ESCAPE

Economic SCreening of Aircraft Preventing Emissions

Main Report

Delft/ Ede
August 2000

Publication data

Library data:

J.M.W. Dings (CE Delft), P.M. Peeters (Peeters Advies), J.R. van der Heijden and R.A.A. Wijnen (Delft University of Technology, Faculty of Aerospace Engineering)
ESCAPE: Economic Screening of Aircraft Preventing Emissions, Main Report
Delft: CE, Solutions for environment, economy and technology, 2000

Aircrafts / Aircraft construction / Innovation / Fuels / Consumption / Reduction / Weight / Engines / Speed / Technology market / Environmental policy / Investments / Return

Price (excl.mail): ƒ 40,00 (€ 18,15)
Publication code: 00.4404.16

Clients:
Dutch Transport Research Centre (AVV)
Dutch Ministry of Housing, Spatial Planning and Environment (VROM)

CE in brief

CE, Solutions for environment, economy and technology, is an independent research and consultancy organisation working at the interface between the environment, the economy and technology. Our aim is to develop innovative, structural solutions which are feasible in both practical and policy terms and which also make economic sense. Such solutions must be rooted in a proper understanding of the various interests at play in contemporary society.

CE is organised in four divisions with the following areas of work:
- environment & economy
- transport & traffic
- materials & waste
- (renewable) energy.

If you are interested in the activities of a particular division, simply contact CE and ask for a list of their publications. More information is available twice yearly in CE's Newsletter, which reviews current projects and can be subscribed to free of charge. Tel. (+31)(0) 152 150 150, fax (+31)(0) 152 150 151, E-mail: ce@ce.nl, URL: www.ce.nl).

Foreword

Air transport is a growth industry: since World War II annual growth rates have run at between 5 and 10%. Although this growth has been accompanied by tremendous improvements in fuel efficiency, total aviation emissions have continued to rise steadily In the estimate of the IPCC's Special Report on Aviation and the Global Atmosphere, the contribution of air transport to global warming was about 3.5% in 1992. Given the decline in both transport growth and rate of environmental efficiency improvement indicated by scenario studies, between 2000 and 2040 the IPCC expects total aircraft carbon emissions to increase by between 100 and 350%.

As these figures indicate, the aviation industry will have to substantially improve the environmental efficiency of its product if future growth is to be secured within sustainability limits. The role of aircraft technology is obviously crucial here. As most technology projections indicate, however, the substantial improvements required are not going to be easy, given the amount of effort the industry has already devoted to enhancing the environmental profile of its product.

The *technical* feasibility of environmentally superior aircraft is an issue that has received considerable attention in recent years. With regard to the *economic* feasibility of such aircraft the situation is very different, however, as no publicly available attempts have yet been made to evaluate the environment-economy trade-offs in aircraft technology, design and operation. This is understandable. The calculations and assumptions involved in such an analysis are anything but straightforward. The aviation industry is particularly complex, moreover, as non-economic factors play a major role in assessing technological feasibility.

We hope that this report, backed up by a background report consisting of seven annexes, will usefully contribute to discussions in this area by providing due information on the environmental and economic benefits of a number of new aircraft technologies and designs.

We gratefully acknowledge the support received from the Dutch Transport Research Centre and the Dutch Ministry of Housing, Spatial Planning and Environment in funding this research. Special thanks are due to the members of the Steering Committee: Angelien van Boxtel, Marlouke Durville, Paulien Feimann, Patrick Haagmans, Rudi den Hertog, Evert Jesse, Diederik de Jong and Frans Vollenbroek, for their support and inspiration. Special thanks also to Nigel Harle for his invaluable editing work.

The authors,

Jos M.W. Dings
CE, Solutions for
environment, economy
and technology
Oude Delft 180
NL - 2611 HH Delft
tel.: (+31)(0) 152 150 150
fax: (+31)(0) 152 150 151
dings@ce.nl
www.ce.nl

Paul M. Peeters
Peeters Advies
Rodestein 12
NL - 6714 CG Ede
tel.: (+31)(0) 318 692 390
fax: (+31)(0) 318 692 287
pmpeeters@peetersadvies.nl

Roland A.A. Wijnen and
Joost R. van der Heijden
Delft University of Technology
Faculty of Aerospace Engineering
P.O. Box 5058
NL - 2600 GB Delft
tel.: (+31)(0) 15 278 5132
fax: (+31)(0) 15 278 3444
r.a.a.wijnen@lr.tudelft.nl
www.lr.tudelft.nl

Contents

Executive summary

At a glance

- It is *technically* feasible in the medium term to reduce the fuel consumption of new aircraft by 30-40%, compared with the expected 2010 average aircraft, without reductions in design speed. This can be achieved by applying ultra-high bypass turbofan propulsion, and by reducing the aircraft's drag and weight;
- Applying high speed propeller propulsion further increases this *technical* potential, albeit at the price of a somewhat lower design speed. The lower the design speed, the higher the reductions in fuel consumption that can be achieved. For example, a high-speed propeller driven aircraft flying about 15% slower could use 50% less fuel than the expected 2010 average aircraft;
- Aircraft that achieve this better fuel economy can also have slightly lower Direct Operating Costs (DOC) per available seat kilometre than the expected 2010 average aircraft, under current market circumstances and current policies;
- Nevertheless, operating these aircraft will probably *not* be *economically* feasible without changes in market circumstances, environmental policies or technology development policies. There should be better perspectives on cost savings from operating these aircraft, and barriers like the huge investment risks should be decreased.

Outline: new aircraft designs to reduce emissions
According to the IPCC's Special Report on Aviation and the Global Atmosphere (1999) in 1992 the contribution of aviation to climate change was about 3.5%. In its Communication on Air Transport and the Environment (November 1999) the European Commission states:

'…the air transport industry is growing faster than we are currently producing and introducing technological and operational advances which reduce the environmental impact at source. The overall environmental impact is bound to increase since the gap between the rate of growth and the rate of environmental improvement appears to widen in important fields such as emissions of greenhouse gases. This trend is unsustainable and must be reversed because of its impact on climate and the quality of life and health of European citizens. The long-term goal, therefore, must be to achieve improvements to the environmental performance of air transport operations that outweigh the environmental impact of the growth of this sector.…'.

Environmentally superior aircraft technologies and designs have an important part to play in achieving the long-term goal identified by the Commission. Although there is plenty of information available on the *environmental* potential of a variety of emission abatement technologies, far less is known about the *economic* potential of these technologies and even less about the economic potential of innovative aircraft designs that are more environmentally sustainable.
This study therefore focuses on the economic potential of new, reduced-emission aircraft technologies and new aircraft designs. The prime focus

here is on fuel consumption, because this provides a good indicator for CO_2 and water vapour emissions and because reduction of fuel consumption is an important driving factor in the aviation industry.
The following key questions are addressed in this study:

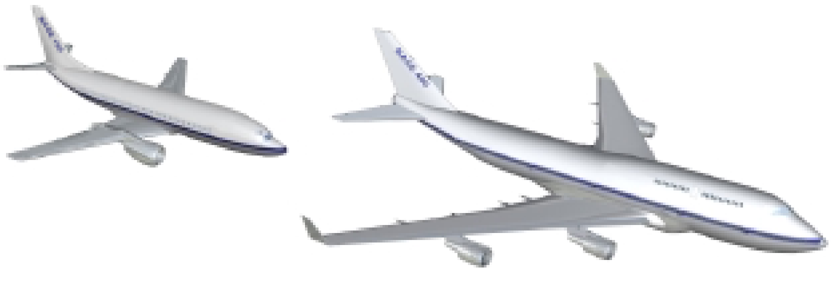
- Are there technologies for reducing fuel consumption which are attractive in the longer term or technologies which are uncompetitive under present market conditions; what would it cost to apply these technologies?
- Could some of these technologies be combined in new aircraft designs, thus leading to synergies with respect to the environment and economics?
- What are the market barriers impeding introduction of these new designs and how can they be removed?

To obtain well-grounded answers to these questions, a model was developed to assess the economic feasibility of new, more fuel-efficient aircraft technologies and designs. The model calculates both fuel and flight time for a given range and uses this information to calculate the Direct Operating Costs (DOC). The model also provides information on payload range and landing and take-off (LTO) performance and includes parameters for assessing environmental effects such as noise, NO_X emissions and contrail formation.

Baseline and new designs
A number of engine and airframe technologies designed to reduce fuel consumption beyond 'baseline' expectations for the year 2010 have been identified and their costs and environmental impact assessed.

Characteristics
For both the short-haul (approx. 150 seats) and the long-haul (approx. 400 seats) markets, four conceptually different new aircraft designs were identified, each equipped with a different package of these technologies. These new aircraft concepts were compared with the 2010 baseline aircraft. The designs considered have been elaborated at their primary, conceptual stage, employing relatively simple relations between parameters of interest and technological characteristics. The descriptions, and first impressions of possible layout of the aircraft, are as follows:

BASE150 and **BASE400**, the anticipated market-average 2010 aircraft for the 150- and 400-seat market, respectively, derived from current representative aircraft in these markets;



U-FAN150 and **U-FAN400**, incorporating ultra-high bypass turbofan engines, wings with a high aspect ratio, aerodynamic enhancements and lighter-weight materials; same cruise speed as BASE150 and BASE400 designs;

H-PROP150 and **H-PROP400**, incorporating counter-rotating high-speed propellers and high aspect ratio wings, and designed for about 5% lower cruise speed;

M-PROP150 and **M-PROP400**, propulsion technology identical to the H-PROP designs, except designed for about 15% lower cruise speed, and finally

F-CELL150 and **F-CELL400**, rather futuristic designs, liquid hydrogen-fuelled aircraft with counter-rotating high-speed propellers driven by electric motors powered by fuel cells; cruise speed about 20% below today’s aircraft. Given the uncertainties surrounding costs, this configuration been assessed in environmental terms only.

Table 1 Technological features and performance data of aircraft designs considered in this study

	short-haul aircraft (approx. 150 seats)			long-haul aircraft (approx. 400 seats)		
	U-FAN	H-PROP	M-PROP	U-FAN	H-PROP	M-PROP
propulsive features						
ultra-high bypass turbofan engine	X			X		
high-speed, counter-rotating propeller, turbine engine		X	X		X	X
non-propulsive features						
high aspect ratio	X	X	X	X	X	X
aerodynamic clean-up	X	X	X	X	X	X
laminar wing section			X			X
active laminar flow control	X			X		
new (lighter) materials	X			X		
performance						
cruise speed (Mach)	0.745	0.72	0.64	0.84	0.74	0.70
cruise speed (% diff. from BASE)	-0%	-3%	-14%	-0%	-12%	-17%
cruise altitude (km)	10.0	10.0	9.0	11.0	10.0	9.5
energy consumption, *full flight* (% diff. from BASE150/400)	**-31%**	**-35%**	**-46%**	**-38%**	**-42%**	**-49%**

Environmental performance

The U-FAN concepts reduce fuel consumption by about 30-35% with no sacrifices in speed relative to the BASE aircraft.

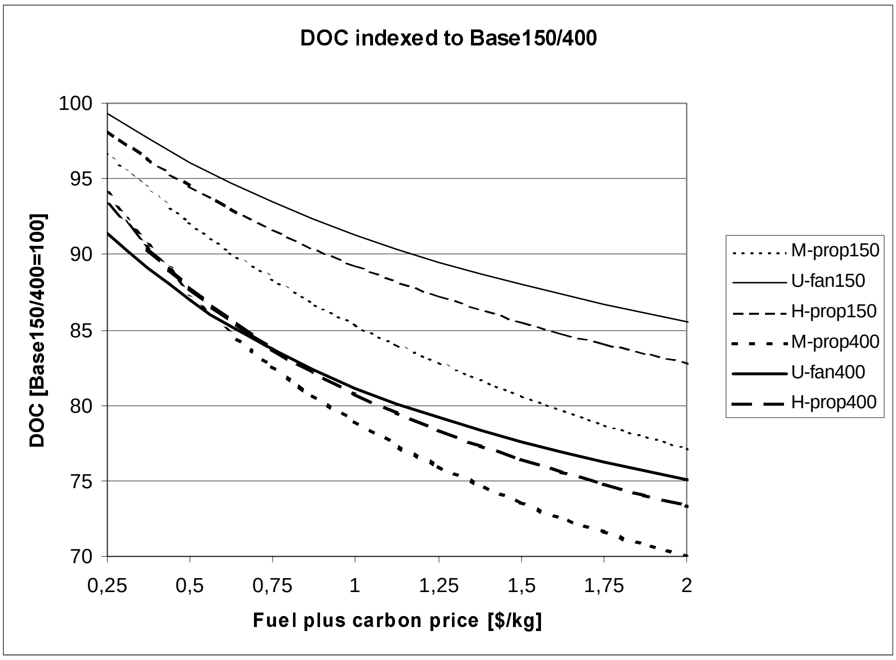
The H-PROP concepts reduce fuel consumption by 35-40% at the expense of about 5-10% lower cruise speeds.

The M-PROP concepts reduce fuel consumption by about 45-50%, at about 15% lower cruise speeds.

Direct Operating Costs

The Direct Operating Costs (DOC) of the U-FAN, H-PROP, and M-PROP designs are shown in Figure 1.

Figure 1 Direct Operating Costs (DOC) of the U-FAN and H-PROP designs as a function of fuel plus carbon price*, relative to the BASE aircraft



* In this study the 'fuel plus carbon price' is used as an indicator for the economic 'weight' of fuel consumption and CO_2 emissions. It is expressed in dollars per kg of kerosene and governed on the oil market and on environmental policies like charges or emission reading regimes.

The figure shows that the new concepts may have lower DOC than the BASE designs in terms of dollar cents per available seat-kilometre, even at normal fuel plus carbon price levels of around $0.25 per kg. These cost savings will be greater at higher fuel plus carbon prices: at $1.00 per kg, the DOC edge over the BASE designs rises to 15-30%. Calculations indicate that the long-haul, 400-passenger designs become particularly attractive as the price of carbon emissions rises, which can be explained by the high share of fuel in DOC on long-haul flights.

The payload range and field performances of all six designs are comparable with those of the 2010 baseline aircraft.

Barriers to overcome, opportunities to grasp

Although all the new concepts considered have lower DOC than the baseline aircraft, they have not yet been introduced in the fleet. This is because DOC is not the only parameter of relevance for the development and successful introduction of new aircraft designs. There are a number of other barriers hampering market entry, of which the following appear to be the most important:

- Under the present circumstances the prospect of DOC reduction provides insufficient incentive for running the development and investment risks associated with new aircraft designs; the record shows that substantially lower costs are a *sine qua non* for introduction of a new aircraft.
- The propeller-equipped aircraft (H-PROP and M-PROP) have been designed for lower cruise **speeds**. In a range up to a few thousand kilometres, model simulations indicate that this is unlikely to lead to any major operational problems. On long-haul flights, however, passengers may be

willing to pay less for tickets, there may be difficulties incorporating the slower flying aircraft in certain long-range networks and standing maximum crew duty hours may cause incremental rises in cost.

- Penetration of technologies in the civil aviation industry is **slow**, owing to prevailing safety considerations and high development costs.
- The U-FAN designs may lead to somewhat higher **NO_X** emissions if combustion technology remains unchanged; the propeller designs have intrinsically lower pressure ratios and therefore lower NO_X emissions.
- The propeller designs are often associated with higher **noise** levels. However, the technical background study shows that this problem can be addressed through prudent choice of propeller tip speed and climb-out angle.
- There is considerable uncertainty about the impact of the new aircraft designs on the formation of **contrails** and subsequently cirrus clouds, which contribute to global warming. This is an aggregate impact that can be reduced by using thermally more efficient engines and propeller rather than high-bypass turbofan propulsion and by flying at a lower altitude. Whatever the design, however, contrail formation can be greatly reduced through minor revisions of flight altitude and route to allow for actual local weather conditions.
- Airports can currently accommodate aircraft no larger than **80x80** m, which excludes the H-PROP400 and F-CELL400 designs because of their large wing span. This is a ‘chicken and egg’ type of problem of an economic rather than technical nature.

