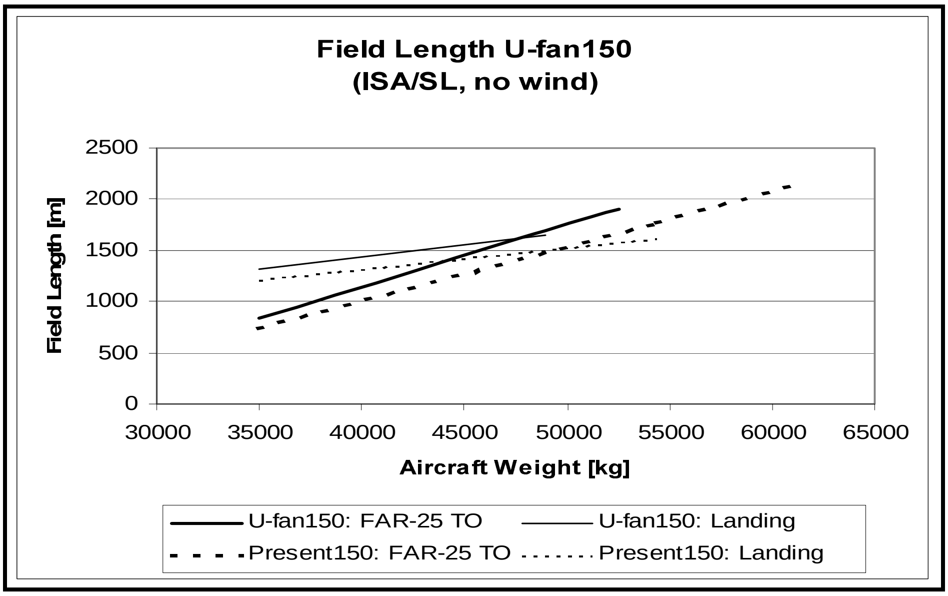
The fuel consumption has been reduced to the PRESENT150 with 1,461 kg or 37.0%. With respect to the 2010 technology turbofans the reduction is 1,101 kg or 30.7%. The lowest attainable fuel consumption (with mach 0.70/10,000 m) is 37.8% below the PRESENT150 aircraft.
The payload range capability of the U-FAN150 is given in Figure 94. From this figure it is clear the high fuel economy results in a range extension at partial payload, but less than for the M-PROP150 (see Figure 79). The extension may enhance flexibility of the aircraft. Also it will be possible to substantially extend range for full payload at less cost than for the BASE150.

Figure 94 The payload range capability of the short haul U-FAN150 aircraft for a standard atmosphere and the standard speed schedule and cruise altitude



The field performance for take off and landing has also been calculated roughly. Figure 95 gives the resulting performance on a standard day, ISA, with no wind and no runway gradient and compares it with BASE150. From this figure it is clear the take off performance is slightly better at MTOW. For low weights it is worse. The landing distance is slightly longer for all weights.

Figure 95 Field length performance of the U-FAN150 for a standard day, ISA, no wind and no runway gradient. The lines are drawn up to MTOW respectively MLW



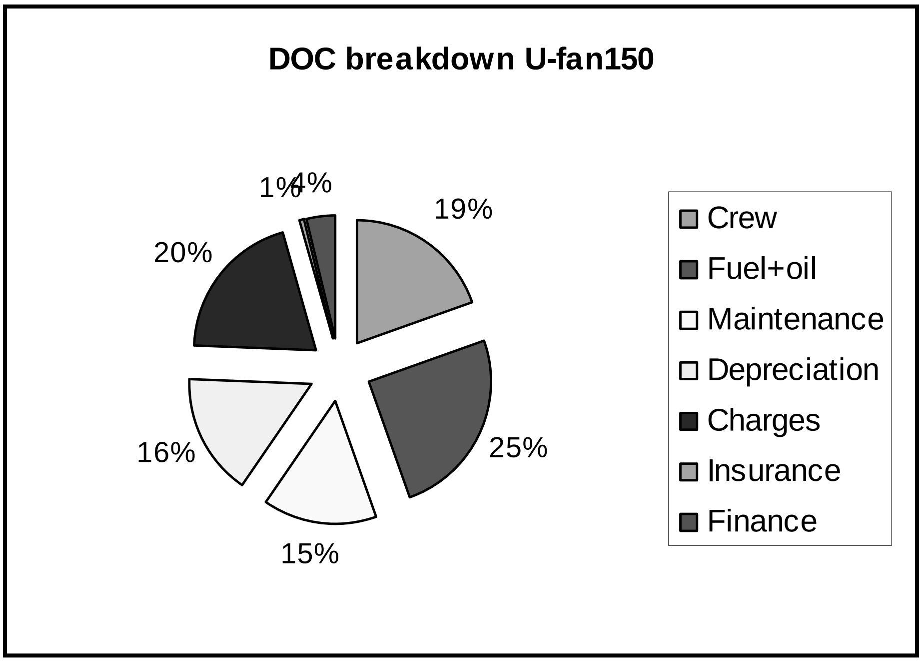
8.6.7 DOC

As we designed for a $1.00/kg fuel plus carbon price environment we give the DOC for this situation:

- Total for the flight: $10,251;
- per block hour: $5,482;
- per block kilometre: 10.251;
- per RTK: $0.877;
- per passenger-km: $0.1003.

The DOC breakdown for $1.00/kg fuel plus carbon price can be found in Figure 96. The DOC (at $1.00/kg fuel plus carbon price) is 13.1% lower compared to PRESENT150 and 8.7% lower compared to BASE150. At $0.27/kg fuel price the DOC will decrease with 3.9% compared to the PRESENT150 and with 1.0% compared to BASE150.

Figure 96 DOC breakdown for the U-FAN150 New design aircraft at $1.00/kg fuel plus carbon price



8.6.8 Environment

The environmental impact of U-FAN150 in terms of emissions is much less than for BASE150. All emissions will be reduced by about the same factor as the reduction in fuel consumption. The noise impact of the aircraft will be influenced by the following:

- The propulsion system has been de-rated with about 20% (in terms of static thrust). This will reduce the total noise emissions.
- Sideline noise of the UHB engines will be lower compared to the base-line.
- Fly-over noise will decrease due to lower noise emission of the UHB engines.
- Fly-over noise will slightly decrease due to the 1% higher initial rate of climb.

The net effect of these is difficult to predict and will have to be determined in further study. However, noise does not seem a very large problem. For this design.

8.7 U-FAN400: New design for $1.00/kg with UHB engines

8.7.1 Combining technologies

The UHB engine allows for fuel efficiency up to high mach numbers at cruise. The cost-effectiveness of a technology will in general be higher on fast aircraft than on slower examples. Therefore we will use the UHB engine combined with all other technologies considered. Summarised the aircraft will be equipped as follows:

- Two UHB engines;
- Optimum high aspect ratio;
- Large use of new materials (NML);
- Introduction of aerodynamic clean-up plus (active) laminar flow control (LFC).

The main objective of the design will be to minimise wing area and to reduce the engine within the current flight-envelope and performance. Further we will define the optimum aspect ratio after we have introduced the first effects on weight, drag and cost of the other technologies.

8.7.2 Initial changes

Initial weights
The introduction of the UHB engine increases the net weight of the dry engine with 1.25% compared to the current turbofan engine. This is the result of a 8% decrease of the weight due to the expected development of the conventional engine, and an increase of this weight with 10% due to the change to an UHB engine. Further the undercarriage will have to be enlarged (with 25%) as well as the diameter of the nacelles (also with 25%). The introduction of active LFC increases the empty weight with 0.5%, but the use of new materials decreases it with 8%, making a net decrease of 7.5%.
With these initial changes introduced to the weight design tool and assuming 35% fuel saving the following initial weights have been calculated:

- MRW: 307,316 kg;
- MTOW: 305,956 kg;
- MLW: 245,512 kg;
- MZFW: 227,822 kg;
- OEW: 165,907 kg;
- EW: 156,588 kg.

Initial drag
The drag will initially decrease due to the introduction of laminar flow control and aerodynamic cleanup, but increase due to the larger nacelle diameter. The parasite drag will initially be reduced with 12.5% due to these effects.

Initial cost
The airframe price will change due to the new empty weight and the replacement of conventional materials with new materials like carbon fibre reinforced resins. Following assumptions now apply:

- the material to be replaced is 59.8% of the structural weight before replacing;
- structural weight before replacing it with new materials of 108,786 kg;
- a cost penalty for new materials of $300 per kilogram of material replaced (Van der Heijden and Wijnen, 1999);

- 450 new aircraft are produced with a 10% profit on the program;
- 2.5% extra cost due to LFC.

From these assumptions the net price increase is $11,170,018.-, giving $159,570,000.- as the initial price for the U-FAN400.

Van der Heijden (1999) gives a general engine cost reduction for conventional turbofans with 1% per annum. Accounting for half of this cost reduction for the UHB turbofan this means a total engine price reduction between 1999 and 2010 with $100 \bullet (1-0.01)^{11} - 100 = -10.5\%$. Relative to this reduction the price will increase due to the introduction of the UHB technology with 10%. The net engine price decrease becomes now with 1.5%. The engine price will decrease from $5,400,000 to $5,319,000. This figure has been inserted into the DOC_data sheet.
Other cost factors changing are the following:

- Engine maintenance cost +10%;
- Airframe maintenance hours +20% due to LFC;
- Airframe maintenance hours +15% due to NML[30].

8.7.3 Sizing

Aspect ratio
Based on the initial costs and airframe definition given in §8.7.2 the effect of wing aspect ratio on fuel consumption and DOC for a fuel plus carbon price of $1.00/kg has been derived using following trend factors for empty weight changes on fuel consumption and DOC:

- 0.261% increase of DOC per 1,000 kg increase of OEW
- 0.269% increase of fuel consumption per 1,000 kg increase of OEW

In Figure 97 the effect on fuel consumption has been given. It seems the lowest fuel consumption will be reached at an aspect ration of a little more than 17. However the cost for this in terms of DOC is quite large as is shown by Figure 98: the optimum aspect ratio is somewhere between 11 and 12.

[30] This figure has been derived from a 50% increase on airframe maintenace hours for 60.0% of the airframe weight and assuming a 50/50 division between airframe and system maintenance hours (excluding engines).

Figure 97 Effect of wing aspect ratio on fuel consumption, corrected for wing weight (U-FAN400, initial aircraft set-up)

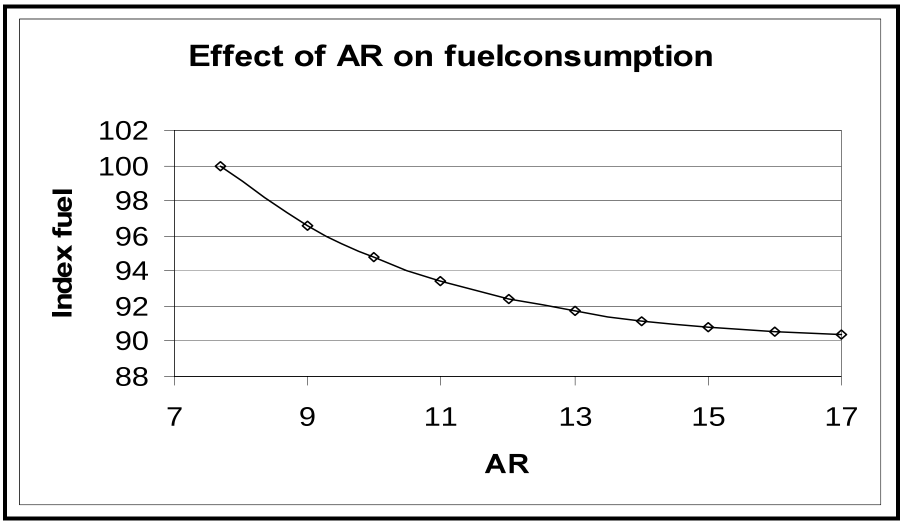
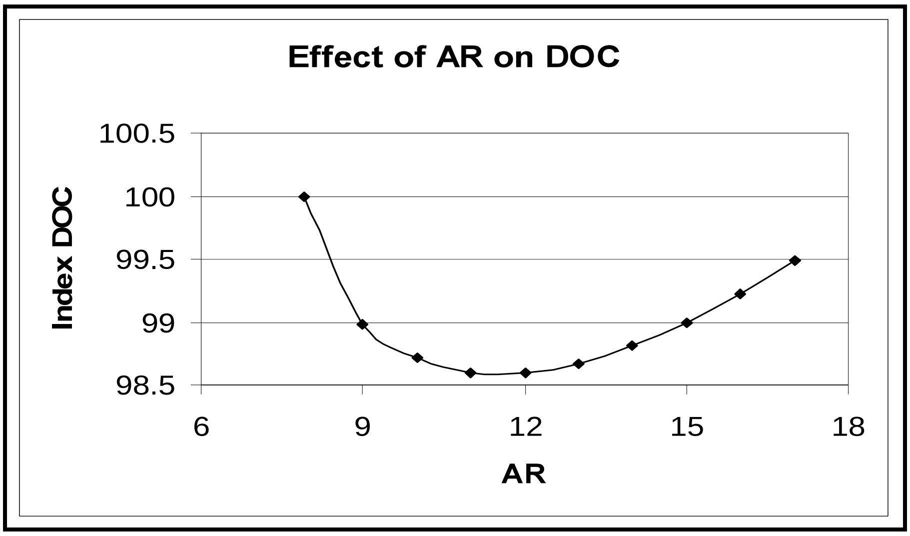


Figure 98 Effect of wing aspect ratio on DOC for the initial U-FAN400 (initial aircraft set-up) assuming a fuel plus carbon price of $1./kg



We have chosen for an aspect ratio of 12, saving almost 1% extra on fuel consumption with respect to an AR of 11.

Engine
Scaling the engine has been based on the performance of PRESENT400. The engine scale factor has been chosen such that:

- TOP (Take off parameter) does not increase;
- The engine rating for top of climb does not increase above the value for PRESENT400 the at TOC weight at 11,000 m and mach 0.84.

The top of climb condition turns out to be limiting the engine scaling factor to 0.65 (so a reduction in engine size of 35%). Following engine dimensions have now been found:

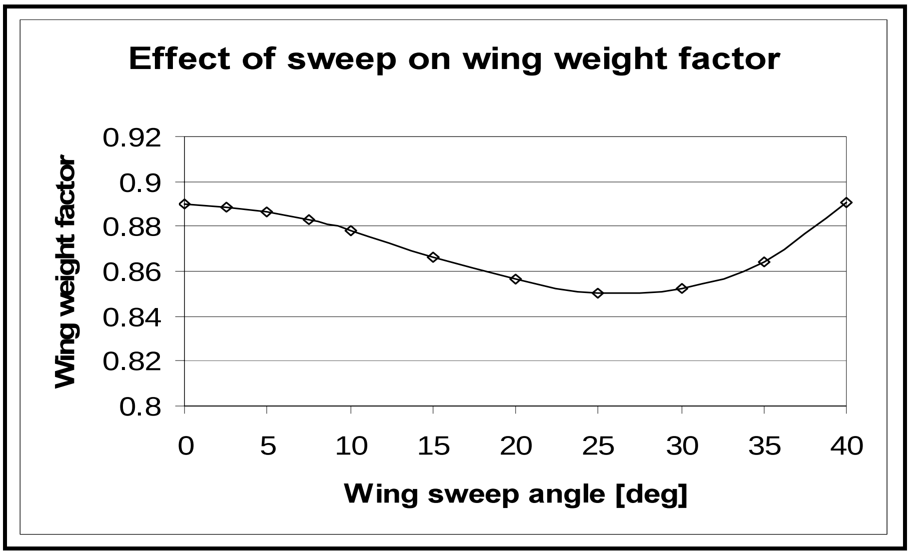
- MTO thrust: 183,580 N;
- Nacelle length: 4.76 m;

- Nacelle diameter: 2.762 m;
- Dry engine weight: 3,140 kg;
- Engine price: $4,223,500.

Wing design
The wing area is sized for optimum cruise performance. To find the new wing area S_{ref} following assumptions apply for the U-FAN400:
- Design cruising mach number is 0.84;
- Cruising altitude is 11,000 m;
- Cruising weight is the mean weight found iteratively for the evaluation flight of 7,000 km at 75% load factor (223,409 kg).

From the calculations it appeared the wing area must be decreased for optimum cruise performance. Further the use of a supercritical airfoil (M_{str}=1.15) with emphasis on high subsonic capabilities and a larger wing section thickness ratio to reduce wing weight and increase wing maximum lift coefficient has been assumed. For this wing the wing sweep angle has been optimised for lowest wing weight. This turned out to be 26° (see Figure 99).

Figure 99 Effect of wing sweep angle on the wing weight factor for the long haul U-FAN400



Summarising the following wing dimensions apply (between parenthesis the baseline value):
- Wing area: 415 m^2 (541.16 m^2);
- Wing aspect ratio: 12 (7.7);
- Wing sweep back angle (quarter chord): 26° (39.5°);
- Wing thickness ratio: 0.0925 (0.08);
- Wing Span: 70.569 m (64.44 m);
- Thickness of mean chord: 0.544 m (0.671 m);
- Taper ratio is 0.25 (0.269).

For this high aspect ratio wing aircraft the ICAO box of 80*80 m^2 turns out to be no limit.

Aerodynamics
With the help of the Mathcad sheet for parasite drag calculation (see §3.5) based on the flat plate analogy and corrected for the baseline drag polar the influence of a change of dimensions for the empennage, fuselage, struts, nacelles and wing area have been determined. The parasite drag has been reduced with 12.5% due to aerodynamic cleaning-up and the introduction of active LFC. The final result is a reduction of the parasite drag area with 18.6% (the parasite drag coefficient has been increased with 6.1% due to the much smaller wing area).

8.7.4 Weights

The empty weight as well as the operational weights (MTOW, MLW) have been calculated with a reduction of the fuel consumption of 44%. This reduction is the result of the down scaled UHB Turbofan engine, the high aspect ratio wing and the lower drag and weight due LFC and new materials. The final result of the iteration is a total empty weight decrease of 32,676 kg with respect to the PRESENT400. The following weights now result:

- MRW: 278,668 kg;
- MTOW: 277,308 kg;
- MLW: 227,684 kg;
- MZFW: 209,994 kg;
- OEW: 148,079 kg;
- EW: 138,760 kg.

8.7.5 Airframe and engine price

The engine price has been scaled down with the help of the method described in §3.7.2 from $5,319,000 to $4,223,400.
The airframe price has been calculated using the aircraft price Mathcad sheet with the following assumptions:

- The investment is written off over 450 aircraft (it is a totally new design);
- The replaced airframe weight (empty weight minus the engines) is 154,200 kg;
- The new airframe weight is 133,320 kg;
- The by new materials replaced structure weight of the new aircraft is 93,261 kg, costing $300.- per kg (Van der Heijden and Wijnen, 1999).

These assumptions give a final airframe price increase of $4,132,000 to a price of $152,532,000. The engine maintenance cost has been increased with 10% as given by Van der Heijden (1999).
The airframe maintenance hours have been increased with 20% due to the introduction of LFC and with 15%[31] due to the introduction of the new materials (a total increase with 38.0%). The flight crew wages depend on cruising speed and MTOW (Raymer, 1992). As the MTOW has been reduced from 362,875 kg to 284,429 kg the wages will be 7.0% lower.

8.7.6 Performance

Before calculating the performance the DOC- and fuel-optimum flight profiles have been redefined. From Figure 100 we find the fuel optimum speed is

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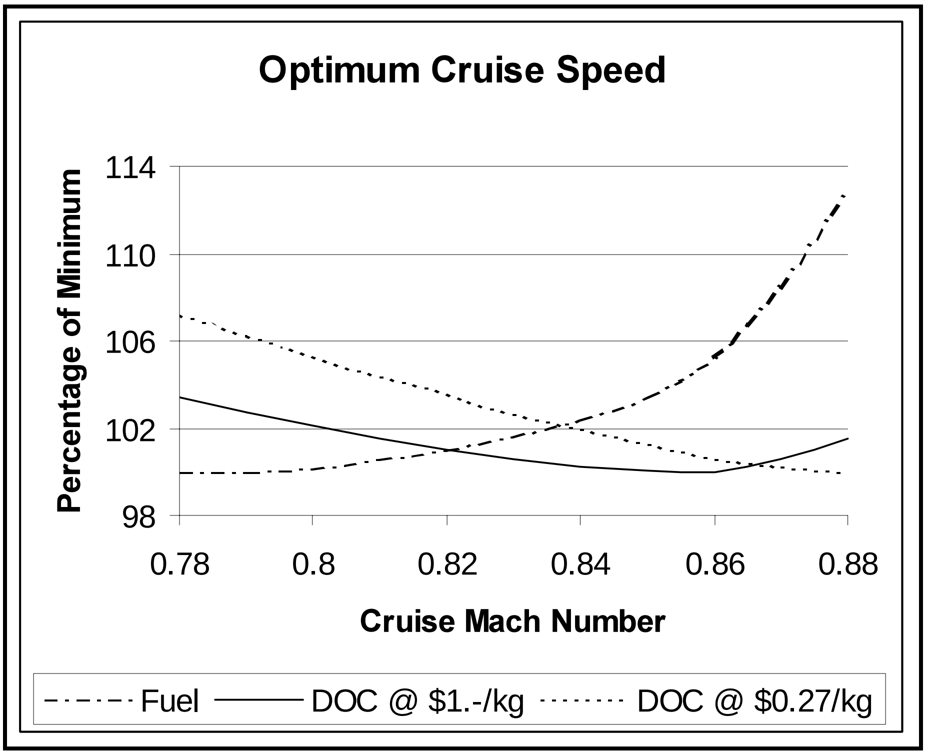
[31] This figure has been derived from a 50% increase on airframe maintenace hours for 60.0% of the airframe weight and assuming a 50/50 division between airframe and system maintenance hours (excluding engines).

slightly below mach 0.78 while the DOC optimum comes to 0.85. It turned out from calculations the cruising altitude of 11,000 m is practically the optimum cruising mach number (at 12,000 m DOC for both fuel plus carbon prices are only 0.15% lower than at 11,000 m). As this is close to the initial speed schedule of mach 0.84 at 11,000 m cruising altitude we will retain these for reasons of comparability (the PRESENT150 cruises also slightly below the DOC optimum speed).

Figure 100 Fuel and DOC optimum speed schedules (cruise mach number) for the U-FAN400 aircraft for the $1.00/kg and $0.27/kg fuel plus carbon price cases at a cruising altitude of 11,000 m



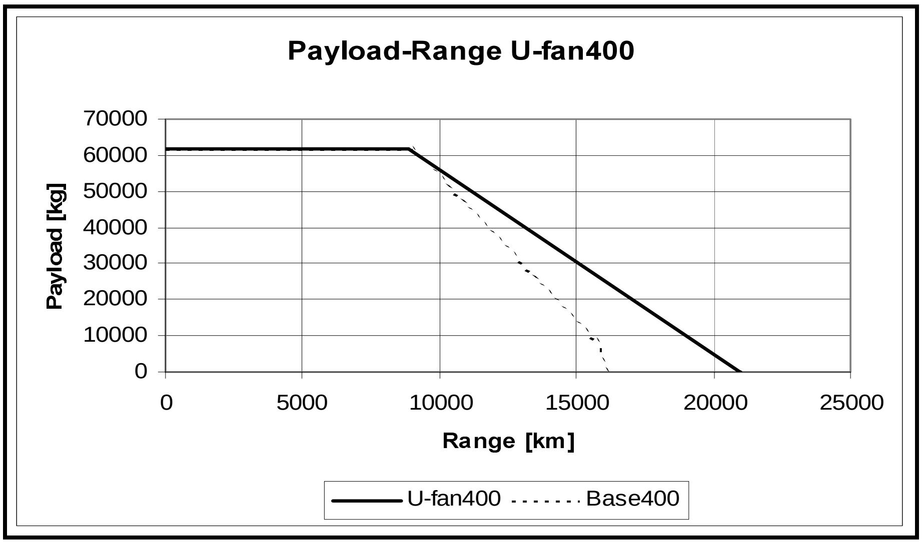
Flight schedule and reserve fuel strategy have therefore been chosen the same as for the PRESENT400 (see §4.3.4. The Evaluation flight for Short Haul has been calculated with APD (see §3.8) for a block distance of 7,000 km. The following performance has been calculated for a 75% load factor (46,436 kg):

- Block time: 8 hour and 30 minutes;
- Block fuel used: 42,569 kg;
- Take off weight: 246,340 kg;
- Reserve fuel: 9,256 kg.

The fuel consumption has been reduced with respect to the PRESENT400 with 34,699 kg or 44.9%. Compared to the BASE400 the reduction is 25,944 kg or 37.8%. The lowest attainable fuel consumption (at mach 0.78/11,000 m) is 46.2% below the PRESENT400.
The payload range capability of the U-FAN400 is given in Figure 101. From this figure it is clear the high fuel economy results in a range extension at partial payload. This extension is less compared to the M-PROP400 (see Figure 87). This may enhance operational flexibility of the aircraft. Due to the

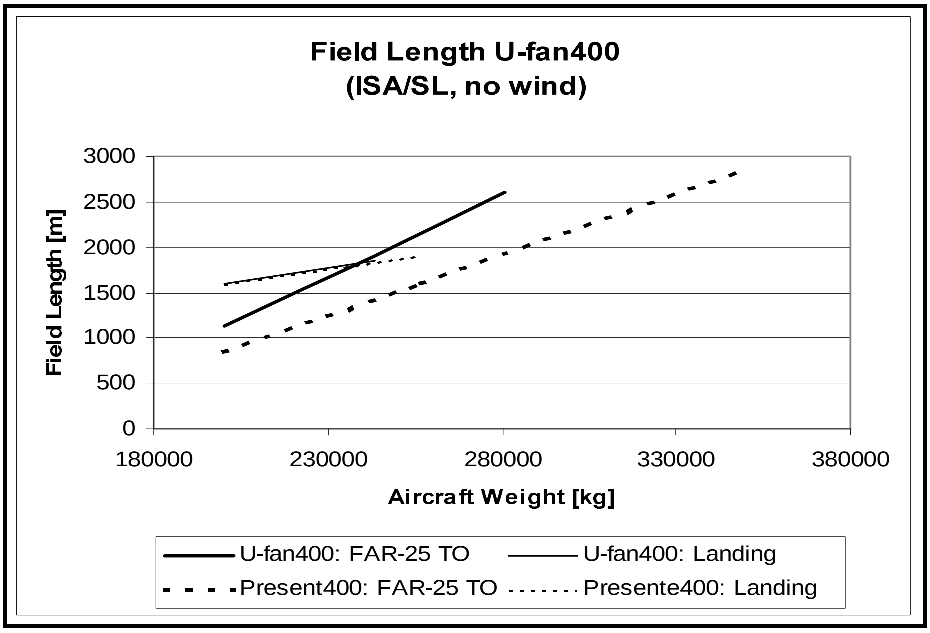
same fuel economy it is possible to extend range for full payload at much less cost than for PRESENT400.

Figure 101 The payload range capability of the long haul U-FAN400 aircraft with UHB engines for a standard atmosphere and the standard speed schedule and cruise altitude



The field performance for take off and landing has also been roughly calculated. Figure 102 gives the resulting performance on a standard day, ISA, with no wind and no runway gradient and compares it with the BASE400. From this figure it is clear the take off performance is slightly better at MTOW. For low weights it is slightly worse, but this will normally not be limiting. The landing performance is better due to the lower MLW.

Figure 102 Field length performance of the U-FAN400 with UHB engines for a standard day, ISA, no wind and no runway gradient. The lines are drawn up to MTOW respectively MLW



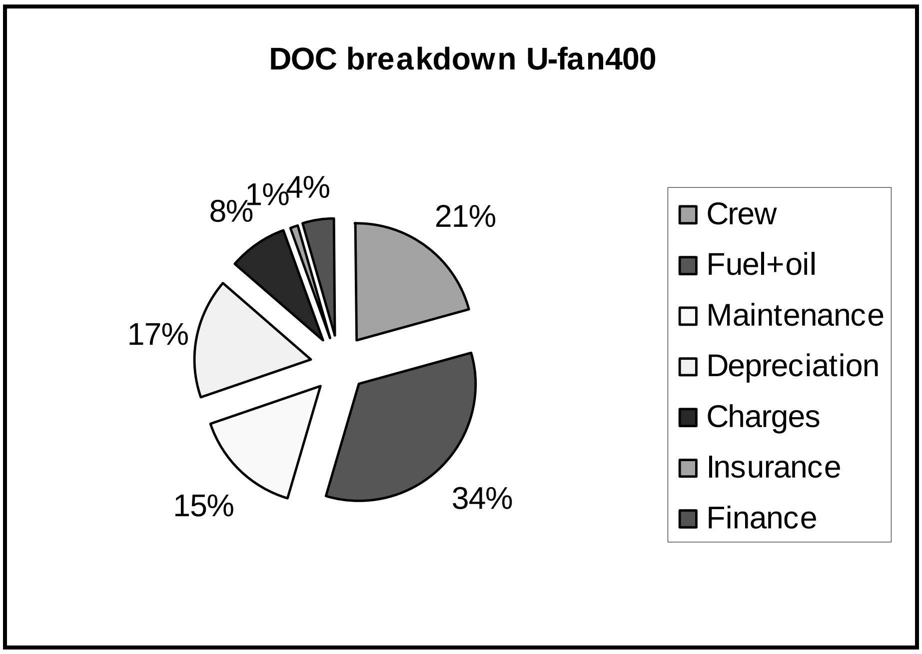
8.7.7 DOC

As we designed for a $1.00/kg fuel plus carbon price environment we give the DOC for this situation:

- Total for the flight: $133,036;
- per block hour: $15,637;
- per block kilometre: $19.005;
- per RTK: $0.4093;
- per passenger-km: $0.0609.

The DOC breakdown for $1.00/kg fuel plus carbon price can be found in Figure 103. The DOC (at $1.00/kg fuel plus carbon price) is 24.2% lower compared to the current aircraft and 18.8% lower compared to the BASE400. At $0.27/kg fuel price the DOC will decrease with 12.7% compared to the PRESENT400 and with 9.1% compared to the BASE400.

Figure 103 DOC breakdown for the U-FAN400 New design aircraft at $1.00/kg fuel plus carbon price



8.7.8 Environment

The environmental impact of U-FAN400 in terms of emissions is much less than for the BASE400. All emissions will be reduced by about the same factor as the reduction in fuel consumption. The noise impact of the aircraft will be influenced by the following:

- The propulsion system has been de-rated with 33% (in terms of static thrust). This will reduce the total noise emissions.
- Sideline noise of the UHB engines will be lower compared to the base-line.
- Fly-over noise will be lower due the lower noise emission of the UHB engines.
- Fly-over noise will slightly increase due to the 5% lower rate of climb.

The overall effect on noise impact of U-FAN can be only determined in further study.

8.8 F-CELL150: New design with Fuel Cell Technology

8.8.1 Combining technologies

To show the possibilities of fuel cell technology we will design an aircraft around it, based on the short haul BASE150. As both power required and fuel consumption have large weight and drag penalties, we will use every technology available to reduce them. This means an aircraft around electrically powered High Speed Propellers with a moderate air speed and mach number and a not too large cruising altitude. This last characteristic is also necessary because the fuel cells emit water vapour and at specific (high) altitudes this may result into contrails and add to the warming of the atmosphere[32]. But also the use of new materials to reduce the aircraft weight and laminar flow control as well as an aerodynamic clean up and a high aspect ratio wing will reduce required power and fuel consumption.
Because many characteristics of the propulsion system are not well known it seemed not valuable to optimise the aircraft on all aspects. Specifically it is difficult to find the cost parameters. Therefore we will only size the power and wing loading and optimise the speed schedule and cruising altitude.

8.8.2 Sizing the aircraft

Wing
Because of the use of the High Speed Propeller we have reduced the M_{DD} from mach 0.82 to mach 0.70. We have not optimised the aspect ratio of the wing, but chosen for the same AR as for the M-PROP150 design: AR=12. The sweep back angle of the wing has been chosen for a design speed of mach 0.64 and 8,500 m cruising altitude and comes at 10°. This gives a mean wing thickness ratio of 12.5%. After several iterations the wing area stabilised at the rather high value of 144 m^2.
Summarising the following wing dimensions apply (between parenthesis the baseline value):

- Wing area: 144.0 m^2 (105.4 m^2);
- Wing aspect ratio: 12 (7.9);
- Wing sweep back angle (quarter chord): 10° (26°);
- Wing thickness ratio (for M_{str}=1.00): 0.125 (0.09);
- Wing Span: 41.57 m (28.88 m);
- Thickness of mean chord: 0.432 m (0.329 m);
- Taper ratio is 0.25 (0.239).

Engine
The engine has been scaled giving the following engine parameters:

- TO rating: 8,197 SHP;
- TOC rating: 5,000 SHP;
- Propeller diameter: 12.00 ft;
- Number of blades: 2*6;
- Activity factor: 120;
- Nacelle length: 3.86 m;
- Nacelle diameter: 1.03 m;
- Propeller weight: 1,357 kg;
- Weight including systems and propeller: 7,269 kg.

[32] The emissions of particles is almost zero, making the forming of contrails or cirrus clouds less likely than for a kerosene fuelled power system.

Fuselage

The fuselage has been stretched to accommodate the LH_2 fuel tanks. Stretching is only a simplified method to find the influence on drag and weight. It will be more likely the fuel will be stored into long tanks in extensions on the roof of the passenger cabin.

The fuselage length will have to be increased with 3.508 m (an increase of almost 10%) to accommodate a weight of 2400 kg of LH_2, which represents a total of 33,800 litre fuel net volume.

Aerodynamics

With the help of the Mathcad sheet for parasite drag calculation based on the flat plate analogy and corrected for the baseline drag polar the influence of a change of dimensions for the empennage, fuselage, struts, nacelles and wing area have been determined. The laminar flow on wings and empennage has been increased, due to the introduction of airfoil sections better suited for medium cruising speeds. Also the parasite drag has been reduced by aerodynamically cleaning-up the aircraft. The final result is a reduction of the parasite drag coefficient for clean cruising configuration with 30.2% or a decrease of the total drag area with 4.9%[33].

8.8.3 Weights

The empty weight as well as the operational weights (MTOW, MLW) have been calculated with a reduction of the fuel consumption weight of 88%. This reduction is the result of the use of LH_2, the fuel cell system, the high aspect ratio wing, the lower drag due to LFC and the lower weight due to the use of new materials. The final result of this iteration is a total empty weight increase of 11,810 kg with respect to the PRESENT150, mainly due to the much higher weight of the propulsion group. The following weights now result:

- MRW: 64,683 kg;
- MTOW: 64,453 kg;
- MLW: 64,453 kg;
- MZFW: 63,066 kg;
- OEW: 46,375 kg;
- EW: 43,541 kg.

8.8.4 Performance

As no DOC could be calculated lacking some crucial cost information we have fixed the speed schedule to the following assumptions have been made:

- Take off and Ground manoeuvring:
  - 26 minutes at 7% MTO engine rating (all fuel weight for taxi is pre-TO);
  - Take-off 0.7 minutes at 100% MTO rating;
  - Climb-out from 35 ft to 3,000 ft at 85% MTO rating; climb-out time is 2.2 minutes;
- Operational Climb:
  - Speed schedule 260 kCAS/0.66;
  - Max climb engine rating;
- Operational Cruise:

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[33] The reduction of the total drag area seems surprising as the totale wing area and the fuselage both are larger as for the baseline aircraft. However, due to the lower design cruising altitude and the larger mean aerodynamic chord and fuselage length the Reynolds number increases, reducing the dragcoefficient.

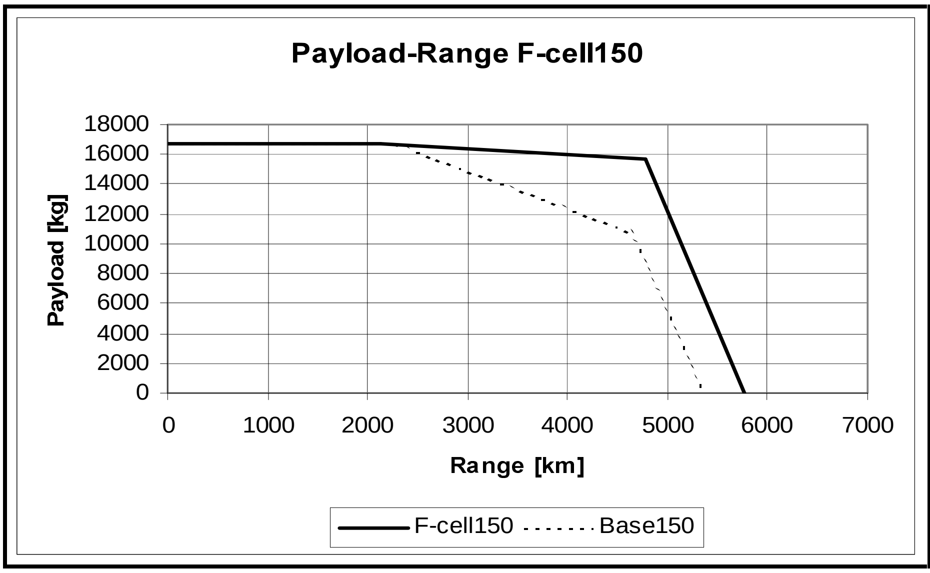
- Long range speed (mach 0.66);
- Cruise altitude 8,000 m;
- Operational descent:
  - Speed schedule: 0.66/260 kCAS;
  - Thrust set for maximum cabin rate of descent (300 ft/minute and maximum cabin altitude 6,000 ft);
- Approach and landing:
  - Approach from 3,000 ft to SL at 71.4 m/s TAS (Jane's, 1998);
  - Approach time 4 minutes at 30% MTO rating;
- Reserves:
  - Go around from 3,000 ft at destination;
  - Flight to alternate at 200 NM with flight speed schedule, but at 8,000 m cruising altitude;
  - 30 minutes hold as extended cruise.

The Evaluation flight for Short Haul has been calculated with APD (see §3.8) for a block distance of 7,000 km. The following performance has been calculated for a payload at 70% load factor of 11,684 kg:

- Block time: 2 hour and 2 minutes;
- Block fuel used: 445 kg hydrogen (1,246 kg kerosene equivalents);
- Take off weight: 58,825 kg;
- Reserve fuel: 321 kg hydrogen.

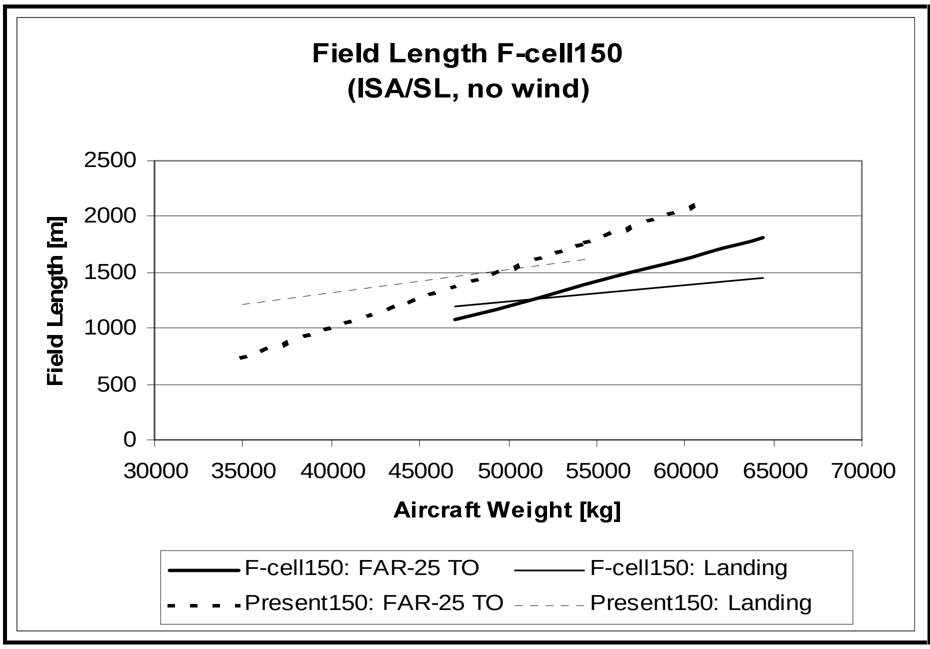
The fuel consumption has been reduced, in terms of kerosene equivalents for energy, compared to the PRESENT150 with 2,705 kg or 68.5%. With respect to BASE150the 2010 technology turbofans the reduction is 2,345 kg or 65.3%. The aircraft is slower with a 8.9% higher block time.
The payload range capability of the F-CELL150 is given in Figure 104. From this figure we can see the payload range capability has been extended largely at partial payloads. Because the weight limited range line is very flat, it is possible to extend the range of the aircraft with a factor three by reducing payload less than 10% compared to the PRESENT150. This is caused by the high specific energy content of hydrogen and the low energy consumption of the aircraft. All this will enhance the operational flexibility of the aircraft. Due to the large weight and drag penalties for increasing fuel capacity it will not be very attractive to increase the payload range capability any further.

Figure 104 The payload range capability of the short haul F-CELL150 fuel cell technology aircraft for a standard atmosphere and the standard speed schedule and cruise altitude



The field performance for take off and landing has also been calculated roughly. Figure 105 gives the resulting performance on a standard day, ISA, with no wind and no runway gradient and compares it with the PRESENT150. From this figure it is clear the take off performance is better at MTOW but worse at low weights. The landing performance is better for all operational weights up to the MLW.

Figure 105 Field length performance of the F-CELL150 fuel cell technology aircraft for a standard day, ISA, no wind and no runway gradient. The lines are drawn up to MTOW respectively MLW



8.8.5 Environment

The in-flight emissions of the F-CELL150 are non-existent except for water vapour. This vapour will be emitted at moderate cruising altitudes (8,000 m) and will normally cause not as many contrails as the BASE150 does at this moment. This is mainly due to lack of condensation nuclei in the exhaust gases of a fuel cell. Also the fuel economy of this aircraft is remarkably good, saving 65% in terms of energy used.
The noise impact of the aircraft will be influenced by the following:

- The propulsion system has been de-rated with about 33% (in terms of static thrust). This will reduce the total noise emissions.
- The electrical engine itself will have lower noise emissions compared to a turbine engine. Therefore sideline noise of the fuel cell technology powered aircraft will be lower compared to the baseline.
- Fly-over noise will be lower, due to the high position of the engines and the lower noise emission of the propellers and the much lower noise emissions of the electrical engines.
- Fly-over noise will increase due to the 16% to 36% lower rate of climb[34].

The net effect of these is difficult to assess. How much the effect will be can only be determined with further study.

8.9 F-CELL400: New design with Fuel Cell Technology

8.9.1 Combining technologies

To show the possibilities of fuel cell technology we will design an aircraft around it, based on the long haul BASE400. As both power required and fuel consumption have large weight and drag penalties, we will use every technology available to reduce them. This means an aircraft around electrically powered high speed propellers with a moderate air speed and mach number and a not too large cruising altitude. But also the use of new materials to reduce the aircraft weight and laminar flow control as well as an aerodynamic clean up and a high aspect ratio wing.
Because many characteristics of the propulsion system are not well known it seemed not valuable to optimise the aircraft on all aspects. Due to a lack of reliable cost parameters we will not try to calculate the DOC.

8.9.2 Sizing the aircraft

Wing
Because of the use of the high speed propeller we have reduced the M_{DD} from mach 0.88 to mach 0.735. We have not optimised the aspect ratio of the wing, but chosen for the same AR as for the M-PROP400 design: AR=14.

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[34] The F-cell150 design suffers from a too low one engine out climb speed. Adjusting the total power with 17% will solve this and will decrease the climb speed reduction from 36% to 16%, but at the price of a large amount of extra weight for the fuel cells. It may reasoned the one-engine out case does not mean 'half of the stacks out', if the engines are cross-feeded. then the one-engine out case can be met with increasing the electrical engines and propellers with 17% , without the weight of the fuel cells. In that case the all engines climb will reduce with 36%. However, it is known fuel cells may deliver 10% above their design power at the price of a lower efficiency. A heavy take off and climb out may be enhanced by using this extra power with the oversized engines.

