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AVIATION AND THE BELGIAN CLIMATE POLICY: INTEGRATION OPTIONS AND IMPACTS

«ABC IMPACTS»

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FINAL REPORT

AVIATION AND THE BELGIAN CLIMATE POLICY: INTEGRATION OPTIONS AND IMPACTS

"ABC IMPACTS"

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ACRONYMS, ABBREVIATIONS AND UNITS

A1	Annex I countries of the UNFCCC
AAGR	Annual Averaged Growth Rate
AERO2k	European project on global aircraft emissions for climate impacts evaluation
AIC	Aviation Induced Cloudiness
ATM	Air Traffic Management
BAU scenario	Business-As-Usual scenario
BEST	Board of European Students in Technology
CCD	Climb Cruise Descent
CCIEP	national Coordination Committee on International Environmental Policies
CCS	Carbon Capture and Storage
CDA	Continuous Descent Approach
CLM	Climate version of the 'Lokal Modell', which is the operational weather forecasting model used by the 'Deutscher Wetterdienst' (DWD). (http://clm.gkss.de)
EEA	European Environment Agency
EPA	Environmental Protection Agency (USA)
ESRA	Eurocontrol Statistical Reference Area
EU-ETS	European Union's Emission Trading Scheme
FLAP	Frankfurt-London-Amsterdam-Paris
FT fuels	Fischer-Tropsch fuels
GHG(s)	Greenhouse gas(ses)
GTP	Global Temperature Potential
GWP	Greenhouse Warming Potential
HRJ fuels	Hydroprocessed Renewable Jet fuels
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IFR	Instruments Flight Rules
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
JCM5	Java Climate Model, fifth version
LTO	Landing and Take-Off
MCA	Multi-Criteria Analysis
MBL	Marine Boundary Layer
NECTAR	Network on European Communication and Transportation Activities Research
pkm	Passenger kilometre

QUANTIFY	European project: "*The main goal of QUANTIFY is to quantify the climate impact of global and European transport systems for the present situation and for several scenarios of future development*." (http://www.pa.op.dlr.de/quantify)
RCM	Regional Climate Model
RFI	Radiative Forcing Index
RPK	Revenue PassengerKilometre
RTK	Revenue Tonne-Kilometre
SARS	Severe Acute Respiratory Syndrome
SESAR	Single European Sky Air traffic management Research programme
SRAGA	IPCC Special Report on Aviation and the Global Atmosphere
SRES	IPCC Special Report on Emissions Scenarios
TAR / AR4	Third / Fourth Assessment Report of IPCC
TH	Time Horizon
tkm	Tonne kilometre
TR	Traffic Regions
TRADEOFF	European project on aviation and climate (from the 5th framework program)
TREMOVE	European project:: *"TREMOVE is a policy assessment model, designed to study the effects of different transport and environment policies on the emissions of the transport sector."* (http://www.tremove.org/index.htm)
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United Nations Framework Convention on Climate Change
VAT	Value Added Tax
VHO	Very Heavy Oils
VOC	Volatile Organic Compounds
WP	Work Package
WTW	Well-To-Wing

For more acronyms, abbreviations and units, see the glossary and synthesis documents (http://www.climate.be/abci – Open Section - Glossary) on the website of the project.

A pdf version of the glossary is also available on the ABC Impacts website (http://www.climate.be/abci - Open Section - Project publications).

All the words underlined (dotted line) within the text of this report are explained in the glossary.

SUMMARY

A. Context

Since the publication of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Aviation and the Global Atmosphere (SRAGA, 1999), the international scientific community has become aware of the importance of the impacts of emissions from the aviation sector on global warming. This report confirms that in addition to CO_2, condensation trails (contrails), induced cirrus cloud formation and NO_x emissions contribute significantly to climate change (IPCC, 1999; Sausen et al., 2005; IPCC, 2007; Lee et al., 2009). Yet, emissions from international air transport are not targeted by the Kyoto Protocol commitments but part of ongoing international negotiations at the United Nations Framework Convention on Climate Change (UNFCCC) is dedicated to accounting for emissions from international air and maritime transport (UNFCCC, 2009).

In November 2008, the European Union has officially published its Directive to include the aviation sector in the EU-ETS (EU, 2008). ICAO had already expressed its support to voluntary agreements and to the integration of the aviation sector in existing emission markets, but so far ICAO seems to be reluctant to accept the application of the EU Directive to non-EU carriers without bilateral agreements (ICAO, 2007) and IATA (International Air Transport Association) has intended a legal action at the European Court of Justice against it.