Overall feasibility assessment

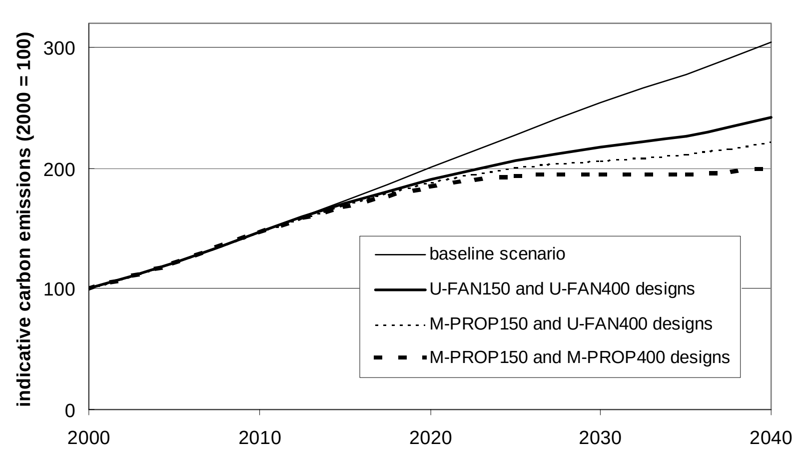
Overall economic feasibility has been assessed by examining considerations of DOC in conduction with the aforementioned barriers, leading to the following conclusions:

- If market conditions, environmental policies and technology (development) policies remain unchanged, none of the new designs considered is likely to be introduced in the foreseeable future.
- In a scenario with changes in these areas the U-FAN400 concept may be the first option to become attractive, followed by the short-haul turbofan or propeller concepts and eventually the H-PROP400 and M-PROP400 designs.
- For the long-haul market, only under fairly extreme circumstances will the propeller concepts considered in this study become economically viable. It would most probably have been better to design these aircraft for higher speeds than has been done in the present study.

Effects on fleet emissions

A computer model was constructed to calculate the impact of gradual introduction of the new designs in the world aircraft fleet (Figure 2).

Figure 2 Estimated impact of introduction of selected new aircraft designs on world fleet fuel consumption.



For a description of the fleet penetration model used, see Sections 2.3 and 5.10. The baseline scenario is a middle estimate based on the IPCC Special Report. No allowance has been made for possible changes in transport demand, average load factors, average aircraft size or aircraft operations. The figure merely indicates the direct impact of new aircraft introduction.

As the figure shows, the scenario in which sales of the M-PROP150 and U-FAN400 designs start to rise in 2010 leads to a 25-30% reduction of carbon emissions in the year 2040 compared with the baseline scenario. Because of the slow penetration of new technologies in the fleet, tangible results would only begin to be felt in 2020,.

More futuristic options: blended wing body, hydrogen, fuel cells

The study also considers more futuristic designs that are certainly not anticipated to penetrate the market before 2010. These include blended wing body aircraft (BWB), and use of liquid hydrogen fuel and fuel cell propulsion.

As the fuel cell option has thus far received only limited attention in the literature, in this study the concept was elaborated a little further. Cost estimates are not included, however.

The two designs considered, F-CELL150 and F-CELL400, are relatively light compared with the concepts previously encountered in this field. An important reason is that our concepts were not designed using the performance specifications of current aircraft as a reference but with specifications more appropriate to this specific technology. Fuel cells and storage tanks for liquid hydrogen are heavy and bulky. F-CELL was therefore given a relatively low design cruise speed of about Mach 0.66, a relatively low cruising altitude (8.5 km) and every available technology to reduce power requirements, and thus weight, costs and energy consumption. This results in 30-50% lower power requirements and 50-65% lower energy consumption, giving a design with a good payload-range and moderate field performance.

The environmental impact is low, owing to the absence of CO_2, NO_X, sulphur and soot emissions and the low in-flight energy consumption. Drawbacks may include:

- the extra low-temperature water emission at cruising altitudes, possibly leading to the formation of contrails and adding to the warming of the global atmosphere;
- the environmental impact of liquid hydrogen production on the ground, which varies widely with the method used but will not be negligible;

- safety, a potential problem owing to the complicated fuel handling and conditioning system; in addition, the use of liquid hydrogen has not been proven, although there are indications that the fuel will be safer to use than kerosene.

Incentives for introduction

Incentives to improve the competitive position of the aircraft concepts considered and accelerate their introduction could consist of a combination of technology ‘pull’ and ‘push’ policies.

On the ‘pull’ side consideration might be given to economic incentives to reduce emissions, such as fuel or emission levies or emission trading regimes. This would increase the economic edge of environmentally superior aircraft over their less efficient counterparts. The revenues ensuing from these policies might, for example, be used to finance ‘push’-type policy options (see below) or be recycled to the airlines according to transport performance. Both these options would improve the environmental efficiency of air transport.

‘Push’-type policies could be employed to reduce the development risks on the supply side. It is recommended to place greater emphasis on environmental performance in technology development programmes such as the European Union’s forthcoming Sixth Framework Programme. More specifically, the following measures will encourage introduction of more fuel-efficient aircraft configurations:

- further study of the pros and cons of high aspect ratio wings, ultra-high bypass engines and high-speed propellers (noise, NO_X, vibration, gearboxes or pitch fans, de-icing and aero-elastic issues) and especially their integration in aircraft configurations;
- further study of the interrelations between design speed, design cruise altitude and environmental impact and the scope for preventing in-flight contrail formation;
- further investigation of alternative designs such as the blended wing body concept;
- incorporation of research on fuel cell power in hydrogen aircraft research programmes.

In particular, the development of *military* freight transport aircraft may represent an opportunity to try, test and prove technologies for the civil market.

1 Introduction

Aviation has always been a high-growth industry and this trend is expected to continue in the coming decades, albeit at a somewhat lower rate. Because of this growth and despite the industry's unceasing efforts to reduce the fuel consumption of new aircraft, greenhouse gas emissions from aviation are still expected to rise by a factor of between 2 and 4.5 between 2000 and 2040, with a factor 3 representing a reasonable average.

The aviation industry therefore faces the tremendous challenge of substantially improving the environmental efficiency of its products in order to secure sustainable growth. It is by no means clear, however, whether suitable technologies exist, whether they are economically viable under current market conditions or whether these conditions must be changed to render these options feasible.

The first part of the study consists of a review of the costs and environmental impacts of a number of specific aircraft technologies. This part of the study was performed by the Delft University of Technology, Faculty of Aerospace Engineering, under the umbrella of the TRAIL Research School for Transport, Infrastructure and Logistics.

A model was consequently developed to evaluate the effects of applying these technologies in two existing aircraft (short-haul and long-haul). The APD (Aircraft Performance and DOC) model consists of a flight and emissions module and a DOC (Direct Operating Costs) module, allowing it to be used for economic optimisation under different environmental policy regimes. This work was carried out by Peeters Advies, an independent consultancy firm specialised in transport and the environment.

Finally, the results were assessed and integrated in the present report, written and edited by CE, Solutions for environment, economy and technology.

Seven separate technical reports have also been prepared as background annexes to the present synthesis report:

1. Peeters Advies, Designing economic aircraft for low emissions, technical basis for the ESCAPE project, P.M. Peeters, Ede, July 2000
2. ADSE, A review by ADSE of 'Designing economic aircraft for low emissions, technical basis for the ESCAPE project', E. Jesse, Hoofddorp, June 2000
3. TRAIL the Netherlands' research school for TRAnsport, Infrastructure and Logistics, with Delft University of Technology, Faculty of Aerospace Engineering, ESCAPE: an overview of technologies to reduce emissions, Heijden, J.R. van der and R.A.A. Wijnen, Delft/Rotterdam, February 2000
4. Delft University of Technology, Faculty of Aerospace Engineering, ESCAPE: Using a more fuel efficient aircraft in a hub & spoke network, R.A.A. Wijnen, February 2000
5. CE, Solutions for environment, economy and technology, ESCAPE: Fuel prices and fuel efficiency: a historic overview, J.M.W. Dings, January 1999
6. CE, Solutions for environment, economy and technology, ESCAPE: Kerosene from biomass, H.C. Croezen, Delft, March 1999

7 CE, Solutions for environment, economy and technology, ESCAPE: Policy options to reduce aviation emissions, J.M.W. Dings, Delft, April 2000

1.1 Project aim

The project aims to answer the following key questions:

- Are there technologies for reducing aircraft fuel consumption which are attractive in the longer term or technologies which are uncompetitive under present market conditions; what would it cost to apply these technologies?
- Could some of these technologies be combined in new aircraft designs, thus leading to environmental-economic synergies?
- What are the market barriers impeding introduction of these new designs, and how might they be removed?

1.2 Project demarcation

This project is concerned with improvements in the environmental efficiency of aviation and in particular with emissions reductions per unit transport performance such as RTK or pax.km[1]. No consideration is given to other options for emissions reduction such as substitution of transport to other modes or loss of demand for aviation.
The market has been divided into two segments: short-haul (SH) flights up to 3,000 km and long-haul (LH) flights of 3,000 km or more.
As year of scope we have taken 2010 and as baseline aircraft current average designs updated with 11 years of conventional engine development in terms of cost, weight and specific fuel consumption.

1.3 Report outline

In Chapter 2 we review trends in world aviation emissions and the likely environmental impact of these emissions.

Chapter 3 describes the input of Delft University of Technology to this project: an elaboration of the emissions reduction potential and costs of several abatement technologies.

In Chapter 4 we introduce the assessment model used (APD, Aircraft Performance and DOC) and present the results obtained.

In Chapter 5 we examine potential barriers that could not be evaluated using the APD model, qualitatively assess the feasibility of the concepts studied and discuss several policy options for accelerating fleet introduction of environmentally enhanced aircraft.

Chapter 6, finally, summarises the main conclusions drawn from the analyses performed.

---

[1] All abbreviations used are explained at the end of this report.

2 Aviation emissions and environmental impacts

2.1 Introduction

This chapter reviews the impact of aviation emissions on the natural environment. Following an introduction on the general nature of these emissions and their projected growth, discussion turns to the atmosphere and the various atmospheric impacts of aviation emissions. Particular consideration is given to the possible effects of supersonic aircraft, before the chapter closes with several concluding remarks.

This chapter is based mainly on the *IPCC Special Report on Aviation and the Global Atmosphere* of May 1999 and a summary of the *White Paper of the Netherlands on Air Pollution and Aviation* of 1995*.*

2.2 Review of aviation emissions

Modern aviation fuels are obtained from the refining of crude oil and consist mainly of hydrocarbons. When complete, the combustion of aviation fuels gives rise to emissions of carbon dioxide (CO_2), water (vapour) (H_2O) and sulphur dioxide (SO_2). Although the combustion efficiency of jet engines is generally very high, in practice combustion is incomplete and a number of other combustion products are also generated, in particular carbon monoxide (CO), volatile organic compounds (VOC) and ‘particulates’, a term referring to a range of substances. Besides products of incomplete combustion, oxides of nitrogen (NO_X) are also formed owing to the high temperatures prevailing in the combustion chamber. Although aircraft engines produce nitrous oxide (N_2O) as well as methane (CH_4), emissions of these two gases are extremely low and have therefore been ignored in this study.

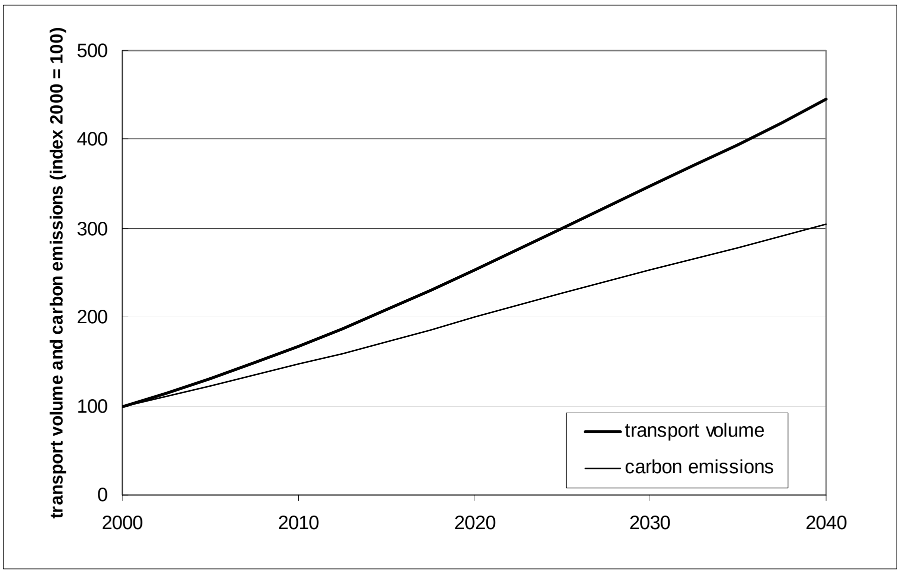
2.3 Current emissions and future trends

At present CO_2 and NO_X are to be deemed the principal aircraft pollutants. In each case 1990 aircraft emissions accounted for 2-3% of global emissions due to combustion of fossil fuels.

Civil aviation is a high-growth market. Over the last two decades air travel has been the fastest growing mode of transport and this trend is expected to continue. Since the early 1960s growth has averaged 2.4 times GDP growth and in the future, too, air transport is projected to grow faster than the economy as a whole.
A literature overview of future emissions scenarios is available in an earlier CE study: 'European aviation emissions: trends and attainable reductions’ |CE 1997a|. The conclusions of this study are consistent with those of the IPCC Special Report and are presented below.

In all likelihood technological and operational environmental efficiency improvements will not be sufficient to offset the growth of civil aviation emissions, especially those of CO_2. Most aviation emission scenarios take a figure of 3-5% for long-term growth of air transport and 1-2% for annual environmental efficiency improvement |IPCC 1999|. These models consequently indicate an annual rise in CO_2 emissions of between 1 and 4%. This implies that the upper and lower 2050 forecasts reviewed in the IPCC report differ by a factor 6 with respect to transport performance and by a factor 9 with respect to fuel consumption |IPCC 1999, p. 329|. Ignoring the high-growth forecasts deemed “probably less plausible” and the low-growth forecasts deemed “likely to be exceeded” reduces the spread to a factor 2.5 for transport performance and 4.5 for fuel consumption. Taking this spread we constructed a transport volume and fuel consumption scenario lying between the ‘base’ and ‘high’ FESG forecasts, which tallies well with the UK’s DTI forecasts but is still below the lowest of the eight EDF scenarios[2]. As the present study is concerned more with aircraft technology than emissions projection we used only a single scenario, shown in Figure 3.

Figure 3 The scenario used for transport volume and carbon emissions for global aviation from 2000 to 2040



The situation is rather different for NO_X emissions, the magnitude of which depends on the quantity of fuel burned and the specific emission index (EI) of the engine under the given circumstances. Despite introduction and progressive tightening of engine emission standards and the existence of potentially promising options to reduce the EI of new engines, there is still little sign of the latter being implemented. This stagnation is due mainly to the fact that the pressure ratio of aircraft engines is increasing (for fuel efficiency reasons). Consequently, NO_X emissions are also expected to grow, at a rate unlikely to deviate much from the projected trend in CO_2 emissions.

2.4 The atmosphere

The atmosphere, the envelope of gases that girds our planet, can be divided into a number of layers, characterised by their temperature profile. In the lowest of these, the troposphere, the temperature drops with rising altitude.

---

[2] DTI: UK Department of Trade and Industry; FESG: Forecasting and Economic Support Group, a CAEP working group on scenarios and economic analyses of environmental policy options; EDF: Environmental Defense Fund.