The sweep back angle of the wing has been chosen for a design speed of mach 0.65 and becomes 15°.
This gives a wing thickness ratio of 9.92%. After several iterations the wing area stabilised at 550 m^2.
Summarising the following wing dimensions apply (between parenthesis the baseline value):

- Wing area: 550.0 m^2 (541.16 m^2);
- Wing aspect ratio: 14 (7.7);
- Wing sweep back angle (quarter chord): 15° (39.5°);
- Wing thickness ratio for (M_{str}=1.00): 0.0992 (0.08);
- Wing Span[35]: 87.75 m (64.44 m);
- Thickness of mean chord: 0.622 m (0.671 m);
- Taper ratio is 0.25 (0.239).

Engine
Scaling the engine with a factor 2.0 using a method given by Raymer (1992), but with the scaling coefficients fitted for the two engines given by ADSE (1999) supplemented as given under the heading 'Propulsive unit' in §5.6.3 resulted into the following engine parameters:

- TO rating: 16,390 SHP;
- TOC rating: 10,000 SHP;
- Propeller diameter: 14.27 ft;
- Cruise propeller rotational speed: 870 rpm;
- Number of blades: 2*6;
- Activity factor: 120;
- Nacelle length: 4.646 m;
- Nacelle diameter: 1.252 m;
- Propeller weight: 2,671 kg;
- Weight including system and propeller: 15,816 kg.

Fuselage
The fuselage has been stretched to accommodate the LH_2 fuel tanks. Stretching is only a simplified method to find the influence on drag and weight. It will be more likely the fuel will be stored into long tanks in extensions on the roof of the passenger cabin.
The fuselage length will have to increase with 11.24 m to give a weight of 24,000 kg of LH_2, which represents a total of 338,000 litre fuel net volume.

Aerodynamics
With the help of the Mathcad sheet for parasite drag calculation based on the flat plate analogy and corrected for the baseline drag polar the influence of a change of dimensions for the empennage, fuselage, struts, nacelles and wing area have been determined. With an aerodynamic clean-up the parasite drag has been reduced. The laminar flow on wings and empennage has been increased, due to the introduction of laminar airfoil sections suited for medium cruising speeds. The final result is a reduction of the parasite drag coefficient for clean cruising configuration with 11.4% (and a decrease of the total drag area with 9.9%)[36].

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35 This wingspan is larger as the ICAO 80*80 m^2 maximum box for airports and will require special measures to receive this aircraft on many airports.

36 The reduction of the total drag area seems surprising as the totale wing area and the fuselage both are larger as for the baseline aircraft. However, due to the lower design cruising altitude and the larger mean aerodynamic chord and fuselage length the Reynolds number increases, reducing the dragcoefficient.

8.9.3 Weights

The empty weight as well as the operational weights (MTOW, MLW) have been calculated with a reduction of the fuel consumption weight of 84%. This reduction is the result of the use of LH_2, the fuel cell system, the high aspect ratio wing, the lower drag due to LFC and the lower weight due to the use of new materials. The final result of this iteration is a total empty weight increase of 34,799 kg with respect to the PRESENT400, mainly due to the much higher weight of the propulsion group. The following weights now result:

- MRW: 298,061 kg;
- MTOW: 296,701 kg;
- MLW: 295,159 kg;
- MZFW: 277,469 kg;
- OEW: 215,554 kg;
- EW: 206,235 kg.

8.9.4 Performance

As no DOC has been calculated it was not possible to find the optimum speed schedule. Therefore somewhat arbitrary following assumptions has been made:

- Take off and Ground manoeuvring:
  - 26 minutes at 7% MTO engine rating (all fuel weight for taxi is pre-TO);
  - Take off 0.7 minutes at 100% MTO rating;
  - Climb-out from 35 ft to 3,000 ft at 85% MTO rating; climb-out time is 2.2 minutes;
- Operational Climb:
  - Speed schedule 250 kCAS/0.65;
  - Max climb engine rating;
- Operational Cruise:
  - Long range speed (mach 0.65);
  - Cruise altitude 8,500 m;
- Operational descent:
  - Speed schedule: 0.65/250 kCAS;
  - Thrust set for maximum cabin rate of descent (300 ft/minute and maximum cabin altitude 6,000 ft);
- Approach and landing:
  - Approach from 3,000 ft to SL at 71.4 m/s TAS (Jane's, 1998);
  - Approach time 4 minutes at 30% MTO rating;
- Reserves:
  - 120 minutes hold as extended cruise.

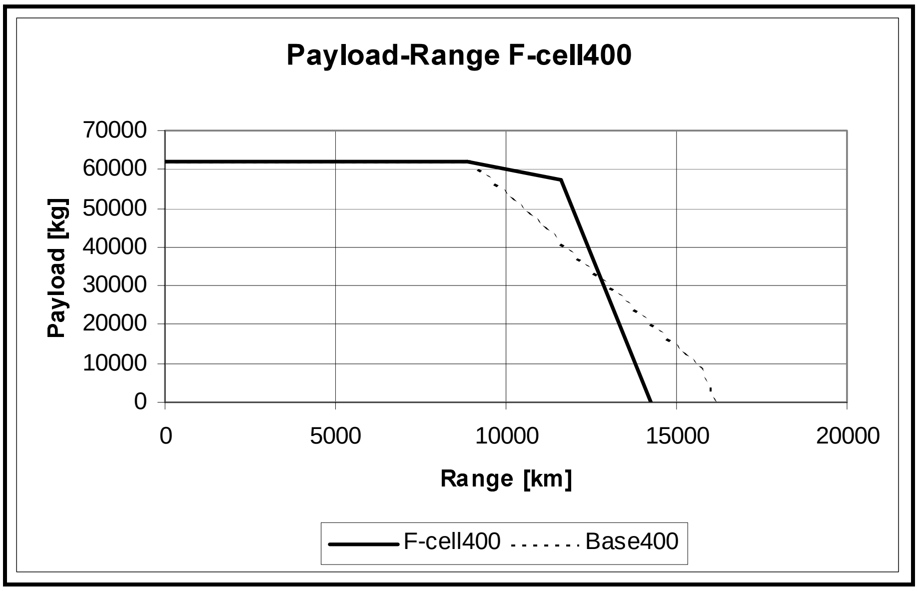
The Evaluation flight for Long Haul has been calculated with APD (see §3.8) for a block distance of 7,000 km. The following performance has been calculated for a payload at 75% load factor of 46,436 kg:

- Block time: 10 hour and 28 minutes;
- Block fuel used: 12,435 kg hydrogen (which is 34,818 kg in kerosene energy equivalents);
- Take off weight: 276,822 kg;
- Reserve fuel: 2,379 kg (hydrogen).

The fuel consumption has been reduced, in terms of kerosene equivalents for energy, compared to PRESENT400 with 42,450 kg or 54.9%. With respect to the 2010 technology turbofans the reduction is 33,695 kg or 49.2%. The aircraft is slower with a 23.1% higher block time.

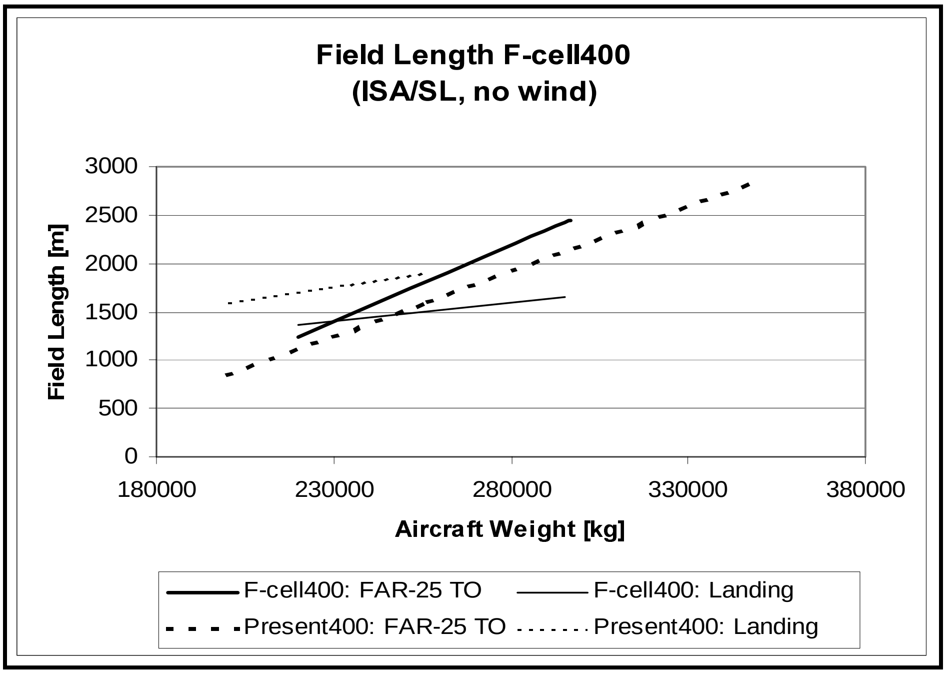
The payload range capability of the F-CELL400 is given in Figure 106. The payload range capability of the long haul fuel cell technology aircraft is better at the high partial payloads. The range can be extended with 43% from the full payload range, sacrificing only 12% of the payload. However the range with less then 20% payload becomes shorter than for PRESENT400, because of the fuel capacity constraint. At normal operations this will not be of any limitation.

Figure 106 The payload range capability of the long haul F-CELL400 for a standard atmosphere and the standard speed schedule and cruise altitude



The field performance for take off and landing has also been calculated roughly. Figure 107 gives the resulting performance on a standard day, ISA, with no wind and no runway gradient and compares it with BASE400. From this figure it is clear the take off performance is better at MTOW, but worse at low weights. The landing performance is better for all operational weights up to the MLW. Also the difference between MTOW and MLW is very small which means less fuel dump during emergencies will occur with this aircraft than with the baseline aircraft.

Figure 107 Field length performance of the long haul F-CELL400 for a standard day, ISA, no wind and no runway gradient. The lines are drawn up to MTOW respectively MLW



8.9.5 Environment

The in-flight emissions of the F-CELL400 are almost non-existent except for water vapour. As these are emitted at a lower cruise altitude (8,500 m) this may cause a less severe impact in terms of contrail forming than PRESENT400 and BASE400 do. The noise impact of the aircraft will be influenced by the following:

- The propulsion system has been de-rated with 50% (in terms of static thrust). This will largely reduce the total noise emissions.
- The electrical engine will emit less noise than a conventional turbine engine. Therefore sideline noise will be lower compared to the baseline.
- Fly-over noise will be lower, due to the high position of the engines and the lower noise emission of the propellers and the electrical engine.
- Fly-over noise will increase due to the 43% lower rate of climb[37].

The net effect of these will have to be subject of further study.

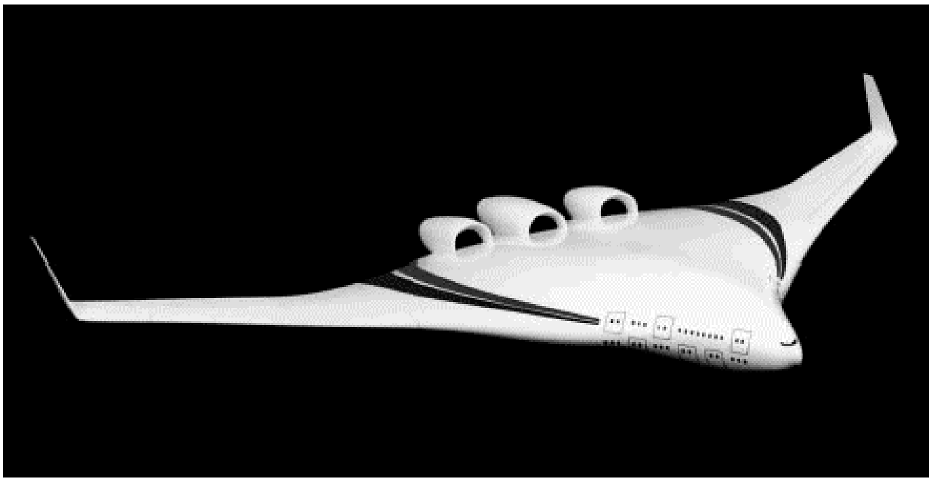
8.10 New design configurations

So far we have considered only the classical layout of aircraft: non-lifting fuselage for easy storage of cargo/passengers, wings as lifting surfaces and aft tail planes for stability. In this paragraph we discuss other solutions. The main possibilities are: tail first, tail-less and blended wing body (BWB). The tail-first or canard and the tail-less aircraft are mainly used for transonic and supersonic aircraft, though the canard configuration may save some per-

[37] In the case of the F-cell400 there is no problem with the second segment climb gradient requirement, so the remark given by footnote 34 for the F-cell150 does not apply here. on the other hand: an increase of the engine-propeller power with 10% may be used here as well, reducing the climb gradient with 33% in stead of 43%.

cents of fuel consumption if well designed on a subsonic aeroplane (Torenbeek, 1982). This leaves the blended wing body (see Figure 108) as a non-classical configuration with a possibility for rather large reductions of fuel consumption. These possibilities have been recently stated again by Boeing and NASA, who are co-operating in a flight test programme with a flying model of a large BWB transport (Phillips, 2000). Main problem of the BWB design seems the low-speed controllability and stability. According to NASA the design could reduce fuel consumption with 15% up to 25% compared to a wide body aircraft with the same technology level. The DOC may be reduced with up to 20%. This is a major step in DOC possibly offering manufacturers enough prospect to cancel the risks of such a major project.
The BWB has received attention during the past decades. The Cranfield College of Aeronautics did a preliminary design study on a BWB (the BW-89) and published the results on the internet (Cranfield, 2000). In a short history they describe the existence of flying wings in 1912 designed by John W. Dunne. This aircraft is reported to have had excellent flying characteristics. Later examples are the AW-52 Horten from Germany and the Northrop YB-49.

Figure 108 Example of a Blended Wing Body (BWB) design as given by NASA (1997)



The benefits arising from a BWB are given by Cranfield (2000) to be:
- Aerodynamics:
- low wetted area to volume ratio;
- form conducive to low interference drag;
- Structures:
- efficient deep sections;
- favourable span loading;
- Human factors:
- huge volumetric capacity;
- flexible cabin layout potential;
- Systems:
- potential for highly integrated airframe/engine;
- ideal configuration for application of laminar flow technology;
- significant advantages from control configuring the vehicle;
- Economics:
- particularly suitable for high capacity applications;
- significant D.O.C. reduction should be achievable.

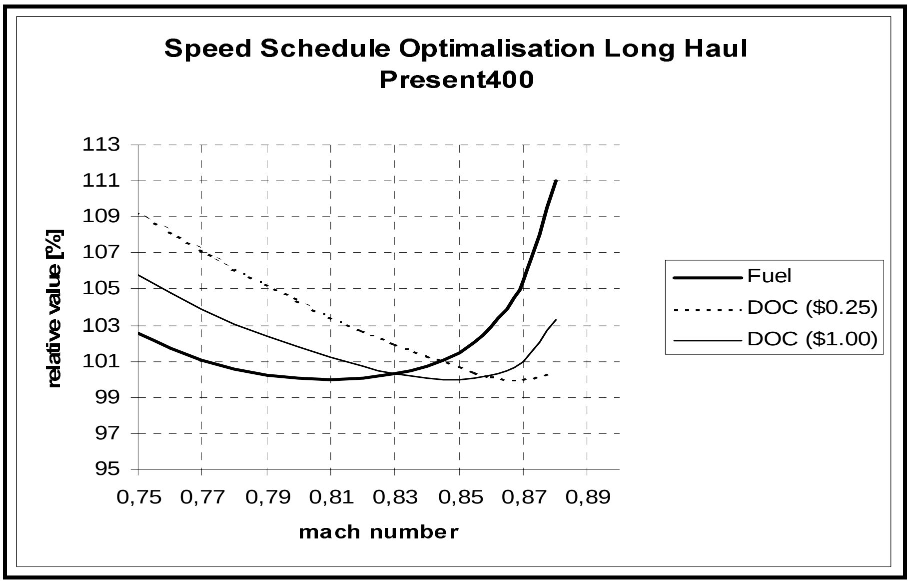
Main problems of the configuration are controllability and layout of the cabin (Torenbeek, 1989 and Phillips, 2000). Specifically the low-speed flight-envelope, like stall and spin behaviour, is largely unknown and needs investigation. To study this NASA and Boeing recently announced flight tests on a low speed scale model to start early in 2002. The 14%-scale model will be remotely piloted and represents the latest 450-passenger second-generation BWB under study at Boeing and NASA.
The passenger cabin layout presents a number of challenges to the designer like the emergency evacuation time within the 90 seconds required by the Airworthiness Rules. Also the normal embarkation time may be a problem with 700 or 800 passengers. On the other hand, designers tent to reduce the maximum capacity to 450 seats.
A difficulty may also be the construction of a noncircular pressurised cabin. This may reduce the effects of the favourable span loading. On the other hand, the use of materials like GLARE seem to have more benefits if used on a BWB than on a conventional wide body aircraft.
Another difficulty in designing a high speed BWB is the high mach drag arising from the relatively high wing thickness ratio required. It would be of much interest to look at the total design opportunities from an environmental point of view and including several propulsion technologies and performance specifications. Also it will be interesting to study the possibilities for aircraft with less then 450 passengers.

The possibilities for smaller short haul aircraft seem limited as it will be difficult to get enough height for a cabin in a lifting surface of not too large a thickness ratio. On the other hand solutions for this has been proposed already decades ago (Torenbeek, 1982).
Due to the layout a BWB will generally offer more volume for a given payload volume: this offers changes for hydrogen powered aircraft. And this may further reduce the environmental impact of this kind of aircraft. For the same reason it offers extra possibilities for the use of fuel cell technology. Pusher propellers will have to be mounted on the trailing edge of the flying wing body, driven by electric engines.
It is strongly recommended to do a study on the possibilities and possible problems of the BWB in conjunction with the other technologies presented in this study and for both long haul and short haul aircraft.

9 Fuel plus carbon price and aircraft operations

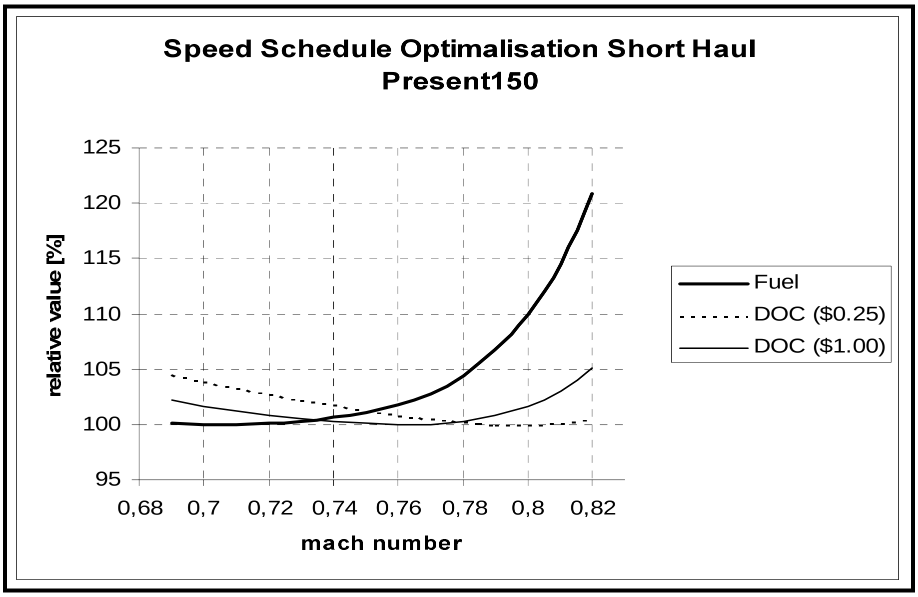
As we have seen in previous chapters of this report the DOC optimised flight speed differs normally much from the fuel optimum. Therefore the fuel consumption will be higher for the DOC-optimum than for the fuel optimum speed. To understand the effects it is useful to look at the built up of DOC. Most parts of DOC (i.e. crew cost, depreciation) reduce with increasing speed because they are lower for a shorter flying time. The cost of fuel however depends on the overall fuel consumption. And for this an optimum speed can be found depending on the characteristics of the aircraft and payload-range under consideration. Figure 109 gives the DOC and fuel consumption for a typical long range flight at 11,000 m cruise altitude.

Figure 109 The relationship between DOC and fuel consumption and the cruise mach number for a block distance of 7000 km at 11,000 m altitude for the PRESENT400 long haul transport aircraft



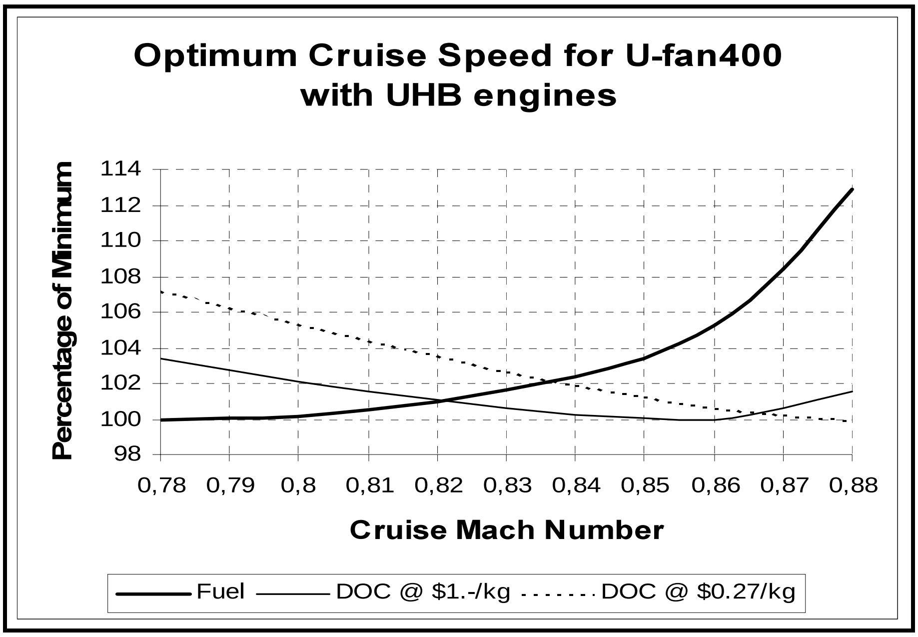
It is clear from this figure that at the low fuel price ($0.25/kg) the DOC-optimum speed is slightly below mach 0.87, while the fuel optimum (long range) mach number is 0.81. Flying at the DOC optimum will result into a rise of the fuel consumption with just over 5%.
If we raise the fuel plus carbon price substantially to $1.00/kg the DOC optimum shifts down to mach 0.84, saving 4% on fuel. The fuel consumption is less than 1% above the fuel optimum.
The same relationships exists for the short haul operation as can be seen in Figure 110. The fuel optimum is mach 0.71, while the DOC optimum at $0.25/kg fuel price comes to mach 0.80 and for $1.00/kg fuel plus carbon price at mach 0.76. Flying at mach 0.80 will cost about 10% extra fuel with respect to the fuel optimum, while flying at mach 0.76 costs about 2% of fuel.

Figure 110 The relationship between DOC, fuel plus carbon price and fuel consumption and the cruise mach number for a block distance of 1,000 km at 10,000 m altitude for the PRESENT150 short haul transport aircraft



Raising the fuel plus carbon price will certainly lead to savings due to operational changes. However, at this moment most operators will not fly at the DOC-optimum, while this optimum is too close to the maximum allowable speed, thus making it for example difficult to run in on a delay to the scheduled flight-time. The total gain in fuel consumption by quadrupling the fuel plus carbon price and due to slowing down the aircraft will be in the order of several percents.
A point of serious consideration is now the following: if we reduce the fuel consumption substantially the difference between fuel optimum speed and DOC-optimum speed will become larger. Also the difference in fuel consumption will rise. This effect is demonstrated for the LH-U-FAN in Figure 111. From this figure we can see the fuel consumption will rise with 13% if we fly at the DOC optimum for a fuel price of $0.25/kg and with 5% for $1.00/kg fuel plus carbon price. This is a much larger difference compared to the baseline figures of 5% respectively 1%.
The effect is even much larger for the fuel cell technology aircraft, because the influence on fuel consumption of the High Speed Propeller seems to be larger than for the turbofans.

Figure 111 Optimum cruising speed for the long haul U-FAN400 with UHB turbofans cruising at 11,000 m with 75% load factor



10 Summary of results and conclusions

10.1 Introduction

How will the future aircraft design be if the fuel price will rise substantially? That is the main question we try to answer in this report. For example a theoretical relationship between fuel price and aircraft design has been shown by Morrison (1984). He shows the general relationship between time, cost and fuel price and the probable difference in a DOC or a fuel optimised design. When the designer is convinced of a high price for fuel in the future market, he will fundamentally choose for solutions different from those in case a low fuel price is the prevailing forecast.
Though the theory seems sound it does not give much quantitative information on the strength of the effects. To find these we have investigated the benefits and costs of several conceptual designs meant for a hypothetical higher fuel price or the fuel price including a levy on carbon emissions or the price formed for tradable carbon rights. The effects have been evaluated by calculating block time, fuel and distance and DOC for a standardised evaluation flight.
The development and evaluation of the conceptual designs have been based on two typical representatives of the short haul and the long haul market. These baseline aircraft have been updated to an expected technology level of 2010 to create the BASE150 for the short haul market and the BASE400 for the long haul market. All individual technologies and new designs have been compared at the 2010 technology level.
To come to a fully optimised and balanced aircraft design will require a large working force and millions of dollars. Therefore this study does not have the intention to deliver full preliminary designs for a high fuel plus carbon price market. The here presented 'designs' have been based on relatively simple relations between the most important parameters and characteristics of technologies. They are in the state of a first conceptual reconnaissance of possible solutions giving something like 90% of the eventual final value of the main design parameters.

10.2 Models and methods

10.2.1 Introduction

In this paragraph we give a short description of the methods and models used for the design part of the study. The methods and models are used for giving examples of the development of derivatives and new designs of two baseline aircraft. The characteristics of the designs are found by 'modifying' the two baseline aircraft and evaluating their performance and Direct Operating Costs compared to the baseline.
In the following subparagraphs we will not only describe the models and design tools used, but also the definition of the two markets and the evaluation flight. Also the validation of the models will be given.

10.2.2 Definition of markets and evaluation flight

We have divided the air transport market in a short haul market (up to a range of 3,000 km) and a long haul market (over 3,000 km). For the short haul market the PRESENT150 is represented by the dimensions, weights and performance of the 146-seats Boeing 737-400. For the long haul market the 416 seats Boeing 747-400 has been chosen to represent the PRESENT400.
As we are looking at designs and technology not currently available but likely to be developed for introduction into service after 2010 we have decided to base and compare the new technologies and designs to the PRESENT150 and PRESENT400 including the most likely conventional development for the next eleven years. From the literature it has been found the most likely development is expected in engine technology. The conventional Turbofan engine technology evolves to a higher fuel efficiency at a lower weight and lower engine purchase price. Eleven years (from 1999 to 2010) of this trend has been presumed for the baseline aircraft in 2010. These are designated the BASE150 for the short haul market and the BASE400 for the long haul market.
For the short haul market the evaluation flight is defined over a block distance of 1,000 km with a 70% load factor. For the long haul evaluation flight the definition is a block distance of 7,000 km with 75% load factor.
Based on the survey of Van der Heijden and Wijnen (1999) new technologies or design changes in the field of propulsion, aerodynamics and materials are introduced. Technologies included in this study are Ultra High Bypass Turbofans (UHB), High Speed Propellers (HSP), Fuel Cell propulsion technology, Aerodynamic clean-up/Laminar Flow Control (LFC), High Aspect Ratio (HAR) wing design and the extensive use of New light weight Materials (NML).
The new designs are compared to the BASE150 and BASE400 for fuel consumption and DOC at current fuel price and a hypothetical high fuel plus carbon price in the future. Another important criterion has been the 'break even fuel plus carbon price'. The effect of fuel plus carbon price on DOC is a characteristic for each design depending on the fuel consumption and the non-fuel related parts of the DOC. The lines for the BASE150/BASE400 design and the new design cross at a certain value of the fuel plus carbon price. When the fuel plus carbon price is below this point the BASE150/BASE400 aircraft are economically the best proposition. Above this value the new design has a more favourable DOC.

10.2.3 General overview of model and design tools

Detailed information on models and tools used in this study can be found in Chapter 3 of this report. Below we will give a summary. Tools are used for scaling and sizing the PRESENT150 and the PRESENT400. They were used to create the input files on aerodynamics, weights, cost and engine performance. The main tools are:

- Weight tool: a tool to determine the weight change of all parts of the airframe as a function of dimensions and materials of these parts as well as the maximum landing and take off weights defined. The tool is based on the statistical method given by Raymer (1992) but has been fitted to represent the known weights of the PRESENT150/400 aircraft.
- Drag tool: this tool uses the flat plate analogy and factors for interference, leakage and fuselage wake drag as given by Raymer (1992). Also this method has been fitted to represent the baseline designs.
- Airframe/engine pricing tool: for finding the sales price of the modified or new design this sheet calculates the total programme cost (development, material and labour cost for engineering and production) and di-

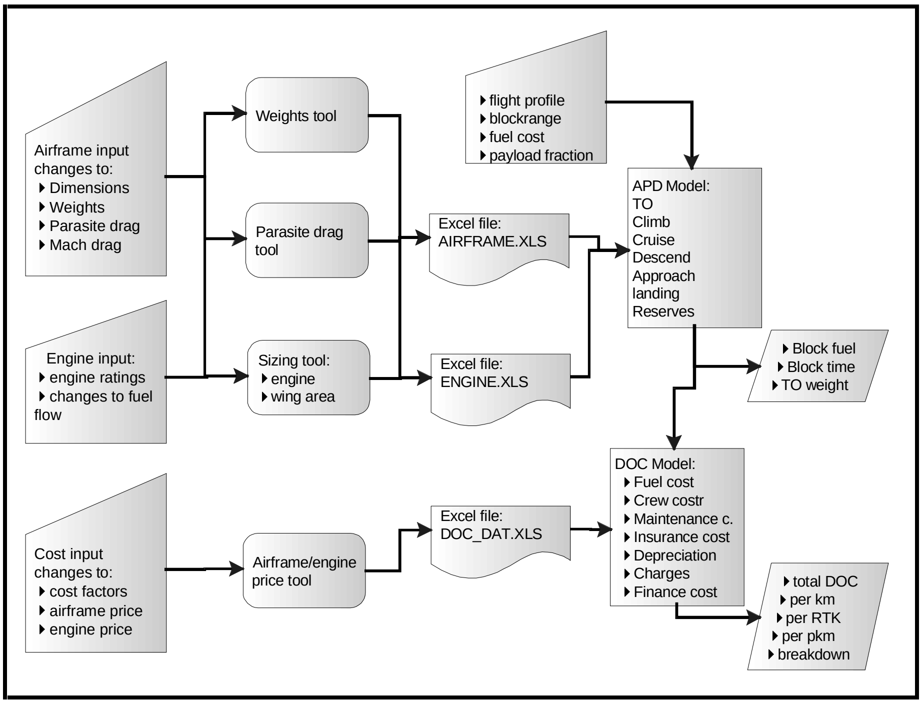
vides it by the given number of aircraft expected to be sold within the programme. Again the method has been fitted to the PRESENT150/400.

- Sizing tools: this tool consists of several sheets which help to find the right size of engines and wing area by defining power- and wing-loading. The wing area is primarily optimised for fuel consumption during cruise. The engines are sized for the required take off field length (hard requirement) and the top of climb capability as well as service ceiling (giving the largest practical cruise altitude). The propeller for propeller driven aircraft (like the High Speed Propeller) is also sized for the maximum propeller tip speed (less then mach 1.0).

With the help of these tools several aircraft definition input files are filled with data: the airframe, engine and cost spreadsheets. These files are used by the APD model. APD stands for Aircraft Performance and DOC. This model gives the aircraft performance for a given block range, payload, reserves strategy and speed/altitude schedule. The model uses data on engine performance and airframe drag and weight characteristics for a stepwise calculation of the whole flight profile consisting of taxi, take off, climb out, climb, cruise, descent, approach and landing. A total of over about 200 points for altitude, aircraft velocity (mach number), weight, thrust required, distance and time are calculated to define the flight profile and to find the total block fuel and time for the given block range.
After the aircraft performance has been found the data are transferred to a module for calculating DOC. This module is used to find the Direct Operating Costs for a given flight from the output of the APD model (block time and block fuel) and the given block range. The DOC is based on the method given by Roskam (1989, Part VIII) but has been fitted for the current cost levels and practices in the industry. The DOC contains the cost for crew (wages and training of pilots and cabin attendants), fuel and oil, maintenance hours and cost of airframe and engines, depreciation, insurance, finance and landing fees.

Figure 112 gives an overview of the tools and models. All tools and modules of the APD model are written with Mathcad 8 running on a desktop PC. The APD model is programmed in Mathconnex 8. The tools were of course only used where appropriate for the design under development. Input changes are made within the math sheets to find weights drag, price of airframe and engines and the right size of wing area and engine thrust or power.
With the help of the tools the three input spreadsheets for the models are filled. The AIRFRAME sheet contains all information on dimensions, weights and drag. ENGINE contains tables for the maximum thrust for take off, climb and cruise as a function of aircraft velocity and altitude and the fuel flow as a function of thrust, altitude and mach number.
The APD model is run with manual input on the block range, speed schedule and cruise altitude. Block fuel, block time and take off weight as well as DOC are given as output. Not indicated in Figure 112 is the output to Excel sheets of intermediate results on all steps in the flight profile calculations and a detailed break down of DOC.

Figure 112 Overview of the design and performance toolbox used in this study



10.2.4 Validation

The APD model results have been validated with the help of performance data published by the National Aerospace Laboratory NLR for their FLEM model (Flights and Emissions Model) (Ten Have and Witte, 1997). In Table 18 we compare these results from FLEM with the results from APD.

Table 18 Validation of the APD results with results by the FLEM model from NLR

Block Distance	Block time		Block fuel	
[km]	Index FLEM=100		Index FLEM=100	
	PRESENT150	PRESENT400	PRESENT150	PRESENT400
1,000	100	-	102	-
6,000	-	99	-	97

The block time is predicted within 1% deviation for both short haul and long haul market transports. For fuel flow APD predicts 2% more for the short haul aircraft. The long haul aircraft shows a deviation of 3% lower fuel consumption than predicted by FLEM.

The DOC model has been validated against general data from AVMARK (AVMARK, 1999). The mean value of the DOC model has been weighted for the traffic volume for short and long haul. Assuming Internal European flights from all European airports to be short haul and intercontinental flights to be long haul, the long haul should be weighted two times the short haul (Peeters et al., 1999). After fine tuning the model and parameters the final validation shows a good resemblance between AVMARK and the weighted mean (Table 19).

Table 19 Validation of the DOC model

Cost item	AVMARK (mean)	PRESENT150 at 1,000 km	PRESENT400 at 7,000 km	Weighted Mean for the two example planes
Flightdeck crew:	4.5	6.1	3.7	4.5
Cabin crew	4.0	6.0	3.0	4.0
Fuel&oil	5.7 (22%/17%)	6.8	5.1	5.7 (22%/17%)
Maintenance&Overhaul	5.6	7.5	4.6	5.6
Charges	6.3	13.0	2.9	6.3
Insurance	0.3	0.4	0.2	0.3
Finance	0	0 (1.9)	0 (1.0)	0 (1.3)
Depreciation (plus rentals)	(6.4)	0 (9.8)	0 (5.4)	0 (6.9)
TOTAL	26.4 (32.8)	39.8 (51.5)	19.6 (26.0)	26.3 (34.5)

10.3 Baseline aircraft

10.3.1 Definition of BASE150 and BASE400

Data for the two baseline aircraft have been gathered from many sources and from unpublished data from Peeters Advies and partners. The engine data have been updated to represent a 2010 technology level Turbofan in the appropriate thrust class. This means the specific fuel consumption has been reduced with 9% and the engine weight with 8% compared to the current values of respectively the CFM56-3B-2 turbofan engine (short haul) and the CF6-80C2B1F turbofan engine (long haul). See Table 20 for an overview of the characteristics of the two baseline aircraft.

Table 20 Overview of basic characteristics of the two Baseline aircraft used for comparison

	BASE150	BASE400
Number of seats	146	416
Maximum payload	16,690	61,915
Wing area [m^2]	105.4	541.2
Wingspan [m]	28.88	64.44
Wing Aspect Ratio	7.9	7.7
Operating Empty Weight	34,025	177,171
Number of engines	2	4
Dry engine weight	1,795	3,967
Maximum Take off Weight	61,241	348,474
Airframe market price [k$]	37,800	148,400
Engine market price [k$/engine]	2,775	4,833

10.3.2 Evaluation flight definition

The flight profile used for calculating block-time and block fuel is a simplification of the flight profile given by Torenbeek (1982). The engine ratings and times below 3,000 ft are taken from the standard ICAO LTO-cycle[38]. The following assumptions have been made for the evaluation flight of the BASE150:

- block distance: 1,000 km;
- payload: 70% of maximum;

[38] For climb-out this standard time is compared to the real time given the aircraft and engine-parameters; the largest of the two has been used.

- 26 minutes at 7% MTO engine rating (all fuel weight for taxi is pre-TO);
- take off 0.7 minutes at 100% MTO rating and Climb-out from 35 ft to 3,000 ft in 2.2 minutes at 85% MTO rating;
- climb at 300 knots[39] constant CAS/mach 0.745 with maximum climb thrust;
- cruise at 10,000 m altitude with mach 0.745;
- descent with constant mach 0.745/300 knots CAS;
- approach from 3,000 ft to SL at 71.4 m/s TAS; Approach time 4 minutes at 30% MTO rating;
- reserves: go around from 3,000 ft at destination, flight to alternate at 200 NM with flight speed schedule, but at 8,000 m cruise altitude and 30 minutes hold as extended cruise.

For the Long haul evaluation flight the same flight profile has been used with following exceptions:

- block distance 7,000 km;
- payload: 75% of maximum;
- speed schedule for climb and descent: 320 knots CAS/mach 0.84;
- cruising speed mach 0.84 at 11,000 m altitude;
- reserves: 120 minutes hold as extended cruise.

10.3.3 Performance of BASE150 and BASE400

Table 21 gives a comprehensive overview of the performance of the BASE150/400.

Table 21 Performance result for the BASE150/400

	BASE150	BASE400
Evaluation load factor [%]	70	75
Evaluation Payload [kg]	11,684	46,436
Block range [km]	1,000	7,000
Block time [hr.min]	1.52	8.30
Block fuel [kg]	3,591	68,513
Take off weight [kg]	52,160	306,376
Reserve fuel [kg]	2,860	14,255

10.3.4 DOC of Base150 and Base400

The DOC has been calculated with the DOC model (see §2.6) from the block time, block distance and block fuel. The result has been given for a 1996 fuel price level of $0.27/kg (see Table 22).

Table 22 Direct Operating Costs (DOC) at the 1996 fuel price ($0.27/kg) for the BASE150/400

	BASE150	BASE400
Total cost of the flight [$]	8,311	108,262
per block hour [$/hr]	4,471	12,740
per kilometre [$/km]	8.311	15.47
per revenue ton kilometre [$/RTK]	0.711	0.333
per passenger kilometre [$/p-km]	0.0813	0.0496

In Figure 113 a DOC breakdown has been given for the BASE150 short haul baseline aircraft. Fuel accounts for 12% of the total Direct Operating Costs.

[39] Below 10.000 ft the speed is restricted to 250 kTAS (Torenbeek, 1982).

Current charges (landing fee, ATC-fees and environmental fees) form in the short haul market the largest part and surpass the total crew cost (flight deck crew and cabin crew).

Figure 113 DOC breakdown for the BASE150 at 70% load factor on a 1,000 km block distance flight

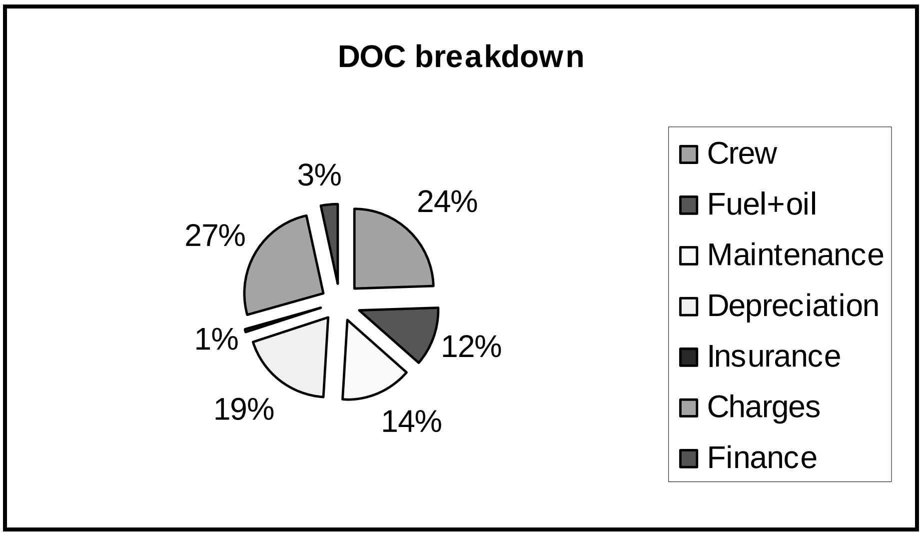
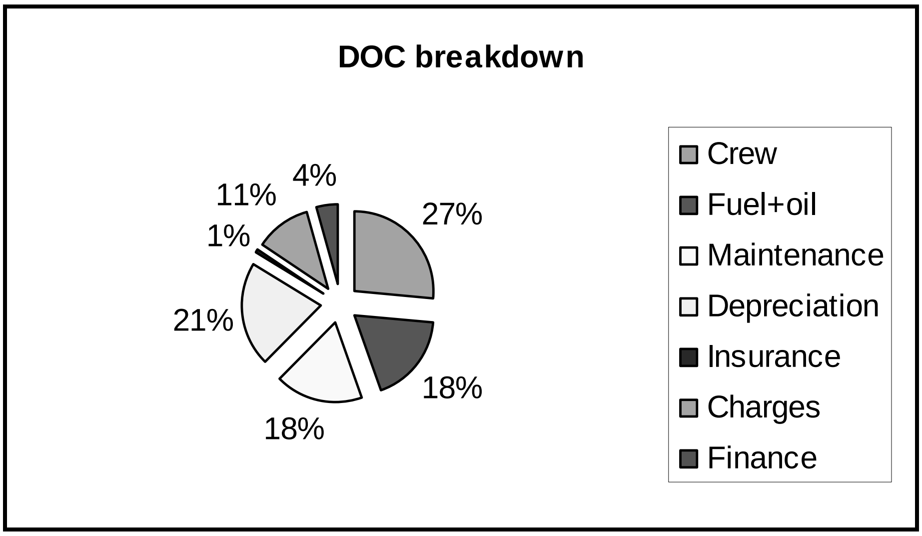


Figure 114 represents the DOC breakdown for the long haul BASE400. Fuel takes about 18% of the total Direct Operating Costs. Crew cost form in the long haul market the largest part (27%) of DOC.