The current negotiations on the review of the existing EU-ETS at the European level and those on the post-2012 scheme and commitments at the UNFCCC level illustrate how climate impacts of the aviation sector have become a high-priority issue but also how complicated and interdependent policy options to include aviation in climate policy are.

Concerning scientific progress related to climate impacts of non-CO_2 emissions from the aviation sector, major scientific advances have been included in IPCC's Fourth Assessment Report (IPCC, 2007), resulting in particular from European projects such as TRADEOFF and QUANTIFY. Both projects estimates of the impact of NO_x and contrails have been lowered but the impact of cirrus cloud formation seems to be greater than was previously thought although there is still a large uncertainty. Overall, the total climate impact of aviation is dominated by the non-CO_2 impacts, particularly in the short term or in specific areas such as Belgium (cf. air traffic density).

Different options may thus be considered for the inclusion of aviation into climate policy. The analysis of these options is of particular interest for Belgium, given the value added multiplier effect of airport related activities in the local economy (Kupfer and Lagneaux, 2009), but also the impact of take-off noise and the intensity of airborne traffic above the Belgian territory with the related regional climate impacts.

B. Objectives

In this context, the *ABC impacts* project analyses the different climate policy options (as well as their consequences) and provides a wide study of the technical, economic and physico-chemical characteristics of the aviation sector, that are linked to climate change.

This research project serves two main objectives: 1- to inform political decision-makers about the environmental, political and socio-economic implications for Belgium of integrating the international aviation transport sector into climate policy; 2- to help with the preparation and assessment of Belgian climate policy, on the context of the negotiations concerning the expansion of the European Emission Trading Scheme (EU-ETS) and the post-2012 phase at the UNFCCC level.

The ABC Impacts project has been split into two phases. The report explaining more in details the work carried out during the first phase is available on Belspo's website: http://www.belspo.fgov.be/belspo/ssdh/science/Reports/ABC_IMPACT_FinalReport.def.pdf.

The whole project covers the evolution of the climate policy and the analysis of policy options to tackle aviation total climate impacts, the creation of an emission database for Belgium and a new emission calculator tool (Aviactor), a better understanding of non-CO_2 aviation climate impacts and metrics through the integration of a specific module in the general climate model JCM5 and the use of regional climate modelling, a multi-criteria analysis (MCA) to synthesize several characteristics of selected policy options, as well as some considerations about total climate impacts from the international maritime transport.

C. Main conclusions/recommendations

Technical and management potential emission reductions

Through important innovative adaptations, the aviation sector succeeded in implementing significant reductions of the emissions (CO_2, H_2O, Soot, CO, SO_x, NO_x, etc.) and fuel consumption of individual aircrafts. In the future, several evolutions (implementation of synthetic fuels or agro-fuels, aircraft design and engine improvements, etc.) as well as potentially some radical changes in the long-term perspectives (like the use of hydrogen as a fuel for aircraft) can be expected. Moreover, some specific management changes (improved air traffic flow management, Reduced Vertical Separation Minimum, Continuous Descent Approach, etc.) might reduce the impact of aviation on climate by more than 10% compared to the BAU scenario without the need for new technologies to be implemented on board.

However, these evolutions alone do not appear sufficient to reduce climate impacts from the aviation sector enough to be consistent with scenarios avoiding global warming of more than 2°C above pre-industrialisation levels. These efficiency improvements (fuel consumption decreases by 0,5%-2% per year) are in fact smaller than the long-term high growth rate of the sector (average of 6,4% per year between 1991 and 2005 and growth in demand likely to recover to rates similar to the pre-economic crisis long-term forecast). Therefore, complementary climate policy measures are necessary to mitigate future aviation climate impacting emissions.

Modelling aviation climate impacts

Aviation impacts on climate may be much more significant at the local/regional scale than on global average due to short term non-CO_2 effects and concentration of the air traffic above specific regions of the globe. As an illustration, the radiative forcing due to aviation is estimated to 78 mW/m^2 on global average (for the year 2005), to 400 mW/m^2 over Europe (in 2002), and to 1 W/m^2 over Belgium. The largest impact of aviation on climate, outside that from CO_2 in the long term, is likely to be that from induced cirrus clouds.