The troposphere is turbulent and the substances present within it undergo vertical mixing within a few days. Above the troposphere lies the stratosphere. At the bottom of this layer the temperature is fairly constant; higher up it rises with altitude. At the planetary level this makes the stratosphere much more stable than the troposphere. At smaller scales, however, there is exchange between the layers.

The upper boundary of the troposphere is termed the tropopause. The exact position of the tropopause depends on latitude and season and is also influenced by weather systems; it fluctuates strongly and on a day-to-day basis. Near the poles the tropopause is at an average altitude of 6-8 km and near the equator at an average of 16-18 km.

It is precisely in this very complex region of the atmosphere that aircraft fly. The different characteristics of these two layers mean that aircraft emissions differ in their respective effects there. In addition, recent studies indicate that interlayer exchange is greater than previously suspected. It is therefore no simple matter to answer the question 'What are the atmospheric effects of aviation?'

2.5 Greenhouse effect

CO_2

The climate effects of aircraft CO_2 emissions are no different from those of other CO_2 emissions and are relatively clear.[3]

NO_x / O_3 / CH_4

The role of aircraft NO_X emissions has come to be better understood in recent years. Changes in ozone (O_3) concentrations due to aircraft NO_X emissions disturb or influence the earth's radiative field. The quantitative effects depend on location and season and are therefore difficult to compare with the global effects of persistent greenhouse gases such as CO_2. It is currently estimated that the indirect effect on the enhanced greenhouse effect of aircraft NO_X emissions, as a result of ozone formation, is of the same or a smaller order of magnitude than the direct effect of aircraft CO_2 emissions. The increase in O_3 concentrations will be strongest in the Northern Hemisphere.

However, aircraft NO_X emissions are also anticipated to reduce the concentration of methane (CH_4), a strong greenhouse gas. At the global level the radiative forcing effect of increased O_3 and less CH_4 is anticipated to be of the same magnitude, but of opposite sign. At the regional level, though, the radiative effects of O_3 and CH_4 do *not* cancel.

Water vapour (clouds and contrails), sulphate and soot aerosols

There is greater uncertainty about the effects of emissions of water vapour, SO_2 and soot particles than in the case of CO_2 and NO_X. These aircraft pollutants may have a substantial share in the greenhouse effect, because of their influence on the formation of contrails, clouds and aerosols. The radiative effect of aerosols and their ability to modify the properties of clouds are highly dependent on their concentration in the atmosphere and this exhibits pronounced local variation in terms of both magnitude and composition.

The *water vapour* emitted by aircraft accumulates in the lower stratosphere, where it is a potent greenhouse gas. Its radiative effect is relatively minor, however.

---

[3] In this report we shall not discuss the scientific intricacies of the greenhouse effect of CO_2 emissions.

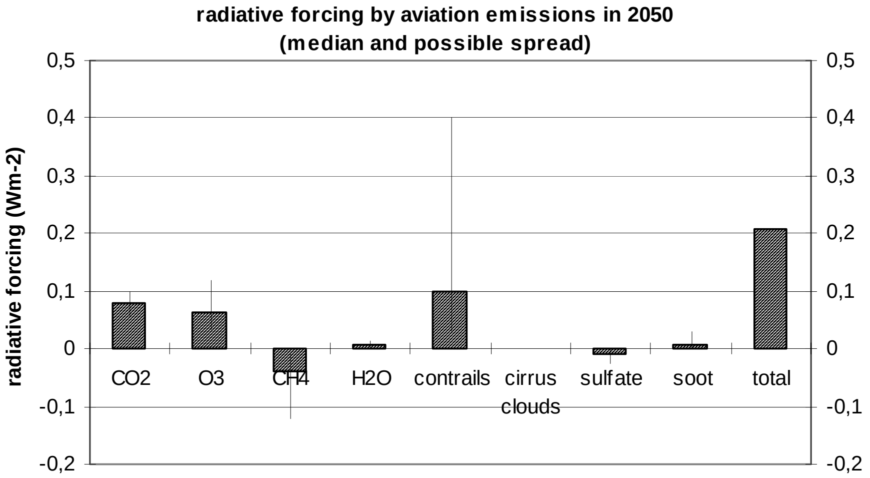
Contrails are triggered by these water vapour emissions, with their optical properties depending on the nature of the particles emitted or formed in the aircraft plume. Contrail formation is governed by the humidity and temperature of the ambient air and the exhaust gas, the presence of particles and the degree of mixing between the exhaust and atmosphere. The lower the exhaust gas temperature and the higher the humidity of the ambient air and exhaust gas, the more readily contrails are formed. On average, contrails cover about 0.5% of central Europe. The radiative effect of these contrails is relatively high.

Extensive *cirrus clouds* have been observed to develop after the formation of persistent contrails. Accumulation of aircraft aerosols may play a part in enhanced cloud formation and/or changes in the radiative properties of clouds. The dynamics of these relationships are still rather unclear, however.

Radiative forcing by *soot aerosols* is of an opposite sign to that due to *sulphate* and both are rather minor.

Figure 4 reviews these findings with respect to the greenhouse effect.

Figure 4 Review of IPCC estimates of globally and annually averaged instantaneous radiative forcing due to aircraft at the tropopause in 2050 in a standard scenario



For comparison: the total radiative forcing due to all anthropogenic greenhouse gases and aerosols is estimated to be 3.8 Wm^{-2} for a mid-range scenario to 2050. The implication of this medium estimate is that in 2050 5.5% of all radiative forcing due to anthropogenic emissions would accrue from aviation.

The IPCC draws the following conclusions with regard to the greenhouse effect:

1 Overall radiative forcing due to aircraft emissions is one to three times higher than that due to CO_2 emissions alone.[4]
2 In 2050 overall radiative forcing due to aviation will be amount to 3 to 15% of total radiative forcing due to all anthropogenic activity (currently about 2-5%).

---

[4] For human activity as a whole, overall radiative forcing is at most 1□ times that of CO_2 alone.

2.6 Ozone layer depletion

The aircraft pollutant that is probably of principal importance in depleting the ozone layer is NO_x. In quantitative terms, however, model calculations indicate that its contribution will only be minor. Scientific understanding of the indirect effects of SO_2, soot and water vapour emissions by aviation is still incomplete and the possibility of these effects proving important, i.e. more so than NO_x, cannot be excluded.
Recent scientific evidence suggests that subsonic aviation, in the troposphere and tropopause, might increase ozone concentrations, while supersonic aircraft, flying substantially higher in the stratosphere, might lead to ozone depletion.

2.7 Acidification

The contribution of aircraft emissions to acidification can, in principle, be readily quantified. Of greatest importance are NO_x emissions, with SO_2 emissions less significant in this respect. At the global level aviation contributes about 0.7% to acidifying emissions of NO_x and SO_2, expressed in terms of acid-equivalents |VROM 1995|.

2.8 Local and regional air quality

The fourth environmental problem due to aviation emissions are their contribution to local and regional air quality problems in residential areas around airports. For some airports this contribution is low, while for others it is high and may cause severe problems. The emission products of greatest potential importance are HC, NO_X, particulates (PM_{10}), SO_2, CO and odours.

2.9 Impacts of supersonic aircraft

A second generation of supersonic aircraft, if developed, might cruise at altitudes about 7-8 km higher than subsonic aircraft, i.e. in the lower stratosphere.

Per unit of fuel burnt the greenhouse effect of stratospheric emissions (i.e. from supersonic aircraft) may be five times greater than that of tropospheric emissions (i.e. from subsonic aircraft). In particular, water vapour and contrails may have a much greater radiative effect in the stratosphere. A fleet of 1,000 supersonic aircraft might thus increase overall radiative forcing due to aviation by about 40%.

In addition, stratospheric NO_x emissions may cause rather serious depletion of the ozone layer, even if the NO_x emission index is reduced to only 5 g per kg of fuel. Any increases in tropospheric ozone concentrations due to subsonic aircraft emissions will be rapidly offset by the ozone depletion caused by a limited number of supersonic aircraft.

2.10 Summary

The overall environmental impact of aviation emissions is briefly summarised in Table 2.

Table 2 Importance of controlling emissions of individual aircraft pollutants for relevant environmental problems |VROM 1995|

environmental effect	control important	control unimportant	importance uncertain
greenhouse effect	CO_2, NO_X, H_2O	VOC, CO	particulates, SO_2,
ozone depletion	NO_X	CO_2, VOC, CO	SO_2, H_2O, particulates
acidification	NO_X	CO_2, SO_2[1], H_2O, VOC, CO, particulates	-
local air quality[2]	VOC, CO, SO_2, NO_X particulates, odours	CO_2, H_2O	

[1] Although SO_2 is an important acidifying agent, the contribution of aircraft emissions is small compared with that of other sources.

[2] The actual impact of the various pollutants depends on local circumstances.

At the global level, the starting point of this study, the principal environmental concerns are the greenhouse effect and ozone layer depletion. The most significant emissions are therefore those of CO_2, H_2O and NO_X.

According to the recent IPCC Special Report on Aviation and the Global Atmosphere, the radiative forcing impact of aviation emissions is about 100 to 300% that of CO_2 alone. In 2050 the this impact may be 3-15% of the radiative forcing due to aggregate anthropogenic emissions, with 5.5% as a medium estimate.
The stratosphere is far more sensitive to ozone depletion (due to NO_X emissions) and radiative forcing (due to water vapour) than the troposphere. Consequently, even a relatively small fleet of supersonic airliners will probably substantially increase the atmospheric impact of aviation.

Aircraft emissions of CO_2 and H_2O are linearly dependent on fuel consumption, while the NO_X emission is dependent on fuel consumption and engine characteristics. As engine emission standards are already in place for NO_X control, the emphasis in this study is on reducing aircraft fuel consumption.

3 New technology input

3.1 Introduction

This chapter describes ongoing technical developments in the aerospace industry that may lead to future reduction of gaseous emissions. The chapter is a summary of a more extensive background report |Delft University of Technology, 1999|. This technology scan considers the following emissions categories:

- CO_2 and H_2O;
- NO_X.

The focus has been on CO_2 and NO_X abatement technologies. The most promising technologies served as input for the *APD model* |*Peeters Advies*, 2000|, described in the next chapter, to establish the effect of fuel and emission charges on aircraft design.

Emissions of CO_2 and H_2O can be cut by reducing fuel consumption. The most important means of reducing the NO_X emission is via development of new combustion chamber technologies. Non-propulsion technologies for the reduction of fuel consumption also have a favourable effect on the NO_X emission and this also holds for certain propulsion technologies. Use of alternative fuels may also contribute to emissions reduction. The various technologies for reducing gaseous aviation emissions considered in the present study have therefore been grouped together in the following categories:

- reduction of fuel consumption;
- reduction of NO_X emission;
- alternative fuels.

The information presented here has been taken from existing literature, with appropriate data being extracted for use as input parameters for analysing the effect of fuel charges on aircraft design. This analysis was performed using the APD model, which compares the Direct Operating Costs associated with application of a given technology at different levels of fuel price. Both short and long-haul flights were thus analysed. For a given technology the main input parameters for the APD model concern the following:

- effects on engine-specific fuel consumption;
- weight effects;
- cost effects;
- purchasing costs;
- maintenance costs.

We shall now briefly describe the principal technologies considered here.

3.2 Reduction of fuel consumption

This study considers three kinds of technology for reducing fuel consumption:

- propulsion;
- aerodynamic features;
- light-weight materials.

3.2.1 Propulsion

In the realm of propulsion there have been a number of developments of relevance for fuel consumption reduction, summarised below.

Conventional turbofans
In the course of the eighties and nineties ongoing development of conventional turbofans resulted in a third generation of turbofans, a trend expected to continue in the future. Possible improvements that might lead to reduced fuel consumption include higher pressure ratios and temperatures, application of new light-weight materials and improvement of combustion chamber technologies. Development of conventional turbofans has been used in this study as a reference for comparison with other technologies.
For the 2010 baseline the following input has been implemented in the APD model for conventional turbofans:

- 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%.

High-speed propeller engines
We also examined use of high-speed propeller engines, a compromise between a so-called ’propfan’ and a conventional turboprop engine. The propfan works on the principle of increasing the engine bypass ratio beyond the ratio of current turbofans, which is between about 5 and 9. The equivalent bypass ratio of propfans may be 30 to 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 favourable effect on the NO_X emission. Because of their larger fan diameters, the fan pressure ratios of propfans are generally 1.05-1.3, compared with 1.6-1.7 for conventional turbofans.
With propfans it is anticipated that fuel consumption can be reduced by up to 35%. Possible disadvantages of propfans relative to conventional turbofans are high noise and vibration levels, high weight due to the large propeller and need for a gearbox, and high purchase and maintenance costs due to the technical complexity. Noise, vibrations and maintenance costs can be reduced to some extent by lowering the fan speed.
The high-speed propeller considered in this study is such a ‘lower-speed’ propfan. For the 2010 baseline the following input has been implemented in the APD model for high-speed propeller engines:

- Fuel consumption: according to ADSE engine table.
- Engine weight for the basic engine scaled for a 150-seater, incl. propeller and nacelles: 3,400 kg.
- Cost effects: +20% maintenance costs.

The impact of conventional turbofan development on fuel consumption has been factored in to propfan development.

Ducted ultra-high bypass ratio engines
The class of ducted ultra-high bypass ratio (UHB) engines can be roughly divided into ultra-high bypass ratio turbofans and ducted propfans. UHB turbofans generally feature fan pressure ratios of between 1.45 and 1.7 and bypass ratios of up to 12. Ducted propfans have pressure ratios of 1.30-1.45 and bypass ratios of 12-20. At fan pressure ratios below 1.5 and bypass ratios over 9 a gearbox may be required between the fan and turbine. At larger bypass ratios ducted UHB engines may exhibit drawbacks similar to those mentioned for propfans. Besides nacelle shielding, another advantage

of the ducted engine with respect to noise is that adaptive liners can be applied.

For the 2010 baseline the following data has been used in the APD model for ducted ultra-high bypass ratio engines:

- Fuel consumption: -15% SFC;
- Engine weight effect: +10%;
- Engine price effect: +10%;
- Engine maintenance costs effect: +10%;
- Nacelle diameter: +25%.

The impact of conventional turbofan development on fuel consumption, engine weight and engine price has been factored in to UHB engine development.

3.2.2 Aerodynamic features

Aircraft have a variety of aerodynamic features, the most important of which 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 means of specially designed shapes and smoothed surfaces. Active laminar flow control uses suction to smooth air flow over the aircraft. Hybrid laminar flow control is a combination of natural and active laminar flow control. Laminar flow control is applied mainly on the wings. Full realisation of the potential drag reduction achievable by means of laminar flow control requires intensive cleaning and therefore increases maintenance costs. LEBU provisions include small grooves or thin plates applied on aircraft parts (generally fuselage and nacelles) to break up large vortices and reduce drag. It is also possible to reduce parasite drag by aerodynamically ‘cleaning up’ the design.

For the 2010 baseline the following input has been implemented in the APD model for the effect of active laminar flow control and aerodynamic clean-up:

- 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 impact of conventional turbofan development on fuel consumption, engine weight and engine price has been taken into account in the APD model calculations.

For passive laminar flow the same reduction of drag can be achieved, but with only 10% increase in airframe maintenance hours. Aerodynamic clean-up of the aircraft alone accounts for about 5% lower parasite drag at negligible cost.

3.2.3 Light-weight materials

A variety of new lightweight materials are used in modern aircraft, the most important of which are metal alloys, composites and ceramics. Composites can be subdivided into fibre-reinforced plastics, fibre-metal laminates and metal-matrix composites. Although these new materials are often significantly more expensive than their conventional counterparts, there are several incentives for application. Besides weight reduction they also have significant advantages with respect to safety, corrosion, fatigue and production costs.