Figure 114 DOC breakdown for the Long Haul BASE400 at 75% load factor on a 7,000 km flight



10.4 Designing for low fuel consumption

10.4.1 Introduction

In this paragraph we will discuss briefly the results of the conceptual design study. As we presume the fuel plus carbon price will rise substantially the main bias of the modification and new design is to find ways to reduce the high cost of fuel and carbon in the hypothetical market conditions presumed. The major areas for reducing fuel consumption are: engine technology, weight reduction and drag reduction. Further the total design configuration (not only the conventional wing-fuselage tail plane configuration, but also for example the flying wing) may help to reduce fuel consumption.
This last possibility has not been worked out as it requires a design effort beyond the purpose of this study. Included however are four conceptual designs per market combining new technologies and resizing engines and wing area. An unconventional aircraft configuration (the blended wing body) is considered only based on the literature.
To come to a fully optimised and balanced aircraft design will require a large working force and millions of dollars. Therefore this study does not have the intention to deliver full preliminary designs for a high fuel plus carbon price market. The designs have been based on relatively simple relations between the most important parameters and characteristics of technologies. They are in the state of a first conceptual reconnaissance of possible solutions (the designs we will present) giving about 90% of the eventual final value of the design parameters.

10.4.2 Engine technology

Introducing new engines with a lower fuel consumption is a direct way to improve the environmental performance of the aircraft. As will be shown the fuel consumption may be reduced with up to about 30% compared to conventional 2010 turbofan technology. The effect on DOC is wide spread giving break even fuel plus carbon prices between \$0.28/kg up to \$0.56/kg.
Retrofitting an existing aircraft design with new engines may have strong effects on the total aircraft design, ranging from effects on the weight and drag of the aircraft to changes in undercarriage design or even fuselage- and wing-design in case the new engines differ much in their dimensions. Much depends on the differences between the current engine and the new one. Therefore in many cases it will not be possible to retrofit an existing airframe economically with new engines. For example nobody would suggest a retrofit of the Boeing 747-400 with High Speed Propellers for commercial purposes. Therefore we have evaluated the pure effects of a new engine type by 'virtually retrofitting' the baseline designs with them.
A wide range of propulsion options exist. The most conventional technologies are those aimed at improving current turbofan engines. An example is the ultra high bypass turbofan engine (UHB). Another possibility are normal turboprop engines. As this would mean a large reduction in aircraft speed and therefore increase of block time and DOC a lot of research has been done in the development of Propfans: shrouded or unshrouded fans that work efficiently up to mach 0.82. However, these technologies present unsolved problems like high vibration levels and high exterior and interior noise as well as probable de-icing problems. An interesting compromise may be found in the development of high speed propeller technology or High Speed Propellers (HSP). In this study we describe the effects of a 'moderate' High

Speed Propeller designed for a cruising speed of mach 0.75 as defined by ADSE (1999).
A more or less exotic solution may be found in a combination of fuel cells powering electrical engines driving high speed propellers. Fuel cells use hydrogen as fuel, deliver electricity and emit water vapour. Their energy efficiency is high: up to 75% of the energy content of the fuel may be out-putted to the electrical engine. The problem of fuel cells is the high weight and volume of them and the high volume and difficult handling of liquefied hydrogen. Though the last two decades much progress has been made with the reduction of the specific weight and volume of a fuel cell system, its current weight of about 1.3 kg/kW is still quit high. It would add 30% to the empty weight. This propulsion system lays a few extra design constraints to the aircraft. Considering these the practical feasibility of fuel cells in aircraft design has been demonstrated in this study.
The UHB Turbofan is a fair proposition for both markets: 14% to 15% of fuel is saved compared to the BASE150/400 and the break even point for the SH_UHB and the LH_UHB is 73% respectively 29% above current fuel price. In both cases the larger diameter of new engines requires new larger nacelles. These are heavier and increase parasite drag as well as airframe price. For the short haul aircraft design the ground clearance of the engines will become too low. Therefore a higher undercarriage has been defined adding to airframe weight and price.
High Speed Propellers offer a much larger reduction in fuel consumption. For the short haul market the High Speed Propeller gives the best opportunities. This is mainly caused by the fact the High Speed Propellers were designed for mach 0.74, which is near the current cruising speed for the BASE150, but 15% below the cruising mach number of the BASE400.
This is represented by the results for break even point: where the SH_HSP comes at a very favourable $0.276/kg fuel plus carbon price (a rise of only 3%), the LH_HSP shows a high $0.59/kg (a rise of 119%). The resulting reduction in fuel consumption with respect to the BASE150 is 28.5% and for BASE400 32.2%.
To prevent the propellers to 'scrape' the runway the engines will be mounted directly on the wing instead of below as is the case in the baseline designs. This saves pylons and part of the drag of the nacelles. It is the usual way to install engines on a low wing turboprop transport aircraft of which many examples fly today.

10.4.3 Drag reduction

Aerodynamically two ways to improve the aircraft performance have been studied: reducing parasite drag and reducing the 'induced' or lift-related drag. The first one can theoretically most effectively be reduced by using passive or active laminar flow control (LFC). An aerodynamically clean-up of the aircraft (removing protuberances, smooth surfaces and a smooth faring between the various airframe parts) is seen as a more practical possibility to reduce parasite drag.
With LFC one tries to keep the flow over parts of the airframe as long as possible 'laminar' before it changes to a 'turbulent' state. Reason for this is the much lower resistance force of a laminar flow compared to the turbulent one. A clean and smooth airframe surface is a method to enhance laminar flow. Normally, without this method, not more then 5-10% of the wings will have laminar flow.
Passively the transition point from laminar to turbulent can be postponed by using specially designed laminar airfoils for wings and tail surfaces. The use of large eddy break up (LEBU) devices by bringing a plastic film on the air-

frame surface with little grooves on them also reduces the parasite drag. An active way of retaining laminar flow is by ‘boundary layer suction’. Via small holes in the airframe surface the air flowing along it is sucked away partly, preventing the built up of a turbulent boundary layer.

Van der Heijden and Wijnen (1999) expects an overall reduction of 12.5% of the parasite drag by using a combination of an aerodynamic clean-up and passive or active LFC. The active laminar flow goes at the expense of extra weight, airframe acquisition cost and extra maintenance hours, due to cleaning the aircraft thoroughly before every flight. Passive laminar flow requires only a moderate increase of the airframe maintenance hours. Passive laminar flow cannot be used on a wing designed for a high subsonic mach number.

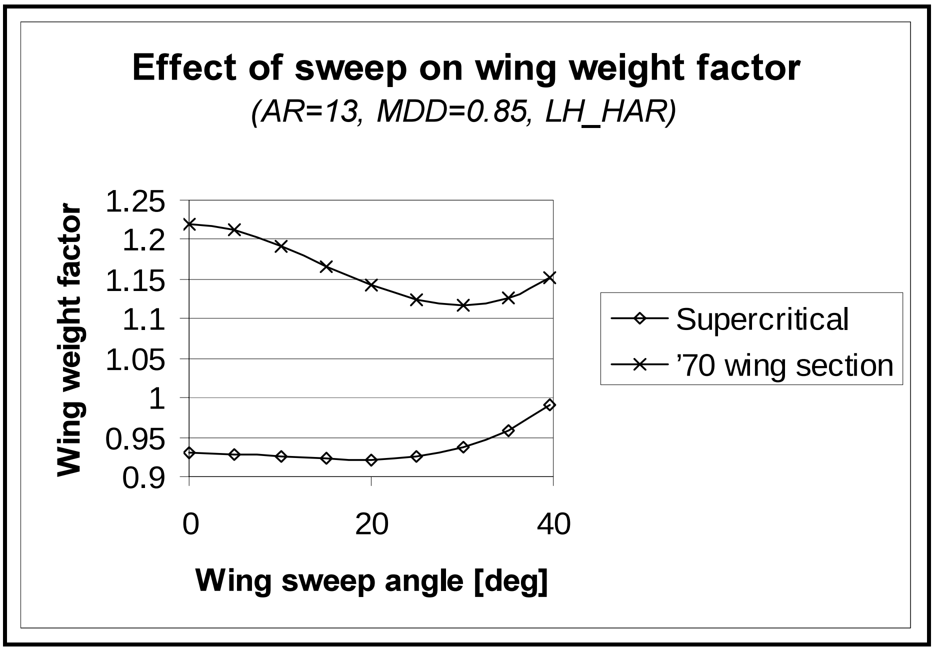
Two aircraft have been developed: the SH_LFC and the LH_LFC. The effect of the reduction of the parasite drag with 12.5% gives a reduction of 5% for the SH_LFC and 8% of fuel consumption for the LH_LFC. As laminar flow control also is relatively cheaper to introduce on the long haul aircraft than on the short haul it is not surprising the break even point for long haul is much lower than for the short haul aircraft: $0.303/kg respectively $0.913/kg. The extra cost for maintenance (extra cleaning of the aircraft, keeping the surface smooth) and the extra weight seems for the long haul aircraft almost offset by the fuel savings, even at the low fuel price of today.

To reduce the induced drag a common method is increasing the wing aspect ratio by increasing its span and reducing its mean chord. Another way is to fit the aircraft with ‘winglets’, small vertical wings at the wingtips as can be seen on many long range aircraft today. These devices are already part of the BASE400 and therefore not considered further. The PRESENT150 has an aspect ratio of 7.9 and the PRESENT400 of 7.7. The latest models of Boeing and Airbus have aspect ratios up to 10. To find the optimum aspect ratio in this study we have assumed a high fuel plus carbon price of $1.00/kg. From this optimisation it became clear an aspect ratio of 13 is best suited for the SH_HAR and 14 for the LH_HAR.

If this really will be possible depends mainly on the possibilities of new structural design methods and materials to prevent aeroelastic problems with such a high aspect ratio at high speeds. On the other hand: some sail planes have aspect ratios of more than 30.

A larger aspect ratio gives an increase in bending moments and forces at the wing root section while the thickness of this section will be reduced for a given airfoil profile, thickness distribution, wing section and wing taper ratio. Therefore the designer is likely to choose for a wing section with a larger thickness ratio. But then mach drag will rise, which is undesirable as it will increase fuel consumption at higher cruising speeds. A way to combat the extra mach drag is to sweep the wing backwards. But this will add to the wing weight and may give undesirable low speed characteristics of the wing. From all these contradicting effects an optimum wing sweep angle may be found for a given design mach number and aspect ratio (see for example Figure 115). The wing sweep has been optimised for the lowest wing weight.

Figure 115 Optimum sweep back angle for long haul LH_HAR new wing design



For the high aspect ratio designs we assume a new wing will have a more sophisticated wing section design for transonic capabilities. These 'super-critical' wing sections will replace the '70 technology wing sections from PRESENT aircraft.
It appeared from an optimisation for cruise flight the total wing area could be reduced as well. For the short haul with 2.3% and for the long haul with 16.5%. In spite of this latter figure a decrease of the take off field length has been reached, due to the lower weight of the aircraft (a reduction with 13,000 kg in OEW) and the larger maximum lift coefficient possible with a smaller wing sweep and a thicker wing profile.
The new wing design will increase the airframe cost and therefore the air-frame purchase price. Still the break even point for the LH_HAR is $0.19/kg at a fuel saving of 16% and $0.85/kg for the SH_HAR with 7.1% fuel saving.

10.4.4 Weight reduction

Weight reduction has always been a driving force in aircraft design because every kg of weight saving may be used for increasing the payload or the range (extra fuel) of the aircraft. Though still new developments are possible it is difficult to save substantial on empty weight for a given maximum take off weight and airframe. And it is also expensive. To save 8% of the empty weight it is necessary to replace 60-70% of the original structure with strong and lightweight new materials. The most likely materials for reducing weight are composites like fibre reinforced plastics and fibre metal laminates. The calculations showed the fuel saving is not very spectacular: for short haul only 2.9% and for long haul 4.5%. These figures are without the effect of a smaller engine or wing, which may be possible when reducing the empty weight. But effects of these will be small as the change in take off weight is in the range of only a few percent.
The cost for redesigning a large part of the aircraft is high: the airframe price will be 11% (short haul) or 14% (long haul) higher. Further total airframe (plus systems) maintenance hours will rise with something like 15% to 18%, because repairing damage on a composite is generally more labour inten-

sive. Therefore it is not surprising the break even fuel plus carbon price is high: $1.38/kg for short haul and $0.93/kg for long haul. However the changes in DOC are relatively small: the DOC at current fuel price ($0.27/kg) will rise with respect to the BASE150/400 by 1.6% for SH_NML and with 2.1% for LH_NML.

10.4.5 New designs

General description
In this paragraph we will look at eight new designs (four per market) in which several technologies are combined. In the individual technologies paragraph we evaluated three different propulsion options: ultra high bypass turbofans, high speed propellers and fuel cells. As the characteristics of the engines dictate large differences in operational speeds we will design the new aircraft ‘around these engines’. Also we have given attention to the influence of design speed by introducing both a high speed and a medium speed design with high speed propellers. This gives the following designs:

- U-FAN150 and U-FAN400: combines the ultra high bypass turbofan with all other non-propulsive technologies.
- H-PROP150 and H-PROP400: combines high speed propellers at their highest possible design cruise speed with a high aspect ratio plus aerodynamic clean-up.
- M-PROP150 and M-PROP400: combines high speed propellers at a medium design cruise speed with a high aspect ratio and laminar flow control/aerodynamic clean-up for the long haul market only.
- F-CELL150 and F-CELL400: a new design combining fuel cell power and electric/high speed propeller propulsion with all other non-propulsive technologies.

Table 23 gives an overview of the configuration of the new designs.

Table 23 Overview of the technologies used in the new designs

	H-PROP150	H-PROP400	M-PROP150	M-PROP400	U-FAN150	U-FAN400	F-CELL150	F-CELL400
Propulsion options								
High Speed Propeller turboprop engine	+	+	+	+			+	+
Turbine engine	+	+	+	+				
Ultra High Bypass turbofan engine					+	+		
Fuel cells, super-conducting electric engine							+	+
Fuel options								
Kerosene	+	+	+	+	+	+		
Hydrogen							+	+
Other aircraft technology options								
High Aspect Ratio	+	+	+	+	+	+	+	+
Laminar flow wing section			+	+			+	+
Active laminar flow control					+	+		
Aerodynamic clean-up	+	+	+	+	+	+	+	+
New materials					+	+	+	+

Table 24 Overview of properties of the new designs

Design	OEW	MTOW	aspect ratio	wing area	wing span	price (incl. eng.)	W[40] propulsion
	tonnes	tonnes	-	m^2	m	M$	tonnes
BASE150	34.0	61.2	7.9	105.4	28.88	43.35	5.121
H-PROP150	36.4	60.1	11.0	103.0	33.66	43.65	6.573
M-PROP150	33.8	56.2	12.0	109.5	36.25	40.81	5.053
U-FAN150	28.6	52.5	10.0	82.5	28.72	45.88	4.521
F-CELL150	46.4	64.5	12.0	144.0	41.57	N/a	14.908
BASE400	177.2	348.5	7.7	541.2	64.44	167.73	22.460
H-PROP400	167.5	290.7	14.0	460.0	80.25	152.10	24.178
M-PROP400	163.8	281.0	14.0	490.0	82.83	144.56	20.535
U-FAN400	148.1	277.3	12.0	415.0	70.57	169.43	17.784
F-CELL400	215.6	296.7	14.0	550.0	87.75	N/a	64.412

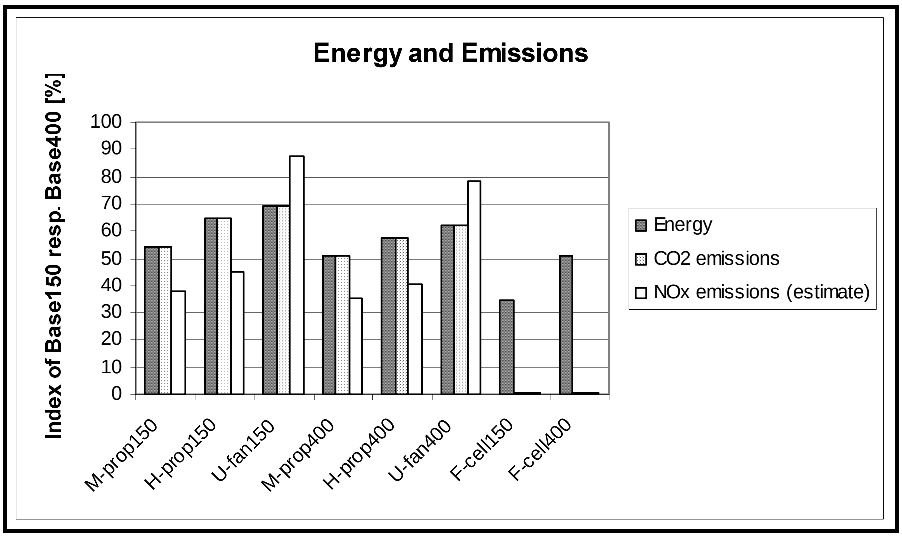
In all designs we have optimised wing- and power-loading. For M-PROP, H-PROP and U-FAN we have optimised the wing aspect ratio for the case of a $1.00/kg fuel plus carbon price. The M-PROP aspect ratio has also been used for the F-CELL designs. The main properties of the aircraft are summarised in Table 24. From this table it becomes clear the high speed propeller (M-PROP) gives a cheap aircraft, while the ultra high bypass turbofan asks for an 'lean' but expensive aircraft. Fuel cells result into a relatively heavy aircraft, mainly due to the high weight of the propulsion system. The cost of fuel cell aircraft has not been determined because too many cost factors are largely unknown for these designs.

Environmental impact of new designs

To determine the environmental impact we have concentrated on the emission of CO_2 and thus on fuel consumption. Also a first estimate of emissions of NO_x and of noise have been made. Anon. (1997) gives a difference of specific NO_x emissions per kg fuel of about 1 to 1.8 for Propfan to UHB. In this report we have assumed this difference upon a reduction of the specific emission with 30% for the HSP. As some designs use LH_2 and others use kerosene as fuel we will replace the fuel consumption with energy consumption to make them comparable.

[40] Propulsion weight is the sum of engine (plus propeller) weight, exhaust system weight, fuel system weight and engine installation weight.

Figure 116 Environmental impact of the new designs as index of the BASE150/400



As the results for the fuel cell designs are more tentative as the other results, we will first dices this figure without the F-CELL designs. From this figure it becomes clear the M-PROP designs give the lowest emissions and energy consumption and the U-FAN designs the highest. Interesting is the cruise design speed increase of the H-PROP designs results also in an increase of energy consumption and emissions. This is mainly due to the required higher power loading compared to the M-PROP.

The results for the F-CELL are better than for the other designs. We must however keep in mind, the technology used in the F-CELL designs will not be available within a few decades, while the other technology is available now or within the near future. Further, part of the effect on emissions is also created by the use of hydrogen, which is not limited to F-CELL, but may as well be introduced (in the long term) on the other designs. Further, the production of hydrogen will impose some environmental effects as does the production of kerosene. Both second order effects are not further studied here.

The noise impact is influenced by two parameters: the direct emissions of noise from airframe and engines and the flight path at low altitudes during climb and approach. Both low noise emissions and a steep flight-path will reduce the noise 'footprint' (area within some pre-defined noise level) and therefore the impact of noise on the environs of the airport. The noise emissions are influenced by the power rating and the type of the engine. Due to many unknowns of the new designs and the complexity of the material we will only make some qualitative remarks on this subject (see Table 25). The final result requires extensive analysis on the subject, which is beyond the scope if this study.

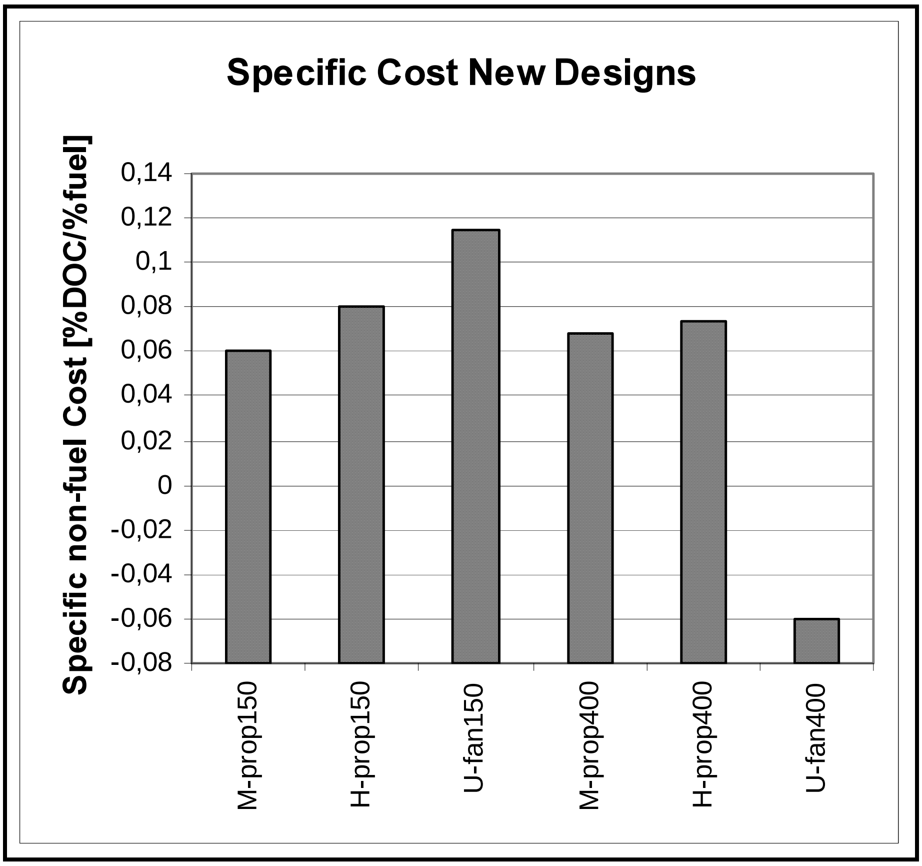
Table 25 The effect of the new designs on noise compared to the baseline 2010 (tentative estimates). The noise impact will be reduced if the engine rating is lower, the number of '–' for direct noise and installation effects increases and the climb gradient is higher

Parameter	Short haul				Long Haul			
	M-PROP	H-PROP	U-FAN	F-CELL	M-PROP	H-PROP	U-FAN	F-CELL
Engine rating [% of BASE static TO thrust]	75%	90%	80%	67%	57%	70%	67%	50%
Engine direct noise emission (relative change)	--	--	-	---	--	--	-	---
Engine installation effect on noise emission	-	-	0	-	-	-	0	-
Initial climb-out gradient [% change with respect to BASE]	-23%	+7%	+1%	-36%	-22%	-3%	-5%	-43%
Total noise effect (tentative estimate)	worse	better	better	worse	same	better	better	worse

Economics of new designs

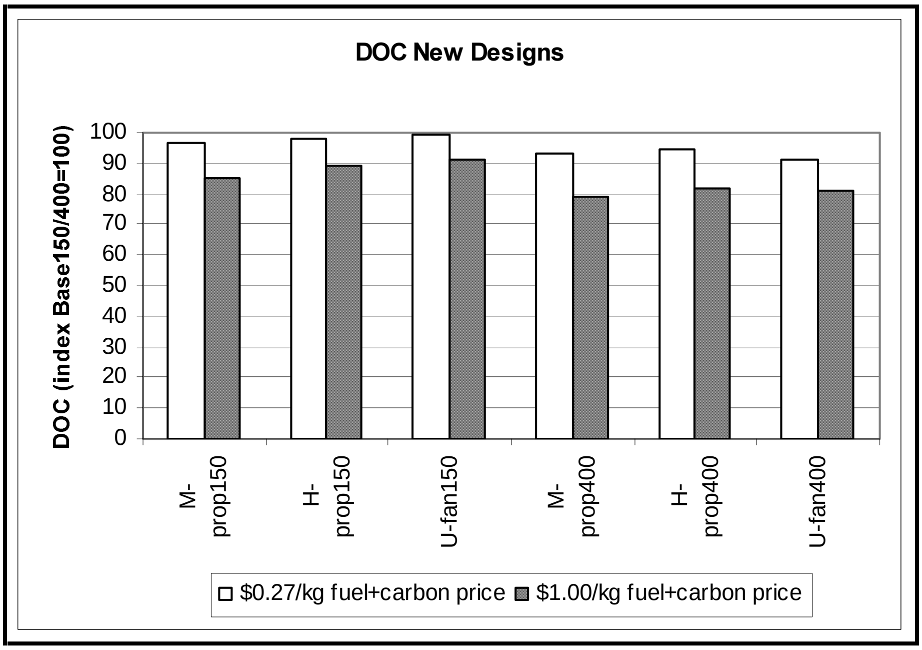
From Figure 117 we can see the most cost effective designs for short haul is the high speed propeller at medium cruising speed (M-PROP150), while the least cost effective is the U-FAN150. For long haul the U-FAN400 is much better as both other designs, while M-PROP400 has a small advantage over H-PROP400.

Figure 117 Specific non-fuel cost of the new designs in % change in DOC per % fuel saving with respect to the BASE150/400



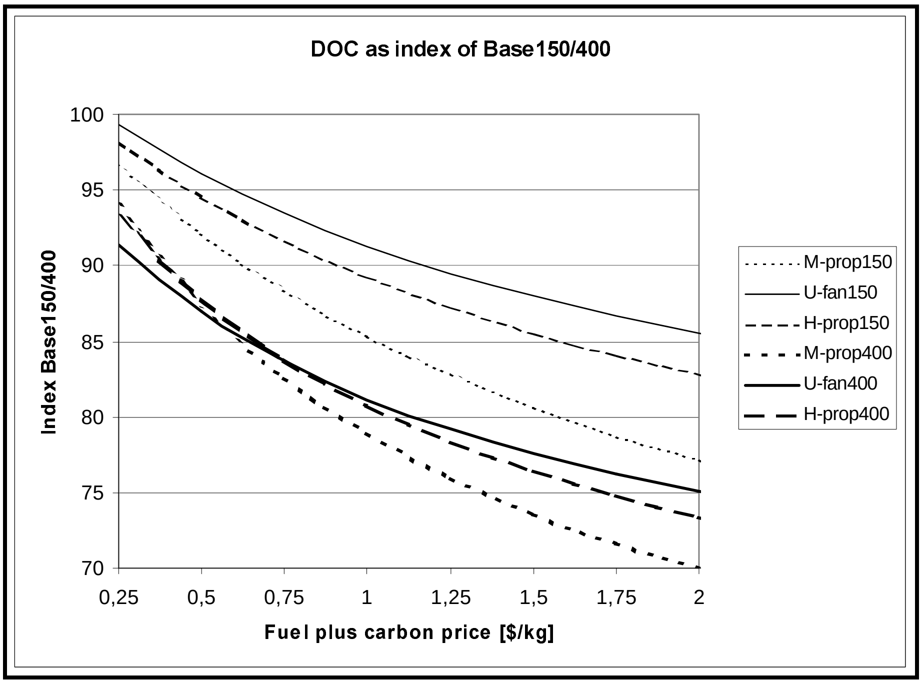
Looking at the DOC of the new designs (see Figure 118) we may conclude the DOC of all designs is lower than for the BASE150/400, even at a fuel plus carbon price of only $0.25/kg. At the high fuel plus carbon price of $1.-/kg H-PROP has the lowest DOC for both markets and U-FAN the highest.

Figure 118 The DOC of the new design in indexes of the BASE150/400



The DOC is influenced by the assumed fuel plus carbon price. To find the cross-over points for the designs we have drawn Figure 119. This figure gives the DOC relative to the short haul and long haul baseline aircraft BASE150 respectively BASE400 as a function of the fuel plus carbon price. Now we see that for short haul the DOC of the M-PROP150 is the lowest for the whole range given and the cost of U-FAN150 the highest. H-PROP150 has intermediate costs for all fuel plus carbon prices.
For the long haul designs a different picture arises. Here U-FAN400 is the most economic option up to fuel plus carbon prices of about $0.60/kg, where the M-PROP400 becomes cheaper to operate. The H-PROP400 has always a higher DOC compared to the two other new designs. In competition with U-FAN400 the DOC of H-PROP400 becomes lower above a fuel plus carbon price of $0.75/kg.
As has been shown in Figure 119 the higher the fuel plus carbon price becomes the more advantageous the DOC of the most fuel-efficient aircraft. During the conceptual design it appeared optimising for example the wing aspect ratio resulted into larger wing aspects ratios if the presumed fuel plus carbon price was taken higher. This also results in a more fuel-efficient aircraft to be optimal at higher fuel plus carbon costs.

Figure 119 DOC of the new designs as a function of the fuel plus carbon price



Performance of new designs

The performance of the aircraft should be within operational requirements of the airline. Important are the following items:

- Performance on the evaluation flight;
- Payload range performance;
- Take off and landing performance.

The operational performance in the evaluation flights is shown in Table 26. As can be seen the block time for M-PROP increases substantially for short haul and long haul with respectively 11% and 16%. Also the fuel cell aircraft have a lower cruise speed resulting in an increase of 9% of block time for short haul and 23% for long haul.

Table 26 Performance of the new designs on the evaluation flights. Block distance for short haul is 1,000 km, for long haul 7,000 km

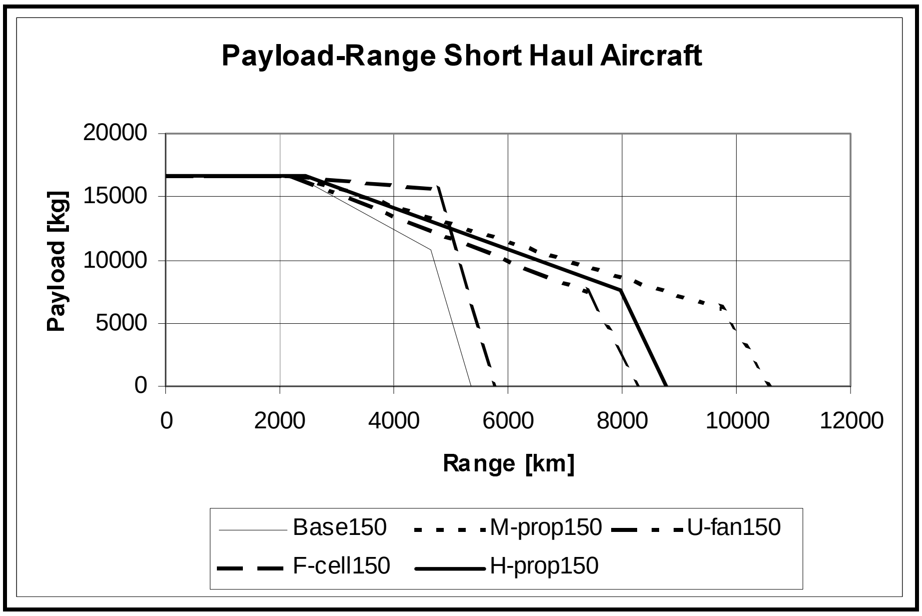
Design model	TO Weight	Block		Cruise	
		time	fuel	Mach	altitude
	kg	hr.min	kg	-	m
BASE150	52,160	1.52	3,591	0.745	10,000
M-PROP150	48,785	2.04	1,943	0.640	9,000
H-PROP150	52,157	1.55	2,323	0.720	10,000
U-FAN150	44,760	1.52	2,490	0.745	10,000
F-CELL150	58,825	2.02	1,246[41]	0.660	8,000
BASE400	306,376	8.30	68,513	0.840	11,000
M-PROP400	251,676	9.53	34,799	0.700	9,500
H-PROP400	261,155	9.26	39,400	0.740	10,000
U-FAN400	246,340	8.30	42,569	0.840	11,000
F-CELL400	276,822	10.28	34,818[42]	0.650	8,500

[41] This figure gives kg kerosene equivalents. The hydrogen weight is 445 kg.

[42] This figure gives kg kerosene equivalents. The hydrogen weight is 12,435 kg.

The payload-range diagram gives the payload capability as a function of range. The first flat part of the diagram gives the maximum space limited payload (it is the maximum payload weight allowed for the construction of the aircraft, normally limited by the difference between the operational weight empty and the maximum zero fuel weight). Increasing the range means increasing the amount of fuel. At a certain point the maximum take off weight will be reached. If we want to increase the range further, we will have to trade payload for the extra fuel needed. This is given by the first bend in the graph (see Figure 120). The second bend marks the point where no longer maximum take off weight is limiting, but maximum tank volume. We will not be able to add more fuel, but by decreasing the payload weight, the total aircraft weight will reduce, giving a slight decrease of fuel consumption per kilometre and therefore a further increase of range.

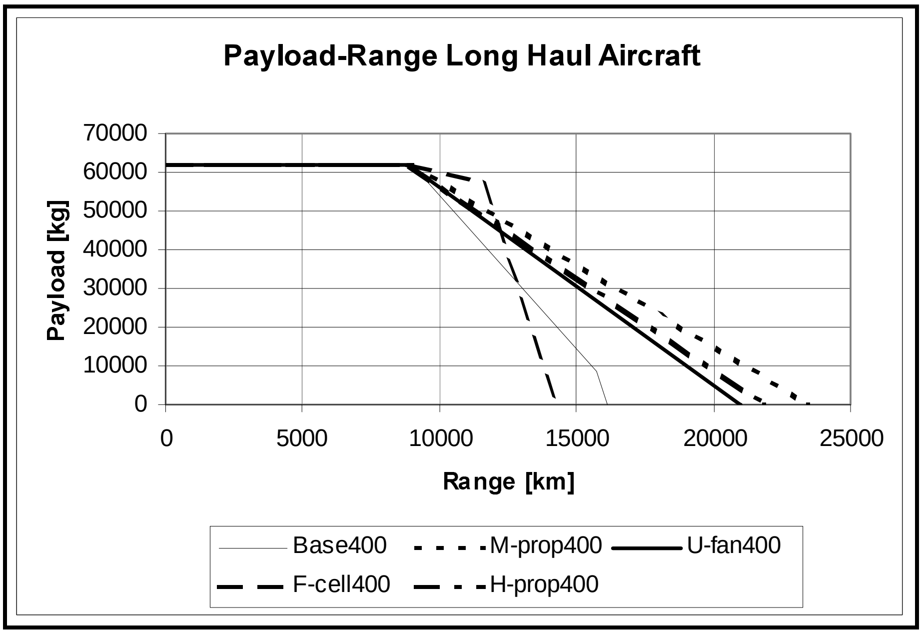
Figure 120 Payload range performance of the short haul designs



The payload range capability of the short haul designs is better than for the BASE150. However, the most important point (range with full payload) is the same for all designs (see Figure 120). The design with fuel cell technology shows a very flat rate and therefore offers twice the maximum payload range at almost full payload.

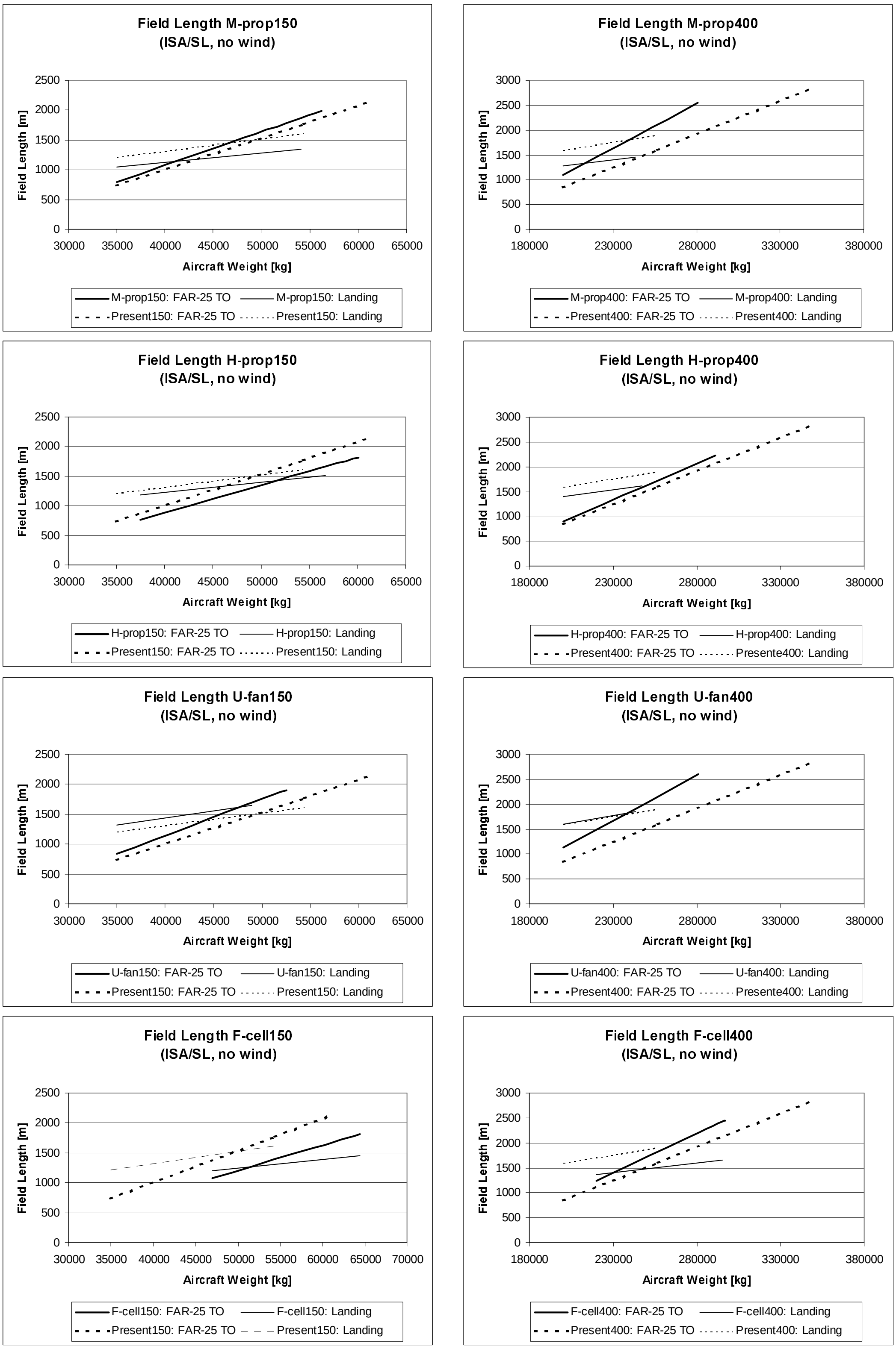
For long haul there is no fuel volume limit for the U-FAN400, M-PROP400 and H-PROP400, because we did not adjust the tankvolume to the lower fuel consumption (see Figure 121). Only the F-CELL400 has a volume limit, because the LH_2 storage tanks are too haevy to make them bigger than strictly necessary. The range at almost full payload is about 1.5 times the range at full payload for the F-CELL400.

Figure 121 Payload range performance of the long haul designs



A last important performance item is field performance. As airports have runways of limited length it is important the aircraft does not need too much take off or landing field length. From a rough calculation it was found the new designs have comparable or better field performance than the PRESENT150/400 at the higher operational weights (see Figure 122). This is the result of the much lower fuel weight, requiring lower maximum take off and landing weights for a given mission, and the thicker wing profile on the slower aircraft (M-PROP and F-CELL) allowing for a higher maximum lift.

Figure 122 Overview of estimates of the field performance of the new designs compared to PRESENT150/400



10.5 Overview of assumptions and results

10.5.1 Overview of assumptions

In Table 27 an overview of the assumptions per model has been given. The first column gives the model indication code, the second a short description. Then follow four columns with airframe information: the inputted initial change in airframe weight, drag, price and maintenance cost. The Conventional engine development gives the number of years assumed for the effect of conventional Turbofan development as given by Van der Heijden and Wijnen (1999):

- Fuel consumption –0.85%/year;
- Engine weight –0.75%/year;
- Engine Price –1.00%/year.

The last group of columns gives the total inputted change to the main engine parameters (fuel consumption, weight, price and maintenance cost).

Table 27 Overview of assumptions for all aircraft models

Model	Description	Initial Input Airframe Properties					Conventional engine development			Engine (overall compared to current Turbofans)			
		AR	ΔW_{empty}	ΔC_{D0}	ΔPr_{af}	Δmaint	ΔFuel C.	ΔW_{eng}	ΔPr_{eng}	ΔF.C.	ΔW_{eng}	ΔPr_{eng}	ΔMaint.c.
		-	%	%	%	%	Year	year	year	%	%	%	%
PRESENT150	Short Haul; current Turbofan	7.9	0	0	0	0	0	0	0	0	0	0	0
BASE150	Short Haul; 2 2010 Turbofan	7.9	0	0	0	0	11	11	11	-9	-8	-10.5	0
SH_UHB	Short Haul; Ultra High Bypass	7.9	0	0	0	0	11	11	11	-22	1.3	1.5	10
SH_HSP	Short Haul; High Speed Propeller	7.9	0	0	0	0	11	0	0	0[43]	Scaled	0	20
SH_LFC	Short Haul; Laminar Flow Control	7.9	+1	-12.5	+7.5	20[44]	11	11	11	-9	-8	-10.5	0
SH_HAR	Short Haul; High Aspect Ratio Wing	Opt.	0	0	0	0	11	11	11	-9	-8	-10.5	0
SH_NML	Short Haul; New Materials	7.9	-8.0	0	340[45]	17.6[44]	11	11	11	-9	-8	-10.5	0
M-PROP150	Short Haul; medium speed HSP	Opt.	0	-11,0	0	10[44]	11	0	0	0[43]	Scaled	0	0
H-PROP150	Short Haul; high speed HSP	Opt.	0	-5.0	0	10[44]	11	0	0	0[43]	Scaled	0	10[46]
U-FAN150	Short Haul; UHB	Opt.	-7.0	-12.5	7.5/340[45]	[4144]	11	0	0	-22	Scaled	Scaled	10
F-CELL150	Short Haul; Fuel Cell technology	Fixed	-7.0	-12.5	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a
PRESENT400	Long Haul; current Turbofan	7.7	0	0	0	0	0	0	0	0	0	0	0
BASE400	Long Haul; 2010 Turbofan	7.7	0	0	0	0	11	11	11	-9	-8	-10.5	0
LH_UHB	Long Haul; Ultra High Bypass	7.7	0	0	0	0	11	11	11	-22	1.3	1.5	10
LH_HSP	Long Haul; High Speed Propeller	7.7	0	0	0	0	11	0	0	0[43]	scaled	0	20
LH_LFC	Long Haul; Laminar Flow Control	7.7	+0.5	-12.5	2.5	20[44]	11	11	11	-9	-8	-10.5	0
LH_HAR	Long Haul; High Aspect Ratio Wing	Opt.	0	0	0	0	11	11	11	-9	-8	-10.5	0
LH_NML	Long Haul; New Materials	7.7	-8.0	0	300[45]	15[44]	11	11	11	-9	-8	-10.5	0
M-PROP400	Long Haul; medium speed HSP	Opt.	+0.5	-12.5	0	10[44]	11	0	0	0[43]	scaled	0	0
H-PROP400	Long Haul; high speed HSP	Opt.	0	-5.0	0	10[44]	11	0	0	0[43]	scaled	0	20[46]
U-FAN400	Long Haul; UHB	Opt.	-7.5	-12.5	2.5/300[45]	38[44]	11	0	0	-22	scaled	scaled	10
F-CELL400	Long Haul; Fuel Cell technology	Fixed	-7.5	-12.5	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a

43 The fuel consumption is based on de High Speed Propeller Engine Table produced by ADSE, 1999.

44 Airframe maintenance hours only.

45 Cost in $ per kg replaced structure weight.

46 Engine maintenance hours only.

10.5.2 Overview of input

The assumptions given in Table 27 lead to the numerical input used in the model as given in Table 28. The columns under ‘Airframe’ give respectively the Operating Weight Empty, the Maximum Take off Weight, the parasite drag coefficient, the wing aspect ratio, the wing area and the airframe price (excluding engines).