For the 2010 baseline the following data on light-weight materials use have been implemented in the APD model:

- Weight effect with maximum application: -8% aircraft empty weight;
- Aircraft purchase price effect:
  - short-haul: +$ 340 per kilogram replaced conventional material;
  - long-haul: +$ 300 per kilogram replaced conventional material;
- Maintenance costs effect:
  - +50% airframe (structure excluding systems) maintenance man-hours.

The impact of conventional turbofan development on fuel consumption, engine weight and engine price has been factored in to the APD model calculations.

3.3 Reduction of NO_X emission

The main approach to aircraft NO_X emission reduction is through improved combustion chamber technology. NO_X formation increases with combustion temperature, reaching a maximum when the fuel-air ratio in the combustion chamber is stoichiometric, i.e. such that all the oxygen in the air is consumed, yielding only CO_2 and H_2O as exhaust gases. In conventional engines combustion takes place mainly in the primary zone of the combustion chamber, where part of the engine air is mixed stoichiometrically with the fuel. In the dilution zone the gas temperature is lowered by admixing more air. To reduce formation of NO_X the stoichiometric temperature must be avoided, which can be accomplished by applying a leaner or richer than stoichiometric fuel-air ratio. In order to avoid excessive emissions of CO and HC (unburned hydrocarbons) the mixture may not be too lean, however, nor may it be too rich, to avoid smoke discharge. The majority of the technologies currently used employ 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 optimised at different thrust levels by using two combustion zones, each with its own set of burners.
- *Variable geometry*
  Variable airflow inlets are used to achieve a leaner air-fuel mix following primary combustion.
- *Lean premixed pre-vaporised (LPP) combustion*
  A lean mixture is created in the combustion chamber at all thrust levels. This requires a very homogeneous air-fuel mix, which can be achieved by premixing or pre-vaporation. Mixing may take place either inside or outside the combustion chamber. External mixing carries a risk of flashbacks, i.e. ignition in the premixing section, internal mixing a risk of ignition before completion of the mixing process.
- *Rich-burn, Quick-quench, Lean-burn (RQL) combustion*
  The principle of this concept is two-stage combustion, using a rich fuel-air mix in the first stage of the combustion chamber and a lean mix in the second, where the excess fuel from the first is burned. RQL combustion requires a very homogeneous air-fuel mix and rapid admixture of air after the rich-burn phase (quick-quench) in order to avoid the stoichiometric ratio.

- *Chemical additives and catalysts*
  There are two types of catalytic combustion. Catalysts are used in two ways. The first is catalytic combustion, which requires a lower inlet temperature than conventional combustion processes. Again, a homogeneous air-fuel mix is necessary. The second is catalytic reduction of pollutants in the exhaust stream.

LPP and RQL combustion appear to be the most promising options, with some sources claiming up to 90% reduction of NO_X emissions.

The APD model used in the present study makes no allowance for technological developments in the field of NO_X abatement, for several reasons:

- Insufficient data on the weight and cost effects of NO_X abatement technologies.
- Insufficient data on NO_X reduction in the various flight phases.
- The complexity of NO_X emission calculation for the entire flight.
- The complexity of NO_X emission charge implementation.

3.4 Alternative fuels

The alternative fuels evaluated in this study are liquid hydrogen, liquefied natural gas and alternative kerosene. Liquid hydrogen (LH_2) and liquefied natural gas (LNG) are cryogenic fuels. Use of LH_2 could reduce emissions of CO_2 and soot particles by 100%. Per unit mass the heating value of LH_2 is three times that of conventional fuels, a favourable figure for operational aircraft weight. The volume of LH_2 per unit mass is four times that of conventional fuels, however, implying a need for larger on-board fuel tanks. Furthermore, LH_2 cannot be carried in the wing but must be stored in the fuselage. This implies significant structural changes to the fuselage, while also the wing weight increases due to the lack of weight relief. The major engineering modifications involved may complicate use of LH_2 in the near term.

Other disadvantages of LH_2 are the large amount of energy required for production and additional emission of the greenhouse gas H_2O. Furthermore, liquid hydrogen would require new infrastructure for distribution and storage. An advantage of LH_2 is its favourable impact on aircraft energy consumption. All these aspects are currently being investigated in the so-called CRYOPLANE project, part of the 5th Framework Programme of the European Union.

On-board storage requirements for LNG are approximately 50% greater than for kerosene and a switch to this fuel therefore also implies major engineering modifications, which may hamper use of LNG in the near term. The infrastructure for LNG distribution is already largely in place. Changes would be required at airports, however. Although use of LNG is accompanied by a slightly H_2O emissions, it offers prospects for reducing fuel consumption and NO_X emissions.

The most important variant of alternative kerosene evaluated in this study is biomass-based kerosene. Because the vegetation from which this is produced absorbs CO_2 from the atmosphere, the CO_2 emitted by aircraft using this fuel forms part of a closed cycle. There are two main processes for producing biomass-based kerosene: the HTU/HDO process and gasification followed by Fischer-Tropsch synthesis, yielding a kerosene price of approximately $ 300 and 450 per tonne, respectively. For more detailed information see Annex F.

Because of the uncertainties concerning the cost effects of LH_2 and LNG use and the major engineering modifications implied, use of these alternative fuels has not been evaluated with the APD model. The fuel charge that would render use of biomass-based kerosene economically viable can be readily established by comparing the cost per tonne of biomass-based and conventional kerosene. No price for conventional kerosene is mentioned here, as this price is subject to significant fluctuation.

4 Assessing new technologies and designs

4.1 Introduction

In this core chapter, four short-haul and four long-haul new aircraft are designed and evaluated. The primary focus is the potential trade-off between flight economics, fuel consumption and the so-called 'fuel plus carbon price'[5], which have been assessed within boundary limits with respect to noise and NO_X emissions, payload range performance and field performance (runway requirements).
The main question is how these trade-offs work out in practice. Theoretically these have been demonstrated (e.g. Morrison, 1984), but the theory provides little quantitative information on their practical impact. To quantify the effects of these trade-offs we examined the benefits and costs of eight conceptual designs differing significantly in terms of fuel consumption.

In developing and evaluating these designs we have based ourselves on two typical representatives of the short-haul and the long-haul market. These so-called 'baseline aircraft' have been updated to the anticipated technological state-of-the-art in 2010 to create the BASE150 for the short-haul and BASE400 for the long-haul market. Each individual technology and new design has been compared with this 2010 state-of-the-art.

Full optimisation and balanced aircraft design obviously requires a large workforce and a budget of millions and this study has no pretension of delivering full preliminary designs for a high fuel plus carbon price market. The 'designs' presented here are based on relatively simple relations between technological characteristics and the main parameters of interest. They represent an initial reconnaissance of possible solutions yielding something like 90% of the final value of the main design parameters. What we have done is use a high fuel plus carbon price in the design process to establish design speeds and parameters such as wing aspect ratio.
In the following sections we first discuss the methods used in this study, after which the results for the individual technologies are presented. From this evaluation it can be concluded that several technologies are in themselves prohibitively expensive as options for reducing environmental impact. However, if these technologies are combined in a new design the result is a

---

[5] In this study the 'fuel plus carbon price' is used as an indicator for the economic 'weight' of aviation fuel consumption and CO_2 emissions. It is expressed in dollars per kg of kerosene, and governed on the oil market and on environmental policies like charges or emission reading regimes.

much more economic aircraft. This design is described in § 4.4. Promising unconventional configurations are described in § 4.5.

4.2 Evaluation and models

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

- 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 MTO rating;
- enough reserve fuel for an alternative destination and maintaining a hold pattern of specified duration.

The DOC module calculates the costs of oil and fuel, flight crew, cabin crew, landing charges, depreciation and maintenance based on the block fuel, distance and time calculated by the performance model. In all cases aircraft utilisation in hours per year was kept constant at the baseline value. The direct effect of lower cruise speeds on revenue tonne kilometres (RTK) is thus included in all DOC calculations.

In adjusting the baseline aircraft for new technologies and designing new aircraft use has been made of appropriate tools for the sizing and scaling of dimensions, weights, costs and drag. Most of these tools are based on statistical methods from the literature and have been adjusted as far as possible to the baseline models.

4.3 Individual technologies

4.3.1 Description

The technologies examined come under three headings: propulsion (three technologies), aerodynamics (two) and materials (one). These have been evaluated by ‘virtually’ introducing them into the baseline aircraft as a kind of part-redesign or retrofit, although in the real world it is obviously not recommended to retrofit a Boeing 737-400 with propeller engines, for example. Fuel cell technology has not been evaluated as a virtual retrofit, because it requires too many design changes. Consequently, it has been evaluated only as a new overall aircraft design (§ 4.4).

The conventional approach to enhancing the fuel efficiency of turbofan engines is to increase the by-pass ratio, which reduces both fuel consumption and CO_2 emissions as well as noise. Because of the higher temperature and pressure ratio of the core engine, however, NO_X emissions may likewise be higher. This line of development has been evaluated by modelling introduction of ultra-high bypass engines (UHB).

In the eighties the development of ‘Propfans’ drew considerable attention owing to the oil crisis and high prevailing fuel prices. Propfans are turbine engines driving a special high-speed counter-rotating propeller with a large number of highly swept blades. Propfans are designed for flight at high mach numbers up to 0.85. The literature studied indicates that these engines have faced many problems, including high vibration and noise levels. However, they promised a major reduction in specific fuel consumption. As oil prices fell in the nineties, interest in the propfan diminished and only a few research projects survived.

In one of these, the Dutch Green Aircraft project, it transpired that an aircraft equipped with 2*6 high-speed counter-rotating swept propellers designed for mach 0.75 can alleviate the aforementioned problems while maintaining 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 futuristic one: use of high-speed propellers driven by a super-conducting electric motor powered by fuel cells. This option requires the use of liquid hydrogen fuel (LH_2). Fuel cells convert hydrogen and oxygen (from the ambient air) directly into electricity, which is used to drive the motor. Cryogenic engine cooling is accomplished with the LH_2. Fuel cells hold out the promise of high energy efficiency. However, they take up a lot of space and are relatively heavy, both undesirable characteristics in a fuel-efficient aircraft.

Use of liquid hydrogen may improve the environmental performance of both UHB and HSP engines. However, this has not been studied in further detail here.

Aircraft designers have three options at their disposal for decreasing aerodynamic drag: reducing parasite drag, induced drag and mach drag. The first two options are elaborated here. In the full designs (§ 4.4) consideration is also given to mach drag.

Parasite drag can be reduced by aerodynamically ‘cleaning up’ the aircraft (by removing protuberances, for example, and by advanced design of the fairing between wings and fuselage) and by adding passive or active ‘laminar flow control’ to the wing and empennage. This latter option will smoothen the flow over certain parts of aircraft, thus reducing drag. This requires intensive daily aircraft maintenance, however, to ensure that surfaces are kept as clean as possible, since even small disturbances 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. One way of reducing induced drag is therefore to increase wing slenderness, or aspect ratio (AR).

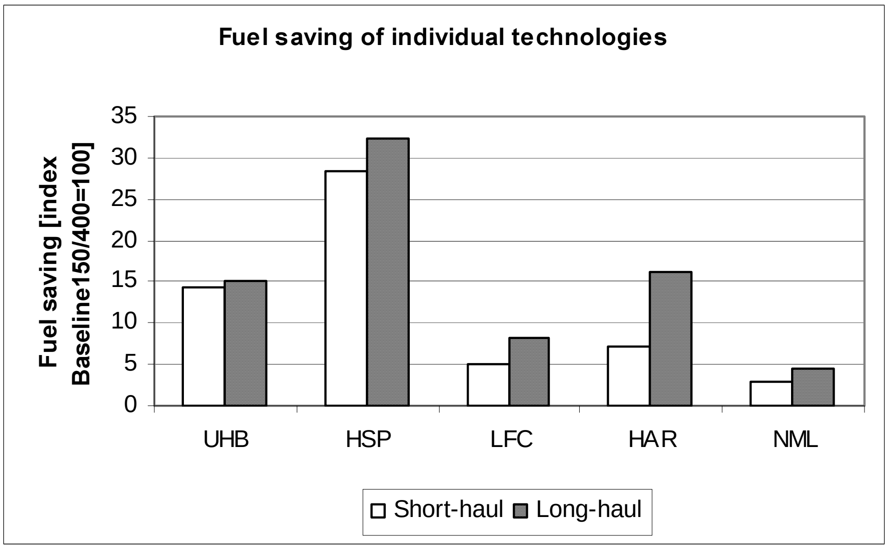
At infinite AR induced drag becomes zero. Increasing wingspan has two disadvantages, however: a higher wing bending moment at the wing root and reduced wing thickness. Both increase wing weight and airframe cost. In terms of the lowest DOC, optimum AR are found to be between 11 and 14, depending on the design under consideration. In terms of the lowest attainable fuel consumption, the optimum lies somewhere between 15 and 20.

Reducing weight has always been a prime goal of aircraft designers and strong, light-weight materials like fibre-reinforced plastics or GLARE (a fibre-metal laminate developed by Delft University of Technology) have a major contribution to make. In this study we assess the effect of employing such materials for a large part of the airframe structure.

4.3.2 Fuel consumption

Figure 5 reviews the fuel savings relative to the BASE150/BASE400 baseline attainable with the respective technologies considered. As can be seen, there are considerable differences. In both the short-haul and long-haul markets the highest fuel savings are to be achieved with the HSP: about 30%.
With ultra-high bypass engines about 15% fuel savings are possible in both markets. A high aspect ratio gives about 15% reduction for long-haul but only 7% reduction for short-haul aircraft. Laminar flow and aerodynamic clean-up reduce fuel consumption by 5 to 8%. Use of new materials, finally, yields less than 5% fuel savings. A general observation is that, individually, each technology has greatest potential on long-haul aircraft.

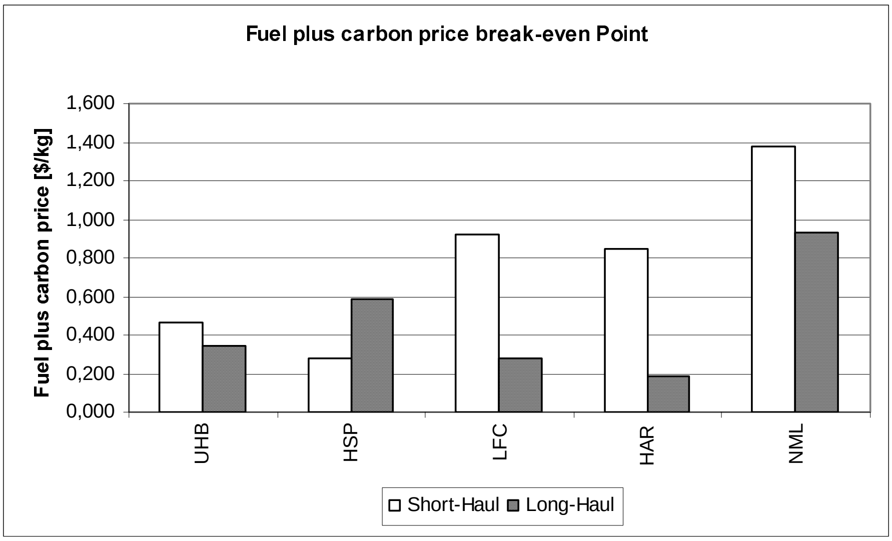
Figure 5 Fuel savings potential of individual technologies compared with BASE150 (short-haul) and BASE400 (long-haul)



4.3.3 Economics

One way to assess the economic performance of a given technology is to calculate the direct operating costs of an equipped aircraft and compare these with the baseline and with other technologies. However, the result of such a comparison depends largely on the fuel plus carbon price assumed. A better indicator is therefore the so-called ‘break-even point’, the fuel plus carbon price at which an aircraft fitted with the technology in question has lower DOC than the baseline aircraft. A low break-even point indicates that the technology is a cost-effective means of reducing fuel consumption. Figure 6 shows the break-even points relative to BASE150/400 for the individual technologies considered.
From this figure it is clear that HSP represents the most economic solution for the short-haul market. High aspect ratio, LFC and UHB are cost-effective for the long-haul market. That HSP lags behind in the long-haul market is due mainly to the high cruise mach number of the long-haul baseline aircraft compared to the slower HSP-fitted aircraft. For the short-haul market aerodynamic enhancement appears to be a less cost-effective solution. From the economic angle use of new materials is the least effective option in both markets.

Figure 6 Fuel plus carbon price break-even points of individual technologies relative to BASE150/400



4.3.4 Conclusions on individual technologies

From this analysis the following conclusions can be drawn:

- Use of the high-speed propeller (HSP) yields the greatest fuel savings for both the short and the long haul.
- For the long-haul market, the two most *economic* means of reducing fuel consumption are to increase the wing aspect ratio and reduce parasite drag, for the short haul to introduce the HSP.
- Introduction of new lightweight materials is neither effective nor economic as a means of reducing fuel consumption.

4.4 New designs

4.4.1 General description

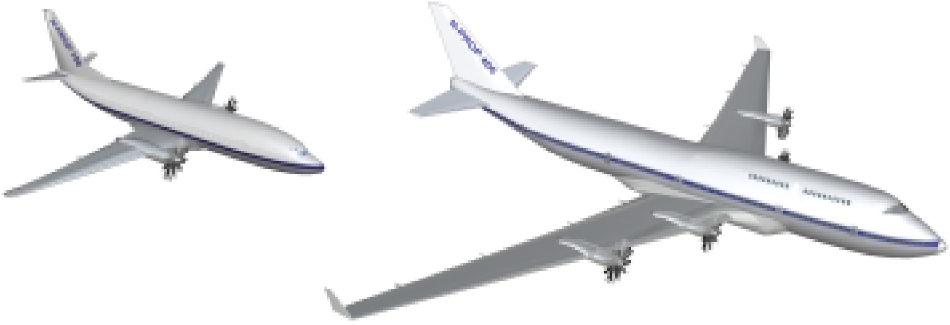
In this section we examine eight new designs (four per market) combining several different technologies. Entirely new aircraft configurations are addressed in the following section (§ 4.5). Combining technologies into a novel design has three potential consequences:

- Reduced benefits: the fuel consumption benefits of the individual technologies gradually decrease as more technologies are combined: the first 10% reduction option will give 10% fuel savings, the second only (100%-10%)*10% = 9% savings.
- Greater benefits: reduction of operational weight (due to reduced fuel consumption) allows engine and wing area to be redefined, leading to further efficiency improvements.
- Reduced costs: technology costs may be reduced because of synergistic effects in engineering and production; in addition, development costs can be written off over a larger number of aircraft built (the better a design performs, the longer it will be in production).

As engine characteristics lead to major differences in operational speeds, we have designed our new aircraft around these engines. Due consideration has also been given to the influence of design speed by introducing both a high-speed and a medium-speed concept 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 3 Characteristics of the new aircraft designs

Design	OEW	MTOW	aspect ratio	wing area	wing span	price (incl. eng.)	$W_{propulsion}$[6]
	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 features of the aircraft are summarised in Table 3. As the table shows, the high-speed propeller (M-PROP) gives a cheap aircraft, while the ultra-high bypass turbofan requires an expensive but ‘lean’ aircraft. The price of the fuel cell technology aircraft has not been calculated because of major uncertainties in the cost of certified systems.

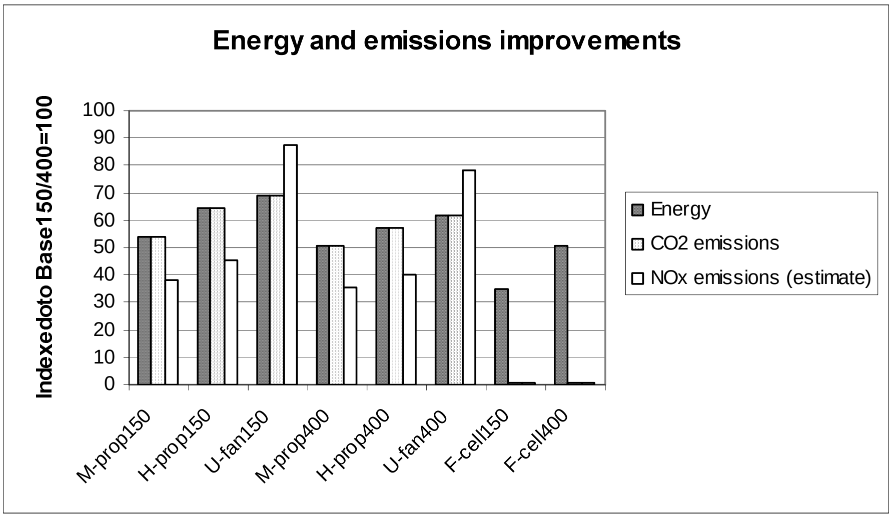
4.4.2 Environmental impact

In assessing the environmental impact the main focus was on CO_2 emissions and thus on fuel consumption. In addition, an initial estimate of NO_X and noise emissions was made. As the F-CELL designs use LH_2 as a fuel and others kerosene, we have replaced fuel consumption by energy consumption to render them comparable. It should be noted that the results for the F-cell are tentative, as these designs are accompanied by far more uncertainties than the other six.

---

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

Figure 7 Environmental impact of the new aircraft designs indexed to the 2010 baseline. The results for fuel cell technology are very tentative and have been added for comparison only



As the figure shows, 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 and M-PROP designs 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.

In principle hydrogen can be used as a fuel in all designs, probably making them slightly more (up to 10%) fuel-efficient and reducing in-flight CO_2 emissions to zero and probably also largely reducing NO_X emissions but increasing those of water vapour.

Noise impact is influenced by two parameters: direct noise emissions from the airframe and engines, and the low-altitude flight path taken during climb and approach. Low noise emissions and a steep flight path both reduce the noise ‘footprint’ (area within some pre-defined noise level) and therefore noise impact on the airport environs. The power rating and type of engine influence noise emissions. Because of the many unknowns in the new designs and the complexity of the issue we merely offer some qualitative remarks on the topic (Table 4). More definitive conclusions require extensive analysis, which is beyond the scope of the present study.

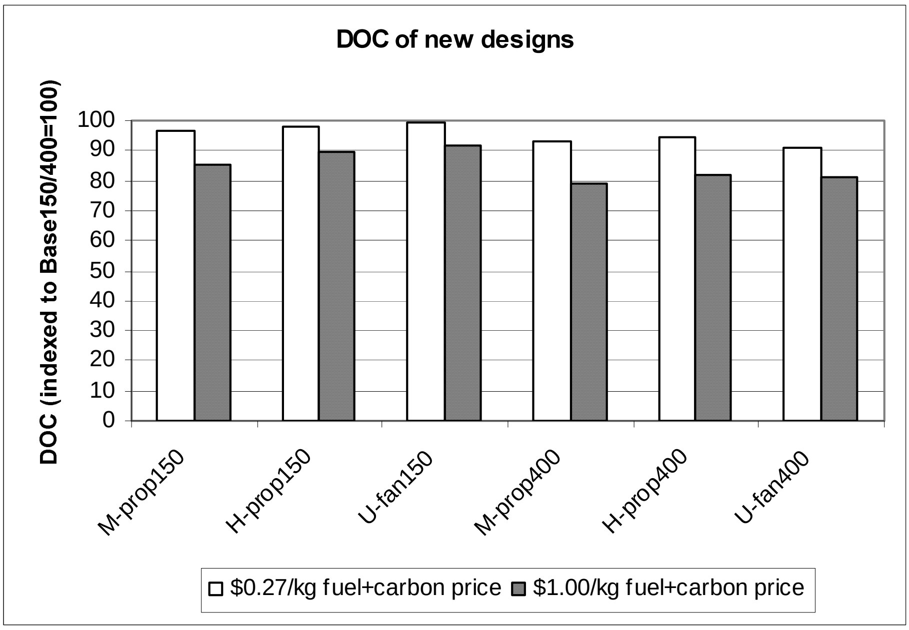
Table 4 Influence of the new designs on noise compared to the 2010 baseline (tentative estimates). Noise impact declines with decreasing engine rating and with increasing number of '–' for direct noise and installation effects and increasing climb gradient

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

4.4.3 Economics

As the cost factors for the F-CELL designs are largely unknown we consider the economics of the six other designs only. Perusal of the DOC of all the new designs (Figure 8) shows that these are consistently lower than those of the 2010 baseline, even at current fuel prices of $0.27/kg. At the high fuel plus carbon price of $1.00/kg M-PROP has the lowest DOC in both markets. U-FAN150 and H-PROP400 have the highest DOC.

Figure 8 DOC of the new designs indexed to BASE150/400

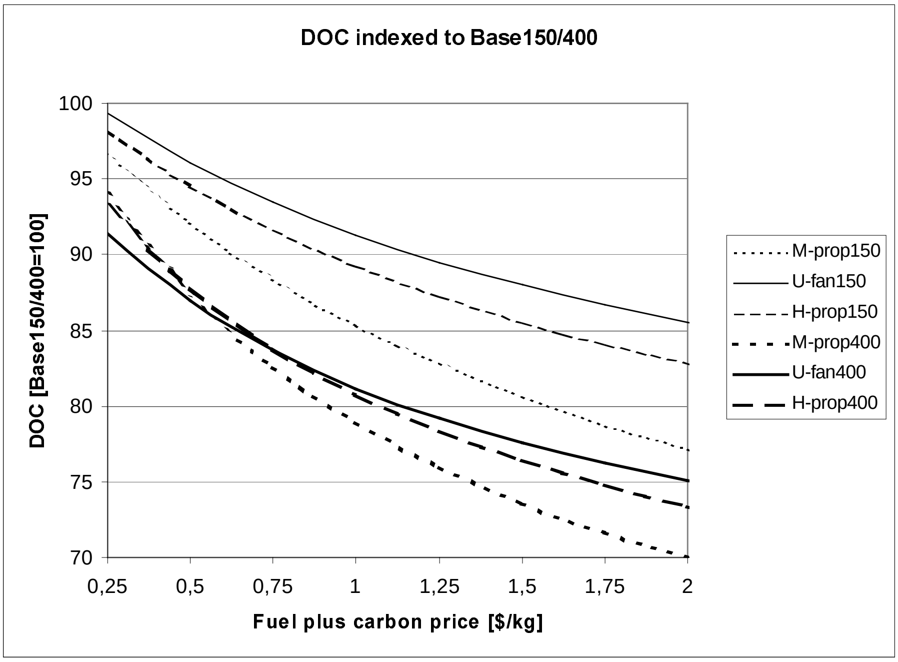


DOC are influenced by the assumed fuel plus carbon price. To find the cross-over points for the designs we drew up Figure 8, which shows the DOC relative to the short-haul and long-haul baseline aircraft (Base150/400) as a function of the fuel plus carbon price. We now see that for the short haul the DOC of the M-prop150 are the lowest across the whole range considered and those of the U-fan150 the highest. H-prop150 has intermediate costs for all fuel plus carbon prices.

For the long-haul designs a different picture emerges. Here U-fan400 is the most economic option up to fuel plus carbon prices of about $0.60/kg, when the M-prop400 becomes cheaper to operate. The H-prop400 design always has higher DOC compared with the two other new designs. In competition with U-fan400, the DOC of H-prop400 become lower above a fuel plus carbon price of $0.75/kg.

As Figure 9 shows, the higher the fuel plus carbon price the more advantageous the DOC of the most fuel-efficient aircraft become. In addition, during the conceptual design exercise optimised wing aspect ratios were found to increase with the assumed fuel plus carbon price, which also yields a more fuel-efficient optimum aircraft at a higher fuel plus carbon price.

Figure 9 DOC of the new designs as a function of the fuel plus carbon price



4.4.4 Performance

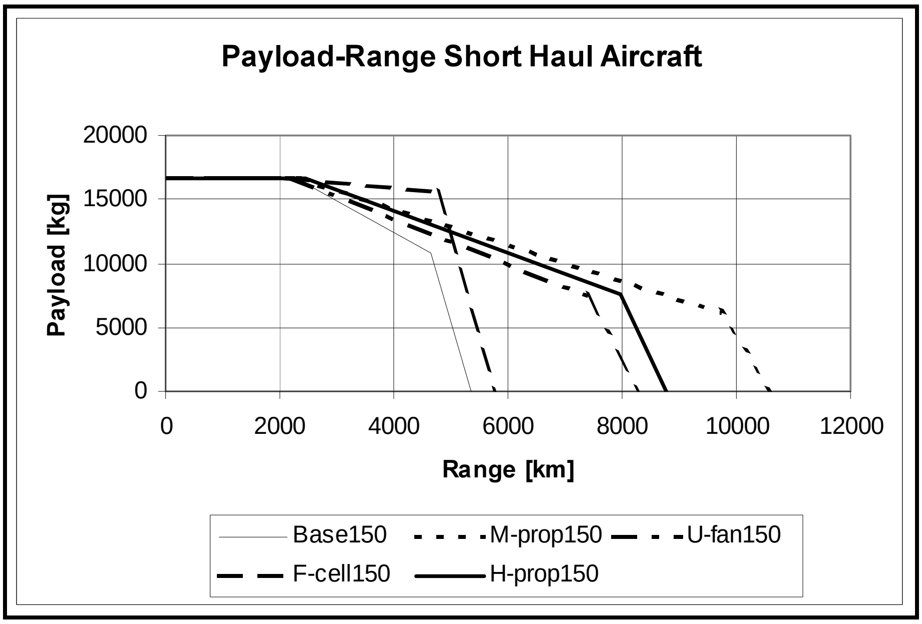
Aircraft performance must obviously conform to the operational requirements of airlines. The three key parameters here are evaluation flight performance, payload range performance and landing and take-off performance. Operational performance on the evaluation flights is shown in Table 5. As can be seen, the M-prop aircraft have 11% and 16% greater block times for the short and long haul, respectively. The fuel cell aircraft likewise have a lower cruise speed, resulting in 9% and 23% greater block times for the short and long haul.

Table 5 Performance of the new designs on the evaluation flights (block distance for short haul: 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[7]	0.660	8,000
BASE400	306,376	8.30	68,513	0.840	11,000
M-PROP400	252,319	9.53	35,447	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[8]	0.650	8,500

Figure 10 is a payload range diagram showing the maximum payload that can be transported as a function of range. The payload range capability of the short-haul designs is better than baseline. As can be seen, however, the most important point (range with full payload) is the same for all designs. The design with fuel cell technology shows a very flat rate and therefore offers twice the maximum payload range at almost full payload.

Figure 10 Payload- range performance of the short-haul designs



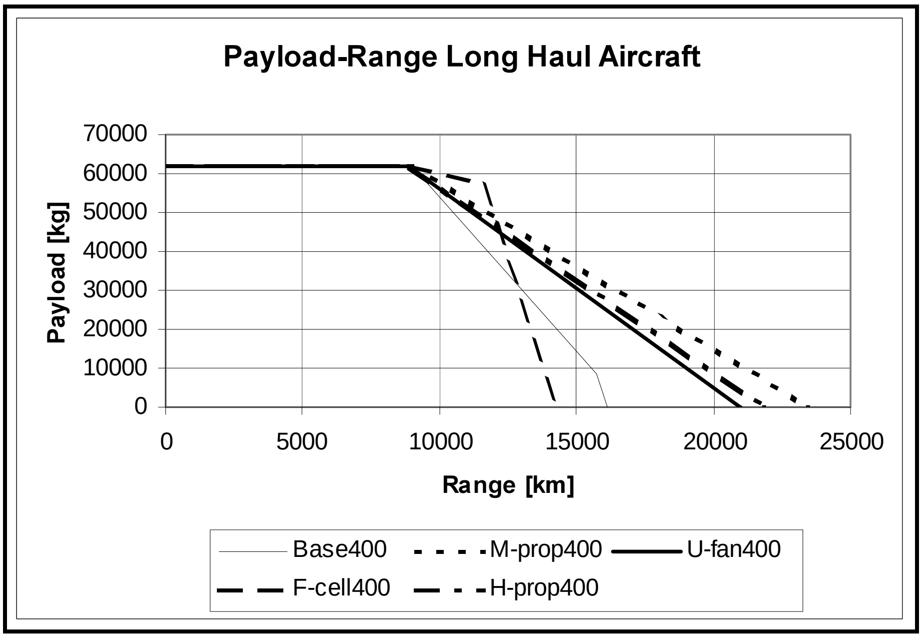
There is no fuel volume limit for the M-PROP400, H-PROP400 and U-FAN400 designs, because we did not adjust the tank volume to the lower fuel consumption (see Figure 11). Only the F-CELL400 has a volume limit, because the LH_2 storage tanks are too heavy for them to be made larger than strictly necessary. The range at almost full payload is about 1.5 times that for the F-CELL400.