Table 28 Overview of input values for the model system of the aircraft models considered

Model	airframe							en-gine price
	OEW	MTOW	C_{D0}	asp. ratio	wing area	wing span	price	
	kg	kg	-	-	m^2	m	M$	M$
Short haul aircraft: 146 seats								
PRESENT150	34,564	62,820	0.0186	7.9	105.4	28.88	37.800	3.100
BASE150	34,025	61,241	0.0186	7.9	105.4	28.88	37.800	2.775
SH_UHB	34,583	60,526	0.0190	7.9	105.4	28.88	40.599	3.053
SH_HSP	35,236	59,445	0.0193	7.9	105.4	28.88	40.677	3.100
SH_LFC	34,400	61,152	0.0163	7.9	105.4	28.88	40.635	2.775
SH_HAR	34,081	61,180	0.0186	13.0	103.0	36.59	41.362	2.775
SH_NML	31,111	57,632	0.0186	7.9	105.4	28.88	42.114	2.775
M-PROP150	33,785	56,201	0.0163	12.0	109.5	36.25	35.230	2.792
H-PROP150	36,385	60,061	0.0188	11.0	103.0	33.66	37.430	3.109
U-FAN150	28,578	52,532	0.0199	10.0	82.5	28.72	40.509	2.685
F-CELL150	46,375	64,454	0.0130	12.0	144.0	41.57	N/a	N/a
Long haul aircraft: 416 seats								
PRESENT400	180,755	362,875	0.0169	7.7	541.2	64.44	148.400	5.400
BASE400	177,171	348,474	0.0169	7.7	541.2	64.44	148.400	4.833
LH_UHB	177,696	333,371	0.0173	7.7	541.2	64.44	159.524	5.319
LH_HSP	175,318	311,760	0.0169	7.7	541.2	64.44	158.056	5.400
LH_LFC	179,285	355,395	0.0148	7.7	541.2	64.44	152.110	4.833
LH_HAR	167,670	319,739	0.0169	14.0	452.0	79.55	156.611	4.833
LH_NML	160,502	324,592	0.0169	7.7	541.2	64.44	169.119	4.833
M-PROP400	163,782	280,991	0.0163	14.0	490.0	82.83	126.064	4.624
H-PROP400	167,512	290,732	0.0178	14.0	460.0	80.25	131.560	5.134
U-FAN400	148,079	277,308	0.0179	12.0	415.0	70.57	152.532	4.224
F-CELL400	215,554	296,701	0.0150	14.0	550.0	87.75	N/a	N/a

10.5.3 Overview of results

The main results are given in Table 29. The first three columns give the characteristics of the evaluation flight. Short haul: 1,000 km with 70% load factor and long haul 7,000 km with 75% load factor. The fuel saving is given with respect to the BASE150/400. The break even DOC gives the price for fuel in $/kg for which the model has the same DOC as the BASE150/BASE400 models.

Table 29 Overview of the results

Model	Evaluation flight			reduction fuel consumption, % relative to BASE150/400	break even fuel+carbon price, $/kg	DOC at eval. flight in $/km		
	TO Weight (kg)	block: time hr.min	block: fuel kg			at fuel+carbon price: $0.27/kg	at fuel+carbon price: $1.00/kg	at break even
Short haul aircraft: 146 seats, 70% load factor, 1000 km block range								
PRESENT150	53,356	1.52	3,951	+10.0	N/a	8.56	11.80	N/a
BASE150	52,160	1.52	3,591	0.0	N/a	8.31	11.23	N/a
SH_UHB	51,807	1.52	3,077	-14.3	0.467	8.42	10.92	9.11
SH_HSP	51,443	1.52	2,568	-28.5	0.276	8.32	10.40	8.34
SH_LFC	52,191	1.52	3,410	-5.0	0.922	8.44	11.21	10.92
SH_HAR	51,802	1.54	3,335	-7.1	0.849	8.48	11.19	10.63
SH_NML	49,087	1.52	3,488	-2.9	1.377	8.44	11.27	12.74
M-PROP150	48,785	2.04	1,943	-45.9	0.103	8.01	9.58	N/a
H-PROP150	52,157	1.55	2,323	-35.3	0.106	8.13	10.02	N/a
U-FAN150	44,760	1.52	2,490	-30.7	0.203	8.23	10.25	N/a
F-CELL150	58,825	2.02	1,246[47]	-65.3	N/a	N/a	N/a	N/a
Long haul aircraft: 416 seats, 75% load factor, 7000 km block range								
PRESENT400	320,224	8.30	77,268	+12.8	N/a	16.10	25.07	N/a
BASE400	306,376	8.30	68,513	0.0	N/a	15.47	23.42	N/a
LH_UHB	294,690	8.30	58,181	-15.1	0.348	15.59	22.35	16.32
LH_HSP	276,635	9.48	46,428	-32.2	0.589	16.59	21.97	18.94
LH_LFC	301,637	8.30	62,848	-8.3	0.282	15.48	22.77	15.60
LH_HAR	283,037	8.41	57,411	-16.2	0.186	15.32	21.98	14.55
LH_NML	286,083	8.30	65,403	-4.5	0.926	15.79	23.38	22.61
M-PROP400	251,671	9.53	34,799	-49.2	0.077	14.43	18.47	N/a
H-PROP400	261,155	9.26	39,400	-42.5	0.027	14.60	19.18	N/a
U-FAN400	246,340	8.30	42,569	-37.9	0.000	14.06	19.01	N/a
F-CELL400	276,822	10.28	34,818[48]	-49.2	N/a	N/a	N/a	N/a

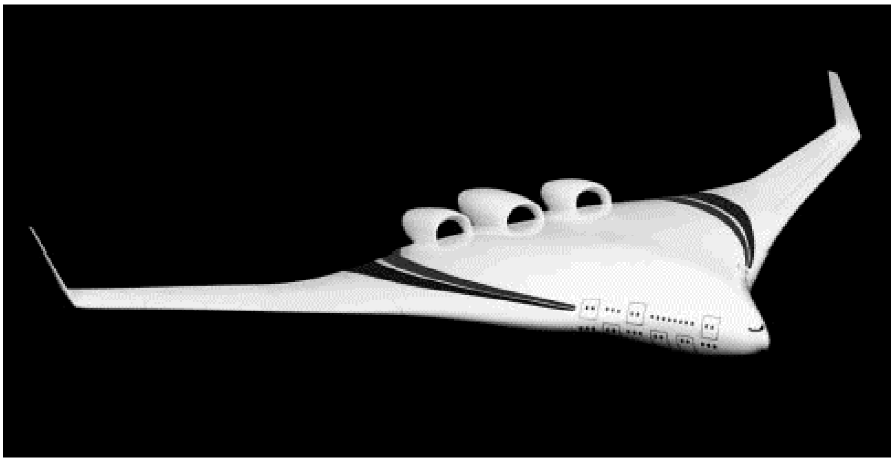
10.6 New aircraft configurations

So far we have considered only the classical layout of aircraft: non-lifting fuselage for easy storage of cargo/passengers, wings as lifting surfaces and aft tail planes for control and stability. In this paragraph we discuss other solutions. The main possibilities are: tail first, tail-less and blended wing body (BWB). The tail-first or canard and the tail-less aircraft are mainly used for transonic and supersonic aircraft. Their ability to increase fuel efficiency on a subsonic aeroplane is considered to be not spectacular. Therefore the blended wing body (see Figure 123) is at this moment the only non-classical configuration with a possibility of a large reduction of fuel consumption with up to 25% compared to state of the art wide body aircraft. Important is also the DOC may be reduced with up to 20%.

[47] This figure gives kg kerosene equivalents, the hydrogen weight is 445 kg.

[48] This figure gives kg kerosene equivalents, the hydrogen weight is 12435 kg.

Figure 123 Example of a blended wing body design as given by NASA (1997)



Main problems of the configuration are controllability and layout of the cabin. Specifically the low-speed flight-envelope, like stall and spin behaviour, is largely unknown and needs investigation. To study this NASA and Boeing recently announced flight tests on a low speed scale model to start early in 2002. The 14%-scale model will be remotely piloted and represents the latest 450-passenger second-generation BWB under study at Boeing and NASA.
Another difficulty in designing a high speed BWB is the high mach drag arising from the relatively large wing thickness ratio required. It would be of much interest to look at the total design opportunities from an environmental point of view and including several propulsion technologies and performance specifications. Also it will be interesting to study the possibilities for aircraft with less then 450 passengers.

10.7 Conclusions

From the technical study we may conclude the following:

- The introduction of the high-speed propeller (HSP) gives the highest fuel savings for both short and long haul.
- For the long haul market the most *economic* ways to reduce the fuel consumption are increasing the wing aspect ratio and reducing parasite drag; for short haul this is the HSP.
- A Propfan (high speed propeller with a design speed of mach 0.8 or more) seems a more economic way to reduce fuel consumption of long haul aircraft; however such Propfans still suffer from many technological problems like high levels of vibration and noise.
- The introduction of new lightweight materials is neither an effective nor an economic way to reduce fuel consumption.
- Fuel savings of 40-45% with respect to the baseline with 2010 technology turbofans are conceivable for new designs, without sacrificing the performance of the aircraft or the economy in terms of DOC, payload-range and field-length.
- A long-term stable increase of the fuel plus carbon price may advance the introduction of more fuel-efficient new designs.
- The fuel savings of the high-speed propeller designs may be enlarged by reducing cruising speed below the design point of this propulsion

system. At high fuel plus carbon prices the DOC for these lower speed aircraft may be better than for the high-speed variant.

- New aircraft configurations (especially the blended wing body) have the promise of further substantial increases of fuel efficiency.
- Fuel cell technology gives interesting opportunities for a zero CO_2/NO_X aircraft. For the short haul aircraft, the energy consumption of this concept may be lower than for the kerosene concepts studied. However, this design still requires a lot of development work. Therefore, these results are less certain than for the other designs and it is not possible at this moment to establish the DOC and other costs.
- To cut energy consumption further, the fuel cell seems the technology required for short haul, while the blended wing body may be the solution required for long haul.

10.8 Recommendations

10.8.1 Environment

Although fuel consumption, and thus CO_2 and H_2O emissions, is an important environmental indicator, other environmental aspects need to be further researched as they play an important role in the discussion on aviation and the environment:

- the increased engine efficiency, that may lead to an increase in contrail formation;
- the changes in cruise altitudes, that may have an impact on the formation of contrails and the lifetime of ozone.

10.8.2 Performance specifications

The influence of performance specifications on DOC and environmental impact needs to be studied further. Specifically the relation between design speed and environmental impact seems to present opportunities for reducing environmental impact.

10.8.3 High speed propellers

High-speed, probably counter rotating, propellers are one of the most promising technologies for reduced emissions because they enable aircraft transport at quite economic speeds (mach 0.72-0.75) with significantly reduced fuel burn and emissions. It is recommended to further study this technology in order to reduce the risks associated with noise, vibration and reliable high power gearboxes and propeller de-icing.
Further it is recommended to reconsider development of faster propeller engines for the long haul market (suitable for mach numbers above 0.8). Such a propulsion device may give better DOC and fuel efficiency figures than UHB engines will.

10.8.4 UHB engines

It is recommended to further study pros and cons of engine concepts exceeding the bypass ratios considered in this study (beyond 9:1), as it is not sure whether such an increase still is beneficial to the environment. Past studies on these types of engines suggest increasing problems in terms of a) the required heavy fan gearbox, b) ever increasing fan reverser areas, and c) increased nacelle diameter leading to increased weight and drag. On the one hand, a fan gearbox or a combination with a variable pitch fan might lead to lighter and more reliable designs, on the other hand it is also possible that the much larger nacelle will lead to ever diminishing returns due to more weight and drag.

10.8.5 Higher aspect ratio wings

Today's high Aspect Ratio (AR) wings on Airbus aircraft have ARs between 10 and 11. However, the report suggests an advantage for ARs in the 14-15 range. Therefore, it is recommended to further study this problem comparing counter-rotating propeller and UHB aircraft at these high ARs[49] to obtain information on:

- Aeroelastic (flutter) limits;
- Sizing parameters.

10.8.6 Blended wing body

It is strongly recommended to issue a study on the possibilities and problems of the blended wing body configuration in conjunction with the other technologies presented in this study both long haul and short haul aircraft.

10.8.7 Hydrogen and fuel cell

Applying hydrogen as a fuel on high-speed propeller or UHB powered aircraft has not been evaluated in this study. In comparison to kerosene aircraft, these concepts lead to zero in-flight carbon dioxide and carbohydrates emissions, and lower nitrogen oxide emissions. On the other hand it will impose technological and economical problems, specifically for the fuel systems both in the aircraft and on the ground.
It is recommended to include the fuel cell technology issue into running studies on liquid hydrogen aircraft or to combine these subjects in new studies. Special attention is needed for costs, fuel system design and integration, cryogenic cooling of electrical engines, the full design integration of propulsion and airframe, and safety, including special requirements with respect of the amount of fuel cells required for the one engine out climb.

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[49] This can be done by making 'point designs' (further detailing of concepts with a fixed high aspect ratio and the mentioned engine types, instead of simultaneously optimising the aspect ratio and other design parameters).

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ESCAPE

Economic SCreening of Aircraft Preventing Emissions

Annex III: An overview of technologies to reduce aviation emissions

The Netherlands Research School for Transport, Infrastructure and Logistics

TRAIL

Abstract

This report describes on-going technical developments in the aerospace industry that could lead to future reduction of gas emissions. This technology scan focuses on the following categories of emissions:

- CO_2 and H_2O;
- NO_x.

CO_2 and H_2O are greenhouse effect enhancing gasses. NO_x emission can have several undesirable effects on the atmosphere, such as ozone depletion in the stratosphere and the production of tropospheric ozone, which is a greenhouse effect enhancing gas, in lower layers of the atmosphere. The emission of CO_2 and H_2O can be reduced by the reduction of fuel consumption. The most important means to reduce the emission of NO_x are the development of new combustion chamber technologies. Non-propulsion technologies for the reduction of fuel consumption also have a favorable effect on NO_x emission. This is also the case for some propulsion technologies. Also the introduction of alternative fuels can contribute to the reduction of emissions. The different technology developments aimed at the reduction of aviation gas emissions taken into account in this study are therefore subdivided into the following categories:

- Reduction of fuel consumption;
- Reduction of NO_x emission;
- Alternative fuels.

The information in this report has been gathered from a scan of available literature. From this information data has been extracted to be used as input parameters for the analysis of the effect of fuel charges on aircraft design. This is done by comparing the Direct Operating Costs resulting from the applications of different technologies for different levels of the fuel charges. This analysis is carried out using the so-called APD (Aircraft Performance & DOC) model, developed by *Peeters Advies* in Ede, the Netherlands (See Annex 1 in this background report). The analysis is done for both a short haul and a long haul mission. The input parameters for the APD model for a certain technology are mainly in the following areas:

- Effects on engine specific fuel consumption;
- Weight effects;
- Cost effects:
    - Purchase costs;
    - Maintenance costs.

Below the most important technologies described in this report are covered briefly.

Reduction of fuel consumption

Three areas of technologies are covered in this study with respect to the reduction of fuel consumption:

- Propulsion;
- Aerodynamic features;
- Lightweight materials.

Propulsion
The most important developments with respect to the reduction of fuel consumption in the propulsion area are the following:

Conventional turbofans
Development of conventional turbofans has resulted in a third generation of turbofans through the eighties and nineties. This trend is expected to continue in the future. Possible improvements that could lead to the reduction of fuel consumption are for instance higher pressure ratios and temperatures, the application of new lightweight materials and the improvement of combustion chamber technologies. The development of conventional turbofans is used in this study as a baseline for comparison with other technologies. The following input has been selected for implementation in the APD model for conventional turbofans in the baseline for 2010:
- *Fuel consumption*: -0.85% SFC per year;
- *Engine weight effect*: -0.75% per year;
- *Engine price effect*: -1% per year;
- Engine maintenance costs effect: 0%.

Propfans
The principle of the propfan increases the bypass ratio of engines beyond the bypass ratios of current turbofans, which are approximately 5 - 9. The equivalent bypass ratio of propfans can be 30 - 40 or even higher. Propfans are basically advanced turboprops. They use the same gas generator as a turbofan, but the gas turbine drives external propellers. Propfans can be applied at higher speeds than turboprops. An advantage of the propfan is its low overall pressure ratio, which has a favorable effect on NO_x emission. Fan pressure ratios of propfans are generally 1.05 - 1.3 as a result of their larger fan diameter, compared to 1.6 - 1.7 for conventional turbofans. Propfans are expected to offer possibilities to obtain reductions in fuel consumption in the order of 35%. Possible disadvantages with respect to conventional turbofans of propfans are a high level of noise and vibrations, high weight as a result of the large propeller and the application of a gearbox, and high purchase and maintenance costs as a result of its complexity. The following input has been selected for implementation in the APD model for propfans:
- Year of scope: 2010;
- Fuel consumption: According to ADSE engine table;
- Engine weight for the basic engine scaled for a 150-seater incl. propeller and nacelles: 3400 kg;
- Cost effects: +20% maintenance costs.
- The effect on fuel consumption of the development of conventional turbofans will be taken into account for the development of propfans.

Ducted ultra-high bypass ratio engines
The class of ducted ultra high bypass ratio (UHB) engines can roughly be divided in ultra high bypass ratio turbofans and ducted propfans. Generally, UHB turbofans feature fan pressure ratios of 1.45 - 1.7 and bypass ratios up to 12. Ducted propfans feature pressure ratios of 1.30 - 1.45 and bypass ratios of 12 - 20. For fan pressure ratios below 1.5 and bypass ratios over 9, a gear between the fan and the turbine may be required. For larger bypass ratios similar disadvantages as mentioned for propfans can occur for ducted UHB engines. An advantage of the ducted engine with respect to noise, besides nacelle shielding, is that adaptive liners can be applied. The following input has been selected for implementation in the APD model for ducted ultra-high bypass ratio engines:
- *Year of scope*: 2010;

- *Fuel consumption*: -15% SFC;
- *Engine weight effect*: +10%;
- *Engine price effect*: +10%;
- *Engine maintenance costs effect*: +10%;
- *Nacelle diameter*: +25%;
- The effects on fuel consumption, engine weight and engine price of the development of conventional turbofans will be taken into account for the development of UHB engines.

Aerodynamic features

Several aerodynamic features exist. The most important are natural, active and hybrid laminar flow control, and large eddy break-up devices (LEBU). Natural flow control aims to reduce skin friction drag by specially designed shapes and smoothed surfaces. Active laminar flow control uses suction to smooth the flow over the aircraft. Hybrid laminar flow control is a combination of natural and active laminar flow control. Laminar flow control is mainly applied on the wing. Full realization of the drag reduction possible from the application of laminar flow control requires a lot of cleaning and therefore increases maintenance costs. LEBU devices can be small grooves or thin plates applied on parts of the aircraft, mostly fuselage and nacelles, that break up large vortices to reduce drag. Further it is possible to reduce parasite drag by aerodynamically clean up the design.
The following input has been selected for implementation in the APD model for the effect of active laminar flow control and aerodynamic cleanup.

- *Year of scope*: 2010;
- *Aerodynamic effect*: -12.5% C_{D_0} ;
- *Weight effect*
  - Short haul: +1% aircraft empty weight;
  - Long haul: +0.5% aircraft empty weight.
- *Aircraft price effect*
  - Short haul : +7.5%;
  - Long haul : +2.5%.
- *Maintenance costs effect*: +20% airframe maintenance costs;
- *The effects on fuel consumption, engine weight and engine price of the development of conventional turbofans will be taken into account in the APD model calculations.*

For passive laminar flow the same drag effect may be achieved, but with only 10 % increase in airframe maintenance hours. Aerodynamic cleanup of the aircraft alone accounts for about 5 % lower parasite drag at negligible cost.

Lightweight materials

Several types of new lightweight materials exist. The most important types are metal alloys, composites and ceramic materials. Composites can be subdivided in fibre-reinforced plastics, fibre metal laminates and metal matrix composites. Though these new innovative materials are often significantly more expensive than conventional materials, there are several incentives to apply these materials. Besides weight reduction these materials can offer significant advantages with respect to safety, corrosion, fatigue and production costs. The following input has been selected for implementation in the APD model for the application of lightweight materials:

- *Year of scope*: 2010
- *Weight effect:* -8% aircraft empty weight (new materials applied as much as possible)

- *Aircraft price effect*
  - Short haul: +$340 per kilogram replaced conventional material;
  - Long haul: +$300 per kilogram replaced conventional material.
- *Maintenance costs effect: -8% empty weight*: +50% airframe (structure excluding systems) maintenance man-hours;
- *The effects on fuel consumption, engine weight and engine price of the development of conventional turbofans will be taken into account in the APD model calculations.*

Reduction of NO_x emission

NO_x reduction can mainly be achieved by the improvement of combustion chamber technology. NO_x production during combustion increases with higher temperatures. NO_x production reaches its maximum when the temperature in the combustion chamber is the stoichiometric temperature. This temperature is reached for the fuel/air ratio at which all oxygen in the air is used when the exhaust gasses would be CO_2 and H_2O. In conventional engines combustion mainly takes place in the primary zone of the combustion chamber, where part of the air in the engine is mixed with the fuel at a stoichiometric level. The gas temperature is lowered in the dilution zone by mixture with another portion of the air. By avoiding the stoichiometric temperature, the production of NO_x can be reduced. This can be achieved by the application of a leaner or richer fuel/air mixture than the mixture that results in the stoichiometric temperature. However, the mixture cannot be too lean in order to avoid excessive emission of CO and UHC (unburned hydrocarbons), and not too rich to avoid the exhaust of smoke. Several technology developments aim at the reduction of NO_x emission. Most of these technologies aim to reduce NO_x emission by the application of a leaner fuel/air ratio in most flight phases. The following combustion chamber designs have been evaluated in this study:

- Year of scope: 2010
- Staged combustion
  NO_x emission can be optimized at different thrust levels by the application of two sets of burners in two different combustion zones;
- Variable geometry
  The leaner mixture is achieved by diluting the air/fuel mixture after primary combustion. This is achieved by the application of variable airflow inlets;
- Lean pre-mixed pre-vaporized (LPP) combustion
  A lean mixture is created in the combustion chamber for all thrust levels. This requires a very homogeneous air/fuel mixture. This can be achieved by pre-mixing and pre-vaporization. The mixing can take place inside or outside the combustion chamber. External mixing implies the danger of flashbacks. This means that the mixture ignites in the premixing section. Internal mixing implies the danger of ignition before the mixing process is completed;
- Rich burn Quick quench Lean burn (RQL) combustion
  The principle for this concept is a two-stage combustion chamber with a rich fuel-air mixture in the first part of the combustion chamber and a lean mixture in the second part. In the second part the surplus of fuel from the first zone is burned. For RQL combustion, the air/fuel mixture should be as homogeneous as possible and the admixing of air after the rich phase should occur as fast as possible (quick quench) to avoid the stoichiometric ratio;

- Chemical additives and catalysts
  Two types of catalytic combustion exist. The first is combustion at the surface of a catalyst. For this combustion lower inlet temperatures are required than for a conventional combustion process. Catalytic combustion requires a homogeneous air/fuel mix. The second is application of a catalyst to remove pollutants from the gas emissions.

LPP and RQL combustion seem to be the most promising. Reductions of NO_x emissions up to 90% are claimed by some references. No developments with respect to NO_x reducing technologies have been evaluated in the APD model in this study due to:
- Insufficient data regarding weight and cost effects of NO_x reducing technologies;
- Insufficient data regarding NO_x reduction in different flight phases;
- Complexity of NO_x emission calculation of complete flight;
- Complexity of NO_x emission charge implementation.

Alternative fuels

The alternative fuels evaluated in this study are liquid hydrogen, liquid natural gas and alternative kerosene. Liquid hydrogen (LH_2) and liquefied natural gas (LNG) are cryogenic fuels. LH_2 could reduce the emission of CO_2 and soot particles by 100%. The heating value per unity of mass for LH_2 is three times as high as for conventional fuels. This is favorable for the operational weights of the aircraft. The volume per unit of mass however is four times larger for LH_2 compared to conventional fuels. This increases the tank volume of the aircraft. Furthermore, LH_2 cannot be carried in the wing, but must be stored in the fuselage. This requires significant structural changes to the fuselage, while also the wing weight increases due to the lack of weight relief. The large aircraft modifications required may complicate the use of LH_2 in the near future. Other disadvantages of LH_2 are the large amount of energy required for its production and the increased emission of the greenhouse gas H_2O. Furthermore, liquid hydrogen would require a new infrastructure for distribution and storage. An advantage of LH_2 is its favorable effect on energy consumption.
As of this moment all of these aspects are being investigated within the so called CRYOPLANE project. This project is carried out within the 5th framework program of the European Union.

LNG requires approximately 50% more space in aircraft than kerosene. Therefore also the use of LNG requires large aircraft modifications. The large aircraft modifications required may complicate the use of LNG in the near future. The infrastructure for distribution of LNG is already largely in place. Airports however would require adjustments. H_2O emission will increase slightly from the application of LNG, but LNG offers prospects for the reduction of fuel consumption and NO_x emission.

The most important representative of alternative kerosene evaluated in this study is biomass-based kerosene. Because the vegetation from which biomass-based kerosene is produced extracts CO_2 from the atmosphere, the CO_2 emitted by aircraft using biomass-based kerosene is part of a closed cycle. Biomass-based kerosene can be produced via two processes. The HTU/HDO process results in a price for the biomass-based kerosene of approximately 300 euro per ton. The process applying gassification and Fischer-Tropsch synthesis results in a price for the biomass-based kerosene of approximately 450 euro per ton.

Because of the uncertainty with respect to cost effects of the application of LH_2 and LNG and the large aircraft modifications connected to the application of these fuels, the use of LH_2 and LNG has not been evaluated in the APD model. The fuel charge that would make the use of biomass-based kerosene economically viable is easy to establish by comparing the cost per ton biomass-based kerosene to the cost per ton conventional kerosene. No price for conventional kerosene is mentioned here, since this price is subject to significant fluctuations.

Contents

1 Introduction

This report describes on-going technical developments in the aerospace industry that could lead to future reduction of gas emissions. The main areas of concern with respect to pollutant gasses emitted by aviation are:

- CO_2 and H_2O;
- NO_x.

Therefore this technology scan focuses on these categories of emissions. CO_2 and H_2O are greenhouse effect enhancing gasses. NO_x emission can have several undesirable effects on the atmosphere, such as ozone depletion in the stratosphere and the production of tropospheric ozone, which is a greenhouse effect enhancing gas, in lower layers of the atmosphere. The emission of CO_2 and H_2O can be reduced by the reduction of fuel consumption. The most important means to reduce the emission of NO_x are the development of new combustion chamber technologies. Non-propulsion technologies for the reduction of fuel consumption also have a favorable effect on NO_x emission. This is also the case for some propulsion technologies. Also the introduction of alternative fuels can contribute to the reduction of emissions. The different technology developments aimed at the reduction of aviation gas emissions taken into account in this study are therefore subdivided into the following categories:

- Reduction of fuel consumption;
- Reduction of NO_x emission;
- Alternative fuels.

This report describes the information on technology developments with respect to the categories above found after a scan of available literature. Besides gathering information for an overview of the different technologies, the purpose of this literature scan is to obtain data that can be used as input parameters for the analysis of the effect of fuel and emission charges on aircraft design. This will be done by comparing the Direct Operating Costs resulting from the applications of different technologies for different levels of fuel and emission charges. This analysis will be carried out using the so-called APD model, developed by *Peeters Advies* in Ede, the Netherlands (see Annex 1 in this background report). The analysis is done for a Boeing 737-400 representing aircraft on short haul missions and a Boeing 747-400 representing aircraft on long haul missions. The input parameters for the APD model for a certain technology will be mainly in the following areas:

- Effects on engine specific fuel consumption or CO_2 /NO_x emission;
- Weight effects;
- Cost effects:
  - Purchase costs;
  - Maintenance costs.

2 Reduction of fuel consumption

2.1 Introduction

The emission of the greenhouse effect enhancing gasses H_2O and CO_2 can be reduced by the reduction of the fuel consumption of aircraft. Non-propulsion technologies for the reduction of fuel consumption also have a favorable effect on NO_x emission. This is also the case for some propulsion technologies. There are several possibilities to attain this reduction of fuel consumption:

- *Propulsion technology*
  - Development of current turbofan technology;
  - Propfans;
  - Ducted ultra high-bypass ratio engines;
  - Integrated high performance turbine engine technology.
- *Design features*
  - Drag reducing aerodynamic features;
  - Lightweight materials;
  - Improvement of design methods.

Reducing fuel consumption not only has a favorable effect on aircraft emissions, but also on direct operating costs of aircraft. Directly by decreasing the fuel costs for the aircraft, and indirectly by the additional weight reductions of for instance the wing, tail, undercarriage and engines. The possibilities for the reduction of fuel consumption mentioned above will be dealt with in more detail in the remaining part of this chapter. Assuming a mix of different technologies to be introduced throughout the world aircraft fleet over the next 15 - 20 years, the possible fuel reductions mentioned in this chapter are in line with the overall 20% reduction in fuel consumption expected from technological innovations by the IPCC report of April 1999 (ref. 42).

2.2 Propulsion technology

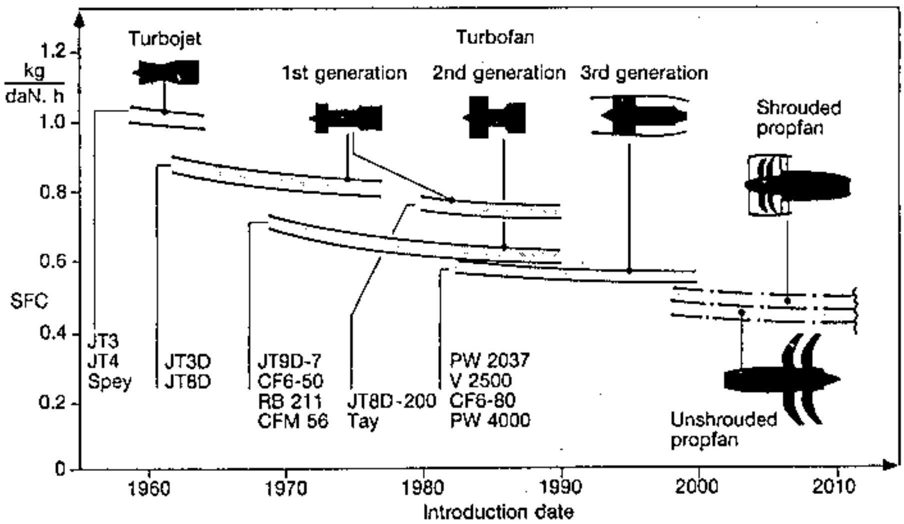
2.2.1 Development of current turbofan technology

General

Development of turbofan technology has resulted in a third generation of turbofans in the eighties through nineties as can be seen in figure 1. This improvement of conventional turbofan technology is still going on. Development of current turbofan technology means for instance increasing pressure ratios and temperatures in the engine. A higher pressure ratio reduces the specific fuel consumption of the engine, while increasing temperature results in a more efficient combustion process and a higher specific thrust. A higher specific thrust results in a smaller and therefore lighter engine. Developments like the increment of the engine pressure ratios and temperatures in the combustion chamber would, however, also result in an increase of NO_x emission. This will be dealt with in more detail in chapter 3. A development that could reduce fuel consumption of conventional gas engines, but also reduce NO_x emission is de application of recuperation and intercooling in the core engine (ref. 13, 14, 16). Naturally higher development costs would be involved in this technique compared to the costs involved in the 'natural' development of gas turbines. Another disadvantage of intercooling is that the intercooler itself is quite large and heavy (ref. 16). Other developments in conventional turbofan technology are for instance improvement of the overall efficiency of the engine, weight reductions by means of new materials, and improvement of the combustion chamber design and manufacturing processes of the engine.

Table 1 shows the development of engine fuel efficiency in percentage per year found in different references. The third column shows the unit of the efficiency improvement per year. *SMPG* stands for Seat Miles Per Gallon, while *SFC* is the abbreviation of Specific Fuel Consumption. The last column shows until what year the estimate is valid. Based on these data it is expected that a SFC reduction of 0.85% per year is a fair estimate for the development of conventional turbofan technology. A price reduction of conventional turbofans of 1% per year is assumed for conventional turbofans, based on data found in ref. 13. Furthermore a weight reduction of 0.75% per year is assumed. These figures will be used in this study to represent the development of an aircraft equipped with conventional turbofans. By calculating this development, new technologies that will be introduced in the future can be compared to the characteristics of the state-of-the-art aircraft equipped with conventional turbofans at the moment of introduction.

Figure 1 Historical development of the specific fuel consumption of aircraft engines



Source: ref. 14

Table 1 Fuel consumption reduction for conventional turbofans

Ref. (year)	***Efficiency Improvement Per year***	***Unit***	***Scope***
1 (1992)	1.3%	SMPG	2010
11 (1997)	0.4-1.0%	SFC	2010
13 (1994)	0.5%	SFC	-
15 (1995)	0.94-1.25% 0.7%	SFC SMPG	2005 -

Conventional turbofans – Input parameters for APD model

- *Fuel consumption*: -0.85% SFC per year;
- *Engine weight effect*: -0.75% per year;
- *Engine price effect*: -1% per year;
- *Engine maintenance costs effect*: 0%.

2.2.2 Propfans

General propfan characteristics

One of the means to reduce fuel consumption is increment of the bypass ratio of engines. This increases the slower, cooler airflow around the core engine, which results in more efficient engines. The principle of the propfan increases the bypass ratio of engines beyond the bypass ratios of current turbofans, which are approximately 5 - 9. The equivalent bypass ratio of propfans can be 30 - 40 or even higher.

Propfans are basically advanced turboprops. They use the same gas generator as a turbofan, but the gas turbine drives external propellers. Propfans can be applied at higher speeds than turboprops. Blades of propfans are especially designed to act at high tip speeds. The blades are curved and highly swept to reduce tip speeds. Furthermore the blades can be wider and more blades are applied on one rotor than is normally the case for turboprops. This minimizes the diameter of the rotor (ref. 13). The exact shape of the blades and the blade spacing depend on for instance the speed at which the engine has to operate. Two propfan types exist. The single-rotating propfan applies one propeller, while the counter-rotating propfan applies two propellers that rotate in opposite directions. The counter-rotating propfans can achieve higher speeds at smaller propeller diameters and move the air more efficiently than single-rotating propfans (ref. 7). The amount of air blown sideways instead of backwards is reduced by the application of counter-rotating propellers, which increases the efficiency of the engine (ref. 7). Furthermore they show better blade stability than the single-rotating variant. Other differences which can exist between propfans are the application of a gearbox to accommodate the turbine and the fan at their preferred speeds (Pratt & Whitney - Allison), or matching of the speeds of both components and tying them together mechanically (General Electric). An advantage of the propfan is its low overall pressure ratio (ref. 11), which has a favorable effect on NO_x emission. Fan pressure ratios of propfans are generally 1.05 - 1.3 (ref. 5, 29) as a result of their larger fan diameters, compared to 1.6 - 1.7 for conventional turbofans.

Propfans are expected to offer good possibilities to obtain a significant reduction in fuel consumption. Predictions range from 15% to 50% reduction in fuel consumption possible for propfans compared to turbofan technology of the early nineties. Counter-rotating propfans will offer larger reductions than single-rotating propfans and can achieve higher speeds, because they accelerate the air more efficiently. The year for which widespread introduction of propfans is predicted differs from 2000 (ref. 1) to 2015 (ref. 11). The year of introduction also has an effect on the price of the engine. According to ref. 13, the price of a propfan introduced in 2000 would be approximately $9M versus $6M for a third generation turbofan. In 2015 this ratio would be $6.5M versus $5M. Weight and costs of propfans are generally expected to be higher than for conventional turbofans. This would require a considerably higher fuel price to make propfans economically viable. Ref. 10 for instance expects propfans to be economical at $1.5/gallon. In this light ref. 1 mentions $1/gallon. However, there are factors that counteract these weight and cost effects. The weight and cost effects of propfans are considered in more detail later in this section. Most studies indicate a rear fuselage mounting for propfans (ref. 1, 5, 10). Reasons for this engine location are:

- Aft fuselage mounting reduces interior noise. Mounting propfans under the wing would require extensive provisions to reduce interior noise, with its consequences for aircraft weight. Aft-fuselage mounting allows more engine noise for the same interior noise;
- Ground clearance could become a problem in case of wing mounted propfans.

This would imply that use is only possible on twin-engine, smaller aircraft. It must be noted that four wing-mounted engines are for instance applied at the AN-70, although interior noise is probably less of a problem in this case, since this concerns a military transport aircraft. However, although most studies indicate an aft-fuselage mounting, this engine location could turn out to be non-applicable for propfans (ref. 39) due to the following phenomena:

- The flow from the engine over the stabilo could result in an unacceptable pitching moment during take-off;
- Noise and vibration characteristics of propfans could result in the requirement for an active noise/vibration reduction system. This would increase the weight of the aircraft;
- To make use of the constriction of the fuselage the propfan will probably feature an aft-fan. The consequential disturbances at the propeller as a result of the airflow over the pylon will however result in a large amount of noise that partly off-sets the available noise margin with respect to wing mounting (ref. 12, 39);
- Swirl-up of debris from the runway by the undercarriage can damage the propeller.

According to ref. 12 and 39, acceptable cabin noise levels can be obtained for wing mounted propfans if propeller tip speeds are kept within limits and if the distance of the engine mounting to the fuselage is sufficiently large. Tip speeds can be kept within limits by limiting the cruise speed of the aircraft. According to ref. 39, noise would not be a limiting factor for wing mounted propfans for air speeds up to Mach 0.74. Current aircraft equipped with conventional turbofans generally fly at higher Mach numbers. The described application of propfans at mach 0.74 would therefore be best suitable for regional aircraft. Mach numbers for these aircraft are generally lower than for long-range aircraft, while speed is less significant with respect to blocktime. Based on the data in this section, wing-mounted propfans are assumed for evaluation in the APD model.

General Electric built a demonstrator propfan, the GE36. The engine was demonstrated in 1985 on the Boeing 727 and the MD-80 at 37000 ft and Mach 0.86. According to ref. 4 the predicted reductions in thrust specific fuel consumption (30%) were achieved during these test flights. As mentioned, the Antonov military transporter An-70 applies four wing-mounted propfans. For this aircraft a 30% reduction in fuel at a speed of approximately Mach 0.75 is claimed (ref. 7). Furthermore it is relatively quiet due to the shape of its blades. Another feature of the An-70 is a lift increase as a result of the flow from the propeller over the wing (ref. 7). Composites are used as a material for the fan blades.

Although they offer good prospects for fuel consumption reduction, application of propfans also can imply several disadvantages, of which several have already been mentioned above. Below general advantages are listed that can occur for the application of propfans. These disadvantages do not necessarily apply for all types of propfans or types of propfan installations.

- *Noise and vibration*
  The blades of propfans are designed to reduce the propeller tip speeds in order to reduce noise. At the speeds at which propfans are intended to be used however, local speed increases over the propeller blades can still result in a considerable noise production (ref. 39). Furthermore, propfans, especially the counter-rotating variants (ref. 7, 16), produce much noise and vibration due to the unpredictable vortices induced by the propellers. Interior noise can be decreased by rear-fuselage mounting, though this can be counteracted by undesired installation effects as mentioned above. Other features that can reduce noise are a larger propeller diameter and an increase of the blade sweep (ref. 11). Also wider spacing of the blades and variation of the number of blades on each propeller could help to reduce engine noise, as demonstrated on the GE demonstrator propfan (ref. 4). Though most references stress the high noise level of propfans, ref.11 mentions recent research has shown that the noise level of propfans may in some cases even be lower than that of current turbofans. Ref. 12 expresses a similar opinion under the condition that tip speeds are kept within limits;

- *Complexity*
  A propfan is more complex than a conventional turbofan, for instance as a result of its specially designed blades, the need for advanced materials, the application of a gearbox and the application of a pitch change mechanism. Furthermore the development of propfans implies more development risks than development of conventional turbofans. Compared to a conventional turbofan this could result in:
  - Higher maintenance costs;
  - Higher purchase costs;
  - Less reliability.

- *Only applicable on small to medium size aircraft*
  According to some references a thrust range of only 15,000 - 25,000 lbs seems possible for propfan aircraft (ref. 1, 4). At higher thrusts, the advantages offered by propfans may be hard to exploit. This is due to the fact that a propfan will have a much higher diameter for the same thrust level than a turbofan. This could result in unfavorable weight and drag increments and problems with, for instance, clearance between ground, engines and aircraft for higher thrust levels. When four wing-mounted 25,000 lbs engines are assumed, this would mean a maximum take-off weight of approximately 150 tons. This means that propfans can only be applied at small to medium size aircraft for up to 200 - 225 passengers, which is approximately the size of a Boeing 767-200. In case of rear fuselage installment, only two propfans can be applied. This would mean that propfans would only be suitable on aircraft up to approximately 75 tons, which would be the size of a Boeing 737-400. An unfavorable aspect in this respect is the fact that capital and maintenance costs are dominant over fuel costs for small to medium range aircraft. For long range aircraft fuel becomes the dominant factor (ref. 29). Despite the arguments mentioned above, a representative from Rolls-Royce claims that the application of propfans on larger long-range aircraft cannot be ruled-out based on technical issues;

- *Rear-fuselage installment*
  According to several publications (ref. 1, 5, 10), propfans must be installed at the rear of the fuselage, because installment on the wing could cause problems with respect to, for instance, ground clearance. Furthermore, rear fuselage installment reduces interior noise. This results in several unfavorable effects compared to wing installment:
  - OEW increase as a result of adjustments on the fuselage (ref. 10). Installation weight of the engine is for instance 50% higher than for a turbofan (ref. 30);
  - Possible stability and load problems as a result of pitch moments and trim loads (ref. 10, 12, 39).
  - Variations in flow to the propeller (ref. 12);
- Requirement for a cooling system for the engine-aircraft interconnection (ref. 39).

- *Weight effects*
  The following implications of propfans could result in weight increases with respect to conventional turbofans:
  - Rear-fuselage installation, requiring a heavy engine-fuselage interconnection;
  - Larger bypass ratio and therefore a larger engine;
  - Application of a gearbox, because of the large speed difference between the turbine that drives the propeller and the propeller itself.

- *Smaller core*
  Ref. 29 and 30 mention that a propfan requires a smaller core than a conventional turbofan. This could result in unfavorable scale effects on engine efficiencies and sensitivity to bleed-air off-takes. On the other hand, a smaller core also results in a lower engine weight;

- *De-icing*
  Special provisions are required for de-icing of the blades of propfans.

Fuel consumption data

Table 2.2 shows data regarding fuel-reducing effects of propfans found in the available literature. If found, the table shows the following data for each reference:

Engine type
This can be a general qualification such as SR (single rotating) or CR (counter-rotating), but also an actual engine type.

Fuel reduction
This is the percentage of reduction in fuel consumption that can be achieved by application of the engine considered.

Unit
The reductions in fuel consumed in the different references are given in different units. *SFC* is the Specific Fuel Consumption. *FB* stands for 'Fuel Burned' (for a certain mission for a certain aircraft), and *SMPG* stands for Seat Miles Per Gallon. SFC is merely a characteristic of the engine only; it is an indication for the efficiency of the engine. FB and SMPG include the installation effects and weight increase induced by the application of the engine.

Year
The year in which the propfan is (expected to be) available.

Baseline
Most percentages are with respect to the most modern turbofans available at the time of publication of the reference. If this is the case for a certain engine the column labeled 'baseline' shows 'current' for that engine. In other references actual aircraft like the Fokker 100 and Airbus A320 are the baseline for the figures shown.

Speed
This indicates the speed (range) for which the engine is considered suitable.

In general the different references consider counter-rotating propfans. Mach 0.65 - 0.85 is indicated as the speed range suitable for propfans. Noise and fuel consumption however become more unfavorable with increasing Mach number, although no reference actually relates certain lower fuel consumption to a lower Mach number and certain higher fuel consumption to a higher Mach number. In general, the data in table 2.2 indicate that mach 0.74 can be regarded as a representative speed for aircraft equipped with propfans.

In most publications the reference engines for fuel use reductions possible by the application of propfans are engines available in the early nineties. This is suitable for the aircraft considered in this study for short haul (Boeing 737-400) and long haul (Boeing 747-400) missions, because these aircraft were introduced around the same period. Two remarks should be made with respect to the data in table 2.2.

1. The reductions in fuel consumption possible by the application of propfans given by the different references are not unambiguous. This complicates the choice of the value for this characteristic to be used in this study;
2. The estimates that are given as reductions in fuel burned (FB) are generally higher than the SFC reduction estimates. This is remarkable because one would expect that the effect of weight increase and installation losses would counteract the effect of a SFC reduction. An explanation could be that the lower fuel consumption of a propfan results in a lower MTOW. This lower MTOW can induce an empty weight reduction.

The data in table 2 indicate a 30% SFC reduction compared to conventional turbofans to be a fair estimate for the fuel reducing effect that can be expected from the application of propfans. For the evaluation of propfans in the APD model however, an engine table (ref. 41) developed by *ADSE* in Hoofddorp, the Netherlands, is used. *ADSE* has been involved in several research projects on the application of propfans, including the *Dutch Green Aircraft Intelligence* study (ref. 11). This table gives the thrust rating and the fuel flow of the engine as a function of speed and altitude. The main parameters of the *ADSE* propfan are as follows for a 150-seat aircraft cruising at Mach 0.74:

Engine power
Top of climb : 6200 SHP
Take-off : 10000 SHP

Propeller
Diameter : 12.5 ft
Number of blades : 6 x 6
Activity factor : 120

Core engine
Length : 2.5 m (excl. gearbox and jetpipe)
Diameter : 0.85 m

Nacelle dimensions
Length : 6.0 m (spinner edge to exhaust jetpipe)
Height : 1.7 m (incl. oil cooler inlet)
Width : 1.8 m (bifurcated)

Weight : 3400 kg (excl. mounting, incl. propeller, systems and nacelle)

Cost : Equal to turbofan (engine including nacelle and installation)

Table 2 Fuel consumption reduction data for propfans

Ref. (year)	***Type***	***Fuel Improvement***	***Unit***	***Available***	***Baseline***	***Speed (Mach)***
4 (1990)	GE36 (CR)	30%	SFC	1986	Current	0.86 (max.)
10 (1990)	-	25%	SFC	-	A320	0.70 - 0.75
11 (1997)	SR CR	25 – 40% 30 – 50%	SFC SFC	2010 2015	F100 F100	0.72 0.72
14 (1990)	-	12 – 18%	SFC	2000	Current	-
15 (1995)	-	40%	SFC	2015	Current	0.65 - 0.85
4 (1990)	-	20%	FB	-	Current	0.70 - 0.85
7 (1998)	Progress D-27 (CR)	30%	FB	1998	Current	0.75
11 (1997)	CR	43%	FB	2005	F100	0.72
12 (1997)	CR CR	30% 40%	FB FB	- -	F100 F100	0.80 0.72
1 (1992)	-	10 – 30%	SMPG	1995 -2000	Current	0.65 - 0.85

Weight and cost effects

Besides the fuel consumption reducing effect, the application of propfans implies secondary effects on weight and costs of the engine and aircraft. The effect on costs mainly concerns capital and maintenance costs. The general trend regarding weight in the different references is that the empty weight of the aircraft increases when propfans are applied instead of turbofans. This can be due to mainly the following reasons:

- A propfan is larger than a turbofan due to its larger fan. This also increases installation weight;
- Application of a gearbox;
- Extra cabin-noise reducing measures in case of wing mounting.

However, others (ref. 39) expect the weight increase resulting from the larger fan and the gearbox to be largely offset by the absence of thrust reversers, a smaller nacelle and, for lower Mach numbers (regional aircraft), the smaller engine core required. Additionally, as already mentioned, noise-reducing measures may not be necessary if tip speeds and engine location are chosen correctly. This view may be supported by remark 2 made above regarding the data in table 2. This however cannot be checked due to lack of sufficient information regarding the calculation of the data in table 2.

Purchase and maintenance costs are generally expected to be higher for propfans compared to turbofans, mainly due to their higher degree of complexity. Examples of this higher degree of complexity are for instance:

- Complex blade design;
- Application of advanced materials;
- Application of a gearbox.

However, for similar reasons as mentioned above for the offset of weight increase, ref. 39 expects the purchase and maintenance costs to be similar for propfans and conventional turbofans, especially for regional aircraft taking into account the mach number of 0.74.

Besides these general trends few concrete data have been found regarding weight and cost effects of propfans. Weight and cost increase data that have been found are listed in tables 3 and 4. As mentioned above, the total weight effect of replacing a turbofan by a propfan consists of the combined effects of:

- A larger fan;
- Application of a gearbox;
- Smaller nacelle;
- Removal of thrust reversers;
- Noise reducing measures.

The 10% OEW increase found in ref. 10 would be the result of a 50% higher engine group weight, assuming the engine group weight to be 20% of the operational empty weight, based on data in ref. 32. The engine group in this case is assumed to consist of engines, nacelles, thrust reversers and installation weight. For evaluation in the APD model a propfan weight of 3400 kg will be used. This is the weight corresponding to the engine table used in the APD model.

With respect to the cost data in table 2.4 it must be noted that from ref. 1, 10 and 13 it is not clear if for instance nacelles and thrust reversers are included in the estimated engine price. Furthermore, it is unknown if the fact that a less fuel consuming engine is generally more expensive is considered. This complicates the estimate of the cost effect of propfans. With respect to the cost data found in ref. 13 it should be noted that according to this reference these data are valid for 300 - 350 kN engines. This explains the relatively high engine prices. However, most references claim that propfans are only viable up to a little over a 100 kN. A 0% purchase cost increase is estimated by *ADSE* for their propfan in ref. 41. Therefore no purchase cost increase with respect to conventional turbofans is assumed for the evaluation of propfans in the APD model. However, for evaluation in the APD model the requirement of wing modification for propfan installation is taken into account. This amounts to an increase in airframe costs of approximately 11.5%. A 20% maintenance costs increase is assumed.

Table 3 Weight data for propfans

Ref. (year)	***Weight Type***	***Weight effect***
10 (1990)	OEW	+10%
41 (1999)	Engine group*	3400 kg**

* *Excl. Mounting, incl. propeller, systems and nacelle*

** *150-seat aircraft at Mach 0.74*

Table 4 Engine and maintenance costs increase data for propfans

Ref. (year)	*Cost Type*	*Cost increase*	*Turbofan*	*Propfan*	*Year*	*Remarks*
1 (1992)	Purchase	100%	$5M	$10M	Current	$30M - $40M a/c
10 (1990)	Purchase	20%	-	-	Current	80 - 120 pax a/c
13 (1994)	Purchase Purchase	50% 33%	£6M £5.25M	£9M £7M	2000* 2010*	Propfan vs. 3rd gen. Turbofan**
41 (1999)	Purchase	0%	-	-	-	150-seat a/c at Mach 0.74
13 (1994)	Maintenance	50%	£12±6	£18±8	-	£/engine.km**
39 (1999)	Maintenance	0%	-	-	-	At Mach 0.74

* *This kind of data is available in ref. 13 for 2000 - 2040.*
** *300-350 kN engine, 2.400.000 km/year.*

Propfans - Input parameters for the APD model

- *Speed*: Mach 0.74;
- *Installation*: wing-mounting;
- *Fuel consumption*: According to *ADSE* engine table (ref. 41);
- *Engine weight for the basic engine scaled for a 150-seater incl. propeller and nacelles:* 3400 kg;
- *Cost effects:* +20% maintenance costs.
- *The effect on fuel consumption of the development of conventional turbofans will be taken into account for the development of propfans.*

2.2.3 Ducted ultra high bypass ratio engines

General

The class of ducted ultra high bypass ratio engines (ducted UHB engines) covers a range of engines that can roughly be divided in two types of engines:

- Ultra high bypass ratio turbofans;
- Ducted propfans.

Generally, UHB turbofans feature fan pressure ratios of 1.45 - 1.7 and bypass ratios up to 12, though some references claim higher bypass ratios for UHB turbofans (see also table 5). Ducted propfans feature pressure ratios of 1.30 - 1.45 and bypass ratios of 12 - 20. To prevent the unfavorable weight and drag effects of high bypass ratios from counteracting the favorable fuel consumption effect completely, ref. 29 states that the bypass ratio of ducted UHB engines should not exceed 15 – 20 (ref. 29). For fan pressure ratios below 1.5 and bypass ratios over 9, a gear between the fan and the turbine may be required (ref. 29 and 31).

According to ref. 29, future propulsion systems for high-subsonic aircraft will be ducted UHB engines, which can be either UHB turbofans or ducted propfans. According to this reference unducted propfans were rejected because of the noise, fan blade limitations and the offset of the SFC reduction due to weight increases. An advantage of the ducted engine with respect to noise, besides nacelle shielding, is that adaptive liners can be applied. An adaptive liner is a noise damping material that can be attached inside different parts of the engine and nacelle.

Ultra high bypass ratio turbofans

Estimates for the decrease in fuel consumption to be gained with UHB turbofans vary from 5% to 25% for the period 1998 - 2015 at bypass ratios varying from 8 to 20. The SFC gain that can be achieved by a UHB turbofan is among other factors depending on the application of a gearbox and the location of the fan. Application of a gearbox or an aft-fan can optimize SFC, but imply other problems, for instance regarding weight and maintainability (ref. 5).

An advantage of UHB turbofans will be a noise decrease as a result of the higher bypass ratio (ref. 12). Another advantage is that the generally estimated thrust for these engines is estimated to be 20,000-60,000 lbs, which means that they can be applied to small aircraft as well as large widebodies. Ref. 29 even mentions 80 - 90 klbs as possible thrust for UHB turbofans. Possible disadvantages of UHB turbofans are:

- Higher internal pressure ratios than conventional turbofans. This increases NO_x emission. Ref. 11 predicts a 40% NO_x emission increase versus a 25% gain in fuel per seat compared to Fokker 100 technology for a 100 pax aircraft with an UHB turbofan with bypass ratio 8. However, this disadvantage is weakened when it is considered that ICAO regulations allow NO_x emission to rise with engine pressure ratio;
- Weight increase as a result of the larger fan and nacelle. For fan pressure ratios below 1.5 (bypass ratios > 9) a gear between fan and low-pressure turbine is required (ref. 31), which further increases weight. An example of such an engine will be described in section 2.2.4;
- Purchase costs will increase as a result of the larger fan and nacelle. Maintenance costs will increase if a gear is applied;
- Friction drag increase as a result of larger nacelles. Fan diameter increases are up to 25% (ref. 29). This drag increment calls for the application of LFC techniques on these engines (see also following section);
- Installation losses as a result of:
  - Nacelle - aircraft interference;
  - Decrement of secondary power as a result of the relatively smaller gas generator.

Ducted propfans

The ducted propfan can be regarded as a combination of a propfan and a very high bypass ratio turbofan. Around 1991 MTU developed the CRISP, the Counter Rotating Integrated Shrouded Propfan, which combines the UHB turbofan with the counter-rotating propfan. MTU claims a 15% SFC reduction for the CRISP compared to 11% for a similar, but simpler, engine developed by P&W (ref. 14). However, the SFC reduction of the CRISP does not compensate its mechanical complexity according to ref. 12. Ref. 31 reports that MTU is developing a new ducted fan concept, building on experience with the CRISP. This engine should, compared to a conventional bypass ratio turbofan, achieve a fuel consumption reduction of 20%, 3% lower DOC, a noise reduction of 10 dB compared to a state of the art conventional turbofan, and 85% lower NO_x emissions against 1995 ICAO standards. BPR of this engine will be 12 or higher, and a gearbox will be applied. A high combustor outlet temperature, high overall pressure ratio and a high-power-density compressor and turbine, should achieve the low fuel consumption. The concept calls for an interdisciplinary collaboration in the fields of aero- and thermodynamics, new materials and designs. According to ref. 29 the typical thrust range for ducted propfans is 40 - 46 klbs, though this same reference gives weight data for this type of engine for thrust levels ranging from 20,000 - 60,000 lbs.

An advantage of the ducted propfan is the reduced noise compared to unducted propfans as a result of the cowling. Disadvantages are:

- Weight increment with respect to current turbofans as a result of the larger fan and nacelle, and the application of a gearbox;
- Purchase costs increase as a result of the larger engine and nacelle, and the application of a gearbox;
- Maintenance cost increase as a result of the application of a gearbox;
- Friction drag increase as a result of larger nacelles. Fan diameter increases are up to 25% (ref. 29). This drag increment calls for the application of LFC techniques on these engines (see also following section);
- Uncertainties regarding possibilities for application on larger aircraft.

Fuel, weight and cost effects of ducted UHB engines

Fuel consumption reduction data for ducted ultra-high bypass ratio engines are listed in table 5. Weight data are listed in tables 6 and 7. In table 7, the column labeled *current* indicates the weight increase with respect to current turbofan weights. The column *advanced* indicates the weight increase with respect to future advanced turbofans. These data assume lightweight materials to be applied in future engines. According to ref. 5 the purchase cost trends for UHB engines are very similar to those for weight. However, it is unlikely that the cost increase with respect to current turbofans will be zero for reasons mentioned above regarding purchase costs of ducted propfans. Furthermore, maintenance costs are expected to rise because of the larger engine and the possible application of a gearbox. Another implication of the application of the UHB engine is the larger nacelle that not only has an effect on weight and cost, but also on friction drag. Assuming that neither the mass of the air flow through the core of the engine nor the speed through the engine change for a UHB engine with respect to a conventional turbofan, the ratio of the diameters of a conventional turbofan (1) and a UHB engine (2) is given by the following expression, where *D* is the diameter and *B* is the bypass ratio:

$$\frac{D_2}{D_1} = \sqrt{\frac{B_2 + 1}{B_1 + 1}}$$

In case of a bypass ratio B_1 = 5.5 for a conventional turbofan and B_2 = 9 for a UHB engine, D_2/D_1 = 1.24. For implementation in the APD model the following general features are chosen for the representative of the ducted ultra-high bypass ratio engine class:

- SFC reduction compared to conventional turbofans: 15%;
- Weight effect: +10% engine weight compared to conventional turbofans;
- Purchase costs: +10% engine price compared to conventional turbofans;
- Maintenance costs: +10%;
- Nacelle diameter: +25% compared to conventional turbofans;
- In this drag increase no flow control technologies are assumed. Nacelle friction drag is 10-15% of total friction drag.

Table 5 Fuel consumption reduction data for ducted UHB engines

Ref. (year)	*Type*	*Bypass Ratio*	*Fan pressure ratio*	*Fuel Improvement*	*Unit*	*Available*	*Baseline*
UHB turbofans							
5 (1992)	-	-	1.4	5%	SFC	-	Current
15 (1995)	- -	8 – 10 15 – 20	- -	15 - 20% 30%	SFC SFC	2005 2015	Current Current
4 (1990)	-	10 – 20	-	12%	FB	-	Current
11 (1997)	-	8	-	25%	FB	2005	F100
12 (1997)	-	12	-	10 - 15%	FB	-	F100
1 (1992)	-	10 –20	-	5 – 17%	SMPG	1992 – 1995	Current
Ducted propfans							
14 (1990)	P&W SR APD MTU CRISP	- -	- -	10 - 11% 14 - 15%	SFC SFC	1991 1991	Current Current
29 (1996)	-	15		14%	SFC	-	
31 (1997)	Engine 3E	12	1.5	20%	SFC	2010	Current

Table 6 Weight increase data for ducted UHB engines (general)

Ref. (year)	*Fan pressure ratio*	*Engine weight Increase*
5 (1992)	1.4 1.5 1.6	25% 10% 2%

Table 7 Weight increase data for ducted propfans

Ref. (year)	*Thrust (lbs)*	*Engine weight increase*	
		Current	**Advanced**
29 (1996)	20,000 40,000 60,000	0% 0% 0%	25% 14% 10%

Ducted ultra-high bypass ratio engines – Input parameters for APD model

- *Year of scope*: 2010;
- *Fuel consumption*: -15% SFC;
- *Engine weight effect*: +10%;
- *Engine price effect*: +10%;
- *Engine maintenance costs effect*: +10%;
- *Nacelle diameter*: +25%;
- The effects on fuel consumption, engine weight and engine price of the development of conventional turbofans will be taken into account for the development of UHB engines.

2.2.4 Geared Turbofans

A conventional turbofan consists of a high-pressure and a low-pressure spool. The fan is normally part of the low-pressure spool so it turns at the same speed as the low spool. This speed however is often a compromise, since a fan operates more efficient at lower rpms while the rest of the low spool is more efficient at higher speeds. By applying a reduction gear be-

tween these components it is possible to operate the fan and the low spool at their optimum speeds (ref. 43).
At the moment Pratt & Whitney is developing such a turbofan, which is called the PW8000 (ref. 44). They expect a fuel burn reduction of around 9 % and a noise reduction of 30 dB (cumulated) below current Stage 3 limitations. By using a more advanced combustor they also expect a 40 % reduced emission level. Furthermore, Pratt & Whitney claims a $600,000 reduction in operating and maintenance cost on a year basis for an aircraft flying two PW8000s instead of conventional engines. The thrust range for the PW8000 will be from 25,000 to 35,000 pounds, which will be suitable for aircraft seating 120-180 passengers. Flight-testing is expected to begin by 2003. This engine has not been considered in the APD model.

2.2.5 Integrated high performance turbine technology

In 1988 NASA and the US department of defense started a program aimed at the improvement of the thermodynamic efficiency of the turbine. The goal was a 40% reduction in fuel consumption for turbofan and turbojet engines. The most important benefits would come from raising ignition and maximum combustion temperatures and reducing engine weight. Advanced ceramic and metal matrix high-temperature materials are required to increase turbine inlet temperatures and to raise the overall pressure ratio. The program is initially meant for military aircraft and helicopters, but the spin-off could also be beneficial for commercial aircraft (ref. 1). Since this is the only information found regarding this technology it is not further considered in this study.

2.3 Design features

2.3.1 Drag reducing aerodynamic features

Drag reduction will reduce the fuel consumption of the aircraft and therefore emissions of CO_2 and H_2O. For this purpose several aerodynamic features are under development. The most important of these features are:

- Computational fluid dynamics;
- Laminar flow control;
- Variable camber wings;
- Large Eddy Break-Up (LEBU) devices.

Computational Fluid Dynamics (CFD)

Advances in supercomputing make it possible to simulate airflow around fuselage, wings, engines and nacelles with increasing detail, accuracy and speed. This results in better optimization of the design with respect to aerodynamics. Sufficiently accurate experimental data are required for tuning of the CFD models. No concrete data on expected savings have been found.

Laminar flow control

- *Natural Laminar Flow (NLF)*
  NLF technology attempts to design shapes and use smooth surfaces to minimize turbulence. This technology seems to be best suitable for small to medium size aircraft (ref. 1, 10 and 13). It can achieve laminar flow over 60-65% of the wing (ref. 1, 10), resulting in a 50% reduction of the

wing friction drag (ref. 10). With the wing accounting for approximately 35-40% of the total friction drag, this could result in a friction drag decrease of up to 20%. Also according to ref. 10, NLF can result in a 10% L/D improvement with respect to A320 technology. Combined with an aspect ratio of 9.4 to 11 the L/D improvement could be 15%. According to ref. 13 these techniques do not add to the cost of the aircraft and contribute approximately 0.5% per annum to the reduction in fuel consumption of the aircraft. The possibilities for application of NLF are limited by the combination of wing sweep, leading edge radius and Reynolds number (ref.10). Furthermore NLF wings are very sensitive to insect debris. This requires a cleaning system, which can ad to maintenance and acquisition costs and to the weight of the aircraft (ref. 10, 39);

- *Active Laminar Flow Control (ALFC)*
  ALFC uses suction to smooth the flow on the wing and to change wing shapes to adapt to changes in speed, altitude and weight. According to ref. 1 ALFC could result in 7% gain in Seat Miles Per Gallon (SMPG) over the 1990's aircraft generation. Application of ALFC on the wing would result in a 12% cruise energy saving (ref. 13). Application to nacelles and tail also would add a saving of another 3%. According to ref. 10 laminarisation and turbulence management by means of suction could result in 20-30% fuel savings compared to A320 technology. However, this technique is more suitable for larger aircraft due to the complex suction systems. Though ALFC systems are not as sensitive to insect debris as natural laminar flow techniques, this system still requires extensive cleaning to fulfil its purpose. This aspect, as well as the complexity of the system, adds to the maintenance costs of the aircraft. In addition capital costs and aircraft weight increase (ref. 13);

- *Hybrid Laminar Flow Control (HLFC)*
  This technology applies grooves or microscopic holes in the front portion of the wing before the spar, through which air is vacuumed to reduce turbulence (ref. 1). Ultra smooth surfaces on the aft part of the wing maximize the area of naturally laminar flow. Ref. 1 (1992) expected HLFC technology to be available for commercial aircraft design around 1997, but to the author's knowledge this technique has not been applied in commercial aircraft yet. HLFC could result in a 50% drag reduction, resulting in a 15-20% SMPG gain over the 1990's aircraft generation (ref. 1). Regarding maintenance and capital costs, generally the same observations as for ALFC systems apply.

Variable camber wings

According to ref. 1, Airbus would introduce wings that could adapt their camber automatically during flight to changes in weight, speed and altitude in the beginning of the 1990's. However, this approach was rejected by Airbus due to additional costs and weight involved (ref. 13). No information has been found on plans for application of this technology on future aircraft, neither has information been found on expected fuel savings.

Large Eddy Break-Up Devices (LEBU)

LEBU devices are attached to the fuselage to reduce skin friction drag. They can be small grooves (riblets), which smooth turbulent flow, or thin plates (ribbons), which can break up large vortices which could otherwise form and increase skin fiction drag (ref. 1). Windtunnel tests have shown that these devices can reduce skin friction drag up to 10%. According to ref. 1, 9-18% SMPG are possible over the 1990's generation. Ref. 13 mentions a 7% drag reduction. An advantage of these devices is that they can be retrofitted to existing aircraft.

Increasing aspect ratio

Increasing the aspect ratio decreases the induced drag of the aircraft and therefore fuel consumption. However, there is a trade-off between drag reduction and weight increase as a result of a more slender wing. Another limit is imposed by the spanwise wing loading that cannot be too low. Modern technologies of new materials and design methods allow the wing to be thicker and less sweep to be applied. This improves the possibilities for aspect ratio increase. No estimates for fuel savings are required, because aspect ratio increase can be directly evaluated in the design model.

Aerodynamic, weight and cost effects

Table 8 shows the different data on expected benefits from aerodynamic features that have been found in literature. The abbreviation *FD* in this table stands for Friction Drag. The table shows that there is no equivocal estimate of the improvements that can be obtained by aerodynamic improvements. There are several possibilities to introduce aerodynamic improvements into the model, for instance:

- A reduction of the aircraft friction drag coefficient C_{D_0} ;
- An increment of the lift to drag ratio L/D.

An L/D increment could also be translated to a C_{D_0} decrease. As an example the following assumptions are made:

- Aerodynamic features do not affect the cruise lift coefficient of the aircraft;
- Average friction drag is 57.5% of total aircraft drag. This number is based on the assumption that friction drag is approximately 50% of total drag for long-range aircraft and 65% of total drag for short/medium range aircraft.

Making these assumptions a 10% L/D increase would for example on average be achieved by a 15.8% decrease of C_{D_0} . Taking into account the practical difficulties of maintaining maximum effectiveness of aerodynamic features, a maximum attainable friction drag decrease of 12.5% is assumed for an optimum combination of aerodynamic features, including natural as well as laminar flow control features. Increasing aspect ratio has not been taken into account in this estimate. The effect of increasing aspect ratio can be calculated directly from the design model.

Empty weight increase resulting from aerodynamic features is estimated to be 1% for the B737-400 and 0.5% for the B747-400. The complexity of the systems will add to purchase as well as maintenance costs of the aircraft (see also table 9). Also the necessary cleaning will add to maintenance costs. Airframe maintenance costs are expected to increase by 20% from the application of aerodynamic features. Purchase costs are estimated to increase by 2.5% for the B747 and by 7.5% for the B737.

Combined aerodynamic features – Input parameters for APD model

- *Year of scope*: 2010;
- *Aerodynamic effect*: -12.5% C_{D_0} ;

- *Weight effect:*
- Short haul: +1% aircraft empty weight;
- Long haul: +0.5% aircraft empty weight;
- *Aircraft price effect:*
- Short haul: +7.5%;
- Long haul : +2.5%.
- *Maintenance costs effect*: +20% airframe maintenance costs;
- *The effects on fuel consumption, engine weight and engine price of the development of conventional turbofans will be taken into account in the APD model calculations.*

For passive laminar flow the same drag effect may be achieved, but with only 10 % increase in airframe maintenance hours. Aerodynamic cleanup of the aircraft alone accounts for about 5 % lower parasite drag at negligible cost.

Table 8 Effects of aerodynamic developments

Ref. (year)	***Improving effect***	***Unit***	***Remarks***
Natural Laminar Flow			
10 (1990)	10% 15% 50%	L/D L/D FD_{wing}	Aspect ratio increase 9.4 → 11
13 (1994)	0.5%	SFC/year	
Active Laminar Flow Control			
10 (1990)	20 – 30%	FB	
13 (1994)	12 – 15% 9% 13%	Cruise FB FB FB	 Short/medium haul Long haul
15 (1995)	10 – 12%	L/D	
Hybrid Laminar Flow Control			
1 (1992)	5 – 40% 10 – 20%	Drag SMPG	
LEBU and riblets			
1 (1992)	15% 9 – 18%	Drag SMPG	
10 (1990)	8%	$C_{DF,wing}$	
13 (1994)	1.5% 7%	FB Drag	Riblets, weight increase 0.05% LEBU
Overall gain from aerodynamic features (excl. Aspect ratio increase)			
1 (1992) 13 (1994) 15 (1995) 39 (1999)	15 – 48% 12 – 25% 20% 0 - 5%	SMPG FD L/D FD	

Table 9 Purchase and maintenance costs increase data for aerodynamic features

Ref. (year)	***Cost Type***	***Cost increase***	***Remarks***
Natural Laminar Flow			
13 (1994)	Capital	0%	
Active laminar Flow Control			
13 (1994)	Capital Capital	+ £M1990 3.4-5.1 + £M1990 3.6-5.5	Short/medium haul. Long haul
	Maintenance	20%	

2.3.2 Lightweight materials

General

Reduction of fuel consumption can be obtained by the application of new lightweight materials. Material developments are expected in both airframe and engines (ref. 1). The weight reductions obtained by the application of these new innovative materials work two ways. A lighter airframe requires less thrust and therefore a smaller engine, while a smaller engine could result in a lighter airframe, for instance as a result of a smaller wing area or a smaller structural engine supporting weight. In other words, weight reductions induce other weight reductions. According to ref. 1, a 1% reduction in airframe weight results in a reduction in fuel consumption of 0.25% for small aircraft to 0.5% for larger aircraft, based on 1984 data.

In general, new materials are more expensive than conventional materials. However, significant advantages in other areas can result in a better price/performance ratio for these materials compared to conventional materials. Examples of these areas are improved safety characteristics, and weight and cost reductions for complete structures as a result of new production methods. An example of a weight reducing feature of new production philosophies is the integration of more functions in the structure, such as the direct integration of stiffeners during the manufacturing process and the inherent fire-resistant properties of the material.

Possible innovative materials that could reduce aircraft weight are:

- *Metal alloys;*
- *Composites*
  - Fibre reinforced plastics;
  - Fibre metal laminates;
  - Metal matrix composites.
- *Ceramic materials.*

These classes of potential weight reducing materials and their characteristics will be dealt with below in more detail.

Metal alloys

Weight savings up to 7% are possible for aluminum-lithium alloys (ref. 13). This material is currently used in the Airbus A340 on a small scale. The price of this material is two to four times higher than for conventional aluminum alloys. In the airframe of the Antonov An-70 aluminum-lithium and titanium-lithium alloys are applied.

Composites

According to ref. 1, composites have the potential to reduce aircraft weight by 30% for an 80% composite aircraft. At this moment there are already aircraft which mainly consist of composites, for instance the EXTRA 400 business aircraft. The Raytheon Premier I and the Hawker Horizon business jets feature composite fuselages and aluminum wings. Airbus Industrie plans to use GLARE, a fibre metal laminated material developed by Delft University of Technology, in its A3XX design. According to ref. 13, 13-15% of the empty weight of the Airbus A320 and A340 consists of composites.

Fibre reinforced plastics

Fibre reinforced plastics consist of fibres in a plastic adhesive. Often these materials are applied in sandwich structures that consist of two composite plates separated by honeycomb or foam materials. Some of the most common materials used for the fibres are glass, aramid and carbon. Table 10 shows some of the most important characteristics for alu-alloys, steel and several fibre reinforced plastics (FRP). This table shows that composites can offer advantages over conventional materials with respect to weight as well as structural efficiency.

Other fields in which FRP structures can offer characteristics that improve their price/performance ratio with respect to conventional materials are:

- *Weight reduction as a result of the integrated effects of:*
  - Material properties;
  - Production methods;
  - Structural design.
- *Cost reduction as a result of:*
  - Weight reduction;
  - Lower production costs;
  - Lower maintenance costs.

- *Improved safety:*
  - Fire resistance;
  - Corrosion resistance;
  - Damage tolerance.
- *Acoustic damping.*

Table 10 Material properties of alu-alloys, steel and fibre reinforced plastics

	***ρ* (kg/dm³)**	***E* (kN/mm²)**	***E*/*ρ***	**$E^{1/2}/\rho$**	**$E^{1/3}/\rho$**
Alu-alloys	2.80	70.00	25.00	2.99	1.47
Steel	7.80	210.00	26.92	1.85	0.76
E-glass epoxy	1.87	20.85	11.06	2.42	1.46
HM-aramide	1.34	30.50	22.76	4.12	2.33
HT-carbon	1.49	50.40	33.83	4.76	2.58

According to ref. 13 a 12.5-15% reduction of the aircraft empty weight can be obtained by the application of carbon fibre reinforced plastics instead of aluminum in aircraft components including structural beams. Material costs are higher by a factor three to five, while manufacturing costs are lower by the same factor. These materials could be introduced over the next 15 years.

Carbon fibre reinforced plastic was selected over glass fibre reinforced plastic for the fuselage of the Extra 400 because of its stiffness versus weight properties. Initially glass fibres were selected based on material costs. Again it must be stressed that the largest weight and cost reductions can be obtained by the integration and simultaneous development of materials, production and manufacturing methods, and structural design. Disadvantages of composites are their brittleness and their sensitivity to notches and stress concentrations. In addition composites are less applicable to large structures such as the fuselage and wing of the A3XX.

Composites cannot only be applied in airframe design, but also in propulsion systems, for instance in propfans. GE has produced fan blades of reinforced, lightweight, laminated graphite/epoxy fibres for its demonstrator propfan. These blades are more resistant to bird strike, tire fragments and lightning. Furthermore they are easy to repair, suffer minimal icing and reduce engine weight. Another reason to use composites is the high stress level that can occur in the fan blades.

Fibre Metal Laminates

Fibre Metal Laminates (FML) are developed at Delft University of Technology (DUT) and consist of bonded thin metal sheets and fibre/adhesive layers. The first FML developed at DUT was ARALL, an FML based on aramid fibres. However, the aramid fibres showed bad compression properties. GLARE, also developed at DUT, is based on glass fibres. This material shows the following favorable characteristics (ref. 24):

- Good fatigue, impact and damage tolerance characteristics;
- Low density;
- Bondlines act as barriers against corrosion;
- Good burn-through resistance;
- Good damping and insulation properties;
- Larger panel size reduces production costs;
- Less maintenance;
- Less structural material required.

Disadvantages of FML compared to conventional aluminum are (ref. 27):

- More aluminum surface needs to be anodized than for conventional aluminum structures. Chromatic acid, which is used in this process, is harmful for the environment;
- GLARE is more difficult to recycle than conventional aluminum alloys, because two different materials that are bonded together must be separated. However, it must be noted that also copper, used in aluminum 2024, hampers the recycling process of this material;
- The primer used for GLARE contains chromates, which are environmentally unfriendly.

The density of GLARE is 10-15% lower compared to conventional aluminum alloys. The density of GLARE is not the same for the different existing GLARE variants and depends on several factors, for instance the lay-up and the fibre direction of the type of GLARE used. A case study of 1990 has shown that a 25% weight reduction may be possible for the A320 fuselage when GLARE would be used as much as possible instead of aluminum (ref. 27). Extrapolation of this result would indicate a possible 20-30% reduction of the structural weight of the aircraft. GLARE is up to five times as expensive as aluminum. However, as a result of lower production costs, the cost of the total structure will be the same or only slightly higher than for the same structure made of aluminum. The buy fly ratio for aluminum for example is 1.8 - 2.0, which means that 1.8 - 2.0 kg of material input is needed for each kg of construction. The remaining 0.8 - 1.0 kg is waist. The buy/fly ratio of GLARE is only 1.2 - 1.3. This not only has a positive effect on costs, but also on the environment. According to ref. 24, the wide scale introduction of pure composites in aircraft design is hampered due to their brittleness and lack of standardization. Fibre Metal Laminates show more favorable characteristics in these areas.

Moreover ref. 27 showed that the use phase of an aircraft determines over 99% of its load on the environment. The production phase only represents less than 1% of the environmental load. The environmental gain of the application of GLARE compared to aluminum can therefore be expressed in terms of fuel consumption only. Because GLARE results in a weight decrease of the aircraft, it also results in a decrease in fuel consumption and therefore in an environmental advantage over aluminum.

Airbus Industrie plans to use GLARE in the entire top half of the A3XX fuselage around the passenger cabin as part of its aim to reduce the A3XX operating costs by 15% compared to the Boeing 747-400 (ref. 24).

Metal matrix and ceramic materials:

Metal matrix and ceramic materials would enable turbine inlet temperatures to be increased. Increased temperatures would increase engine efficiency (ref. 1).

Weight effect

It can be expected that new materials will be more and more widely applied in the near future. Not only because of their weight reducing potential, but also because of their favorable characteristics in other areas such as fatigue, damage tolerance and corrosion resistance. Component weight savings can be up to 30%. This can only be partly extrapolated however to the empty weight of the aircraft, since the empty weight not only consists of structural weight. For instance avionics, furnishing, and hydraulical and electrical systems are also included in the empty weight. To these components weight savings from new materials apply to a much lesser extent. The majority of weight savings will be achieved by applying new materials in structural components such as wing, fuselage, nacelles and tail surfaces. Structural weight is generally 50-60% of the aircraft empty weight. Based on a 30% component weight saving the maximum achievable weight reduction from new materials would be 15-18%. However, a 30% weight decrease will not be possible for every structural component. Furthermore it must be noted that, although new materials have been developed and applied over the past years, aircraft weight basically does not show a decreasing trend. One of the main reasons for this phenomenon is the constant aggravation of airworthiness regulations (ref.11). Some therefore believe that material developments are necessary to prevent the aircraft weight from increasing (ref. 39). In this study empty weight decreases as a result of new materials of 0 (baseline), 4 and 8% will be considered. Assuming an average weight reduction of 20% per component when new materials are applied this means that for instance for the 737-400 0, 35 and 70% of the structural components must be replaced by new materials.

Cost effect

The price of new materials can be up to 5 times as high as the price of conventional materials. Often however more efficient production and component integration can offset part of the price difference, for instance when composites or fiber metal laminates are applied.

According to ref. 39 the additional costs of the application of new materials are between \$0 - \$800 per kilogram replaced (conventional) material. Estimating the average additional costs to be \$400 per kilogram replaced material, the effect on the aircraft costs can be illustrated for the Boeing 737-400 by the following example:

Desired empty weight reduction: 8%
Average weight saving new materials: 20%
Empty weight: 31731 kg
Structural weight: 18078 kg

Desired weight saving: $0.08 \times 31731 = 2538.48$ kg
Structural weight to be replaced to achieve the desired weight saving when new materials save 20% weight on average: 2538.48 / 0.20 = 12692.4 kg
Additional costs new materials: 400×12692.4 = M\$5.08

Assuming a purchase price of M\$44, this means a purchase price increase of 11.5%.

Another approach however would be the following:

Estimated component of airframe structure in aircraft price: 40%
Estimated average component price increase when new materials are applied: 30%

Again we take the example of an 8% weight saving for the Boeing 737-400:

Structural weight to be replaced to achieve the desired weight saving when new materials save 20% weight on average: 2538.48 / 0.20 = 12692.4 kg
Part of structural components to be replaced: $12692.4 / 18078 \times 100\% = 70.2\%$
Aircraft price increase: $0.702 \times 0.30 \times 0.40 \times 100\% = 8.43\%$

This is approximately 73% of the price increase estimated by ref. 39. Decreasing the estimated additional cost of \$400 per kilogram structural weight replaced by new materials in the first approach by 15% to \$340 and increasing the estimated component price increase in the second approach by 15% from 30% to 35% gives the same price increase of the aircraft resulting from the application of lightweight materials for both cases, namely 9.8%.
Based on the analysis above, an additional cost of \$340 per kilogram replaced conventional material is estimated for the Boeing 737-400. It can be assumed that scale effects will decrease the additional cost for larger aircraft. An additional cost of \$300 per kilogram resulting from the application of new materials is therefore estimated for the Boeing 747-400.

Based on ref. 39 a 50% increase in maintenance man-hours is associated with the application of new materials. It could be possible that through a more selective use of new materials, maintenance cost could be maintained at the same level. However, if new materials are only applied in a selective way then it is probably not possible to achieve the desired weight reduction. Therefore, this aspect is not considered here; another reason is that the part of DOC that is associated with airframe maintenance is relatively small.

Lightweight materials – Input parameters for APD model

- *Year of scope*: 2010
- *Weight effect:* -8% aircraft empty weight (new materials applied as much as possible)
- *Aircraft price effect*
  -Short haul: +$340 per kilogram replaced conventional material.
  -Long haul: +$300 per kilogram replaced conventional material.
- *Maintenance costs effect:* -8% empty weight: +50% airframe (structure excluding systems) maintenance man-hours.
- *The effects on fuel consumption, engine weight and engine price of the development of conventional turbofans will be taken into account in the APD model calculations.*

2.3.3 Improvement of design methods

Overall improvements of the (computer aided) design methods for aircraft could reduce fuel consumption by a few percent (ref. 12, ref. 13). However, this percentage will probably often be included in the reductions obtained for other technology developments mentioned in this report. The improved design methods could for instance result in more optimized aerodynamic shapes or a more optimal distribution of materials to reduce airframe weight.

3 Reduction of NO_x emission

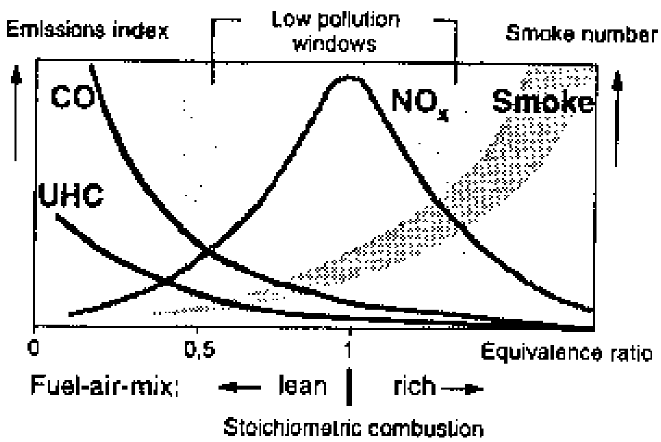
3.1 Introduction

NO_x emission can have several undesirable effects on the atmosphere, such as ozone depletion in the stratosphere and the production of tropospheric ozone, which is a greenhouse gas, in lower layers of the atmosphere. Especially the NO_x emission during cruise is important, since aircraft are the only source of NO_x at higher altitudes. NO_x emission can be reduced by technologies that have an effect on the processes in the combustion chamber. Important parameters in this process are:

- Temperatures in the combustion chamber;
- Compressor exit temperature;
- Air/fuel ratio;
- Overall and compressor pressure ratio.

NO_x production during combustion increases with higher temperatures. NO_x production reaches its maximum when the temperature in the combustion chamber is the stoichiometric temperature. This temperature is reached for a certain fuel/air ratio. For this fuel/air ratio all oxygen in the air is used when the exhaust gasses would be CO_2 and H_2O (ref. 23). This can be seen in figure 2. The temperatures in the combustion chamber determine to a large extent the turbine entry temperature (TET). Therefore this temperature is often indicated as an important parameter for NO_x emission. Also the compressor exit temperature is an important parameter, since this temperature determines to an important extent the temperatures in the combustion chamber. The compressor exit temperature depends on the compressor pressure ratio. Propfans have lower compressor pressure ratios and therefore show lower NO_x emission than conventional gas turbines (ref. 11). The optimum engine pressure ratio rises with TET. Therefore a higher-pressure ratio generally also indicates a higher NO_x emission. Unfavorable for NO_x emissions for conventional gas turbines is that manufacturers aim for both higher-pressure ratios and higher TET, since a higher-pressure ratio reduces fuel consumption, while a higher TET reduces the engine size.

Figure 2 Relation between air/fuel ratio and emission components

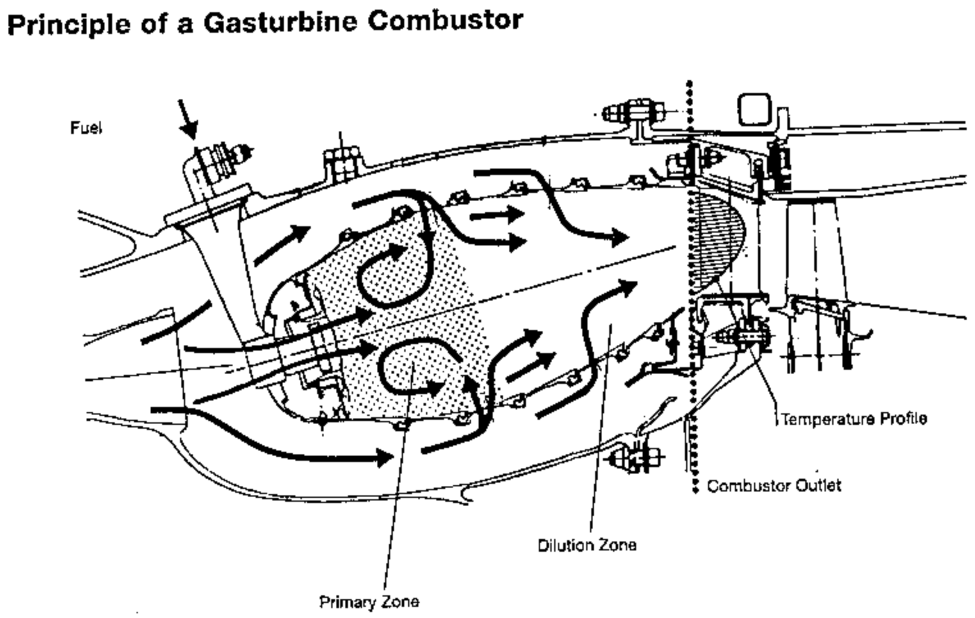


Source: ref. 19

NO_x emission is most important during take-off, climb and cruise. During take-off and climb thrust levels and therefore temperatures in the engine are highest, resulting in a high NO_x emission per hour. Furthermore, this emission takes place around the airport and in lower layers of the atmosphere where it can result in tropospheric ozone. However, as a result of its duration of this flight phase, most NO_x is emitted during cruise in terms of kilograms. In addition, if emission during cruise takes place above the tropopause, it can result in ozone depletion (ref. 14, 21 and 23).