---

[7] This figure gives the mass of kerosene equivalents. The hydrogen weight is 445 kg.

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

Figure 11 Payload-range performance of the long-haul designs

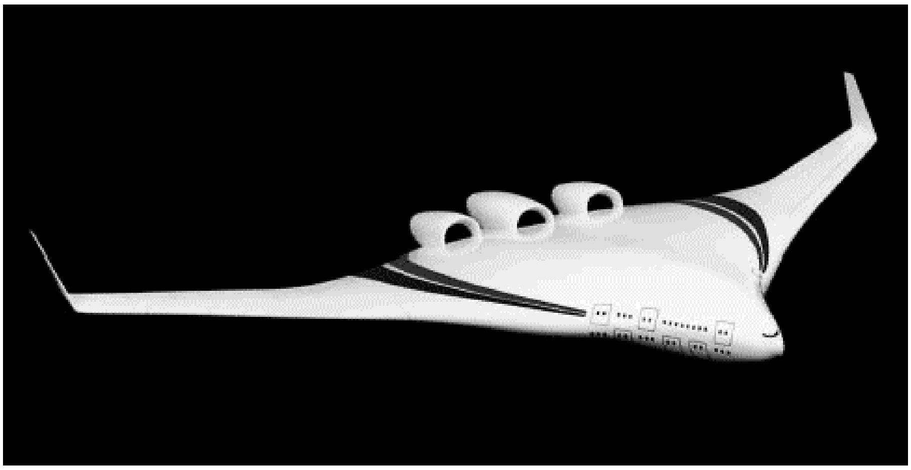


Another important performance item is field performance. As airports have runways of limited length, the new aircraft should not require excessive take-off or landing field length. Rough calculations indicate that our new designs have comparable or better field performance than the baseline at higher operational weights. This is the result of the reduced fuel weight, necessitating 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), which allows for higher maximum lift.

4.5 New aircraft configurations

So far we have considered only the classical aircraft configuration: non-lifting fuselage for easy storage of cargo/passengers, wings as lifting surfaces and aft tail planes for control and stability. In this section we discuss other approaches. The main possibilities are: tail-first, tail-less and blended wing body (BWB). The tail-first, or canard, and the tail-less aircraft are used mainly for transonic and supersonic aircraft. Their capacity to increase fuel efficiency on a subsonic aeroplane is not deemed spectacular. At present, then, the BWB (see Figure 12) is the only non-classical configuration offering scope for reducing fuel consumption by up to 25% compared to state-of-the-art wide-body aircraft. Another important benefit is that the DOC may be reduced by up to 20%.

Figure 12 Example of a blended wing body aircraft designed by NASA (1997)



The main problems of this configuration are controllability and cabin layout. Specifically, the low-speed flight envelope is largely unknown and requires further investigation, as do stall and spin behaviour. NASA and Boeing recently announced they will be starting flight tests on a low-speed scale model early in 2002 to study these issues. 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 created by the relatively high wing thickness ratio that is required. It would be of great interest to investigate the overall design opportunities from an environmental perspective and including a range of propulsion technologies and performance specifications. It would also be interesting to examine the potential for aircraft with less than 450 passengers.

4.6 Conclusions

From the technical study the following conclusions can be drawn:

- Introduction of the high-speed propeller (HSP) gives the greatest fuel savings for both the short and the long haul.
- For the long-haul market the most *economic* means of reducing fuel consumption are to increase the wing aspect ratio and reduce parasite drag, for the short haul to introduce the HSP.
- A propfan (high-speed propeller with a design speed of mach 0.8 or more) appears to be a more economic way to reduce the fuel consumption of long-haul aircraft; however, such propfans still suffer from a variety of technological problems, including high vibration and noise levels.
- Introduction of new light-weight materials is neither an effective nor an economic means of reducing fuel consumption.
- With turbofans fuel savings of 40-45% with respect to the 2010 baseline are conceivable for new designs without sacrificing aircraft performance or economy in terms of DOC, payload range and field length.
- A stable long-term increase of the fuel plus carbon price may advance introduction of more fuel-efficient new designs.
- The fuel savings of the high-speed propeller designs can be increased 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) hold out perspectives of further, substantial increases in fuel efficiency.

- Fuel cell technology provides 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 substantial development work. These results are consequently more uncertain than for the other designs and no figures can presently be given for DOC or other costs.
- For a further reduction of energy consumption the fuel cell appears to be the preferred technology for the short haul, while the blended wing body may be the solution for the long haul.

4.7 Recommendations

Environment

Although fuel consumption, and thus CO_2 and H_2O emissions, is certainly an important environmental indicator, several other aspects of key relevance to the debate on aviation and the environment require further investigation, in particular:

- greater engine efficiency may lead to increased contrail formation;
- changes in cruise altitude may affect contrail formation and ozone lifetime.

Performance specifications

The influence of performance specifications on DOC and environmental impact require further study. Specifically, the relationship between design speed and environmental impact appears to present opportunities for reducing the latter.

High speed propellers

High-speed, probably counter-rotating, propellers are one of the most promising technologies for reduced emissions because they permit 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.

Furthermore, it is recommended to reconsider development of faster propeller engines for the long-haul market (suitable for mach numbers above 0.8). This form of propulsion may yield better DOC and fuel efficiency figures than UHB engines.

UHB engines

It is recommended to further study the pros and cons of engine concepts exceeding the bypass ratios considered in this study (beyond 9:1), as it is unclear whether such an increase is still environmentally beneficial. Past studies on these types of engines suggest growing problems in terms of a) the heavy fan gearbox required, 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 far larger nacelle will lead to diminishing returns owing to the greater weight and drag.

Higher aspect ratio wings

The high Aspect Ratio wings on today's Airbus aircraft have an AR between 10 and 11. However, the study at hand suggests an advantage for ARs in the 14-15 range. Further investigation of this problem is therefore recommended, comparing counter-rotating propeller and UHB aircraft at these high ARs[9] to obtain information on:

- aero-elastic (flutter) limits;
- sizing parameters.

Blended wing body

It is strongly recommended to perform a study on the opportunities and problems associated with the blended wing body configuration in conjunction with the other technologies presented in this study, for both long-haul and short-haul aircraft.

Hydrogen and fuel cells

The use of hydrogen fuel in high-speed propeller or UHB powered aircraft has not been evaluated in this study. Compared with kerosene-fuelled aircraft, these concepts lead to zero in-flight carbon dioxide and hydrocarbon emissions and lower nitrogen oxide emissions. On the other hand, hydrogen fuel will pose technological and economic problems, specifically for the fuel systems, both on-board and on the ground.

It is recommended to include the fuel cell technology issue in current studies on liquid hydrogen aircraft or to combine these topics in new studies. Special attention should be paid to costs, fuel system design and integration, cryogenic motor cooling, full design integration of propulsion and airframe, and safety, including special requirements with respect to the fuel cell capacity required for a one-engine climb-out.

---

[9] This can be done by preparing ‘point designs’ (further detailing of concepts with a fixed high AR and the mentioned engine types, rather than simultaneously optimising AR and other design parameters).

5 Barriers to introduction, and solutions

5.1 Introduction

The calculations in the previous chapter show that potentially DOC gains might be achieved if all the available technologies were combined in a newly developed aircraft design. This raises the question of why these designs are not in fact in current production. This chapter aims to make as explicit as possible the barriers that might be holding back introduction of these promising new designs. The information presented has been derived from a number of interviews with industry experts, some additional literature study and some extra modelling work.

5.2 Applying the new designs in an airline network

An important question to be answered is whether the new aircraft designs considered, especially those with lower cruise speeds (the propeller-equipped H-PROP, M-PROP, F-CELL designs), can be economically operated within airline route networks.

In the previous chapter we examined the economic viability of several individual aircraft designs. One conclusion was that slower-flying high-speed propeller aircraft might lead to lower DOC figures, especially in the case of higher prices for fuel or (CO_2) emissions. An important underlying assumption in that chapter was that propeller and turbine aircraft can be operated for an equal number of block hours. This is a key area of uncertainty, however.

Given the importance of this assumption, extra analysis was undertaken to ascertain how these lower-speed aircraft might function in an airline's route network. This analysis was performed with the Airline System Simulation Programme ASSP model |Delft University of Technology, 2000|. A hub and spoke network with relatively short flight distances was used with eight connections and a given demand function per connection. DOC and investment figures were taken from the APD model results, as described in the previous chapter.

The conclusions from this work can be summarised as follows:

- The economic appeal of more fuel-efficient but slower aircraft is indeed found to increase with rising fuel plus carbon price. The fleet share of slower-flying but more fuel-efficient aircraft will increase as this price rises. It should be noted that a lasting price effect has been assumed.
- For shorter flights (up to a few thousand kilometres) the annual utilisation of slower aircraft (in block hours) is about equal that of faster aircraft. Given their lower speed, slower aircraft are of course less productive in terms of ASK, but this effect has already been taken into account in the DOC calculations.
- It was also found that increasing the fuel plus carbon price to $1.00/kg (from $0.25 per kg), leading to approximately 35% higher DOC, reduces transport demand by about 10% and increases the load factor by about 6%, thus reducing the number of flight movements by about 16%. This corresponds with what is to be expected from transport economics.

It should be noted, however, that these results hold for short-haul distances only. For the long haul, utilisation of slower aircraft may pose more of a problem, especially for destinations that can be serviced precisely on a daily basis, at airports with restrictions on night-flight regimes or in cases involving crew time restrictions.

5.3 Lower speed: less revenue per ticket?

As we have seen, the propeller designs considered in this study are 5-15% slower than competing turbofans. It may be argued that passengers or shippers will not be prepared to pay the same price for a slower service. In that case it is not only DOC figures per ASK that are important, but also revenues per ASK. Studies show that the value of travel time in passenger air transport is fairly high: about $25 per person-hour (mix of private and business passengers).

We have seen that on the *short-haul flights* of 1,000 km the M-PROP150 aircraft increases travel time by about 12 minutes. Assuming the aircraft carries 100 pax, this would imply a loss of time value (and thus, potentially, ticket revenues) of about $500 per trip, or about 5% of DOC. In other words, the lower aircraft speed implies an extra DOC barrier of about 5% due to revenue loss. We reiterate that it is by no means certain whether the relatively modest short-haul time losses would really have much impact on ticket prices. Perhaps a few per cent extra DOC gains are enough to outweigh this effect.

On the *long-haul* distance of 7,000 km the M-PROP400 aircraft leads to substantial time losses, namely 1h23m. Assuming the aircraft carries 300 pax, this means a loss of time value (and thus, potentially, revenues) of about $10,000 per trip, which is about 9% of DOC. For long hauls, then, slower flying has more substantial disadvantages than for short hauls.

In the *freight* market, time is of less essence than in the passenger market. Price is the most important issue; one hour extra flying time is not usually that important. The slower concepts considered in this study may therefore be attractive in the freight market sooner than in the passenger market.

5.4 Certification and safety issues

The aviation sector deems that, in sustaining growth, annual casualties must decline despite this growth. This requires an enormous effort in the part of manufacturers, airlines and certification authorities (JAA and FAA). It is generally recognised that these ever-stricter certification requirements form a barrier for environmental breakthroughs. Technology must be thoroughly proven before it can be applied in civil aviation.

Of course, this barrier can also be expressed in economic terms: the greater the economic benefits on the horizon, the more testing efforts will be made. A case in point is the testing of propfan concepts during the early 80s, when fuel prices were high. When prices fell in 1985, these research efforts rapidly petered out.

It is important to note that more fuel-efficient concepts have an intrinsic safety advantage because they carry less fuel, implying that they may be less vulnerable to explosion, with less catastrophic consequences in the event of explosion (*ceteris paribus*).

Another possible opportunity for making this barrier less steep is to first develop the more efficient technologies in military transport aircraft development programmes. Technologies might then be transposed to civil transport aircraft, finally ending with the market segment facing the strictest standards: the civil passenger market.

5.5 Environmental trade-offs: noise, NO_X, contrails

Other environmental requirements such as aircraft noise and NO_X emissions may also pose barriers for the introduction of more fuel- and CO_2-efficient aircraft.

Noise
Noise is a very complex issue because of the multitude of co-determining factors and the non-linear relations between emission and exposure. As in the case of NO_X, noise is of even greater importance for short-haul flights.
As we saw in § 4.4.2, the U-FAN and H-PROP concepts may lead to lower noise levels as their engines are smaller and their climb-out gradients somewhat steeper. The opposite may hold for the M-PROP and F-CELL concepts, however, owing primarily to their much lower climb-out gradient (these aircraft are somewhat under-powered, to save energy).
All the other concepts will probably score well, as the lower direct noise emissions of these designs seem to outweigh their ‘footprint’ disadvantages. The fuel cell designs score particularly well, because the energy conversion process is noiseless, with the propellers constituting the only engine-related source of noise.

NO_X
The Ultra High Bypass engine technology (U-FAN concepts) embody a trade-off between NO_X emission level and (higher) pressure ratios. These engines emit more NO_X per kg of fuel than the baseline engines. With ever-tighter environmental legislation at airports, this is a serious issue, especially for short-haul flights. If designed more fuel-efficiently, however, engines can be substantially de-rated, hence total aircraft NO_X emissions of the U-FAN designs considered in this report are still about 20% lower than the BASE aircraft (cf. § 4.4.2).
In the case of the H-PROP and M-PROP designs, there is even a positive trade-off: these engines lead to lower NO_X emissions per kg of fuel, and thus to extra NO_X reduction, i.e. on top of the that implied by reduced kilogram fuel requirements. The propeller designs lead to about 50-60% lower NO_X emissions than the baseline designs. Again, this is especially interesting for short-haul flights.

Water emissions and contrails
The new concepts may have a different impact on contrail formation than the baseline (see § 2.5). Three factors are involved:

- the higher thermal efficiency of the core engines considered, leading to cooler exhaust gases. According to the IPCC Special Report, this might lead to increased contrail formation;
- the application, in M-PROP and H-PROP, of turboprop rather than turbofan engines. Within the scope of the present project, insufficient clarity could be obtained on this point;
- the flight altitude, which is lower for M-PROP and H-PROP than for U-FAN or BASE concepts. Overall, the net global effect of this is small, but the effect on contrail coverage in the tropics may have a greater impact on radiative forcing. Over polar and mid-latitudinal regions a lower cruise

altitude leads to a (moderate) increase of contrail coverage, as tropopause levels in these regions are relatively low. Over tropical and subtropical regions, a decrease in cruise altitude leads to a decrease of contrail coverage, since in these regions flights shift towards the warmer, lower troposphere |IPCC 1999|.

In contrast to CO_2 and NO_X emissions, contrails can be fairly readily avoided by a slight change of flight altitude, to allow for local weather conditions[10]. It is therefore recommended that the local tropopause level and atmospheric conditions be duly considered in planning a long-haul flight so that the flight pattern can be optimised not only for fuel consumption but also for environmental impact. As a rule of thumb it might be recommended to fly either at 7-8 km or just above the tropopause.