Combustion chambers in current propulsion systems mainly use single stage combustion. Combustion mainly takes place in the primary zone of the combustion chamber, where part of the air in the engine is mixed with the fuel at a stoichiometric level. The gas temperature is lowered in the dilution zone by mixture with another portion of the air (figure 3). By avoiding the stoichiometric temperature, the production of NO_x can be reduced. This can be achieved by the application of a leaner or richer fuel/air mixture than the mixture that results in the stoichiometric temperature. However, the mixture cannot be too lean in order to avoid excessive emission of CO and UHC (unburned hydrocarbons), and not too rich to avoid the exhaust of smoke. Several technology developments aim at the reduction of NO_x emission. An overview of these technologies is given below.

Figure 3 Principle of a gas turbine combustor



Source: ref. 19

3.2 NO_x reducing technologies

3.2.1 Developments in conventional combustion technology

Because the flame temperature in the combustion chamber is an important parameter in the production of NO_x in the gas turbine, lower peak temperatures offer possibilities for NO_x reduction. Lowering peak temperatures can be achieved by charged cooling, intercooling or injecting water or steam into the air intake (ref. 13, ref. 16). However, large quantities of water, in the same order as the fuel quantities, are necessary. This would imply large practical problems with respect to weight and storage. Other possibilities to decrease NO_x emission are reducing the pressure in combustion chambers and the time for which gasses are maintained at high pressures and temperatures (ref. 13 and 16). This would normally result in less complete combustion, which increases the emission of particles and CO. This can be counteracted by acceleration of the combustion. This means the air/fuel mixing can be improved by raising fuel injection pressures, improvements to the injector nozzle and combustion chamber design, or by pre-vaporizing the fuel (ref. 13).

Improvements in single stage combustion technology available today can amount to 30-40% NO_x reduction according to ref. 11. According to ref. 20 improvements of 10% are possible for conventional combustion chambers. It could be argued that there is a compromise between NO_x control and energy efficiency, because lower peak temperatures and pressures are unfavorable for the efficiency of the engine. However, NO_x emission is mainly associated with inhomogeneous combustion and depends on the very high peak temperatures obtained in very small regions in the engine. The efficiency of the engine is mainly dependent on the average temperature and pressure, which are not very sensitive to the peak temperature and pressure (ref. 13).

3.2.2 Staged combustion

A two-stage combustion chamber contains two combustion zones. At low thrust levels, for instance at engine start-up, taxiing, descent and approach, the combustion takes place in the 'pilot zone' up to near stoichiometric air/fuel ratios. An advantage of this process is that exhaust of CO and UHC at low thrust levels is minimized. At higher thrust levels fuel is also injected into the 'main zone', where a leaner mixture is combusted. Two sets of burners are used for staged combustion concepts, one for the pilot zone and one for the main zone. By means of staged combustion emissions can be optimized at all thrust levels. By controlling the fuel flow, the stoichiometric air/fuel ratio can be avoided. This ratio causes the highest temperatures and therefore the highest NO_x production. This technology could result in 50-80% NO_x reduction in 2005 at modest development risks (ref. 11). According to ref. 13 GE expected 30 – 50% NO_x reduction from the application of two sets of annular fuel injectors in the GE90. The outer set is only used at low thrust levels. According to ref. 13 two-staged combustion ads 10-20% to the manufacturing costs, while the complexity of the fuel injection and control system could add 100% to maintenance costs. According to ref. 16, GE expects a 35% reduction from the application of staged combustion in its GE90. However, according to the ICAO Aircraft Engine Exhaust Emissions Data Bank December 1995 the GE90 shows NO_x emissions similar to emissions from engines not applying staged combustion (45-50 g/kg). The CFM56-5B series also features dual annular combustors. According to the Aircraft Engine Exhaust Emissions Data Bank this engine does achieve significantly lower NOx emissions (15 – 30 g/kg). According to ref. 39 this engine also results in a 1% increase in fuel consumption, which makes the engine very hard to sell. This example shows that NO_x reducing technologies can only be introduced when there is an economical advantage for the airline.

3.2.3 Variable geometry combustion

A variable geometry engine has two variable airflow inlets. The first provides air for the primary combustion zone while the second dilutes the air after combustion. The separation between the primary combustion and the dilution zone can be varied. This variation could be used to reduce CO and HC emission at low thrust levels by means of a lengthened primary combustion zone. At higher thrust levels the emission of NO_x can be reduced. The necessary moving parts in the engine complicate this concept. Variable geometry is estimated to add 5-10% to engine costs (ref. 13).

3.2.4 Lean pre-mixed pre-vaporized (LPP) combustion

Lean combustion means that the operating point of the combustion chamber is shifted to the leaner region (see figure 2). A leaner fuel/air mixture can be achieved by feeding more air into the primary zone than would be the case for stoichiometric combustion.

For lean combustion it is very important that the fuel/air mixture is homogeneous. A homogeneous air/fuel mixture is required to avoid hot spots in the combustion chamber that increase the production of NO_x. Avoidance of inhomogenities in the combustion chamber also decreases the production of CO and smoke. To obtain a homogeneous fuel/air mixture the fuel can be premixed or prevaporised before it enters the combustion chamber (ref. 14). This can be done both internally and externally. Disadvantages of LPP combustion are:

- External premixing and pre-vaporization:
  - Spontaneous ignition or flashback can occur. This means the fuel/air mixture ignites in the premixing section;
  - To avoid flashback, the residence time of the mixture in the premixing section must be very short. This can lead to incomplete mixing and vaporization, which increases the emission of NO_x.
- Internal mixing avoids the problems of external mixing, but implies the danger of ignition before the mixing and vaporization processes are completed, leading to increased NO_x emission;
- An LPP engine has a small control range, which means that the engine is not suitable for all flight phases. Pressures and temperatures in the engine are very high during take-off. Therefore LPP combustion can only be applied during cruise (ref. 14);
- Instabilities in the combustion process can occur, resulting in flame-outs. This can be avoided by the application of a richer mixture for initial ignition, as is the case for variable geometry, staged or RQL combustion (see next section).

LPP combustion with internal mixing could result in NO_x reductions of 30-50% according to ref. 14. According to ref. 11 lean premixed prevaporised combustion could result in 80-90% NO_x reductions, and the technology could be available after 2010. Lean premixed prevaporised combustion could result in 85% NO_x reductions according to ref. 16, that does not expect this technology to be available before 2010. Without the premixing process, ref. 16 expects the reduction to be 30%. Such an engine could be available before 2000.

3.2.5 Rich burn Quick quench Lean burn (RQL) combustion

The principle for this concept is a two-stage combustion chamber with a rich fuel-air mixture in the first part of the combustion chamber and a lean mixture in the second part. In the second part the surplus of fuel from the first zone is burned. For RQL combustion, the air/fuel mixture should be as homogeneous as possible and the admixing of air after the rich phase should occur as fast as possible (quick quench) to avoid the stoichiometric ratio. This technology is more complex than LPP combustion, but the combustion process is probably more stable (ref. 16). Ref. 16 predicts 70% NO_x reduction from this technology. According to ref. 11 this technology could be available after 2010 and result in 80-90% reduction of NO_x emission. Development risks are considered high. Cooling and materials are areas to be looked at and the control range for this engine is smaller than for conventional engines. 60-70% reductions are possible for RQL combustion according to ref. 14, while ref. 12 predicts a reduction of 70-75%. MTU plans to use RQL combustion in its ducted propfan design (ref. 31) to reduce NO_x emission by 85% in 2010. Initial work showed a 57% reduction, but fuel preparation in the engine still needs work.

3.2.6 Chemical additives and catalysts

Chemical additives could be available after 2010 and reduce NO_x emission by 80-100% (ref. 11). The development risk however is very high.

Catalytic combustion can be applied in two forms:

1 Combustion occurs at the surface of a catalyst. For this combustion lower inlet temperatures are required than for a conventional combustion process. Catalytic combustion requires a homogeneous air/fuel mix. This can be achieved by premixing or pre-vaporization, or by the use of gaseous fuels. Advantages of this form of catalytic combustion are (ref. 11, 16, 20):

- Efficiency of the combustion can be very high which reduces the products of incomplete combustion;
- The air/fuel ratio for which stable combustion is possible is larger than for a conventional combustion process. The energy flow to the gas flow is more homogeneous than for a conventional process. As a result thermal loads in the turbine are smaller;
- As a result of lower temperatures NO_x production could be reduced, up to 1 g/kg in cruise flight (ref. 16).

Disadvantages are:

- High temperature materials are required in the engine because of the high temperatures released in the process;
- To ensure acceptable efficiency over the entire operating envelope of the engine, some form of variable geometry is required to control the fuel/air ratio;

2 A catalyst could be applied to remove pollutants from the gas emissions. Disadvantages are lower thrust and higher engine weight (ref. 16). These disadvantages prohibit as of yet the application of this technology in aircraft gas turbines.

It should be mentioned that catalysts are already applied in the extraction process of kerosene from crude oil (ref. 36). In this process catalysts are applied to remove impurities like sulphur and nitrogen from the crude oil (residue).

3.3 Summary NO_x reducing technologies

Table 11 lists the NO_x reducing technologies and their implications found in the literature studied. The possible NO_x reductions found in this chapter for the different technologies are in line with the 70% reduction in NO_x emission expected from technological innovations by the IPCC report of April 1999 (ref. 42). Table 3.1 shows that few data are available on the purchase and maintenance costs effect of NO_x reducing technologies. No data have been found on the weight effects of these technologies. No developments with respect to NO_x reducing technologies have been evaluated in the APD model due to:

- Insufficient data regarding weight and cost effects of NO_x reducing technologies;
- Insufficient data regarding NO_x reduction in different flight phases;
- Complexity of NO_x emission calculation of complete flight;
- Complexity of NO_x emission charge implementation.

Table 11 Effects of NO_x reducing technologies

Ref. (year)	*NO reduction*	*Available*	*Purchase costs Increase*	*Maintenance Costs increase*
Conventional combustion chambers				
11 (1997)	30 – 40%	Today	-	-
20 (1996)	10%	-	-	-
Staged combustion				
11 (1997)	50 – 80%	2005	-	-
13 (1994)	30 – 50%	GE90	10 – 20%	100%
16 (1993)	35%	GE90	-	-
20 (1996)	20 – 30%	-	-	-
Variable geometry				
13 (1994)	-	-	5 – 10%	-
Lean premixed prevaporised (LPP) combustion				
11 (1997)	80 – 90%	2010	-	-
14 (1992)	85%	2008	-	-
16 (1992)	85%	2010	-	-
Rich burn Quick Quench (RQL) combustion				
11 (1997)	80 – 90%	2010	-	-
12 (1997)	70 – 75%	-	-	-
14 (1992)	60 – 70%	-	-	-
16 (1992)	70%	-	-	-
Chemical additives and catalysts				
11 (1997)	80 – 100%	2010	-	-
16 (1992)	95%	-	-	-

4 Alternative fuels

4.1 Introduction

Another possibility to reduce the pollutant emissions of aircraft is the use of alternative fuels. Three possible alternative fuels are:

- Liquid hydrogen (LH_2);
- Liquefied natural gas (LNG);
- Alternative kerosene.

4.2 Liquid hydrogen

The use of liquid hydrogen (LH_2) as a fuel for future aircraft would reduce the emission of C_xO_y and soot particles by 100%. However, the emission of H_2O, which is a greenhouse effect enhancing gas, would increase strongly. NO_x emission does not seem to be significantly affected by the use of LH_2 (ref. 12), because of two opposing effects, though the exact effect is hard to estimate. LH_2 burns at higher temperatures, which increases NO_x emission, but since it is more prone to oxidation it can be burned in a leaner mixture. According to ref. 11, the technology to use LH_2 as an aircraft fuel will not be available before 2015, while the development risks are high. According to ref. 12 LH_2 could be used as a fuel by conventional gas turbines.

The heating value per unity of mass for LH_2 is three times as high as for conventional fuels. This is favorable for the operational weights of the aircraft. The volume per unit of mass however is four times larger for LH_2 compared to conventional fuels. This increases the tank volume of the aircraft. Furthermore, LH_2 cannot be carried in the wing, but must be stored in the fuselage (ref. 12). This requires significant structural changes to the fuselage, while also the wing weight increases due to the lack of weight relief. Because of the large aircraft modifications required, the use of LH_2 will probably not be viable within the next several decades (ref. 42). Another disadvantage of LH_2 is the large amount of energy required for its production. This adds costs and also implies environmental consequences. Furthermore liquid hydrogen would require a new infrastructure for distribution and storage.
As of this moment all of these aspects are being investigated within the so called CRYOPLANE project. This project is carried out within the 5th framework program of the European Union and the section '*Flight Mechanics and Propulsion*' of the Department of Aerospace Engineering of Delft University of Technology is one of the participants, responsible for the design process.

An advantage of a cryogenic, very low temperature fuel is the increment of the thermodynamic efficiency of the gas turbine cycle that could be obtained. Also problems of fuel/air mixing and the formation of particles are avoided because the fuel is gaseous immediately prior to combustion (ref. 13). Ref. 13 expects a 5-10% reduction in thrust specific fuel consumption and a weight reduction from LH_2. This weight reduction has been estimated to be 24% for a Boeing 747. An overall 10-20% payload specific fuel consumption reduction is expected from LH_2 fuelled aircraft.

4.3 Liquefied natural gas

According to ref. 11, the use of Liquefied Natural Gas (LNG), which consists of 80-90% methane (ref. 20), as an aircraft fuel would reduce CO_2 emission by 20%. Other C_xO_y gasses and soot particles could be reduced by 50-80%, while H_2O emission would increase slightly. Development risks are high and the technology is not expected before 2015. According to ref. 14, the use of LNG offers better possibilities to reduce NO_x emission than kerosene and LH_2.

LNG offers the same advantages as mentioned for LH_2. A 5-10% TSFC is expected from the use of liquid methane (ref. 13). No weight advantage is expected. According to ref. 20, LNG requires 50% more space in aircraft than kerosene. Therefore the use of LNG requires large aircraft modifications and may therefore not be viable within the next few decades (ref. 42). The infrastructure for distribution of LNG is already largely in place. Airports however would require adjustments.

4.4 Alternative kerosene

There are several sources to produce alternative kerosene:

- Synthesis of natural gas or coal: Synker;
- Processing of biomass:
  - HTU and HDO processes;
  - Gassification and Fischer-Tropsch synthesis.

4.4.1 Synker

Synker is kerosene synthesized from natural gas or coal (ref. 20). The main argument for *Synker* would be economic, because it does not require a whole new infrastructure. Since the emission improvements are small, it should be considered an alternative in case kerosene extracted form oil becomes scarce.

4.4.2 Kerosene from biomass

Kerosene can be produced from biomass via two processes:

- HTU and HDO processes;
- Gassification and Fischer-Tropsch synthesis.

Both processes are described in more detail in ref. 40. The cost of biomass-based kerosene resulting from these processes is approximately:

- HTU and HDO processes: 300 euro/ton;
- Gassification and Fischer-Tropsch synthesis: 450 euro/ton.

The fuel charge that would make the use of biomass-based kerosene economically viable is easy to establish by comparing the cost per ton biomass-based kerosene to the cost per ton conventional kerosene. No price for conventional kerosene is mentioned here however, since this price is subject to significant fluctuations. More details regarding the cost analysis of biomass-based kerosene can also be found in ref. 40.

A summary of the data found for alternative fuels can be found on the next page.

4.5 Summary alternative fuels

Table 12 lists the alternative fuels and their implications found in the literature studied. Because of the uncertainty with respect to cost effects of the application of LH_2 and LNG and the large aircraft modifications connected to the application of these fuels, the use of LH_2 and LNG has not been evaluated in the APD model. The fuel charge that would make the use of biomass-based kerosene economically viable is easy to establish by comparing the cost per ton biomass-based kerosene to the cost per ton conventional kerosene.

Table 12 Effects of alternative fuels

ef. (year)	***Available***	***Fuel Improvement***	***Unit***	***NO_x effect***	***CO_2 reduction***	***Engine price effect***
Liquid hydrogen						
11 (1997)	2015	-	-	Similar to kerosene	100%	-
2 (1997)	-	-	-	0%	100%	-
13 (1994)	2010	5 - 10%	TSFC	-	100%	0%
	2010	10 - 20%	PSFC	-	100%	
Liquefied natural gas						
11 (1997)	2015	-	-	Similar to kerosene	20%	-
13 (1994)	-	5 - 10%	TSFC	-	-	0%
20 (1997)	-	-	-	30 – 40%	-	-
Alternative kerosene						***Fuel price***
20 (1997) (Synker)	-	-	-	-	Small	-
40 (1999) Biomass HTU	-	-	-	-	100%	300 euro/ton
Biomass Fi.-Tr.	-	-	-	-	100%	450 euro/ton

5 Conclusions

- Technical developments that could lead to future reduction of aircraft gas emissions CO_2, H_2O and NO_x have been described. CO_2 and H_2O will be reduced by the reduction of fuel consumption. Emission of NO_x can be reduced by all non-propulsion technologies to reduce fuel consumption and by the application of new combustion chamber technologies. Also some of the new engine technologies, i.e. the use of propfans, will reduce the emission of NO_x as well. The information has been gathered from a scan of available literature;
- As much as possible data have been gathered for the different technologies regarding the effects of these technologies on fuel consumption or CO_2 / NO_x emission, aircraft weight, purchase costs and maintenance costs;
- For the most promising technologies with respect to the reduction of fuel consumption input data have been established for the analysis of the effect of fuel charges on aircraft design. This analysis is carried out using the so-called APD model, an aircraft design model developed by *Peeters Advies* in Ede, the Netherlands. The input parameters for this model for a certain technology mainly concern the effects of the technologies on fuel consumption, aircraft weight, purchase costs and maintenance costs;
- The technologies with respect to the reduction of fuel consumption for which input parameters for the APD model have been established are propfans, ducted ultra-high bypass ratio engines, aerodynamic features and lightweight materials. When a new technology is expected to be introduced in the future, the development of conventional turbofans through time is taken into account for the baseline aircraft. Aircraft with conventional turbofans at a 2010 technology level are used as a baseline to which aircraft on which new technologies are applied can be compared;
- Several combustion chamber technologies offer prospects for NO_x reduction. Most of these technologies aim to reduce NO_x emission by the application of a leaner fuel/air ratio, because this reduces the temperature in the combustion chamber and therefore the emission of NO_x. Two of the most promising technologies with respect to the reduction of NO_x emission are *lean premixed prevaporised combustion* and *rich burn quick quench lean burn combustion*. For these technologies NO_x reductions up to 90% are claimed. No technologies with respect to NO_x reduction have been evaluated in the APD model however due to:
  - Insufficient data regarding weight and cost effects of NO_x reducing technologies;
  - Insufficient data regarding NO_x reduction in different flight phases;
  - Complexity of NO_x emission calculation of complete flight;
  - Complexity of NO_x emission charge implementation.
- The cryogenic fuels liquid hydrogen and liquid natural gas could reduce CO_2 emission by respectively 100% and 20%. H_2O emission however would increase. The fact that application of these fuels requires large aircraft modifications may complicate the wide-scale introduction of these fuels in the near future. At the moment this topic is being investigated within the 5^{th} framework program of the European Union in a project called CRYOPLANE. Biomass-based kerosene also has a large fa-

vorable effect on CO_2 emission, because the emitted CO_2 is part of a closed cycle. Biomass-based kerosene produced by the HTU/HDO process results in a price for the biomass-based kerosene of approximately 300 euro per ton. The process applying gassification and Fischer-Tropsch synthesis results in a price for the biomass-based kerosene of approximately 450 euro per ton. Because of the uncertainty with respect to cost effects of the application of LH_2 and LNG and the large aircraft modifications connected to the application of these fuels, the use of LH_2 and LNG has not been evaluated in the APD model. The fuel charge that would make the use of biomass-based kerosene economically viable is easy to establish by comparing the cost per ton biomass-based kerosene to the cost per ton conventional kerosene. No price for conventional kerosene is mentioned here, since this price is subject to significant fluctuations.

With regard to these conclusions it is interesting to mention the report on the NASA Environmental Compatibility Workshops (lit. 45). During the workshops issues regarding noise as well as emissions were discussed.

At the first workshop it was recommended that in order to minimize global climate change, efforts to improve fuel efficiency to its practicable and feasible limits should be undertaken. With respect to emissions, the following paragraph from the first workshop is quoted:

“The Emissions Breakout Group also identified a number of issues that needed to be addressed. First among these was the need to improve the understanding of atmospheric chemistry and modeling techniques. It was also mentioned that current levels of basic scientific knowledge regarding cause and effect were insufficient for understanding the effectiveness of the various technical fixes. (…) The application of a systems approach to analyze the benefits of new technologies, operational improvements and procedural changes was also noted.”

These thoughts underline the arguments given above not to evaluate NO_x reducing technologies with the APD Model. The above mentioned Emissions Group also believed that it was important to look beyond fossil fuels for long-term solutions. Another interesting remark with respect to the analysis that has been carried out during this study is the following:

“The Emissions Group also emphasized the need to consider affordability and economic feasibility in evaluating technology options”

This is, to a certain extent, just what has been done in this study. In a way, the APD model is an instrument to evaluate the aspects mentioned above. In this study only fuel-efficiency improving technologies have been evaluated but it would be possible to expand the capabilities of this model in order to investigate other technologies. However, this also depends on the availability of certain input data.

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ESCAPE

Economic SCreening of Aircraft Preventing Emissions

Annex IV: Operational Use
in an Airline's Network

DELFT AEROSPACE
FACULTY OF AEROSPACE ENGINEERING

Preface

This report is part of the study called ESCAPE i.e. Economic Screening of Aircraft Preventing Emissions. This study is carried out by three parties, namely Peeters Advies, Centre for Energy Conservation and Environmental Technology (CE) and the section Flight Mechanics and Propulsion of the Department of Aerospace Engineering of Delft University of Technology.

This report is annex 4 and describes a limited investigation on the use of some of the aircraft that were defined by Peeters Advies in this study. Earlier in this study, these aircraft designs have been evaluated in terms of direct operating costs (DOC) for a specific mission which is described extensively in annex 1.
This didn’t however make directly clear how these aircraft would be used by airlines on their network. Therefore this investigation which makes use of an existing piece of software, that was developed at the section of Flight Mechanics and Propulsion in 1989, was carried out. This software consists of a so-called Airline System Simulation Program and is developed to find the optimal flight schedule of a number of different aircraft designs or types on a hub and spoke airline network in such a way that the net earnings are maximised.

Contents

1 Introduction

This report describes a limited investigation on the use of aircraft that are designed more environmentally friendly. The deployment of a number of aircraft that were defined in annex 1, on a hub and spoke airline network will be investigated.

This will be done by using an existing piece of software that has been developed at the section Flight Mechanics and Propulsion [ref.1]. The software is referred to as the Airline System Simulation Program (ASSP) and this program uses the mathematical technique of dynamic programming in order to solve a given resource allocation problem. In this case the problem is to find the optimal distribution of a number of different aircraft designs or types on a hub and spoke network such that the total net earnings are maximised.

This report is built up as follows. First some more general information is given. After that a more detailed description of the resource allocation problem is given. Then the DOC model will be described that is incorporated in the ASSP program since this model will be adjusted in order to use the same model that is used in the so-called APD model that was set up by Peeters Advies [ref.2]. After that the results of the calculations will be described and the conclusions are presented. Appendix A contains the characteristics of the designs that are considered in this investigation. An outline of the output tables that the ASSP program generates are included in appendix B.

2 General information

The introduction of new aircraft into an airline system causes several changes in the overall operation of an airline network. These changes can be analysed with an airline operations simulation program in order to evaluate the influence of such new aircraft to the airline's fleet composition and operating scheme. Such a program also provides a tool to help airlines in the selection of the most profitable aircraft types on each route, as well as to establish the optimum flight assignments on these routes.

The following quote from the summary of the ASSP program description [ref.1] further illustrates how such a tool can be used in the present study:

> "Airlines must make decisions concerning fleet compositions and flight assignments in the consideration of earnings, competition and growth. Manufacturers must make decisions years in advance concerning the size of the market and the price of its aircraft.
> Development of an airline system simulation program was performed to support the airlines and aircraft manufacturers in making these decisions."

The above mentioned are just the topics that are interesting with respect to this particular study. In the first part of this study a number of technologies that reduce fuel consumption (see annex 3) have been investigated. These technologies have been adopted to a baseline aircraft for both the short and long haul market. In this way a number of different aircraft have been defined. Each of these designs has been evaluated in terms of direct operating cost for a specific mission. However this doesn't make directly clear how these aircraft will be used by airlines on their network. Therefore this limited investigation with the already earlier mentioned ASSP program has been set up. This program makes it possible to evaluate how different aircraft are deployed on a hub and spoke network. Because the program is based on this particular type of network it is only possible to look at the aircraft that have been defined for the short haul market.

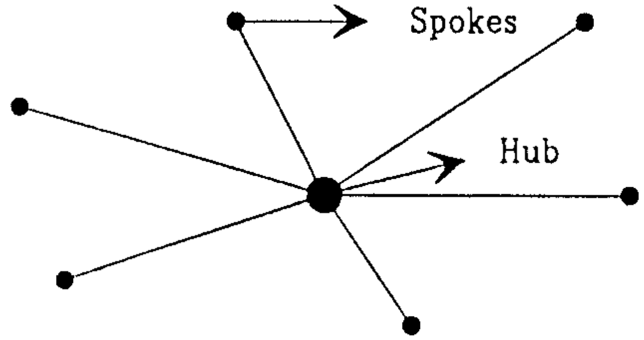
The hub-spoke network (figure 1) that is considered consists of 8 nodes, which are all linked to the hub through non-stop routes with varying stage lengths of up to 1,500 km. The network is build up out of the following city connections:

Hub:
Amsterdam - Netherlands;

Feeders:
- London-Heathrow - England (EGLL);
- Paris/Ch. de Gaulle - France (LFPG);
- Brussels - Belgium (EBBR);
- Rome/Fiumicino - Italy (LIRF);
- Frankfurt - Germany (EDDF);
- Madrid/Baragas - Spain (LEMD);
- Trollhattan - Sweden (ESGT).

Data concerning the several airports, such as runway lengths and ticket-prices are entered as input parameters. The aircraft types operating on the network shall be selected from the aircraft designs that have been made by Peeters Advies. The major characteristics of these aircraft, such as operational weights, payload-range capability and performance parameters shall also be introduced as input parameters to the program. Taking the total net earnings as a measure of effectiveness, the program provides a 24-hour simulation, considering the given demand-for-travel. The airline operations, such as load factors, direct operating costs and return-on-investment are part of the output.

Figure 1 Hub-spoke network



From the aircraft that were defined in the underlying study only four short haul designs (one baseline, two new 'kerosene' concepts and one new 'fuel cell' concept) have been chosen to be used as input for the ASSP program. Initially, only the baseline aircraft and the two kerosene concepts were incorporated; additional calculations have been carried out using the fuel cell concept as well.

Aircraft **M-PROP150** is designed according to a low cost philosophy, which results in a design with less stringent performance requirements. From this point of view and by using the results of the previous part of this study a choice for a design with a high aspect ratio equipped with high-speed propellers has been made. This aircraft flies at about 15% lower speed than conventional turbofan aircraft.
Aircraft **U-FAN150** is designed according to a high cost philosophy, which results in a high-performance design. This is usually the trend that has been followed in aviation industry. In that case an aircraft equipped with Ultra High Bypass ratio turbofans will be designed.
The **F-CELL150** design takes the expected progress in fuel cell development into account.

The ASSP program uses certain characteristics of each aircraft, such as payloads, aircraft weights and blockfuel parameters as input. The corresponding numbers have been collected or determined by Peeters Advies (see appendix A).

The ASSP program is used to select the most favourable aircraft type from the aircraft types that are made available thereby fitting those aircraft in a flight schedule such that the total earnings are maximised. In order to solve the problem of finding the most optimal route out of a number of available routes the mathematical technique of *dynamic programming* is used.

3 Problem analysis

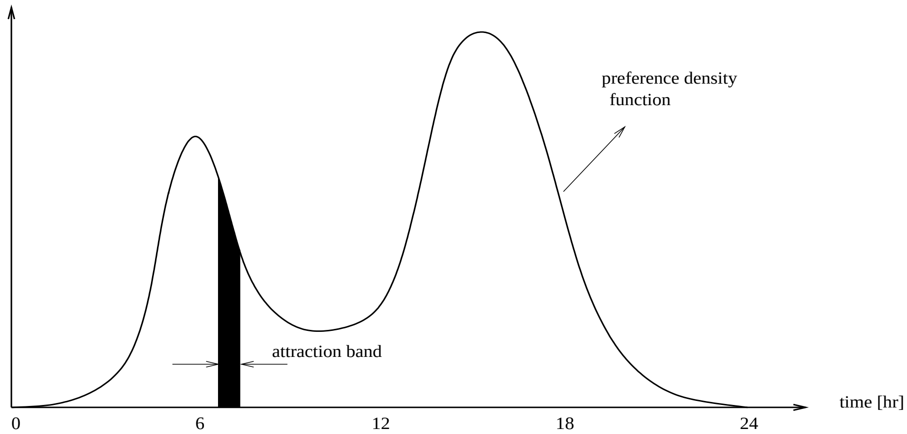
The following description has mainly been taken from the report '*Development of an Airline Systems Simulation Program*' [ref.1]. As was already mentioned in the above introduction the problem that has to be solved is that of choosing a collection of aircraft from a number of available aircraft types, and then schedule each of them so that the aircraft-schedule combinations maximise a specified criterion, here the total net earnings.

One way to solve this problem is to enumerate all possible combinations of aircraft with their respective schedules and then pick out the best. However, this leads to a so-called 'combinatorial explosion' which increases calculation times when number of routes and aircraft increase. That is the reason that the ASSP program is based upon deterministic methods of operations research only. The overall problem can be divided into several subproblems, namely:

1 *A passenger problem*:
In order to schedule a certain aircraft in a way it produces the largest amount of profit, the operator needs to have information about the distribution of demand over the 24 hour scheduling period that is considered here. Therefore a mathematical model is used to predict the number of passengers boarding a certain aircraft at a given time. When the amount of passengers is known it is possible to predict the income of a certain flight.
In general passenger prediction is not so easy because when calculating the number of passengers served, one evaluates competitive differences in passenger preference. Some of the parameters that influence passenger behaviour are:

- flight frequency;
- departure and/or arrival times;
- blocktime: experience has shown that passengers have a strong preference for fast service ;
- comfort level;
- fare: low fares are preferred, even at some sacrifice in seat spacing (except for the business travel market).

Figure 2 Combined route preference density function



In this program the model used by the Lockheed-California Company is implemented. This model uses a 'combined route preference density function', an attraction band with variable wide and the total demand over 24 hours. This model is shown in figure 2.
The number of passengers at a certain time *t* is determined by integration of the density function over the attraction band and multiplication by the total demand. It is remarked that by using this passenger model only the preference with respect to departure times is modelled.

2 *An operating cost problem*: In order to calculate the net earnings of a combination of flights the total amount of operating cost has to be determined. These are not only direct operating costs but also the indirect operating costs. The original ASSP model contained its own DOC model based on information by Fokker. This DOC model has however been adjusted in order to model direct operating costs in the same way as has been done in the ADP model. This will be described in the following chapter.

3 *A performance-operational problem*:
Because every aircraft has performance and range limitations, it is not always possible for every aircraft to fly each route with full payload capacity. Therefore these limitations have to be considered within the program. The aircraft data that is used to check these limitations is part of the input of the program (see appendix A).

4 *The network evaluation problem*:
When the subproblems described above are solved, the hub-spoke network can be evaluated. Predicting the number and choice of aircraft with their respective schedules will then be the final problem. The solution to this problem will cause the objective function, i.e. total net earnings to be maximised as accurate as possible.

4 DOC Model

The ASSP model incorporates its own DOC model. The figures and relations used in this model are however different from those that were used for the DOC calculations that have been done with the APD model earlier in this study. In order to make a fair comparison possible the DOC model that is standard available in the ASSP model has been compared and where needed adjustments have been made in order to match the DOC model used in the APD model. This will be described in this section. First the relevant aspects of the DOC model of the ASSP program will be described shortly and thereafter the changes made to this model will be discussed.

4.1 Utilisation

The ASSP DOC model uses a different utilisation estimate for turbofan and propeller aircraft. For turbofan aircraft the utilisation is determined as a function of range and blocktime. When range and blocktime that were determined for the short haul mission are substituted in this relation a utilisation of 3,267 hours is found. This is nearly the same as the annual utilisation of 3,300 hours that was used when evaluating the aircraft designs earlier with the APD model earlier in this study.
The utilisation estimate for propeller aircraft is a function of blocktime only. When this relation is used a much lower estimate for the utilisation of the aircraft is found. In the present study it is assumed that both new designs have the same annual utilisation. Therefore two kinds of calculations will be done; first when a different utilisation estimate is used for the two designs and second when utilisation is determined in the same manner for both types.

4.2 Depreciation

Deprecation costs per annum are equal to the total investment (aircraft and spares) minus residual value spread over the depreciation period. The DOC model of the ASSP program assumes a deprecation period of 15 years where the value of the aircraft falls to a residual value of 10%. Spares are supposed to represent an extra investment of 15% of the aircraft price.
In the present study depreciation costs have been determined according to Roskam (1989, Part VIII) where the total depreciation costs are build up out of two parts namely one for airframe and one for engine. In formula:
where:

$$DOC_{dep} = T_{block}\,(DF_{af}\,\frac{\Pr_{af}}{DP_{af}U_{ann.bl}} + DF_{eng}\,\frac{2\Pr_{eng}}{DP_{eng}U_{ann.bl}})$$

- T_{block} block time [hr];
- DF depreciation factor;
- DP depreciation period. 15 years for the airframe and 7 years for the engines;
- Pr market price [$];
- $U_{ann.\,bl}$ annual utilisation in block hours.

4.3 Insurance and finance

In the ASSP model interest cost and insurance costs are determined as a function of aircraft price and utilisation. In the present study the costs for finance and insurance is given as a fraction of the sum of fuel, crew, maintenance and deprecation costs. For insurance a percentage of 1% is used and for finance a percentage of 5% is used.

4.4 Crew costs

These costs are to a large degree dependent on the individual airline. In the ASSP model some numbers are given for the labour cost of cockpit and cabin crew. These numbers will be replaced by the numbers used in by the APD model. These are the following numbers and represent the costs per block hour. Different labour cost are applied for both new designs.

Table 1 Labour cost for flight and cabin crew

Employee	Turbofan	High speed propellers
Captain	331	307
First officer	216	200
Cabin attendant	108	99

In the ASSP model the number of attendants depends on whether the aircraft is a turbojet or high-speed propeller aircraft. Here the same number of attendants will be assumed for the baseline design and high-speed propeller design. This means a number of 5 attendants. The cockpit crew consists of two persons.

4.5 Fuel costs

These costs are determined by multiplying fuel price, which is an input parameter of the model, and blockfuel. The APD model also adds 5 % to the total fuel cost for oil.

4.6 Maintenance costs

These costs are divided into costs related to labour and material and are determined for airframe and engine separately. The relations used in the ASSP program use flightcycle and flighttime dependent parameters.
Maintenance costs in the APD model have been calculated according to Roskam (1989, part VIII). This method makes a distinction between labour cost and material cost for both airframe and engine. The maintenance man-hour per block hour for airframe and engine are given by the following equations:

$$MHR_{af.bl} = 3.0 + 0.1467 \frac{W_{af}}{1000}$$

$$MHR_{eng.bl} = (0.718 + 0.0698 \frac{T_{MAX}}{1000})(\frac{1100}{t_{BEO}} + 0.1)$$

where:

- W_{af} airframe weight [kg];
- T_{MAX} maximum take-off thrust per engine [kgf or hp];
- t_{BEO} time between overhaul in flight hours.

Maintenance material cost is given by the following relations ($/block hour):

$$C_{mat.af.bl} = 30 + 0.79 \cdot 10^{-5}\ \mathrm{Pr}_{af}$$

$$C_{mat.eng.bl} = (5.43 \cdot 10^{-5}\ \mathrm{Pr}_{eng}\ ASPPF - 0.47)\frac{1}{0.021\dfrac{t_{BEO}}{100} + 0.769}$$

where:

- Pr_{af} airframe market price [$];
- Pr_{eng} engine market price [$];
- ESPPF engine spare part price policy factor.

The total DOC for maintenance [$] is determined by calculating the parameters for man-hours and material cost as given above and substituting those into the following relation:

$$DOC_{maint} = 0.53T_{block}[Pc_{maint}(MHR_{af.bl} + 1.3n_{eng}MHR_{eng.bl})]$$

where n_{eng} denotes the number of engines and Pc_{maint} is the hourly labour rate [$/hr]. In this equation a factor *Ca* is used on man-hours for the airframe and a factor *Ce* for both man-hours and material cost for the engine. The values of the factors depend on the aircraft design that is being considered.

In the ASSP model it is assumed that the actual labour cost are 100% higher due to maintenance burden. This is not incorporated in the APD model.

4.7 User charges

The landing fee depends linearly on the maximum take-off weight of the aircraft and is set to $ 5.50 per ton weight in the ASSP model. Here a landing fee of $ 30.0 per ton weight will be used.
The ASSP model also uses a navigation charge and ground handling costs. These costs will be set equal to zero in this case since it seems that these costs have been incorporated into the landing fee.

5 Results

First some calculations have been done with the original ASSP program in order to check the program. After that, the DOC model described in the previous section has been implemented in the program and calculations have been performed for two fuel prices, i.e. $0.27 and $1.00 per kg. First, calculations have been done for a different utilisation estimate and then for the same utilisation estimate for turbofan and high- speed propeller aircraft. The first idea was to consider the baseline and new designs only but the design with fuel cell technology has also been incorporated later on. For this design fuel price is 2.8 times as high in order to account for the use of another fuel. These results will be described in the following sections.

5.1 Test results

Calculations have been made for a fuel price of $0.27/kg and $1.00/kg. First, calculations have been done with the original ASSP program. This meant that a different DOC model is used than the DOC model that is used for the APD model. Therefore the only purpose of this calculation is to check if the program functions properly. From the output of the calculations it can be concluded that the program works properly. The results show that the BASELINE aircraft isn't selected which is rather sensible since it's the most fuel inefficient aircraft.

In the $0.27/kg fuel price case 15 aircraft, 10 high-speed propeller and 5 turbofan aircraft, are sold. When a higher fuel price is in effect a total number of 13 aircraft, 12 high-speed propeller and 1 turbofan aircraft, are sold. The shift that occurs is easy to understand since the high-speed propeller design is more fuel-efficient and thus becomes more cost-effective when fuel prices become higher. This result was as expected.

When fuel price becomes higher it can be seen that less aircraft are sold, that is 13 instead of 15, which means that the aircraft are used somewhat more efficiently. The average load factor increases from 0.55 to 0.59.

5.2 Final results

This section describes the final results that have been obtained after adjusting the modelling of direct operating cost (DOC) in the ASSP program. A number of adjustments have been made, which were already discussed in the previous section, that resulted in the same DOC model that was used in the APD model.

It can be seen that the baseline aircraft design will not be employed on the hub-spoke network (see appendix B). This aircraft has nearly the same block times on the various routes as the new turbofan design but is more expensive to operate. This is obvious since the latter design is equipped with more fuel-efficient engines so it uses less fuel for the same flight distance.

From the results follows that:

- in the $0.27/kg fuel price case, 14 aircraft, that is 7 high-speed propeller and 7 turbofan aircraft are sold. The average load factor amounts to 0.59.

- in the $1.00/kg fuel price case, a total of 11 aircraft, 10 high-speed propellers and 1 turbofan, are sold. It can be seen that the turbofan design is utilised on one route only, where demand for travel is high. This is because this design can be operated on those routes for about the same cost but blocktimes are smaller; this means that more passengers can be served which increases the net earnings. Average load factor increases to 0.63, which is logical as marginal transport costs increase. So it can be concluded that, when fuel prices increase, less but more fuel efficient aircraft are sold and load factors increase, which will cause an emission reduction at the price of a reduction of service levels offered by the airline.

The estimate for utilisation of both aircraft designs (high-speed propeller and turbofan) is calculated in a different way, since this quantity differs for high-speed propeller and turbofan aircraft. It can be stated that if high-speed propeller aircraft are being developed one should make a considerable effort in improving the utilisation of those aircraft when they enter into service. This can be shown by using the same relation for calculating utilisation estimate for turbofan aircraft as well as high-speed propeller aircraft.
When this adjustment is made to the ASSP program it follows that:

- in the $0.27/kg fuel price case a total of 12 aircraft, 9 high-speed propellers and 3 turbofan, are sold. The average load factor equals 0.60.
- in the $1.00/kg fuel price case, a total of 11 aircraft, 10 high-speed propeller and 1 turbofan, are sold. The average load factor amounts to 0.63. It must be remarked here that in reality an airline prefers to operate more than one aircraft of a certain type.

When the fuel cell design is made available to the program the results for a low fuel price do not change. For a high fuel price a total number of 10 aircraft are sold, i.e. 3 high-speed propeller and 7 fuel cell aircraft. The average load factor increases to 0.64.

The above results, obtained with the ASSP program, clearly show that more environmentally friendly aircraft could be favourable for the total net earnings of an airline. Their economic advantages increase when fuel prices rise. It can be seen that an airline should buy and utilise those environmentally aircraft, such as a new designed high speed propeller aircraft or an aircraft with fuel cell technology, in order to maximise their total net earnings.
It can also be seen that the DOC model incorporated in the program influences the results. When the utilisation estimate for high speed propeller aircraft is changed it can be seen that even at a low fuel price the usage of such aircraft is already more favourable than turbofan aircraft. However, at higher fuel prices this effect does not appear to be present. This can be explained by the fact that at higher fuel prices utilisation of the aircraft decreases anyway. This conclusion can be drawn from the test results as well as the final results i.e. when fuel price increases less aircraft are sold. This leads to a decreasing service that the airline offers on its network i.e. flight frequency decreases, which means less people will be served.

References

1 Rubbrecht, Philippe, Development of an Airline System Simulation Program, Delft University of Technology, June 1989, Delft, The Netherlands.

2 Peeters Advies, ESCAPE: Aircraft Design and Performance Results, P.M. Peeters, Ede, January 2000, Ede, The Netherlands.

ESCAPE

Operational Use in an
Aircraft’s Network

Appendices

A Aircraft characteristics

This appendix includes the characteristics of each of the aircraft that have been selected for use with the ASSP program. These numbers have been supplied by Peeters Advies. For use as input some of these numbers have to be adjusted. For example, the aircraft price that is needed as input of the program has to be the price of airframe and engines.