Summarising, it is very hard to estimate the impact of the new concepts on contrail formation, except for the U-FAN designs (probably more contrails owing to their lower exhaust temperatures). It is still important to note that contrails can be easily avoided by a slight alteration of flight altitude, depending on weather conditions.

5.6 Airport issues

New aircraft concepts may also have consequences for airport management. A very obvious barrier for high wing aspect ratios, and thus fuel savings, in large aircraft like the A3XX is the 80x80 ‘box’ that is the current limit on aircraft size at larger airports. It can be argued that the A3XX could be developed for 6% less fuel consumption if this limit were set less strict[11]. This is an obstacle for the long-haul propeller concepts considered (H-PROP400, M-PROP400, and F-CELL400). At present, however, there is probably insufficient pressure on the maximum ‘box’ size for the limit to be relaxed.

Besides this maximum size issue, plane handling at gates might be slightly affected by a general change in aircraft sizing, as more space would be required overall. This is an economic issue.

5.7 Passenger appeal

A final objection that is sometimes voiced, particularly vis-a-vis the propeller-based concepts, relates to passenger appeal. It is said that people perceive propeller aircraft as obsolete and possibly even more unsafe than turbofan aircraft, as the propellers are visible. Talks with the industry and the continuing use of turboprop aircraft suggest that this could be interpreted as a trade-off: in cases where the economic performance of propeller and turbofan aircraft do not substantially differ, this might be an argument in favour of the latter.

In addition, current turboprop aircraft are said to be less comfortable, because of the lower flight altitude and the higher noise level. However, the high-speed propeller concepts considered here fly at altitudes of 9 to 9.5 km, or about 2 km above existing turboprop aircraft like the F50. This issue will therefore most probably not be very pressing.

---

[10] Personal communication, Dr Robert Sausen, DLR

[11] Personal communication, Rudi den Hertog, Fokker Services.

5.8 New concepts: substantial DOC gains necessary

We have seen in the previous section that there are some substantial uncertainties and possible barriers on the horizon that might hamper introduction of more fuel-efficient aircraft even when there is a prospect of DOC reduction. This can be better understood by looking at aviation history, which shows that new aircraft concepts are successfully developed only if there are very substantial DOC gains on the horizon.

There have been a number of major historical breakthroughs in aircraft design. A first major leap was achieved when longer-range jets like the DC8 and B707 replaced first-generation propeller aircraft like the DC6, DC7 and Lockheed Super Constellation. A next important step was the introduction of wide-body aircraft like the DC10, Lockheed 1011 and B-747. A final major step in aircraft design was the introduction of long-range wide-body twin-engine aircraft like the B-676/777 and the A310/330 series.

All these historical leaps forward in aircraft design were driven by large DOC gains, sometimes amounting to several dozen per cent. In aviation history, greater-than-marginal DOC gains of new concepts have proved necessary to overcome the enormous investments required and risks incurred and operational changes required in developing a totally new concept of aircraft. For this crucial reason the few per cent DOC gains that can theoretically be achieved with new aircraft concepts (see the previous chapter) are not sufficient for incurring such risks.

As § 4.4.3 shows, the DOC figures of the new concepts are highly dependent on the fuel plus carbon price. In the case of a \$0.50 fuel plus carbon price, DOC advantages of more efficient concepts might amount to 6 to 12%, for example

5.9 Overall score per design

The new U-FAN, H-PROP and M-PROP designs were qualitatively assessed with respect to the potential barriers discussed in the previous section. The results are shown in Table 6.

Table 6 Overall assessment of the new designs.

	short-haul (150 seats)			long-haul (400 seats)		
	U-FAN	**H-PROP**	**M-PROP**	**U-FAN**	**H-PROP**	**M-PROP**
DOC score, relative to BASE concepts						
at 0.25 fuel plus carbon price*	0	0	0	+	+	+
at 1.00 fuel plus carbon price*	++	++	+++	++++	++++	++++
other economic or technical barriers						
revenue losses from low speed	0	0?	-	0	-	--
investment barrier	-	--	--	--	---	---
applicability in network	0	0	0	0	-?	--?
certification/safety barriers	-	--	--	-	--	--
airport barriers	0	0	0	0	-	-
environmental trade-offs						
trade-off on noise	+?	+?	0?	+?	+?	0?
trade-off on NO_X	-?	+?	+?	-?	+?	+?
trade-off on contrails	-?	?	?	-?	?	?
approximate total feasibility score						
at 0.25 fuel plus carbon price*	-	-	--	-/0	--	---
at 1.00 fuel plus carbon price*	+	+	+	++	-?	-?

* fuel plus carbon emissions price, expressed in $ per kg of kerosene fuel
-/+ barrier / advantage
? uncertain

From Table 6 and the remainder of this chapter the following conclusions can be drawn:

- In the short-haul, 150-seat market there are no major prospects for substantially more efficient aircraft designs as long as the economic weight of fuel consumption or carbon emission profile remain unchanged. The current barriers to introduction of new designs, certainly for high speed propeller designs, appear to be too high to overcome the (fairly limited) possible DOC advantages.
- This situation might change if the economic weight of fuel consumption and/or carbon emissions were to increase. The prospects for advanced ultra-high bypass designs then improve substantially, and this also begins to hold for more efficient high-speed propeller designs. Preferences between these two are hard to predict.
- In the long-haul, 400+ seat market there seems to be some economic perspective for more fuel-efficient ultra-high bypass aircraft concepts, even under current economic weighting of fuel consumption and carbon emission profile. In this segment the enormous investments required constitute the main barrier.
- In the long-haul market it is unlikely that high-speed propeller aircraft will be applied, even in the case of high fuel or carbon emission prices. This is because the DOC differences between the U-FAN and PROP designs are probably not large enough to outweigh the market barriers for propeller aircraft. However, prospects for advanced ultra-high bypass designs appear to be good under this high price scenario. The most important barriers for this concept appear to be the required investments, linked with the uncertainties regarding future fuel and/or emission prices.

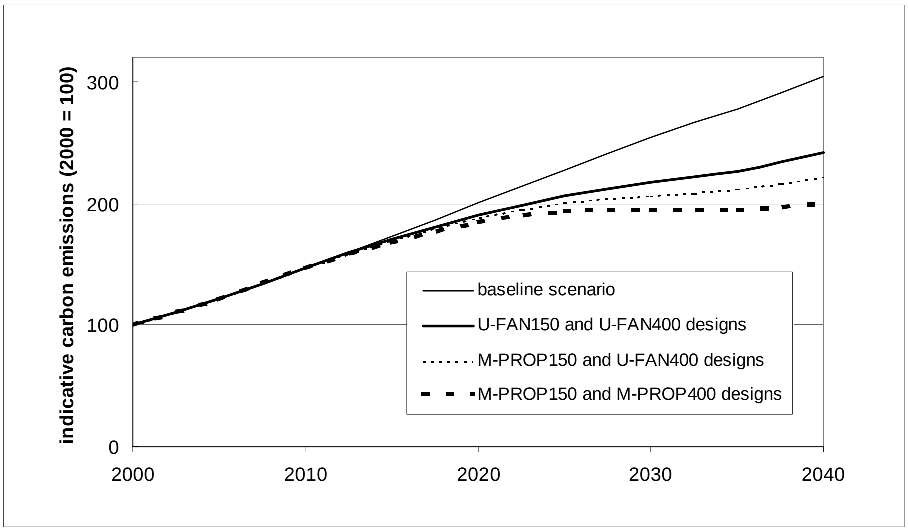
5.10 Approximate effects on fleet emissions

In this paragraph we estimate the approximate effect on global aircraft fleet emissions of introducing a selection of the new aircraft designs considered in the present study. In doing so the following assumptions have been made:

- the baseline scenario is a middle estimate from the IPCC Special Report on Aviation and the Global Atmosphere (see § 2.3);
- for the short haul, aircraft with the fuel savings of the M-PROP150 concept are assumed to be progressively introduced and for the long haul, aircraft with those of the U-FAN400 concept, as these concepts will probably be the first to become economically viable under a more stringent environmental regime (see previous section);
- the aircraft are gradually introduced from 2010 onwards, gaining a 100% market share in sales terms as of 2020;
- possible changes in transport demand, average load factors, average aircraft sizes and aircraft operations have not been taken into account, but only the direct impact of introducing the new designs.

The results are shown in Figure 13.

Figure 13 Approximate impact on world fleet fuel consumption of introducing a selection of new aircraft designs (excluding operational, demand and load factor effects).



It can be seen that the scenario with sales of the M-PROP150 and U-FAN400 designs starting to increase in 2010 leads to a 25-30% reduction of carbon emissions in 2040 compared with the baseline scenario. Visible results would only be achieved as of the year 2020, owing to the slow penetration of new technology in the fleet.

5.11 Special issues relating to fuel cells and hydrogen

In the literature the proposed application of fuel cells in aircraft is generally limited to auxiliary power units. Only one reference to the use of fuel cells for aircraft propulsion has been found (Snyder, 1998). The design presented in this reference is based on current performance, leading to a relatively heavy and expensive aircraft. In our study we therefore reduced aircraft power requirements, leading to lower aircraft weight and costs but also to lower cruise speed and altitude.

The first risk factor is therefore the performance of these aircraft. Will people be prepared to pay for the longer flight times at lower altitudes, not always above the weather? Are there enough advantages for passengers? Will the overall DOC be low enough to overcome the discomfort?

Probably more important, however, is the commercial risk of development of the presented fuel cell aircraft. This risk is huge because several non-proven technologies are combined: fuel cells, use of hydrogen fuel and use of a cryogenically cooled, super-conducting motor. In the development of commercial aircraft, it is rather unusual to take such multiple technical hurdles.

Safety may be a problem because of the complicated fuel handling and conditioning system required. In addition, the use of liquid hydrogen fuel has not been proven, although some studies indicate that the fuel will be safer to use than kerosene. A final issue of concern may be the noise of the high-speed propellers, both exterior during take-off and climb-out and interior in the cruise stage.

Another barrier is the need for new infrastructure for hydrogen fuelling and storage on the ground. Airfield owners must be prepared for timely investment in such facilities. Hydrogen production plants will have to be available in time, furthermore.

In terms of payload range, however, the F-CELL aircraft performs better than the BASE aircraft. This is because liquid hydrogen has a higher energy content per kilogram, implying a 50-100% longer range at the expense of only 10% of less payload. There is also scope for extending the range substantially at relatively little additional cost.

A long course of development and testing will have to be completed before the first commercial fuel cell aircraft emerge. Perhaps small, experimental, private aircraft development will provide an opportunity for gaining experience with this technology. In the military realm, too, there may be interesting prospects for this kind of aircraft. Specifically, the very long range and long flight time attainable are definite advantages from a military point of view.

5.12 Policy options

There are a number of policy options available for promoting the introduction of the aircraft concepts described here. In this context a distinction can be made between technology ‘pull’ and technology ‘push’ policies. The first category increase the economic appeal of environmentally enhanced aircraft by pricing environmental burden, which rewards the best and punishes the worst. The second category, push-type policies in the form of technology development and demonstration programmes, lower the investment barriers holding back the ‘cleaner’ designs. A more detailed description of the available policy options is provided in Annex G of the background report.

Three main policy options can be identified for increasing the economic incentive to introduce environmentally improved technologies:

1. a levy on carbon emissions;
2. a *revenue-neutral* levy on carbon emissions (recycled to the airlines in proportion to their transport performance in RTK or RPK);
3. trading of carbon emission permits.

Although the first option is the only one to substantially reduce air transport *volume*, all options will reduce air transport *emissions*, as they speed up fleet renewal and accelerate environmental innovation in aircraft design, as shown above. Revenues raised from option number 2 might, for example, be

used to fund technology development (see below) or be recycled to the airlines relative to their transport performance.
In addition, all policy options influence the operational parameters of existing aircraft, such as load factor and cruise speed. It was found that a rise in fuel price from $0.25 to about $1.00/kg[12] might lead to a 6% increase of load factor (APSS model simulations) and possibly to 4-15% less fuel consumption if aircraft flew at a speed leading to minimum DOC (APD model simulations). As aircraft do not always fly at this speed, 5% savings seems a reasonable estimate. The conclusion is that load factor and cruise speed effects within the existing fleet might thus also account for reductions of around 10% at the given fuel or carbon emission price levels.

It is recommended, furthermore, to place greater emphasis on environmental performance in technology development programmes such as the European Union's forthcoming Sixth Framework Programme. More specifically, the following incentives are available for introducing more fuel-efficient aircraft configurations:

- further study of the pros and cons of high aspect ratio wings, ultra-high bypass engines and high-speed propellers (noise, NO_X, vibration, gearboxes or pitch fans, propeller de-icing) and especially their integration in entire aircraft configurations;
- further study of the relationships between design speed, design cruise altitude and environmental impact and on the potential for avoiding in-flight contrail formation;
- further study of alternative designs such as the blended wing body concept;
- incorporation of fuel cell power in hydrogen aircraft research programmes.

It could be wise to demonstrate the technologies in the *freight* transport market, because speed is not as much of a requirement here as it is in the passenger market. In particular, the development of *military* freight transport aircraft might be an opportunity to try, test and prove technologies for the civil market.

---

[12] The $1.00 per kg fuel price is equivalent to the current fuel price plus a market price for carbon emissions of about $0.85 per kg.

6 Conclusions

For the aviation industry, the development and deployment of environmentally more efficient aircraft is an important means of securing growth within certain limits of sustainability.

Although the drive for fuel efficiency has always been high on the aviation industry's agenda, the six conceptual designs considered in this study show that in the medium term it is *technically* feasible to further reduce the fuel consumption of new aircraft by about one-third to one-half, relative to the 2010 baseline aircraft.

In new aircraft design, there is a trade-off between fuel consumption and productivity (design cruise speed). Extra reductions of fuel consumption can be achieved by sacrificing design cruise speed, so that application of high-speed propeller propulsion then becomes a viable option. In most markets the disadvantages of lower cruise speeds and propeller propulsion do not outweigh attainable fuel cost savings under current conditions. Aircraft with improved turbofan engines are therefore generally the only propulsion option considered realistic. With changing market conditions, however, propeller propulsion might become viable, allowing fuel reductions of about 50% to be achieved at the expense of a 5 to 15% reduction in cruise speed.

Although all six new aircraft concepts considered lead to Direct Operating Costs (DOC) slightly below those of today's aircraft, they are most probably not economically viable on the current economic playing field. This is because a number of barriers must first be overcome before these aircraft can be introduced, which are especially apparent in the case of propeller aircraft:

- the DOC benefits are not sufficient for the industry to take the development and investment risks implied in aircraft redesign;
- the slower aircraft will probably generate less revenue, because of lower productivity and the fact that passengers on slower (propeller) aircraft might be willing to pay less for their ticket, especially on long-haul trips. Finally, there may be difficulties fitting slower aircraft into airline route networks, especially long-range networks;
- some concepts may give rise to trade-offs with respect to safety and environment (noise, NO_X, contrails). An exploratory analysis suggests that the environmental trade-offs will be rather limited;
- at present, airports cannot handle aircraft larger than 80x80 m. Two of the three long-haul designs exceed this size owing to their large wing span. If there is a real need for change this problem may prove surmountable, however, at it is economic rather than technical.

The new, more fuel-efficient concepts might be made more economically attractive through a mix of policy instruments, of both the 'pull' and 'push' variety. Possible technology-pull policies include tradable emission regimes or levies on fuel or emissions, while push-type policies might include well-focused technology development programmes aimed at removing the barriers holding back introduction of environmentally more efficient technologies. Any revenues from pull-type policies could be used to finance push-type policies.

In a scenario with technology-pull policies in place, the concept with ultra-high bypass turbofan propulsion for long-haul air transport might be the first option to become economically viable, followed by the ultra-high bypass or high-speed propeller design for short-haul air transport.