BASE150

Table 2 Characteristics of the 2010 short haul baseline design

Name of the aircraft	BASE150
Class	0
Number of seats	146
Number of cockpit crew	2
Price of new aircraft (excluding engines) [$]	37,800,000
Price of one new engine [$]	2,774,500
Number of engines	2
Thrust from one engine [lbf]	23,493
Aircraft Empty weight [kg]	31,191
OEW [kg]	34,025
MLW [kg]	54,346
MTOW [kg]	61,241
Block fuel parameters (@70% payload):	
Bfa [kg]	856.8
Bfb [km/km]	2.742
Block time parameters (@70% payload):	
Bfa [hr]	0.6111
Bfb [hr/km]	0.001248
Turnaround time [hr]	0.5
TO distance parameters: (SL/ISA, no wind)	
Toda [m]	-1,129
Todb [m/kg]	0.0534
Landing distance parameters (SL/ISA, no wind)	
Lada [m]	509
Ladb [m/kg]	0.0203
Payload range:	
Range @ maximum payload [km]	2,280
Range @ maximum fuel available [km]	5,560
Range @ zero payload [km]	6,170
Maximum payload [kg]	16,691
Payload @ maximum fuel and MTOW [kg]	8,346

Table 3 Characteristics of new design with high-speed propellers

M-PROP150

Name of the aircraft	M-PROP150
Class	1
Number of seats	146
Number of cockpit crew	2
Price of new aircraft (excluding engines) [$]	35,230,000
Price of one new engine [$]	2,792,000
Number of engines	2
Power from one engine [hp]	9,000
Aircraft Empty weight [kg]	30,951
OEW [kg]	33,785
MLW [kg]	54,106
MTOW [kg]	56,201
Block fuel parameters (@ 70% payload):	
Bfa [kg]	423
Bfb [km/km]	1.5226
Block time parameters (@ 70% payload):	
Bfa [hr]	0.6364
Bfb [hr/km]	0.001432
Turnaround time [hr]	0.5
TO distance parameters (SL/ISA, no wind)	
Toda [m]	-1203
Todb [m/kg]	0.0569
Landing distance parameters (SL/ISA, no wind)	
Lada [m]	509
Ladb [m/kg]	.0156
Payload range:	
Range @ maximum payload [km]	2,345
Range @ maximum fuel available [km]	10,498
Range @ zero payload [km]	11,252
Maximum payload [kg]	16,691
Payload @ maximum fuel and MTOW [kg]	5,040

Table 4 Characteristics of new design with ultra high bypass turbofan

U-FAN150

Name of the aircraft	U-FAN150
Class	0
Number of seats	146
Number of cockpit crew	2
Price of new aircraft (excluding engines) [$]	40,508,900
Price of one new engine [$]	2,685,000
Number of engines	2
Power from one engine [lbf]	18,800
Aircraft Empty weight [kg]	25,744
OEW [kg]	28,578
MLW [kg]	48,899
MTOW [kg]	52,532
Block fuel parameters (@ 70% payload):	
Bfa [kg]	600
Bfb [km/km]	1.8945
Block time parameters (@ 70% payload):	
Bfa [hr]	0.6222
Bfb [hr/km]	0.001248
Turnaround time [hr]	0.5
TO distance parameters (SL/ISA, no wind)	
Toda [m]	-1284
Todb [m/kg]	0.06074
Landing distance parameters (SL/ISA, no wind)	
Lada [m]	509.0161
Ladb [m/kg]	0.02312
Payload range:	
Range @ maximum payload [km]	2,217
Range @ maximum fuel available [km]	8,288
Range @ zero payload [km]	9,061
Maximum payload [kg]	16,691
Payload @ maximum fuel and MTOW [kg]	6,176

Table 5 Characteristics of new design with fuel cell technology

F-CELL150

Name of the aircraft	F-CELL150
Class	1
Number of seats	146
Number of cockpit crew	2
Price of new aircraft (excluding engines) [$]	45,109,500
Price of one new engine [$]	1,908,000
Number of engines	2
Power from one engine [hp]	8,196
Aircraft Empty weight [kg]	43,541
OEW [kg]	46,375
MLW [kg]	64,454
MTOW [kg]	64,454
Block fuel parameters (@70% payload):	
Bfa [kg]	37.8
Bfb [km/km]	0.4073
Block time parameters (@70% payload):	
Bfa [hr]	0.659
Bfb [hr/km]	0.001368
Turnaround time [hr]	0.5
TO distance parameters: (SL/ISA, no wind)	-885.1
Toda [m]	0.0419
Todb [m/kg]	
Landing distance parameters (SL/ISA, no wind)	509
Lada [m]	0.0115
Ladb [m/kg]	
Payload range:	
Range @ maximum payload [km]	2,128
Range @ maximum fuel available [km]	5,500
Range @ zero payload [km]	6,482
Maximum payload [kg]	16,691
Payload @ maximum fuel and MTOW [kg]	15,356

B Output of the ASSP program

This appendix gives an example of part of the output of the ASSP program. Here an outline of the output of the calculations where four aircraft types were available is printed for both fuel prices. It is remarked that in these calculations the same utilisation estimate has been used for turbofan and propeller aircraft.

B.1 Output for a fuel price of $0.27/kg

```
--------------------------------------------------

       AIRLINE SYSTEMS SIMULATION PROGRAM

            by Philippe Rubbrecht
              collno. 714392

              (c) maart 1989

--------------------------------------------------


       **** SYSTEM TO BE CONSIDERED ****

Measure of effectiveness = total net earnings

Number of spokes        :  8
Number of aircraft      :  4
Fuel price              : 0.27 $/kg
Labor rate              : 40 $/hr
Maximum load-factor     : 0.80
Max. daily utilization  : 10h 0min
Min. daily utilization  :  6h 0min
Max. yearly utilization : 3500 hrs.
Min. yearly utilization : 2100 hrs.


CITY    RANGE   RUNWAY   PASS(to)  PASS(fro)  FARE

EHAM            3450 m

EGLL    375 km  3900 m    2000       2000     180 $
LFPG    450 km  3600 m    1000       1000     200 $
EBBR    175 km  3560 m     200        200     110 $
LIRF   1350 km  3900 m     300        300     450 $
EDDF    450 km  4590 m     500        500     200 $
LSZH    650 km  3700 m     500        500     250 $
LEMD   1500 km  4100 m     250        250     500 $
ESGT    750 km  1000 m     250        250     275 $


AIRCRAFT        NO.SEATS
```

BASE150	146
M-PROP150	146
U-FAN150	146
F-CELL150	146

AIRCRAFT : BASE150

	BLOCKTIME	DOC+IOC	CAP(to)	CAP(fro)
EHAM-EGLL :	1.08 hr.	10894 $	116	116
EHAM-LFPG :	1.17 hr.	11672 $	116	116
EHAM-EBBR :	0.83 hr.	9059 $	116	116
EHAM-LIRF :	2.30 hr.	19102 $	116	116
EHAM-EDDF :	1.17 hr.	11672 $	116	116
EHAM-LSZH :	1.42 hr.	13323 $	116	116
EHAM-LEMD :	2.48 hr.	21510 $	116	116
EHAM-ESGT :	Runway-length too short.			

AIRCRAFT : M-PROP150

	BLOCKTIME	DOC+IOC	CAP(to)	CAP(fro)
EHAM-EGLL :	1.17 hr.	10086 $	116	116
EHAM-LFPG :	1.28 hr.	10829 $	116	116
EHAM-EBBR :	0.89 hr.	8348 $	116	116
EHAM-LIRF :	2.57 hr.	17880 $	116	116
EHAM-EDDF :	1.28 hr.	10829 $	116	116
EHAM-LSZH :	1.57 hr.	12398 $	116	116
EHAM-LEMD :	2.78 hr.	20168 $	116	116
EHAM-ESGT :	Runway-length too short.			

AIRCRAFT : U-FAN150

	BLOCKTIME	DOC+IOC	CAP(to)	CAP(fro)
EHAM-EGLL :	1.09 hr.	10443 $	116	116
EHAM-LFPG :	1.18 hr.	11229 $	116	116
EHAM-EBBR :	0.84 hr.	8617 $	116	116
EHAM-LIRF :	2.31 hr.	18591 $	116	116
EHAM-EDDF :	1.18 hr.	11229 $	116	116
EHAM-LSZH :	1.43 hr.	12861 $	116	116
EHAM-LEMD :	2.49 hr.	21038 $	116	116
EHAM-ESGT :	Runway-length too short.			

AIRCRAFT : F-CELL150

	BLOCKTIME	DOC+IOC	CAP(to)	CAP(fro)
EHAM-EGLL :	1.17 hr.	10684 $	116	116
EHAM-LFPG :	1.27 hr.	11424 $	116	116
EHAM-EBBR :	0.90 hr.	8936 $	116	116
EHAM-LIRF :	2.51 hr.	18478 $	116	116
EHAM-EDDF :	1.27 hr.	11424 $	116	116
EHAM-LSZH :	1.55 hr.	12990 $	116	116
EHAM-LEMD :	2.71 hr.	20798 $	116	116
EHAM-ESGT :	Runway-length too short.			

Aircraft : BASE150

ROUTE : EHAM-EGLL
and back.

Number attendants : 5
Estimated utilization : 3021 hrs/year
Depreciation costs : 1047 US$
Interest costs : 170 US$
Insurance costs : 34 US$
Flight crew costs : 590 US$
Cabin crew costs : 582 US$
Fuel costs : 508 US$
Maintenance costs : 661 US$
Landing fees : 1830 US$
Navigation charges : 0 US$
Ground handling costs : 0 US$

ROUTE : EHAM-LFPG
and back.

Number attendants : 5
Estimated utilization : 2873 hrs/year
Depreciation costs : 1196 US$
Interest costs : 189 US$
Insurance costs : 37 US$
Flight crew costs : 641 US$
Cabin crew costs : 633 US$
Fuel costs : 564 US$
Maintenance costs : 718 US$
Landing fees : 1830 US$
Navigation charges : 0 US$
Ground handling costs : 0 US$

Aircraft : M-PROP150

ROUTE : EHAM-EGLL
and back.

Number attendants : 5
Estimated utilization : 3285 hrs/year

Depreciation costs : 996 US$
Interest costs : 158 US$
Insurance costs : 31 US$
Flight crew costs : 594 US$
Cabin crew costs : 580 US$
Fuel costs : 268 US$
Maintenance costs : 723 US$
Landing fees : 1680 US$
Navigation charges : 0 US$
Ground handling costs : 0 US$

ROUTE : EHAM-LFPG
and back.

Number attendants : 5
Estimated utilization : 3137 hrs/year
Depreciation costs : 1139 US$
Interest costs : 176 US$
Insurance costs : 35 US$
Flight crew costs : 649 US$
Cabin crew costs : 633 US$
Fuel costs : 299 US$
Maintenance costs : 789 US$
Landing fees : 1680 US$
Navigation charges : 0 US$
Ground handling costs : 0 US$

Aircraft : U-FAN150

ROUTE : EHAM-EGLL
and back.

Number attendants : 5
Estimated utilization : 3052 hrs/year
Depreciation costs : 1092 US$
Interest costs : 172 US$
Insurance costs : 34 US$
Flight crew costs : 596 US$
Cabin crew costs : 588 US$
Fuel costs : 353 US$
Maintenance costs : 809 US$
Landing fees : 1560 US$
Navigation charges : 0 US$
Ground handling costs : 0 US$

ROUTE : EHAM-LSZH
and back.

Number attendants : 5
Estimated utilization : 3010 hrs/year
Depreciation costs : 1456 US$
Interest costs : 229 US$
Insurance costs : 45 US$
Flight crew costs : 784 US$
Cabin crew costs : 774 US$
Fuel costs : 494 US$

Maintenance costs : 1064 US$
Landing fees : 1560 US$
Navigation charges : 0 US$
Ground handling costs : 0 US$

ROUTE : EHAM-LEMD
and back.

Number attendants : 5
Estimated utilization : 2618 hrs/year
Depreciation costs : 2916 US$
Interest costs : 422 US$
Insurance costs : 84 US$
Flight crew costs : 1364 US$
Cabin crew costs : 1346 US$
Fuel costs : 929 US$
Maintenance costs : 1852 US$
Landing fees : 1560 US$
Navigation charges : 0 US$
Ground handling costs : 0 US$

Aircraft : F-CELL150

ROUTE : EHAM-EGLL
and back.

Number attendants : 5
Estimated utilization : 3281 hrs/year
Depreciation costs : 1030 US$
Interest costs : 161 US$
Insurance costs : 32 US$
Flight crew costs : 594 US$
Cabin crew costs : 580 US$
Fuel costs : 143 US$
Maintenance costs : 875 US$
Landing fees : 1920 US$
Navigation charges : 0 US$
Ground handling costs : 0 US$

ROUTE : EHAM-LFPG
and back.

Number attendants : 5
Estimated utilization : 3122 hrs/year
Depreciation costs : 1176 US$
Interest costs : 178 US$
Insurance costs : 35 US$
Flight crew costs : 646 US$
Cabin crew costs : 630 US$
Fuel costs : 167 US$
Maintenance costs : 952 US$
Landing fees : 1920 US$
Navigation charges : 0 US$
Ground handling costs : 0 US$

AIRCRAFT		NO. SOLD	INVESTMENT($/PLANE)
BASE150	:	0	49851348
M-PROP150	:	9	46936099
U-FAN150	:	3	52760733
F-CELL150	:	0	51875923

ROUTE : EHAM-EGLL

FREQUENCY = 18

DEPARTURE	ARRIVAL	PASS.	LOAD-FACTOR	AIRCRAFT	AIRCRAFT NO.
4h54	6h 0	1	0.01	U-FAN150	6
5h42	6h54	0	0.00	M-PROP150	9
6h18	7h30	111	0.76	M-PROP150	1
7h12	8h18	116	0.79	U-FAN150	3
8h18	9h30	93	0.64	M-PROP150	5
9h18	10h30	116	0.79	M-PROP150	4
9h42	10h54	116	0.79	M-PROP150	1
11h12	12h24	116	0.79	M-PROP150	2
11h24	12h30	69	0.47	U-FAN150	7
13h 6	14h18	116	0.79	M-PROP150	1
14h48	16h 0	64	0.44	M-PROP150	4
15h36	16h48	116	0.79	M-PROP150	2
16h12	17h24	116	0.79	M-PROP150	5
16h54	18h 6	116	0.79	M-PROP150	10
17h42	18h48	116	0.79	U-FAN150	7
18h12	19h24	116	0.79	M-PROP150	4
19h 0	20h12	116	0.79	M-PROP150	2
20h36	21h42	116	0.79	U-FAN150	6

ROUTE : EGLL-EHAM

FREQUENCY = 18

DEPARTURE	ARRIVAL	PASS.	LOAD-FACTOR	AIRCRAFT	AIRCRAFT NO.
6h36	7h42	116	0.79	U-FAN150	6
7h24	8h36	49	0.34	M-PROP150	9
8h 0	9h12	116	0.79	M-PROP150	1
8h48	9h54	116	0.79	U-FAN150	3
10h 0	11h12	109	0.75	M-PROP150	5
11h 0	12h12	116	0.79	M-PROP150	4
11h24	12h36	116	0.79	M-PROP150	1
12h54	14h 6	116	0.79	M-PROP150	2
14h48	16h 0	116	0.79	M-PROP150	1
16h 6	17h12	89	0.61	U-FAN150	7
16h30	17h42	116	0.79	M-PROP150	4
17h18	18h30	116	0.79	M-PROP150	2
17h54	19h 6	116	0.79	M-PROP150	5

18h36	19h48	116	0.79	M-PROP150	10
19h18	20h24	116	0.79	U-FAN150	7
19h54	21h 6	116	0.79	M-PROP150	4
20h42	21h54	116	0.79	M-PROP150	2
22h12	23h18	2	0.01	U-FAN150	6

ROUTE : EHAM-LFPG

FREQUENCY = 9

DEPARTURE	ARRIVAL	PASS.	LOAD-FACTOR	AIRCRAFT	AIRCRAFT NO.
5h42	7h 0	26	0.18	M-PROP150	4
7h36	8h54	116	0.79	M-PROP150	2
8h24	9h42	80	0.55	M-PROP150	8
10h24	11h36	116	0.79	U-FAN150	3
12h18	13h36	80	0.55	M-PROP150	5
14h18	15h30	67	0.46	U-FAN150	3
16h30	17h48	116	0.79	M-PROP150	1
17h42	18h54	116	0.79	U-FAN150	3
19h36	20h54	116	0.79	M-PROP150	5

ROUTE : LFPG-EHAM

FREQUENCY = 9

DEPARTURE	ARRIVAL	PASS.	LOAD-FACTOR	AIRCRAFT	AIRCRAFT NO.
7h30	8h48	115	0.79	M-PROP150	4
9h24	10h42	116	0.79	M-PROP150	2
10h12	11h30	66	0.45	M-PROP150	8
12h 6	13h18	89	0.61	U-FAN150	3
14h 6	15h24	64	0.44	M-PROP150	5
16h 0	17h12	113	0.77	U-FAN150	3
18h18	19h36	116	0.79	M-PROP150	1
19h24	20h36	112	0.77	U-FAN150	3
21h24	22h42	29	0.20	M-PROP150	5

AIRCRAFT NO. 1 : M-PROP150

AIRCRAFT		TOTAL PROFIT	UTILIZATION
BASE150	:	79888 US$	3080 hr
M-PROP150	:	88606 US$	3430 hr
U-FAN150	:	83496 US$	3080 hr
F-CELL150	:	83828 US$	3430 hr

NET EARNINGS : 88606 $
INVESTMENT : 46936099 $

RETURN ON INVESTMENT : 0.56634
UTILIZATION : 3430 hrs.

DEPARTURE	ROUTE	ARRIVAL	PASS.	LOAD-FACTOR	EARNINGS
6h18	EHAM-EGLL	7h30	111	0.76	9894 $
8h 0	EGLL-EHAM	9h12	116	0.79	10794 $
9h42	EHAM-EGLL	10h54	116	0.79	10794 $
11h24	EGLL-EHAM	12h36	116	0.79	10794 $
13h 6	EHAM-EGLL	14h18	116	0.79	10794 $
14h48	EGLL-EHAM	16h 0	116	0.79	10794 $
16h30	EHAM-LFPG	17h48	116	0.79	12371 $
18h18	LFPG-EHAM	19h36	116	0.79	12371 $

AIRCRAFT NO. 2 : M-PROP150

AIRCRAFT		TOTAL PROFIT	UTILIZATION
BASE150	:	83296 US$	3220 hr
M-PROP150	:	89506 US$	3430 hr
U-FAN150	:	86872 US$	3220 hr
F-CELL150	:	84728 US$	3430 hr

NET EARNINGS : 89506 $
INVESTMENT : 46936099 $
RETURN ON INVESTMENT : 0.57209
UTILIZATION : 3430 hrs.

DEPARTURE	ROUTE	ARRIVAL	PASS.	LOAD-FACTOR	EARNINGS
7h36	EHAM-LFPG	8h54	116	0.79	12371 $
9h24	LFPG-EHAM	10h42	116	0.79	12371 $
11h12	EHAM-EGLL	12h24	116	0.79	10794 $
12h54	EGLL-EHAM	14h 6	116	0.79	10794 $
15h36	EHAM-EGLL	16h48	116	0.79	10794 $
17h18	EGLL-EHAM	18h30	116	0.79	10794 $
19h 0	EHAM-EGLL	20h12	116	0.79	10794 $
20h42	EGLL-EHAM	21h54	116	0.79	10794 $

AIRCRAFT NO. 3 : U-FAN150

AIRCRAFT		TOTAL PROFIT	UTILIZATION
BASE150	:	72540 US$	3290 hr
M-PROP150	:	61872 US$	2660 hr
U-FAN150	:	76100 US$	3290 hr
F-CELL150	:	58296 US$	2660 hr

NET EARNINGS : 76100 $
INVESTMENT : 52760733 $
RETURN ON INVESTMENT : 0.43271
UTILIZATION : 3290 hrs.

DEPARTURE	ROUTE	ARRIVAL	PASS.	LOAD-FACTOR	EARNINGS
7h12	EHAM-EGLL	8h18	116	0.79	10437 $
8h48	EGLL-EHAM	9h54	116	0.79	10437 $
10h24	EHAM-LFPG	11h36	116	0.79	11971 $
12h 6	LFPG-EHAM	13h18	89	0.61	6571 $
14h18	EHAM-LFPG	15h30	67	0.46	2171 $
16h 0	LFPG-EHAM	17h12	113	0.77	11371 $
17h42	EHAM-LFPG	18h54	116	0.79	11971 $
19h24	LFPG-EHAM	20h36	112	0.77	11171 $

TOTAL DEMAND FOR TRAVEL : 10000
PASSENGERS SERVED : 6871
SEATS OFFERED : 11388
AVERAGE LOAD-FACTOR : 0.60
TOTAL NET EARNINGS : 531896 $
TOTAL INVESTMENT : 580707090 $
TOTAL RETURN ON INVESTMENT : 0.32058

----------------- END OF PROGRAM ---------------

B.2 Output for a fuel price of $1.0/kg

AIRLINE SYSTEMS SIMULATION PROGRAM

by Philippe Rubbrecht
collno. 714392

(c) maart 1989

**** SYSTEM TO BE CONSIDERED ****

Measure of effectiveness = total net earnings

Number of spokes : 8
Number of aircraft : 4
Fuel price : 1.00 $/kg
Labor rate : 40 $/hr
Maximum load-factor : 0.80
Max. daily utilization : 10h 0min
Min. daily utilization : 6h 0min
Max. yearly utilization : 3500 hrs.
Min. yearly utilization : 2100 hrs.

CITY	RANGE	RUNWAY	PASS(to)	PASS(fro)	FARE
EHAM		3450 m			
EGLL	375 km	3900 m	2000	2000	180 $
LFPG	450 km	3600 m	1000	1000	200 $
EBBR	175 km	3560 m	200	200	110 $
LIRF	1350 km	3900 m	300	300	450 $
EDDF	450 km	4590 m	500	500	200 $
LSZH	650 km	3700 m	500	500	250 $
LEMD	1500 km	4100 m	250	250	500 $
ESGT	750 km	1000 m	250	250	275 $

AIRCRAFT	NO.SEATS
BASE150	146
M-PROP150	146
U-FAN150	146
F-CELL150	146

AIRCRAFT : BASE150

BLOCKTIME DOC+IOC CAP(to) CAP(fro)

EHAM-EGLL :	1.08 hr.	13956 $	116	116
EHAM-LFPG :	1.17 hr.	15066 $	116	116
EHAM-EBBR :	0.83 hr.	11229 $	116	116
EHAM-LIRF :	2.30 hr.	26507 $	116	116
EHAM-EDDF :	1.17 hr.	15066 $	116	116
EHAM-LSZH :	1.42 hr.	17611 $	116	116
EHAM-LEMD :	2.48 hr.	29584 $	116	116
EHAM-ESGT :	Runway-length too short.			

AIRCRAFT : M-PROP150

	BLOCKTIME	DOC+IOC	CAP(to)	CAP(fro)
EHAM-EGLL :	1.17 hr.	11701 $	116	116
EHAM-LFPG :	1.28 hr.	12628 $	116	116
EHAM-EBBR :	0.89 hr.	9468 $	116	116
EHAM-LIRF :	2.57 hr.	21907 $	116	116
EHAM-EDDF :	1.28 hr.	12628 $	116	116
EHAM-LSZH :	1.57 hr.	14693 $	116	116
EHAM-LEMD :	2.78 hr.	24568 $	116	116
EHAM-ESGT :	Runway-length too short.			

AIRCRAFT : U-FAN150

	BLOCKTIME	DOC+IOC	CAP(to)	CAP(fro)
EHAM-EGLL :	1.09 hr.	12574 $	116	116
EHAM-LFPG :	1.18 hr.	13587 $	116	116
EHAM-EBBR :	0.84 hr.	10133 $	116	116
EHAM-LIRF :	2.31 hr.	23723 $	116	116
EHAM-EDDF :	1.18 hr.	13587 $	116	116
EHAM-LSZH :	1.43 hr.	15839 $	116	116
EHAM-LEMD :	2.49 hr.	26630 $	116	116
EHAM-ESGT :	Runway-length too short.			

AIRCRAFT : F-CELL150

	BLOCKTIME	DOC+IOC	CAP(to)	CAP(fro)
EHAM-EGLL :	1.17 hr.	11547 $	116	116
EHAM-LFPG :	1.27 hr.	12429 $	116	116
EHAM-EBBR :	0.90 hr.	9430 $	116	116
EHAM-LIRF :	2.51 hr.	21148 $	116	116
EHAM-EDDF :	1.27 hr.	12429 $	116	116
EHAM-LSZH :	1.55 hr.	14364 $	116	116
EHAM-LEMD :	2.71 hr.	23747 $	116	116
EHAM-ESGT :	Runway-length too short.			

Aircraft : BASE150

ROUTE : EHAM-EGLL
and back.

Number attendants : 5
Estimated utilization : 3021 hrs/year
Depreciation costs : 1047 US$
Interest costs : 242 US$
Insurance costs : 48 US$
Flight crew costs : 590 US$
Cabin crew costs : 582 US$
Fuel costs : 1884 US$
Maintenance costs : 661 US$
Landing fees : 1830 US$
Navigation charges : 0 US$
Ground handling costs : 0 US$

Aircraft : M-PROP150

ROUTE : EHAM-EGLL
and back.

Number attendants : 5
Estimated utilization : 3285 hrs/year
Depreciation costs : 996 US$
Interest costs : 196 US$
Insurance costs : 39 US$
Flight crew costs : 594 US$
Cabin crew costs : 580 US$
Fuel costs : 993 US$
Maintenance costs : 723 US$
Landing fees : 1680 US$
Navigation charges : 0 US$
Ground handling costs : 0 US$

Aircraft : U-FAN150

ROUTE : EHAM-EGLL
and back.

Number attendants : 5
Estimated utilization : 3052 hrs/year
Depreciation costs : 1092 US$
Interest costs : 223 US$
Insurance costs : 44 US$
Flight crew costs : 596 US$
Cabin crew costs : 588 US$
Fuel costs : 1310 US$
Maintenance costs : 809 US$
Landing fees : 1560 US$
Navigation charges : 0 US$

Ground handling costs : 0 US$

Aircraft : F-CELL150

ROUTE : EHAM-EGLL
and back.

Number attendants : 5
Estimated utilization : 3281 hrs/year
Depreciation costs : 1030 US$
Interest costs : 181 US$
Insurance costs : 36 US$
Flight crew costs : 594 US$
Cabin crew costs : 580 US$
Fuel costs : 531 US$
Maintenance costs : 875 US$
Landing fees : 1920 US$
Navigation charges : 0 US$
Ground handling costs : 0 US$

AIRCRAFT		NO. SOLD	INVESTMENT($/PLANE)
BASE150	:	0	49851348
M-PROP150	:	3	46936099
U-FAN150	:	0	52760733
F-CELL150	:	7	51875923

ROUTE : EHAM-EGLL

FREQUENCY = 16

DEPARTURE	ARRIVAL	PASS.	LOAD-FACTOR	AIRCRAFT	AIRCRAFT NO.
4h54	6h 6	1	0.01	M-PROP150	8
6h18	7h30	111	0.76	F-CELL150	2
7h12	8h24	116	0.79	F-CELL150	3
7h48	9h 0	57	0.39	F-CELL150	5
9h12	10h24	116	0.79	F-CELL150	4
9h42	10h54	116	0.79	F-CELL150	2
11h12	12h24	116	0.79	F-CELL150	1
11h12	12h24	86	0.59	F-CELL150	5
13h 6	14h18	110	0.75	F-CELL150	2
14h36	15h48	116	0.79	F-CELL150	1
15h36	16h48	113	0.77	F-CELL150	3
16h12	17h24	116	0.79	F-CELL150	6
17h30	18h42	116	0.79	M-PROP150	8
18h12	19h24	116	0.79	F-CELL150	4
19h 0	20h12	116	0.79	F-CELL150	3

20h36	21h48	116	0.79	M-PROP150	7

ROUTE : EGLL-EHAM

FREQUENCY = 16

DEPARTURE	ARRIVAL	PASS.	LOAD-FACTOR	AIRCRAFT	AIRCRAFT NO.
6h36	7h48	116	0.79	M-PROP150	8
8h 0	9h12	116	0.79	F-CELL150	2
8h54	10h 6	116	0.79	F-CELL150	3
9h30	10h42	116	0.79	F-CELL150	5
10h54	12h 6	116	0.79	F-CELL150	4
11h24	12h36	116	0.79	F-CELL150	2
12h54	14h 6	116	0.79	F-CELL150	1
14h48	16h 0	116	0.79	F-CELL150	2
16h18	17h30	116	0.79	F-CELL150	1
16h18	17h30	116	0.79	F-CELL150	5
17h18	18h30	116	0.79	F-CELL150	3
17h54	19h 6	116	0.79	F-CELL150	6
19h12	20h24	116	0.79	M-PROP150	8
19h54	21h 6	116	0.79	F-CELL150	4
20h42	21h54	116	0.79	F-CELL150	3
22h18	23h30	2	0.01	M-PROP150	7

ROUTE : EHAM-LFPG

FREQUENCY = 8

DEPARTURE	ARRIVAL	PASS.	LOAD-FACTOR	AIRCRAFT	AIRCRAFT NO.
5h36	6h54	26	0.18	F-CELL150	4
7h36	8h54	116	0.79	F-CELL150	1
8h36	9h54	95	0.65	F-CELL150	6
10h36	11h54	116	0.79	F-CELL150	3
12h36	13h54	78	0.53	F-CELL150	4
16h30	17h48	116	0.79	F-CELL150	2
18h 0	19h18	116	0.79	F-CELL150	1
19h36	20h54	116	0.79	F-CELL150	6

ROUTE : LFPG-EHAM

FREQUENCY = 8

DEPARTURE	ARRIVAL	PASS.	LOAD-FACTOR	AIRCRAFT	AIRCRAFT NO.
7h24	8h42	115	0.79	F-CELL150	4
9h24	10h42	116	0.79	F-CELL150	1
10h24	11h42	78	0.53	F-CELL150	6
12h24	13h42	82	0.56	F-CELL150	3

16h 6	17h24	116	0.79	F-CELL150	4
18h18	19h36	116	0.79	F-CELL150	2
19h48	21h 6	116	0.79	F-CELL150	1
21h24	22h42	16	0.11	F-CELL150	6

AIRCRAFT NO. 1 : F-CELL150

AIRCRAFT		TOTAL PROFIT	UTILIZATION
BASE150	:	55392 US$	3080 hr
M-PROP150	:	79004 US$	3500 hr
U-FAN150	:	66448 US$	3080 hr
F-CELL150	:	80416 US$	3500 hr

NET EARNINGS : 80416 $
INVESTMENT : 51875923 $
RETURN ON INVESTMENT : 0.46505
UTILIZATION : 3500 hrs.

DEPARTURE	ROUTE	ARRIVAL	PASS.	LOAD-FACTOR	EARNINGS
7h36	EHAM-LFPG	8h54	116	0.79	10771 $
9h24	LFPG-EHAM	10h42	116	0.79	10771 $
11h12	EHAM-EGLL	12h24	116	0.79	9333 $
12h54	EGLL-EHAM	14h 6	116	0.79	9333 $
14h36	EHAM-EGLL	15h48	116	0.79	9333 $
16h18	EGLL-EHAM	17h30	116	0.79	9333 $
18h 0	EHAM-LFPG	19h18	116	0.79	10771 $
19h48	LFPG-EHAM	21h 6	116	0.79	10771 $

AIRCRAFT NO. 7 : M-PROP150

AIRCRAFT		TOTAL PROFIT	UTILIZATION
BASE150	:	17246 US$	1820 hr
M-PROP150	:	26208 US$	2030 hr
U-FAN150	:	23748 US$	1820 hr
F-CELL150	:	27514 US$	1960 hr

NET EARNINGS : 24046 $
INVESTMENT : 46936099 $
RETURN ON INVESTMENT : 0.15369
UTILIZATION : 2870 hrs.

DEPARTURE	ROUTE	ARRIVAL	PASS.	LOAD-FACTOR	EARNINGS
8h30	EHAM-LSZH	10h 6	83	0.57	6057 $
10h36	LSZH-EHAM	12h12	62	0.42	807 $
17h 0	EHAM-EDDF	18h18	113	0.77	9972 $
18h48	EDDF-EHAM	20h 6	110	0.75	9372 $
20h36	EHAM-EGLL	21h48	116	0.79	9179 $
22h18	EGLL-EHAM	23h30	2	0.01	***** $

TOTAL DEMAND FOR TRAVEL : 10000
PASSENGERS SERVED : 6180
SEATS OFFERED : 9636
AVERAGE LOAD-FACTOR : 0.64
TOTAL NET EARNINGS : 402450 $
TOTAL INVESTMENT : 503939758 $
TOTAL RETURN ON INVESTMENT : 0.27951

----------------- END OF PROGRAM -----------------

ESCAPE

Economic SCreening of Aircraft

Preventing Emissions

Annex V: Fuel prices and fuel efficiency:
a historic overview

ESCAPE

Economic SCreening of Aircraft

Preventing Emissions

Annex VI: Kerosene from Biomass

ESCAPE

Economic SCreening of Aircraft

Preventing Emissions

Annex VII: Policy options
to reduce aviation emissions

ESCAPE

Economic SCreening of Aircraft

Preventing Emissions

Annex VIII: Reviews by the aviation industry

Contents

This last annex contains reviews of the ESCAPE reports written by experts from the aviation industry and scientific institutes. Seven companies and institutes were approached of which five eventually wrote a review. The people were asked to give their opinion on mainly the technical quality of the work.

The people were told before that their comments would be published unchanged, and that their comments would not result in changes to the ESCAPE report or annexes. Therefore, the reviews give a good overview of the opinion of industry and scientific experts in the field on the final quality of the ESCAPE reports.

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1. General Remarks

The report deals with the consequences on economics and environment of modifications of existing conventional transonic transport aircraft (swept wing with engines, fuselage, empennage at the rear fuselage) with respect of introducing more fuel-efficient propulsion concepts (ultra high bypass fan, propfan, high speed propeller) and of introducing new energy concepts with fuel-cells.

Aerodynamic and weight reduction potentials of new technologies like hybrid laminar flow control and substitution of metal structure by carbon fibre have been taken into account in a not so sophisticated and detailed manner as for the propulsion systems.

Fuel consumption reductions, DOC reductions and effects on emissions have been evaluated for six different designs (three short-haul/three long-haul versions), status 2010, related to two baseline aircraft with conventional technology standard extrapolated to 2010.

Fuel consumption reductions of the investigated new aircraft with respect to the baseline aircraft between 31% (short haul 150 Pax) and 49% (long haul 400 Pax) have been estimated.

In this consideration the basis, that means the baseline aircraft 2010, is not completely clear for me. From the report I understood that the baseline aircraft called Base 150/Base 400 are configurations of existing aircraft (B377/B747-type) with an estimated engine performance increase of conventional turbofan engine to the year 2010. From the report I understand that no aerodynamic cleanup or weight reduction potentials for 2010 have been incorporated in the baseline aircraft. These reductions potentials have been stated and have been used for the new designs.

For me therefore, the baseline aircraft have performances with respect to weight and aerodynamics of configurations of the early 70^{th} and do not represent modern now already in service aircraft like A320/A340. It would have been better for the study to have as basis the performance of these already existing modern aircraft. Thus, evaluating fuel consumption reduction and DOC reduction based on more modern baseline aircraft will lead to other figures than stated here in the report.

2. Remarks on economic and environmental performance of investigated concepts

Although the propfan or propeller driven designs estimate a large amount in fuel consumption reduction, which is unquestionable, I doubt that these concepts will be the configurations of the future. As also mentioned in the report there are several reasons against propulsion systems based on propellers:

<u>Technical reasons:</u>

The crucial point of propeller or propfan systems is the exterior noise problem at take-off and landing. The continuous effort of ICAO to reduce the allowable noise levels will lead in the near future to noise regulations which will be very strict, and for me it is not clear if high speed propellers or propfans can fulfil these new regulations.

<u>Operational reasons:</u>

The envisaged reduction of cruise speed between 5% and 10% compared to turbofan aircraft will be unacceptable for the airlines. Especially for long-distance flights aircraft with lower cruising speed will not fit in the existing scheme of routes in the sky with regard to separation distances and flight levels from the flight control aspect.

Passenger comfort reasons:

Passengers will not accept aircraft with a higher level of interior noise and vibration associated with a propeller/propfan propulsion system. Additional measures for noise and vibration compensations have to be installed.

Increased flight time for long distance flights will not be tolerated by the customers.

3. Comments on the feasibility of low speed designs

Low speed design (Ma = 0.6 to 0.7) support the application of propellers, but the trend at the moment in aircraft industry is opposite. The Fairchild/Dornier 328 aircraft, originally developed with a propeller propulsion system has been modified to a turbofan engine propulsion system. This new modification sells better than the original propeller version.

Reducing the cruise speed of aircraft to my opinion is not feasible and will not be accepted by customers for large transport aircraft and large distance flights. It might be acceptable for regioliner aircraft with passenger capacity from 40 – 100 and distances up to 1.000 km.

4. Concluding remarks

The results of the study are plausible and the tools for generating the data are good. But as only aircraft of year 2010 are under considerations, completely new designs like blended wing body configurations or low noise aircraft configurations have only been touched in the study. These configurations will entry into service around 2020/2025 and first data show remarkable reduction in fuel consumption.

The fixation of this study on mainly new propulsion system concepts based on propeller/ propfan engines has a twofold outcome:

Its strength is that the study clearly has worked out the prerequisites/limitations and shortcomings of propeller driven propulsion systems for transonic transport aircraft.

Its weakness is that the study has not considered in more details new unconventional concepts for economic and environmental friendly aircraft for the year 2020/2025.

The strong barriers against propeller/propfan aircraft discussed in the report should inspire people not to solve the problem with these concepts but to direct research and development to new unconventional configurations.

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I would like to thank you for the opportunity to review this work and comment on this effort and my study from 1998. This study considered a lot of variables and options (including both incremental and revolutionary changes) in propulsion and aircraft development. Limiting aircraft choice to two designs allowed a greater matrix of other options to be explored. Much effort was expended and disseminated about the background assumptions, which will make it much easier to extend this work with additional aircraft, missions, technology options and/or changes in the political and social climate.

I must preface my comments with the fact that I speak for myself, a fellow engineer involved in the preliminary analysis of unconventional aircraft and systems. The views I give are not necessarily the views of NASA and are a product of my own experiences and lack thereof.

The following pages will first address some general question you posed, while the next 2 pages are my comments while reading the main report. Thank you again for this opportunity to help share information between co lieges. My review will consist of my response from specific questions.

1) Do you think that the designs considered give a good overview of possible aircraft concepts that are most promising from an environmental and economic point of view?

Although the airplanes chosen (737-400 and 747-400) are derivative designs that have their original births in the 1960s, major portions of the airplanes have been updated with new technologies (most specifically, wings, engines and various other flight systems). With the basic design still intact, the changes and updates are not as significant as a new design might incorporate. But with the large installed base of these (and similar) aircraft and the cautious introduction of new technologies and designs, they are still representative of what I would expect to see in the 2010 time-frame, incrementally updated with technology as it becomes available and makes economic sense to do so. What that means is that they will capture the proper trends of technology or political change, but the actual magnitude of the change is at best, an educated and pretty well defined guess. Most studies don't define their assumptions as well, leaving the reader to draw their own conclusions with incomplete information. This work includes enough information that derivative trends can be estimated if another's view is a bit different.

2) What concepts have been underrated (except the concept of the hydrogen-fuelled aircraft with jet engines, which was left out deliberately)?

With the short timeline (2010) assumed and the cautious nature of the commercial aircraft market, it is hard to see large changes in the aircraft system. Additional new materials will be introduced into airframes that improve weight or cost, but it tends to be in small ways, to gain additional experience before widespread use. Assuming the hub and spoke terminal system may be a large assumption, because airplanes that reduce fuel burn by reduced speed could find a niche market for point-to-point travel for several routes, saving the passenger travel time and aggravation with connections. Although the time is short, the superjumbo (600 pax +) airplane definitely must be considered as travel increases and only so many people can be transported easily on certain routes (if you can't have more planes, use larger ones to carry the increased capacity). Much has been studied about alternative fuels and the effects of combustion products on the atmosphere. Using biomass for kerosene production could alleviate many environmental issues, while maintaining the present aircraft system. This needs additional study and effort to get the "big picture" (although it is probably too large for any one country to get its arms around).

3) Could you give your comments on the feasibility of a low design speed (Mach 0.6 to 0.7) to achieve a high environmental and economical performance?

Although reduced cruise speed would allow designs that have a significantly reduced fuel burn, people want higher speeds and tend to be willing to pay for it. (Case in point, the continued interest in a supersonic large transports and business-class jets, as well as new general aviation planes increasing speeds by 50 to 100 mph). As long as it is obtainable and the cost not outrageous, people will equate technology and progress with speed. Lower speed designs may have a place in point-to-point travel, where the population density is sufficient, and the slower plane can go directly, without hub and spoke connections. Otherwise I don't see it happening without a crisis or government regulation.

4) What is your opinion on the environmental performance of the aircraft concepts included in the study? What are the main technical problems to overcome? What is your opinion on the economic performance of these aircraft?

I would like to believe that new materials will "buy" their way into existing aircraft and new designs by increasing performance and/or flexibility. But it's hard to quantify with the large variety of structures and materials in aircraft. Many improvements are possible, but many require political will or requirement to be used, the business case to include these changes in not conclusive. Various versions of propellers could be incorporated into an advanced fleet, but the public must be ready and the technology first demonstrated to be performance and cost effective. With that in mind, I don't see any major changes without either government intervention or incremental change toward these larger changes from smaller businesses hungry for additional markets.

5) If your estimate on the environmental and economic performance largely differs from ours, could you indicate what technical assumptions are behind of these differences?

Based on previous studies that I know of, I feel comfortable with your assumptions and conclusions with respect to the trends forecasted. As to absolute values, it depends on assumptions. I still have some of the 1970s reports detailing how advanced turboprop (ATP) powered aircraft would be the major vehicles in the sky, using synfuels (produced from coal, shale or biomass). I believe your trends based on your assumptions and the technology available, but have no crystal ball to know how other factors will change the future. Technology often suggests one path, but people's wants and perceptions will generally decide the path taken.

6) What is your overall judgment on the plausibility and the value of this study? What are its strengths and weaknesses? Why? Does it give any inspiration or does it lead to new ideas?

As addressed in previous questions and answers, this report gives a lot of good information about different options, based on reasonable and stated assumptions. It suggests several options to reach a desired goal; it is up to the reader to choose their view of the correct path to reach their goal.

Questions or review comments:

Main report

Section 2.3: NO_x *is expected to grow like* CO_2 *production due to increased operating temperatures and pressures*. Presently there is little financial reason to incorporate new combustor technology (with its higher initial and maintenance cost); however, as individual airports institute more strict emissions limits and/or fees, it will force the lower NO_x designs to become more commonly used, although in limited areas. Once the combustors have been validated for these particular routes, regulations will probably force the technology to be used in all combustors.

Section 3.4, 3rd paragraph: "Although use of LNG is accompanied by a slightly H_2O emissions" – I assume the word "increased" or "higher" goes before H_2O? Higher hydrogen to carbon fuels will tend to increase H_2O vapor production, with reduced CO_2, due to their higher heat content per unit mass.

Section 3.4 - Biomass fuels: Except for the effects of CO_2 in the higher atmosphere, I believe that this is a valid choice to CO_2 problems, if sufficient biomass could be grown to counteract the amount released through combustion. This would reduce the issue of H_2O vapor in the atmosphere as well, and I believe, be a better energy choice than going to H_2. While processing the biomass to a suitable kerosene product, high-carbon products (slurries or distillation "bottoms") could be stored in mines or sequestered to reduce atmospheric CO_2.

Section 4.7 - High speed propellers: An additional problem beyond the technical is public perception. The general population perceives propellers as higher noise and lower technology, performance (speed) and safety. Work is required to understand/mitigate these perceptions, because it helps guide airline decisions.

Section 4.7 - Hydrogen and fuel cells: This area is ripe for further study, because the many necessary issues (assumptions) can define the airplanes and the resultant "opportunities". The integration of many, smaller systems could have significant safety, performance or maintenance gains from a few, large or combined systems.

Section 5.5 - Noise: This is a technical and social issue. The UHB concept is generally considered more acceptable because noise can be treated using the liner. Additional study and understanding of the public perception/annoyance to the sounds patterns of the UHB and propeller, for a given sound level, would help further define potential methods to help alleviate different requirements that could limit the use of either concept.

Section 5.7 – Passenger Appeal: This is partially perception, the rest operation and reality. Propeller aircraft are often flown at lower altitudes, by design, contributing to lower passenger comfort than turbofan concepts. This is can be overcome as suggested in the study. Passenger perception on safety of the propeller versus the UHB or turbofan is understandable. The nacelle/liner of the turbofan or UHB allows for acoustic treatment and the potential of some containment in case of blade separation. Until it can be demonstrated that these issues are sufficiently understood and overcome (with a sufficient decrease in DOC) or partially mitigated with an even larger decrease in DOC (or forced by government regulation/intervention), airlines (and passengers) will be slow to embrace these technologies (as discussed in section 5.8). The issue of block time is harder to quantify; for the short haul aircraft, the difference could be partially or completely alleviated by flight operations (such as giving these advanced aircraft priority access to runways for takeoff and landings). For the long haul aircraft, significantly longer block times are difficult to accept by airlines or the passengers (unless regulated as the only choice or a significantly large penalty for the additional speed of the more traditional aircraft). This suggests that higher speed propellers will be required, if they meet speed, efficiency, noise, and cost requirements. Other barriers to new aircraft and technologies are discussed in section 6.

Note: For the fuel cell aircraft used in the 1998 study, many conservative (hopefully) assumptions were made, some that are different than those used in this report. This is not to infer that either study is right or wrong. Our study assumed a higher speed (read as: higher energy required) aircraft. For the long range assumed (6500 nmi.), cruise speed was kept the same as the base to minimize differences for passengers and the present airline system (flight times, schedules, etc.). The purpose was to point out differences in the general size, weight and fuel used between all concepts. The 1998 work was a preliminary screening, done under a short timeline. That work is being revisited during the 2001 fiscal year to address issues ignored in the previous study, as well as revisit some of the base assumptions to see if the proper integration of the fuel cell into the aircraft could mitigate some of the system weights (most specifically, fuel cell system weights).

For comparison purposes:

	Present study	NASA 1998 Study (Snyder)
Aircraft cruise Mach number	0.65	0.83
LH2 tank weight	0.38*Weight-LH2 (includes fuel system)	0.30*Weight-LH2 (tank and insulation only)
Electric motor, kg/kW	0.20	0.038 (1)
Fuel Cell specific stack density, kW/l	1.4	0.55 (2)
Specific stack power, kW/kg	1.4	0.55 (2)
Power takeoff, hp	100	1500 (3)

1) The initial number used was 0.15 kg/kW, but the study assumed superconductivity could improve efficiency of the motor to approximately 100%, while reducing diameter by 50%. Assuming constant density and length of the motor, this reduces motor weight by a factor of 4. In the final airplane, the electric motor was small compared to the fuel cell. Also significant was the controller and power handling (11400 kg for handling 2 motors @ 45 MW each).

2) The initial fuel cell stack performance was close to the present study (initially 1 kW/l and 1.1 kW/kg). Without a detailed design, manifolding was assumed to add 100% weight and volume. This is being studied further the Zero Carbon Emissions Technology (ZCET) program at NASA Glenn.

3) An additional loss of 20% of gross fuel cell output assumed lost in the power handling.

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The report indicates the complexity of the search for "reduced emission" aircraft. It shows that the trend for aircraft effeciency (in fuel burn terms) has been downwards for many years, and that this is expected to continue.

Further improvements may be possible by radically changing the powerplant (for instance to Ultra-High Bypass ratio engines or High-speed Propellers), or through aerodynamic means (Laminar Flow control, for instance). The report states that Prop-fans intrinsically have lower overall pressure ratio, which reduces NO_x, but if a Prop-fan is designed to minimise fuel burn for a long range aircraft, this effect may disappear (past Prop-fan tests may have used existing turbo-fan gas generators, with lower OPRs due to the lack of fan supercharging). Further more, the requirement to reduce fuel burn and weight on long range aircraft may drive the overall pressure ratios, of these and other engine types, to the levels where NO_x becomes more of a problem.

A reduction in cruise speed is shown to further reduce fuel burn , and at short range to have little effect on flight times. At longer ranges, however, there could be a problem trying to fit in slower and faster aircraft, in the same air corridors. If the flight times are entended significantly, some long range flights may no longer fit in with global time constraints, and this could further adversely affect aircraft utilisation. Recent coverage in the press has indicated that there is a health risk involved with long distance flights (deep vein thrombosis). If flight times on these long range flights are further increased, this will increase the health risks to the passengers. Laminar flow is expected to reduce the parasitic drag of aircraft in the future, but would this be practical behind the turbulent flow from wing mounted propellors (single, double row or high-speed)? High-speed propellers also accelerate the air more than conventional propellers, and this will lead to higher scrubbing drag from any surfaces immersed in their flow, reducing the fuel burn advantage expected of these powerplants.

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Both myself and a member of advanced propulsion systems department have read the main report of your study and we give you the following comments.

The comments are in no particular order:

1. You should also mention the over-riding element of designing for safety in the 'Foreward'.
2. What is meant by 'medium term' in the 'Executive Summary'? If it is 2010 then it needs to be put in context of 'if unlimited resource and money was made available to the manufacturers'. Here you could pick up text you use in the first page of chapter 4 of 'Full optimisation and balanced aircraft design obviously requires a large workforce and a budget of millions and this study has no pretension of delivering preliminary designs for high fuel plus carbon price market.'
3. The greatest mention in industrial circles of something to break the current status of aircraft and engine design is the 'blended wing body aircraft'. This aircraft concept is not given enough attention within the report. Interestingly, the aircraft would not only bring aerodynamic efficiency improvements for the airframe but might enable bigger advantages in engine technology. New airframe concepts where the engine noise can be shielded from the ground are important, as the bigger fan engines (? see item 16) you describe may be unacceptably noisy.
4. Two other issues with large turboprops that you have not brought out in detail are 'cabin noise' and 'fan blade containment'. Both these design constraints would lead to increases in airframe weight, due to acoustic linings in the cabin and strengthening of the structure of the fuselage close to the aircraft. We have not had chance to read the background report, but believe that these constraints need so much thought that they should be included in the main report.
5. Figure 1 should say 'trading' not 'reading' in the title.
6. On page 6 of the report you infer that 'thermally more efficient engines' produce less contrails. This is known to be incorrect. We have debated this subject with Ulrich Schumann of DLR (see his reports), and the simplest way of understanding this is by looking at trends of increasing engine bypass ratio (as you have in your study). As engine bypass ratio goes up more cooler air is involved in the contrailing process, therefore it can be expected that a higher BPR engine will contrail sooner. Similarly, a more fuel efficient core could equate to the turbine taking more work out of the gas stream hence reducing the exhaust core temperature above older engines. Please provide evidence of your statement that 'propeller rather than high-bypass ratio propulsion' is better for contrails, as we see no reason why this should be the case. We fully agree that operational measures could reduce or eliminate contrails.
7. Page 7 on hydrogen, you mention the infrastructure changes needed to support the use in fuel cells etc. It is our opinion that such a dramatic change in power generation could only be led by other transport modes such as cars. We must agree that use of hydrogen will be well beyond 2010, and the IPCC report suggests over 50 years before we see a revolutionary change in fuel! Liquid hydrogen also needs about 40% of its energy content just to liquefy it, which does not seem sensible in overall energy efficiency terms.
8. On page 20 you have captured much of the combustion information very well, but you should state the downside of 'rich-burn, quick-quench, lean-burn (RQL) combustion'. This type of combustion is highly likely to produce visibile smoke! All the major manufacturers are concentrating their research efforts on lean premixed combustion with some kind of fuel staging. The latter being needed to maintain combustion instability at adverse conditions.
9. You have neglected the extreme weights of the motors needed to drive the propellors in the fuel-cell powered aircraft; there is a huge conflict between the requirements of motors (high-speed, to keep the weight down) and propellors (low-speed, to keep the stresses and noise down): a gearbox is clearly then necessary, which adds to cost and weight.

10. As you state laminar flow wings would need additional maintenance. It is not clear if such additions are included in the DOC's. One sentence stating inclusion or not of such costs in DOC's within the main report would be sufficient. This is true of a number of issues.
11. The fuel plus carbon price in Figure.6 looks low. Some of this price should be determined by how much of the manufacturers development costs are passed on to customers. Similarly on page 29 it is surprising that the baseline price of aircraft is more than some of the technology options which would give little incentive for engine and airframe manufacturers. Clearly most technologies you have assessed will cost a lot money to develop, and this money needs to be recouped or come free of charge from funding agencies.
12. We notice that part of the study goes against modern aircraft development by saying 'We have designed aircraft around these engine speeds' (i.e. the lower flight speeds). Industry would suggest that todays aircraft are the best for todays market, but it is certain that engine designs are only produced when an airframe is available or planned.
13. On page 30 it is stated that using hydrogen reduces NO_x. This is not true, and is dependant on producing low emissions technology. In fact without such technology hydrogen burning would produce more NO_x due to the higher peak flame temperatures involved. Theoretically, it is believed that it should be easier to produce a lean burn solution for low NO_x with hydrogen, however very limited testing has been carried out to date.
14. Table 4 may not correctly account for fan noise. Fan noise may outweigh the thrust reduction noise.
15. The recommendations are extremely good. However, in the text of the UHB ratio engine you start with the phrase 'It is recommended to further study the pros and cons of engine concepts exceeding the bypass ratios considered in this study (beyond 9:1)'. We should point out that todays baseline engine could well be considered to be an engine with such a bypass ratio (examples of such engines are the GE90 on the B777 and the Trent500 soon to be certificated on the A340-500). Therefore it is unclear how the report claims benefits for the UHB ratio engine. I would therefore suggest that if a follow on report was commissioned that the baseline be re-calculated.
16. The recommendation on the 'Blended wing body' aircraft should be included in the executive summary.

Answering your specific questions:

i **What is your opinion of the environmental performance of both the high-speed turboprop aircraft and the UHB aircraft included in the study?**
The study is useful, but it neglects many details which compromise the designs of the above aircraft, and hence the likely fuel consumption advantages will not be as great as described in the report (see above comments). The focus on fuel burn and emissions to the exclusion of all other desirable aicraft attributes reduces the credibility of the report.

ii **What is your opinion on the economic performance of these aircraft?**
Similar answer to (i), however it must also be recognised that public perception would play a large part in the market-place. Public acceptance of propellers and slower speeds will be very difficult, especially for the long haul market.

iii **Could you give your comments on the feasibility of a low design speed (Mach 0.6 to 0.7) to achieve a high environmental and economical performance?**
This is a necessity for props, and in fact if you look at any transport mode normally results in increased environmental benefit. The economics of air travel would need to change somewhat to drive this into the market, and it is difficult to envisage such low flight speeds being acceptable for long haul flights. There is, in fact, pressure to increase aircraft speed, both for passenger acceptance and to keep the number of relief crew members down on long-haul flights.

iv Do you see any technical problems within the next ten years for Mach 0.65 and 0.75 propeller engines? And for UHB engines?

Yes, lots of technical problems with noise and propellor blade containment being probably the biggest issues. One other technical issue not mentioned above is matching of cruise to take-off performance for UHB ratio engines (>9 pressure ratio); Fancy gearing would be required which would add a lot of extra weight.

v If your estimate on the environmental and economic performance differs from ours, could you indicate what technical assumptions are behind these differences?

These technical details are scattered throughout this response.

Unfortunately much of your work within the main report neglects details on noise issues which are not easily solved so the potential of the extreme solutions you have assessed for engines may be the order of double those actually achieveable.

vi Does this study give you inspiration for further developing environmentally friendly aircraft engines or do you see better technologies to solve the growing environmental burden of global aviation?

We will continue to improve technology as we have done since the advent of the jet engine. We hope studies such as yours bring to the attention of policy makers that aircraft engine technology development is not easy and that large financial support is needed to keep moving technology forward.

It can be envisaged that a correctly implemented and assessed Market Based Option will eventually help the environmental burden. It must not be forgotten that the airframe has a contribution to make to reduce engine emissions, by reducing the drag of his aircraft!

vii What is your overall judgement on the plausibility and the value of this study? What are the strengths and weaknesses? Why?

The study is plausible, but many of the down sides of the various technologies are underplayed and this results in unrealistic performance improvements. The strength is that the technical detail has been well presented so it can act to help people who may look at these technologies in the future.

Sorry that many of our comments appear negative, but you must realise that engine manufacturers have studied many concepts to reduce fuel efficiency cost-effectively. Much of your work challenges us to study further low CO_2 designs, and you can be assured we will continue to drive fuel efficiency down as much as we can.

Contents

1 Introduction

In the ESCAPE project a number of possible new aircraft technologies or designs to reduce fuel consumption and emissions have been assessed. We have seen that there is scope to reduce the fuel consumption per aircraft kilometre by 30 to 50%, compared with the 2010 baseline aircraft.

We have also seen that, although the designs surveyed might lead to modest gains in costs, currently there is not much scope for the introduction of such aircraft. We have seen that the introduction of new aircraft concepts gives rise to a number of economic and non-economic barriers that have to be overcome. In the past, totally new aircraft concepts were hardly ever introduced when they did not offer a perspective on very substantial DOC gains.

In this annex we will focus on policy options to remove the barriers identified on the previous chapter.

We will first give a brief overview of the international environmental policy context that possible solutions should fit in. Then we will focus on options to reduce the economic barriers. We will close this chapter with a number of other issues that require attention if lower emissions from aircraft are wanted.

2 Global policy initiatives

The Kyoto protocol, signed in December 1997, sets emission reduction obligations for six greenhouse gas emissions by 39 so called 'Annex I Parties'[1]. The European Union, United States and Japan agreed to reduce their greenhouse gas emissions by 8, 7 and 6% respectively in the period between 1990 and 2008/2012. International aviation and international shipping are not included in the Kyoto Protocol, mainly because of allocation problems (allocation of emissions to individual Parties). However, the Protocol calls for:

'Progressive reduction or phasing out of market imperfections, fiscal incentives, tax and duty exemptions and subsidies in all greenhouse gas emitting sectors that run counter to the objective of the Convention and apply market instruments' and *'measures to limit and/or reduce emissions of greenhouse gases not controlled by the Montreal Protocol in the transport sector* (i.e. international aviation and shipping).

It furthermore states:

'The Parties included in Annex I shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organisation (ICAO) and the International Maritime Organisation (IMO), respectively'.

As a result, ICAO's Committee on Aviation Environmental Protection (CAEP) has started evaluating options to reduce emissions at a global level. Five Working Groups have been installed.

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[1] Annex I Parties: 39 developed countries or groups of developed countries.

WG3 (Emissions/Technical) discuss possibilities of developing a standardised fuel consumption calculation cycle for the cruise phase. A cycle to calculate LTO emissions already exists, but this cycle only relates to engine emissions at standardised settings and flight path, while the 'cruise' cycle should take real flight-path, based on characteristics of the airframe into account. Such a cycle could be used as a basis for either economic instruments, or fuel economy standards to be set.

WG5, on Market Based Options, evaluate possible policy options that have no relationship with standard setting, such as fuel charges, emission charges and emission trading schemes.

3 Options to improve the economics of cleaner flying

Introduction: environment into business economics

We have seen that economic barriers, or insufficient economic pressure, is an important barrier for introduction of more environmentally efficient aircraft. Besides, economic factors also play a major role in decisions concerning fleet management: the removal of old aircraft from a fleet. The rate of fleet renewal and there with fleet-average environmental performance is largely determined by economic factors.

Therefore, policy options to improve the competitive position of environmentally more efficient aircraft are an important boundary condition for the introduction of environmentally more efficient aircraft. The competitive position of environmentally efficient aircraft can be improved by enlarging the role of environmental considerations into business economics.

This can be done with so-called *economic instruments*, instruments that give a price to environmental burden. An important advantage of economic instruments in general is that they leave scope for the aviation sector to take the most cost effective measures. When economic instruments are applied, every manufacturer and airline can decide for himself or herself what measures to take. In theory, economic instruments offer possibilities to achieve emission reduction at least (social) cost. Distribution of the burden and of the revenues, however, gives rise to huge discussions in this field.

In order to create an optimum incentive to reduce the environmental effect caused by aviation, economic incentives aiming at reducing environmental impact should ideally satisfy the following conditions:

1. the *base* of the instrument should be linked as closely as possible to environmental effects;
2. the charge *level* should be linked to underlying costs. These can either be damage costs, or prevention (avoidance) costs;
3. when introducing an these instruments, their base, calculation methodology and level should be known for a satisfactorily long period of time, long enough for the aviation industry to properly anticipate in their long term decisions.

Four different instruments can be considered, which are described in the following four paragraphs.

***Fuel levy*: levy on fuel bunkered**

A levy on fuel bunkered has the advantages that it is rather easy to implement and it gives a maximum incentive to reduce fuel consumption and this carbon emissions, e.g. by both technical and operational measures. Its main disadvantages are that it gives rise to economic distortions and legal obstacles when it is not introduced on a global scale. When introduced at a regional level, economic distortions will arise, mainly as a result of the 'border effect' |CE, 1997b|. Besides, a regional introduction will give incentives for so-called 'tankering', taking fuel in aircraft from abroad.
Furthermore, introduction of a fuel levy on a regional scale will also face legal obstacles. For example, in case a European charge on fuel bunkered is introduced, numerous bilateral Air Service Agreements (ASAs) between EU and non-EU countries will have to be revised.

***Emission levy*: levy on calculated emissions**

It is also possible to give a price to emissions caused at certain routes or in certain airspace, e.g. intra-EU flights or EU airspace. This has a major advantage that border effects are much more avoided and tankering will not happen. The major advantage of a charge on calculated emissions on certain routes is that it is easier to introduce at a non-global level. It will then probably face less legal obstacles, and it could cause less economic distortions.

There are several ways to calculate those emissions. One is to calculate the emission characteristic on the basis of certification flight data. Another option is to use officially established models that calculate emissions of engine/airframe combinations with the help of engine and airframe characteristics. A third option is to link a payment mechanism to the fuel flow meter in the aircraft.

Emission levies can be introduced as airport charges or 'en route' levies.

Revenue neutral emission levy

It is possible to design emission levies in such a way that the nett burden for the aviation sector becomes zero (no transactions to governments) while at the same time the incentive for cleaner flying remains at the same level. This can be done by recycling the revenues back to the airlines on the basis of each airline's transport performance in RTK or RPK |CE 1998|.
Such a scheme gives rise to environmental competition between airlines as is rewards the best and punishes the worst. Airlines that manage to transport more RPK or RTK per unit of emission can earn money while airlines that cause many emissions per unit of transport lose money[2].
It has to be stated, though, that such a scheme does not comply with the 'polluter pays principle' because only *relative* instead of *absolute* environmental burden is what counts. Consequently, total air transport growth is

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2 An example here is the Swedish charge on NO_x emissions from power plants, which is refunded to the electricity companies in proportion to the number of kWh they produce. This generates an incentive to improve environmental performance - i.e to minimise NO_x emissions per kWh produced - while it does not impose a financial burden on the electricity sector as a whole (except the burden as a result of measures taken to reduce emissions).

hardly affected, which might well be a consequence of applying the ‘polluter pays principle’ as in the options mentioned in the previous paragraphs.

Emission *trading* schemes

The principle of emission trading is exactly equal to the revenue neutral emission levy treated in the previous paragraph. Emissions get a price, there are no transactions of money to governments (unless permits have to be bought from the government, analogous to GSM frequencies) and both systems thus lead to ‘least cost’ solutions. However, in emission trading the reduction aim is fixed and the price is uncertain, while a charging regime leads to fixed prices but uncertain reductions.

Important issues in designing a trading scheme are the initial division of emission credits, the ceiling to be established, and the choice whether the system should be ‘closed’ (aviation only) or ‘open’ (other sectors involved) ?

Economic policy options: summary

The findings in the previous paragraphs, together with findings from the previous chapter and findings from an earlier CE study |CE 1998| are summarised in Table 1.

Table 1 Qualitative summary of economic policy options considered |CE 1998|.

	fuel levy	emission levy	revenue neutral emission levy	emission trading
affects aircraft technology	yes	yes	yes	yes
affects fleet composition	yes	yes	yes	yes
increases load factor	yes	yes	yes	yes
affects flight operations	yes	depends on measurement/calculation method		
is legally feasible	only global	at global and probably also regional level		
leads to economic distortions	yes when regional	not necessarily		
complies with Poll. Pays Principle	yes	yes	partly	partly
reduces air transport growth	yes	yes	hardy	hardly
reduces emissions	++	++	+	+
generates government revenues	yes	yes	hardly	hardly
gives burden for aviation industry	yes	yes	hardly	hardly

4 Options to decrease investment and development risks

Aviation is an industry with long lead times, enormous investments and high development risks, thus requiring fierce rate of returns on investments. These development risks have often partly been reduced by government participation on aircraft development.

A strategy that could be followed in this respect is to stimulate development of environmentally advanced equipment for the military sector. Once technologies have been tried and tested the risks for commercial aviation could be substantially reduced.

In concrete it could be considered to develop highly efficient counter rotating high-speed propeller propulsion for the A400M, Europe's future military transport aircraft. An example of such an application can already be found in its potential competitor, the AN-70, the first aircraft that will probably go commercially equipped with these counter-rotating propfans. This might reduce fuel consumption by about 30%[3]. The most sensitive parts of this promising technology (propeller de-icing and gearbox) can first be proven under military circumstances before entering the civil market.

A second step might be application in commercial freight transport, where performance and comfort standards are a little more lenient than in commercial passenger transport. A last step could then be application in the civil passenger market.

5 Policy options to oblige application of clean technology

Another option to introduce more environmentally compatible aircraft in the fleet is to oblige use of them. For the aviation industry, working with standards is common practice. Standards exist for the noise emission of engine/aircraft combinations, and for the engine's NO_X, HC, and CO emissions during the LTO cycle.

Both of these standards serve two goals.
The fist us to create a 'ceiling' in order to avoid excessive noise and/or polluting emissions. This ceiling is mostly quite a lot higher than what is technically feasible, in order to protect the various market parties from running out of business. This technology 'baseline' is regularly revised every once in a while.

The second is to create a basis for differentiated treatment of aircraft particularly for airports and governments. The results of certification tests serve as a legal basis for airports' slot allocation and pricing policies.

In a reaction to concerns about the environmental effects of emissions above ground level, currently CAEP Working Group 3 is working to establish a recognised methodology for calculating (CO_2 and H_2O) emission profiles of aircraft outside the LTO phases (climb out, cruise, descent and approach). Once this methodology is available, standards can be set.

In order to establish the feasible emission reductions as shown in this study, the fuel economy standards would have to be about 40% stricter than the performance of today's aircraft. This study has shown that, without any policy measures, it is doubtful whether these types of aircraft would be economically feasible. Therefore, such really technology-forcing standards would inhibit penetration of new aircraft in the fleet, which is undesirable.

Therefore, fuel economy standards could work, however, to improve fuel efficiency of the existing fleet and to create a basis for differentiated treatment of several aircraft types.

[3] CE estimate based on information by Rudi den Hertog, Fokker Services, and several Internet sites.

Contents

1 Introduction

A final approach to reducing (at least CO_2) aviation emissions is to produce the required kerosene from sources other than fossil crude. If the fuel is produced from biomass, the CO_2 chain can be 'closed'.

This chapter provides an indication of the potential for producing fossil fuel substitutes from biomass. It analyses the environmental and economic feasibility of two biomass-based production routes for kerosene:
- conversion of biomass to biocrude via the so-called HTU process, followed by biocrude re-processing;
- gasification of biomass followed by 'Fischer-Tropsch' hydrocarbon synthesis on the basis of the produced syngas.

Another possible route is production of methanol from biomass, followed by conversion from methanol to petrol and similar products using the Mobil-developed process. This process has not been included in the present, preliminary analysis for lack of available data. The first commercial production unit of this kind is now on stream in New Zealand. For information on biomass-based methanol production the reader is referred to |Jager| or to |Williams|, the source of the information reported in |Jager|.

For both of the aforementioned production routes, in this outline analysis the following three parameters have been determined:
- energy efficiency;
- carbon conversion efficiency;
- cost per unit product and per unit biomass;
- cost per tonne reduced CO_2 emission.

The carbon conversion efficiency is the relative quantity of carbon ending up in the target product.

In analysing the two routes we have assumed processing of wood with a moisture content of 35 % by weight. The chemical specifications are as shown in Table 1.

Table 1 Chemical composition of dry wood

Element:	Percentage, dry matter
- C	49.2%
- H	6.2%
- O	43.1%
- N	0.15%
- S	0.01%
- Cl	0.08%
- ash	0.5%

The calorific value of wood is approximately 17.8 MJ/kg.

2 HTU process and hydro-deoxygenation (HDO)

Process description

The core mechanism of the HTU process is decomposition of biomass in water at elevated temperature (> 300 °C) and high pressure (200 bar). The dry biomass is converted into gaseous compounds, water and water-soluble compounds and oil.

Most of the oxygen present in the biomass is converted to CO_2 and drawn off with the other gases. The gas stream also contains small quantities of CH_4, H_2 and CO and is used as a process fuel.

The water-soluble organic compounds consist mainly of alcohols and organic acids. The hydrocarbons are separated off and also used as a process fuel.

The oil is flashed to separate tar-like compounds (bottoms). These bottoms are used for process heat and steam raising. The light oil fraction (biocrude) can either be used as a fuel for motor vehicles or power generation or be worked up to a synthetic crude oil. Part must be used to meet process energy requirements. Captive use of biocrude increases with rising moisture content of the biomass.

The remaining hot biocrude (approx. 350°C) is mixed with hydrogen and passed over a catalyst. The oxygen present in the biocrude reacts with the hydrogen to form water vapour, part of which is used to saturate the aromatic compounds present in the biocrude.

Energy efficiency, mass balance and carbon efficiency

Mass balance
Output of biocrude is about 400 kg/tonne dry wood. The biocrude consists of about 82% carbon, 8% hydrogen and 10% oxygen and has a calorific value of about 36 MJ/kg.

Per tonne of biocrude, hydrogenation requires 40 kg of hydrogen and yields about 900 kg of products. In addition, about 115 kg water and 25 kg gaseous hydrocarbons are formed per tonne of biocrude. In the analysis presented here, these gaseous hydrocarbons are treated as butane.

Hydrogen is produced from the biocrude, 1 kg hydrogen being generated from about 5 kg biocrude. Most of the carbon present in the biocrude is converted to CO_2 and a minor fraction to CO. During hydrogen production a gaseous waste stream is generated that is used as a process fuel.

Per tonne of dry wood, hydrogen production requires about 66 kg biocrude. The quantity of kerosene/gasoil produced is (400 – 66) x 90% ≈ 300 kg/tonne dry wood.

Carbon balance
The respective carbon efficiencies of the HTU process and the HDO process are approximately 70% and 80%. The net efficiency of carbon conversion is about 55%.

Energy efficiency
The net energy efficiency of the HTU process is 80% ± 5%; this figure is for processing wood with a moisture content of 35 % wt. in a stand-alone unit with a capacity of 70 to 80 MWth. The exact efficiency depends on the configuration of the production unit. Process power and heat are generated using by-products (bottoms, gas, hydrocarbons in water) and part of the biocrude.

The biocrude used for hydrogen generation forms (66 ÷ 400) x 80% ≈ 3% of the energy content of the wood. The energy content of the added quantity of hydrogen is about 8% that of the wood.

The gaseous products are used a process fuel and represent about 7% of the energy content of the wood, assuming all the gas to be ethane.

The net energy efficiency is estimated to be 100% - 20% - 13% - 7% + 8 ≈ 70%.

The calorific value of the product is (17,800 x 70%) ÷ 300 ≈ 41.5 MJ/kg.

Emissions
Almost all of the sulphur present in the wood (0.1 kg/tonne) is separated off with the by-products of the HTU process, being converted to SO_2 (0.2 kg/tonne wood) during combustion of these by-products. The amount of SO_2 emitted per tonne of wood depends on the flue-gas treatment employed.

Of the nitrogen present in the wood (1.2 kg/tonne wood) about 80% is removed with the by-products and partly converted to NO_x during combustion of these by-products. The percentage converted to NO_x is governed by the combustion process, among other factors, and is difficult to establish *a priori.* At 50% conversion the flue gases contain about 2 kg NO_x/tonne wood (as NO_2). As with SO_2, the actual NO_x emission depends on the flue-gas treatment applied.

Minerals, chlorine and fluorine dissolve in the aqueous phase and are removed in a treatment unit.

Costs

In calculating costs we have assumed a figure of 18% for annual payback on investment. Annual personnel, maintenance, overhead and contingency costs amount to about 7% of investments. The cost estimate is exclusive of the cost of the biomass.

According to |naber| at 70-80 MWth processing capacity the production costs per tonne of biocrude are approximately $ 145/tonne for a first-of-a-kind plant, possibly falling to $ 75/tonne in the longer term.

Again for a plant of 70-80 MWth capacity, the cost of the kerosene or gasoil produced is an estimated $ 340/tonne for a first-of-a-kind plant. A decrease in the production cost of biocrude to $ 75/tonne would bring the production cost of kerosene/gasoil down to about $ 250/tonne.

Including the cost of the biocrude (approx. $ 10/tonne) would give an ultimate cost figure of about $ 300 per tonne, compared with about $ 170 per tonne of kerosene on the world market. The specific CO_2 reduction costs are then about $ 130/tonne kerosene, or $ 40/tonne CO_2, assuming the production process is CO_2-neutral.

3 Gasification and Fischer-Tropsch synthesis

Hydrocarbon production from synthesis gas via the Fischer-Tropsch reaction was developed in Germany in the 1920s and is employed today in South Africa (Sasol 2 and 3) and Malaysia (Bintulu), among other places. In recent years Fischer-Tropsch synthesis has generated considerable interest as a possible route for producing economically valuable hydrocarbons from by-product or worthless gasoil and natural gas.

The production process consists of two integrated process steps. In the first, organic matter is gasified with oxygen (partial oxidation) and worked up to the quality required for Fischer-Tropsch synthesis (no sulphur, chlorine, metals) and composition (H_2 : CO = 2). Unwanted compounds are removed by means of scrubbing. If the H_2 : CO ratio is too low, it is increased by using H_2 to convert part of the CO into H_2 and CO_2 (shift conversion). Prior to the Fischer-Tropsch reaction, CO_2 is removed by absorption while H_2O is removed by cooling the gas. Gasification and shift conversion are both exothermic processes.

In the Fischer-Tropsch reaction, H_2 and CO react in a molar ratio of about 2 : 1. The reaction products are paraffins and water. The water is so clean that it can be sold as drinking water. The process is exothermic and therefore requires no heat input.

Energy consumption

Table 2 shows the energy efficiency and carbon conversion efficiency of each step of the production process.

Table 2 Energy efficiency and carbon conversion efficiency of process steps

	Preliminary treatment	Gasification	Shift conversion	Fischer-Tropsch synthesis	Whole chain
Energy efficiency	90%	85%	90%	80%	approx. 60%
Carbon conversion efficiency	90%	100%	45%	100%	approx. 40%

According to |Eggels| about 4% of the wood's calorific value is required for electrical power generation to drive pre-gasification treatment in an entrained-bed reactor. It has been assumed that this power is generated in a combined-cycle plant using synthesis gas from biomass. The combined net electrical efficiency of the gasification unit and combined-cycle plant are estimated at 40% (see |Ree). A figure of 10% follows for captive consumption.

The indices for the gasification step have been taken from |Williams| and relate to wood processing in an entrained-bed reactor at a temperature of 1,100°C and a pressure of about 25 bar.

The indices for shift conversion have been calculated using CE's own model, based on a temperature of 320°C. Prior to conversion 1 Nm^3 steam is added

per Nm^3 synthesis gas to attain the right H_2 : CO ratio. The steam is raised using the heat generated in the shift reaction.
The energy efficiency of the Fischer-Tropsch synthesis has been taken from |Goudriaan| and holds for Shell's Bintulu plant. The carbon conversion efficiency follows from the percentage of carbon remaining in the gas as CO after the shift reaction. As mentioned above, CO_2 is removed from the gas stream and emitted.
Energy losses during gasification and Fischer-Tropsch synthesis are in the form of heat released in the course of these process steps. Most of this heat is used to raise steam, the quantity of which is more than sufficient for a steam turbine to be used to meet the entire electrical power demand of the production plant. In principle, steam or power can be sold in the marketplace.

For the process as a whole the energy efficiency is 65% and the carbon conversion efficiency 45%. At the Bintulu plant an energy efficiency of 65% is achieved using natural gas.

Final output

If so required, the end product can consist of about 50% kerosene. Given the CO : H_2 ratio of the synthesis gas and the C : H ratio, the remainder will be mainly gasoil. The product is entirely paraffinic and contains a minimum of 0.1 % vol. of aromatics. The contents of sulphur and other hetero-atoms is below the detection limit of analysis. As a rule the gasoil has a cetane number of 70 (very high). The output of end product is 260 kg/tonne dry wood.

Costs

At Shell's Bintulu plant investments totalled $ 700 mln. This plant has a capacity of about 1,200 MW, about 5,600 tonne dry wood or 8,600 tonne wet wood (35 % wt. moisture) per day. Investment costs include the gasification unit but exclude prior biomass processing (chopping, pulverisation), shift conversion and CO_2 removal. Based on |Williams| the costs of the latter processes are estimated at approx. $ 110 mln.

Annual costs total about $ 220 mln. Depreciation on investments has been calculated based on an annual payback of 18%, the figure also assumed for the HTU route. Following |Williams| maintenance, overhead and general overhead costs are estimated at 6% of investment costs. The Bintulu plant employs 350 people. Assuming an average pre-tax annual salary of $ 45,000/person, personnel costs will total approximately $ 16 mln.

Taking a capacity factor of 97% (based on the Bintulu plant) annual processing costs amount to approx. $ 115/tonne dry wood or $ 410/tonne product. Including the cost of the biocrude, the ultimate cost will be somewhere around $ 450 per tonne of product. Based on the current price of $ 170 and CO_2-free production, this means a cost of $ 280 per 3.3 tonne reduction of CO_2 emission, or $ 85 per abated tonne CO_2.

Literature

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Contents

1 Introduction

This annex aims at a quantification of the role of fuel prices in operating costs. This role has been analysed using five sources:

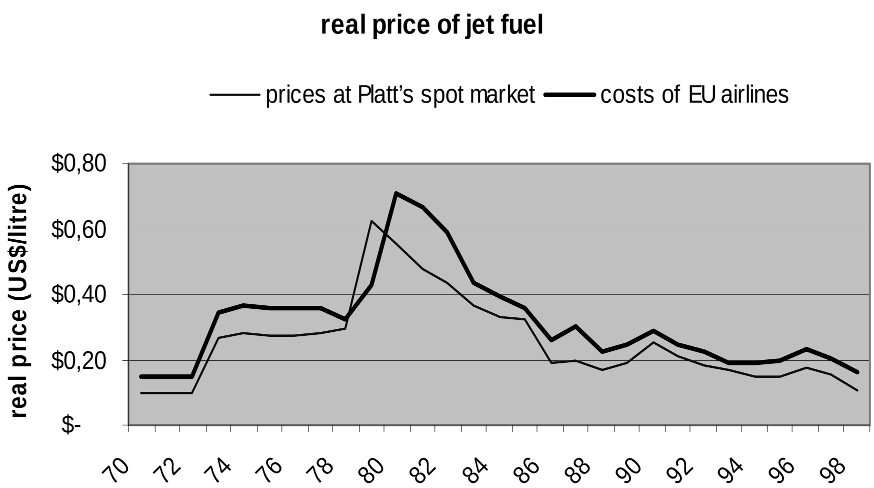
- AVMARK, Airline cost trends and comparisons, 1993;
- AVMARK, Fleet costs report prepared for CE, 1999;
- Doganis, Flying off course, the economics of international airlines, 1992;
- Dempsey, Airline management, Strategies for the 21st Century;
- Database on jet fuel spot market prices 1972-1998, 1999;
- ICAO database on fuel economy trends, used in Michaelis (1996).

2 Trends in fuel prices

The price of aviation fuel has been subject to heavy fluctuations. Before the first oil crisis the price was quite stable. Since then large price shocks have regularly hit the market.

The development of the fuel price has been investigated and corrected for inflation[1]. See Figure 1.

Figure 1 Development of the real price of kerosene (corrected for US inflation). Both world market prices and prices paid by EU airlines are given



The real fuel price has now arrived at the level of before the first oil crisis.

3 Fuel costs as a proportion of Direct Operating Costs

In the beginning of the 1970s the share of fuel in DOC was about 18%. During the first and second oil crises these shares sharply rose to a maximum of almost 50% in 1981. Since then the share readily fell. In 1998 the share of fuel in total costs had fallen to about 17%, back to the level of the early 70s. See Figure 2, Figure 3, and Figure 4 in the next paragraphs.

1 The US consumer price index has been used.

4 Effects of fuel prices on fuel efficiency

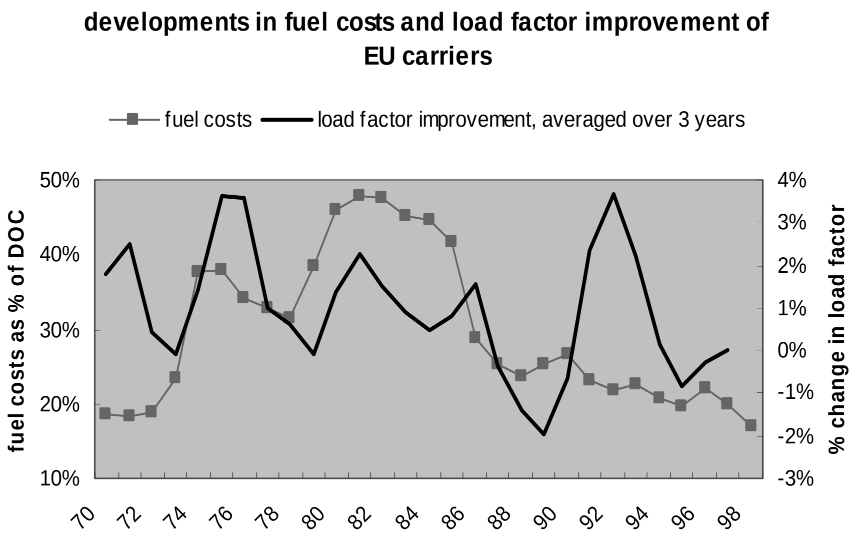
Airlines can react to higher fuel prices in a number of ways.

Short term: flight operations
In the very short term, they can try to change flight operations such that fuel costs are minimised. This implies that flight speeds, and starting and landing procedures may be slightly changed. The likely effect of this kind of changes is quite small, only a few per cent.

Medium term: load factor
In the medium term (one to three years), airlines will have to adapt their operations such that least variable costs are met. When variable costs rise as a consequence of a higher fuel price, the 'break even' load factor increases, and airlines will react to this situation in the medium term.

The development in fuel prices and average load factor of EU airlines can be seen in Figure 2.

Figure 2 Development of fuel costs and load factors of EU airlines (load factors averaged over three years following the fuel price)

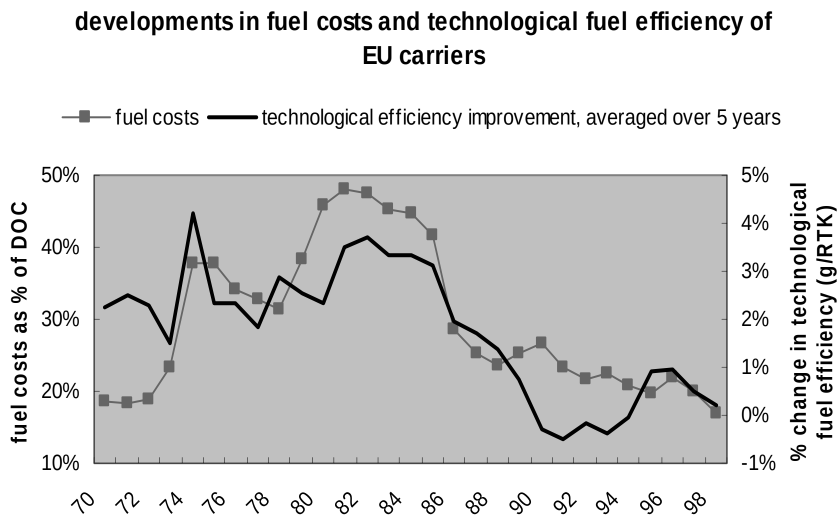


There is a rather apparent relationship between fuel prices and load factors. The stiff decline in load factors in 1990 can be attributed to external circumstances (the Gulf War), just as the powerful recovery after that (undercapacity).

Medium to long term: fleet renewal
In the medium to long term, airlines will adapt the fleet they are flying with. The largest gains in fuel efficiency can be achieved by replacing old aircraft by state-of-the-art versions, or by re-engining existing aircraft. The latter aspect can be currently seen in a reversed way: some airlines are currently replacing slow but energy-efficient turboprop engines by faster, but less energy efficient turbofan engines. With the current fuel prices, the DOC savings as a result of more block hours outweigh the extra fuel costs ||.

The development of fuel costs and technological efficiency improvement is shown in Figure 3.

Figure 3 Fuel costs and technological efficiency improvement (efficiency improvement averaged over five years following the fuel price)



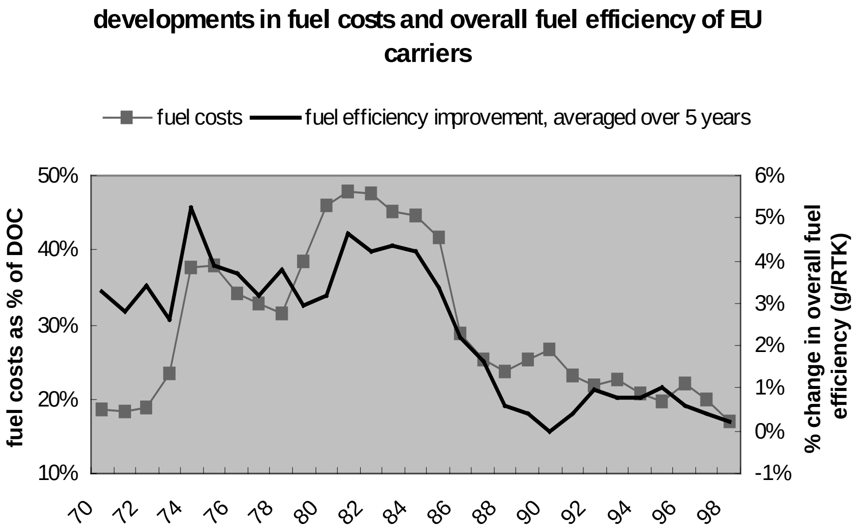
The figure shows a remarkably strong relationship between fuel prices and reaction in terms of technological fuel efficiency improvement.

Long term: technology development
In the very long term, high fuel prices create incentives for new technology development. This can be seen in the early 80s, when the development of the propfan was given much attention. We did not make graphs of this, as these long term developments are not readily statistically identified.

Overall efficiency improvement in reaction to fuel prices
The developments on load factors and technological improvements have together boosted the fuel efficiency of the world's aviation. Since the early 70s fuel efficiency has more than doubled, from about 900 grams of jet fuel per RTK to 400 grams per RTK.

Figure 4 shows how this efficiency improvement evolved over time.

Figure 4 Development of fuel costs and fuel efficiency of EU aviation. Fuel efficiency improvements are averaged over 5 years.



Again, there appears to be a strong medium term relationship between fuel prices and fuel efficiency improvement from technological and operational (load factor) developments.
The very major part of the efficiency improvement has been realised from the early 70s to halfway the 80s, the time of high oil prices. This was related to technological developments: the end of sales of old narrow body aircraft like the DC9 and the world wide introduction of wide body aircraft such as the B-747.

5 Conclusions

The following conclusions can be drawn from this chapter:

1. The real price of jet fuel has been heavily fluctuating. The current level is historically very low. Airlines currently pay about $ 0.15 per litre, while in 1980 (the all time high) they paid about 4 to 5 times as much in real terms;
2. Fuel costs as a proportion of the aircraft's DOC (Direct Operating Costs) are currently about 17%, while in the early 80s this amounted to about 45%
3. Historical data suggest a strong historical relationship between aviation's fuel prices and fuel efficiency. Especially the relationship between fuel prices and technological efficiency improvements has been strong. The relationship between fuel prices and operational (i.e. load factor) improvements is somewhat weaker. As a reaction to the high fuel prices in the late 70s and early 80s, airlines reduced their amount of fuel burned per RTK by 3 to 4% per annum on average. Since the drop in fuel prices in the second half of the 80s, fuel efficiency improvement have been very moderate and interest in innovative engine and aircraft concepts has dropped.