Owing to the long lead times prevailing in the aviation industry, it will be some time before substantial overall emission reductions will be visible in the fleet. A scenario in which sales of long-haul, ultra-high bypass designs and short-haul high speed propeller designs slowly increase from 2010 onwards would lead to a 25-30% reduction of carbon emissions in the year 2040 compared with the baseline scenario. Visible results would only be achieved as of the year 2020. These figures make no allowance for possible changes in transport demand, load factors or aircraft operations.

Abbreviations used

A400M	new European military transport aircraft yet to be produced
ADSE	Aircraft Design and Systems Engineering, Hoofddorp, the Netherlands
APD	Aircraft Performance and DOC, model developed by Peeters Advies, Ede, to calculate DOC and fuel consumption effects of new aircraft technologies and designs
AR	Aspect Ratio, defines the slenderness of a wing. Indicator for induced drag
ASK	Available Seat Kilometre, means of expressing the DOC or productivity of an aircraft
ASSP	Airline System Simulation Program, software package of Delft University of Technology to calculate cost optimal network flight patterns
BASE150/400	baseline aircraft for this study: the technologies and designs anticipated in 2010 under current policies, an extrapolation of the PRESENT150/400 aircraft
BWB	Blended Wing Body, alternative aircraft concept
CAEP	Committee on Aviation Environmental Protection, ICAO's environmental department
CH_4	natural gas
CO	carbon monoxide, toxic and ozone-forming substance
CO_2	carbon dioxide, important greenhouse gas
DOC	Direct Operating Costs, costs relating to an aircraft's operations
DTI	UK Department of Trade and Industry
EDF	Environmental Defense Fund
EI	Emission Index, in aviation generally used to express the quantity of NO_X emissions per kg of fuel burnt
FESG	Forecasting and Economic Support Group, a CAEP Working Group on aviation emission forecasts and economic instruments.
FCT	Fuel Cell Technology, the most futuristic of the three new aircraft designs assessed in this study
FLA	Future Large Aircraft, former title for A400M military transport aircraft with 25 tonnes payload at 2,800 km.
H_2O	water (vapour)
H-PROP150/400	aircraft concept considered in this study with 150 or 400 seats, equipped with high-speed propellers and designed for relatively high-speed flight
HAR	High Aspect Ratio, aircraft technology to reduce induced drag
HC	HydroCarbons, unburned fractions of fuel or lube oil
HSP	High Speed Propeller, propulsion concept between turboprop and propfan
ICAO	the UN's International Civil Aviation Organisation, responsible for global aviation policies
IMO	the UN's International Maritime Organisation, responsible for global maritime policies

IOC	Indirect Operating Costs, aviation costs unrelated to the aircraft's operations
IPCC	Intergovernmental Panel on Climate Change, scientific organisation to draw consolidated conclusions from global climate change research activities
LEBU	Large Eddy Break-up Devices, technology to reduce aircraft drag
LFC	Laminar Flow Control, technology to reduce aircraft drag
LH	Long Haul, in this study an average flight stage of 7,000 km
LH_2	Liquid Hydrogen
LNG	Liquid Natural Gas
LPP	Lean Pre-mixed Pre-vaporised combustion, aircraft engine technology to reduce NO_X emissions
N_2O	Nitrous oxide, greenhouse gas
nm	nautical miles, 1.85 km
NML	New Materials, technology to reduce aircraft empty weight
M-PROP	aircraft concept considered in this study, equipped with high-speed propellers and designed for medium-speed flight
NO_X	Nitrogen Oxides, acidifying and ozone-forming gases
O_3	ozone
pax	passenger(s)
pax.km	passenger-kilometres, one passenger transported over one kilometre, unit of transport performance
PM_{10}	particulates with a maximum diameter of 10 micron
PRESENT150/400	typical present-day aircraft with 150 or 400 seats
RPK	Revenue Passenger Kilometre, measure of transport performance in passenger transport. One passenger displaced over a distance of one kilometre
RQL	Rich-burn Quick-quench Lean-burn combustion, aircraft engine technology to reduce NO_X emissions
RTK	Revenue Tonne Kilometre, measure of aircraft productivity (one metric tonne displaced over a distance of 1 km)
SH	Short Haul, in this study an average flight stage of 1,000 km
SO_2	sulphur dioxide, acidifying and possibly contrail-forming substance
U-FAN150/400	aircraft concept considered in this study with 150 or 400 seats, equipped, *inter alia*, with ultra-high bypass turbofan engines
UHB	Ultra High Bypass, aircraft engine technology to reduce fuel consumption
VOC	Volatile Organic Compounds
WG3	Working Group 3 of CAEP, studying feasibility of environmental standards for complete engine/airframe combinations
WG5	Working Group 5 of CAEP, studying feasibility of so-called MBOs (Market Based Options), economic incentives to reduce emissions

References

The literature for this study can be broken down into two parts. The first consists of the technical background studies specially prepared for this report by Peeters Advies, Delft University of Technology and CE. These background studies are available as a separate volume. The second block is the complete literature used for this study and the background studies.

Technical background studies to this report
available as ‘ESCAPE; background report’

1 Peeters Advies, Designing economic aircraft for low emissions, technical basis for the ESCAPE project, P.M. Peeters, Ede, July 2000
2 ADSE, A review by ADSE of ‘Designing economic aircraft for low emissions, technical basis for the ESCAPE project’, E. Jesse, Hoofddorp, June 2000
3 TRAIL the Netherlands’ research school for TRAnsport, Infrastructure and Logistics, with Delft University of Technology, Faculty of Aerospace Engineering, ESCAPE: an overview of technologies to reduce emissions, Heijden, J.R. van der and R.A.A. Wijnen, Delft/Rotterdam, February 2000
4 Delft University of Technology, Faculty of Aerospace Engineering, ESCAPE: Using a more fuel efficient aircraft in a hub & spoke network, R.A.A. Wijnen, February 2000
5 CE, Solutions for environment, economy and technology, ESCAPE: Fuel prices and fuel efficiency: a historic overview, J.M.W. Dings, January 1999
6 CE, Solutions for environment, economy and technology, ESCAPE: Kerosene from biomass, H.C. Croezen, Delft, March 1999
7 CE, Solutions for environment, economy and technology, ESCAPE: Policy options to reduce aviation emissions, J.M.W. Dings, Delft, April 2000

Other literature
ADSE b.v., Hoofddorp
- Milieubelasting & luchtvaarttechnologie (Environmental effects and aircraft technology), Jesse, E. et al., 1997
- Dutch Green Aircraft Intelligence Pilot Study (DGAIPS), 1997
- High-speed propeller characteristics, 1999

AVMARK, London
- The competitiveness of the European Community's air transport industry, 1992
- Study into the technical capability, cost efficiency and financial performance of Europe's leading scheduled airlines, Beyer, B.L., June 1993
- Airline cost trends and comparisons,. Beyer, B.L., November 1993
- Overview of cost trends of EU airlines, January 1999

Brewer, G.D.; Hydrogen Aircraft Technology; CRC Press, London, 1991

CE, Solutions for environment, economy and technology, Delft
- A European environmental aviation charge, 1998
- European aviation emissions: trends and attainable reductions, 1997a
- Potential economic distortions of a European environmental aviation charge, 1997b

Cohen, H., G.F.C. Rogers and H.I.H. Saravanamuttoo; Gas Turbine Theory; Second Edition; Longman Group; London, 1972

Collozza, A.J.; Effect of Power System Technology and Mission Requirements on High Altitude Long Endurance Aircraft; NASA CR 194455; Cleveland, Ohio, 1994

Corning, G.; Supersonic and subsonic, CTOL and VTOL, Airplane design; 4th edition; Maryland, 1976

Cupsty, N; Jet Propulsion, A simple guide to the aerodynamic and thermodynamic design and performance of jet engines; Cambridge University Press; Cambridge, 1997

Delft University of Technology
- Fundamentals of conceptual design, optimisation of subsonic transport aircraft, E. Torenbeek, August 1980
- Introduction to Preliminary Aircraft Design, Torenbeek, E., April 1988

Dempsey, P.S., Airline management: Strategies for the 21st century, Chandler, Arizona, 1997

Doganis, R.; Flying off course, The economics of international airlines; second edition, Harper Collins Academic, London, 1991.

EFCG, European Fuel Cell Group, http://www.fuelcell-eur.nl/, 1999]

Eggels, P.G., S. van Loo, Milieu-effecten van de energie-winning uit (afval)hout, TNO-MEP, Apeldoorn, 1995

ETSU, Aircraft engines, 1994
Williams, R.H. et al., Methanol and hydrogen from biomass for transportation, with comparisons to methanol and hydrogen from natural gas and coal, Princeton University, the Centre for Energy and Environmental Studies, Princeton, New Jersey, July 1995.

European Commission, Communication on Air Transport and the Environment, Brussels, November 1999

Goudriaan, F., D.G.R. Peferoen, Liquid fuels from biomass via a hydrothermal process, Chem.eng.sci, Vol. 45, No. 8, pp. 2729 – 2734, 1990

Gray, D.E. et al., ‘Turbofans turn to UHB propulsion', Aerospace America, July, 1990

Haven, H.B.G. ten and T.D. de Witte; Flights and Emissions Model (FLEM) general Report model version 3.11; NLR CR 97327 L; NLR (Nationaal Lucht- en Ruimtevaartlaboratorium), Amsterdam, 1997

Hemker, H., Neue Turbofans für den Super Jumbo, Flug Revue, December 1996

ICAO
- ICAO examining the impact of proposed larger aeroplanes on airport design specifications, A.K.R. Rao, ICAO Journal, September 1997
- Report on environmental charges and taxes, IACO Assembly, 32nd session, agenda item 21, 17 July 1998

ICAS Proceedings

- DNW test highlights related to aircraft environment, H.U. Meier, J.C.A. van Ditshuizen, 1990
- Aerodynamic design for a new regional aircraft, E. Greff, 1992
- Impact of operational and environmental aspects on commercial aircraft design, Haberland, Ch. (et al), 1994

IPCC, IPCC Special Report on Aviation and the Global Atmosphere, Geneva, May 1999

Ivanov-Smolensky, A.; Electrical Machines; Volume 3, MIR Publishers, Moscow, 1982

Jager. D. de, A.P.C. Faaij, W.P. Troelstra, Kosten-effectiviteit van transportbrandstoffen uit biomassa (Cost-effectiveness of transport fuels from biomass), University of Utrecht, 1998.

Jane’s; All the world’s aircraft 1998-‘99; London, 1998/1999

Kahammer, F.R., P.R. Prokopius, V.P. Roan and G.E. Voecks; Status and prospects of fuel cells as automotive engines; A report of the Fuel Cell Technical Advisory Panel; California, 1998

Kermode, A.C.; Mechanics of Flight; Introduction to Aeronautical Engineering Series; Eighth Edition; Pitman publishing; New York, 1972

Lloyd’s Aviation; Aircraft Types and Price Guidelines including Turbine Engines; London, 1997/1998

McCall, E. et al., Advanced ducted engine nacelle aerodynamics and integration testing, 1992

Michaelis, L.A., 'Policies and Measures for Common Action', Special Issues in Carbon/Energy Taxation: Carbon Charges on Aviation Fuels (Draft), OECD, Paris, December 1996

Moore, R.M.; Fuel cell Vehicles: Efficiency and emissions; Paper presented at Commercializing Fuel Cell Vehicles 97; Frankfurt, 1997

Morrison, S.A.; An economic analysis of aircraft design; Journal of Transport Economics and Policy, pp123-124; 1984

Naber, J., F. Goudriaan, A.S. Louter, Further developments and commercialisation of the Shell Hydrothermal Upgrading Process for the liquefaction of biomass, Proceedings of the 3rd Biomass conference of the Americas, Montreal, August 24 – 29, 1997.

NLR, ‘Brandstofverbruik en emissies door vliegtuiggasturbinemotoren’ (Fuel consumption and emissions by aircraft gas turbine engines), A. Peper, 1993

Greene, D.L., Oak Ridge National Laboratory, Centre for Transportation Analysis

- Commercial air transport energy use and emissions: is technology enough?', 1995
- Energy-efficiency improvement potential of commercial aircraft, 1992

Padilla, C.E.; Optimizing Jet Transport Efficiency, Performance, Operations & Economics; McGraw-Hill; New York, 1996

Peeters Advies

- Ontwikkeling Europese lange afstandsmobiliteit, samenvatting (Development of long distance mobility), Peeters (et al), Haarlem, 1997
- Milieu en Netwerkvorm in de luchtvaart, Pilot study; Peeters, Paul, Kees van Goeverden, Youdi Schipper, Piet Rietveld, Barbara van der Kerke, Bouke Veldman en Wieger Dijkstra; Ede, 1999

Ree, R. van, A.B.J. Oudhuis, A. Faaij, A.P.M.W. Curvers, Modelling of a biomass-integrated-gasifier/combined cycle (BIG/CC) system with the flowsheet simulation programme Aspen^{plus}, ECN, Petten, 1995

Rolls Royce, Advanced propulsion systems for large subsonic transports, N.J. Peacock (et al), Derby, 1992

Raymer, D.P.; Aircraft Design: A conceptual Approach; AIAA Education Series; second edition; Ohio, 1992

Roskam, dr. J.; Airplane Design; Part I to VIII; Ottawa, Kansas, 1989

Royal Aeronautical Society, The new large aircraft, Royal Aeronautical Society proceedings 1993, October 1993

Schumann, U. (Editor), Air traffic and the environment - Background, tendencies and potential global warming effects, Springer Verlag, 1990

Snyder, Chris; Zero-Emissions Aircraft? Scenarios for Aviation's Growth: Opportunities for Advanced Technology: "Zero Emissions" Aircraft; paper presented at the NASA Environmental Compatibility Research Workshop III, Monterey, 1998

The MVA Consultancy, AERO, Aviation emissions and evaluation of reductions options (AERO), S. Woodhouse, S. Lowe, 1997

Torenbeek, E.

- Ir10B Ontwerpen van Vliegtuigen II, deel A: Optimalisatie van subsone verkeersvliegtuigen; TU Delft; Delft, 1989
- Synthesis of Subsonic Airplane Design; An introduction to the preliminary design of subsonic general aviation and transport aircraft, with emphasis on layout, aerodynamic design, propulsion and performance; Kluwer Academic Publishers; Dordrecht, 1982

Trego, L., Das turbine engine developments, Aerospace Engineering, Jan. / Feb. 1997

Unique Mobility, Inc; PowerPhase^{TM} 1000 Fact Sheet, http://www.ubq.com/

Vedantham, A. and M. Oppenheimer, Long term scenarios for aviation: demand and emissions of CO$_2$ and NOx, Energy Policy, vol. 26 No. , 1998
VROM Ministry, White Paper of the Netherlands on Air Pollution and Aviation, The Hague, 1995

Wildi, Th.; Electrical Machines, Drives, and Power Systems; second edition; Prentice Hall; New Jersey, 1991

Special thanks to:

- Mrs. A. van Boxtel (AVV, Dutch Transport Research Centre)
- Mrs. M. Durville (Dutch Ministry of Economic Affairs)
- Mrs. P. Feimann (RIVM, Dutch National Institute for Public Health and the Environment)
- Mr. P. Haagmans (Dutch Ministry of Economic Affairs)
- Mr. R. den Hertog (Fokker Services)
- Mr. C. Huisson (Pratt & Whitney Canada)
- Mr. E. Jesse (ADSE, Aircraft Design and Systems Engineering)
- Mr. D. de Jong (VROM, Dutch Ministry of Housing, Spatial Planning and the Environment)
- Mr. F. Vollenbroek (VROM, Dutch Ministry of Housing, Spatial Planning and the Environment)
- Mr. R. Sausen (DLR, Deutsches Zentrum für Luft- und Raumfahrt)
- Mr. U. Schumann (DLR, Deutsches Zentrum für Luft- und Raumfahrt)
- Mr. N. Harle, editor