Test simulations were first made by assuming a homogeneous spatial distribution of flights, providing results that appear coherent with other studies. The potential AIC cover is larger in winter than in summer, resulting from the colder temperatures and the more frequent occurrence of super-saturation in winter. A simulation has been done with an actual flight distribution over Europe, based on the AERO2k database (Eyers et al., 2004). The initial comparison with satellite data is promising. Other satellite data are used for validating the temperature and humidity variables of the model prior and suggest a very good agreement.

Non-CO_2 aviation climate impacts

Our research confirms that impacts on climate from causes other than carbon dioxide, and specifically those from aircraft induced cloudiness, are non-negligible and likely to be substantial. Therefore, these need to be taken into account in mitigation objectives and related legislation, which is currently not the case. We included aviation impacts on climate and reference future scenarios in an interactive global climate model, and made it available on the internet (www.climate.be/jcm), enabling users to experiment with hypotheses regarding scenarios, uncertain climate parameters, and choices such as time-horizon. Our own analysis with this tool shows that to achieve a relatively ambitious mitigation target (such as limiting temperature increase compared to pre-industrial times to 2°C), it is very likely that the net emissions and climate impact from aviation will need to be much lower than in BAU scenarios. In the absence of efforts in the aviation sector, other sectors would need to reduce their emissions a lot more.

Non-CO_2 effects must also be taken into account to reflect the effective climate impact of aviation transport when comparing or adding it to the impacts from other sectors, such as in the EU-ETS. Failing to do so would result in emission units from aviation that would represent a higher effect on climate than units from another sector, so that trading emission reductions may result in reduced climate benefit. This aspect should also be taken into account when trying to inform the general public about aviation and climate change. Therefore, it is essential to include it in offset calculators for example.

Metrics of impact on climate and inclusion of aviation in cap-and-trade systems

The difficulties associated with attributing a weight to non-CO_2 impact from aviation, i.e. defining a metric for these effects, may have given the impression that uncertainties are so large that no reliable numbers can be provided to policymakers. However, we conclude that current knowledge is sufficient to provide estimates of aviation impacts on climate in spite of remaining uncertainties, with the caveat that metrics of non-CO_2 impacts have a fundamental limitation that will probably always require a compromise: a choice regarding the relative weight of short and long term effects (from days to centuries) must be done. In line with the recent expert meeting of the IPCC on metrics (IPCC, 2009), we currently recommend the use of Greenhouse Warming Potentials (GWP) to express the climate impacts of aviation in terms of CO_2 amounts having a comparable effect on climate, with a 100-years time horizon to match the choice made in the Kyoto Protocol.

Once GWP is selected as a climate impact metric, a remaining issue is that the uncertainty is still significant (roughly a factor of 2 or 3 between the low and high end of the 90% confidence interval). However, in the specific case of a trading system, we suggest that there is a rationale to simply select the best-guess value, as selecting the high estimate would not represent a more cautious approach – it would be more likely to overestimate the "climate value" of reduction units in the aviation sector as compared to other sectors. Based on the current literature, the simplest solution that we may advise is to use a multiplier of CO_2 emissions (based on GWP) equal to or slightly above 2 (cf. conclusions of the ABC Impacts workshop on "Aviation and offset programmes"). Similar values have been proposed for a long time, and although this should remain revisable as research progresses, it is now more supported by research than it was before.

However, a fixed value for all flights is not fully satisfying, as the actual impact may differ for each flight and specific measures (e.g. flight management to mitigate persistent contrails) may reduce the non-CO_2 impacts but slightly increase fuel consumption (and thus CO_2 emissions). We discussed variable multipliers and similar measures in a note to policymakers (Ferrone and Marbaix, 2009). A complementary approach may be to have specific legislation for certain non-CO_2 impacts (as the EU is planning for NO_x). However, this does not eliminate the issue of trade-offs that may exist (e.g. techniques that reduce non-CO_2 impacts at the expense of more CO_2 emissions: in some cases, regulation outside the CO_2 cap-and-trade may also result in more CO_2 emissions).

Belgium and aviation climate impacts

The Belgian aviation market has a very specific position within Europe due to its geographical situation; in the middle of the so-called FLAP area which is delimited by four of the five main airport areas of Europe: Frankfurt, London, Amsterdam and Paris. This also implies that the number of overflights is already considerable through Belgian airspace and could become even more important due to the sector growth and potential route adaptations (according to Statfor-Eurocontrol, the adoption of shorter routes could increase overflights above the Belgian territory by 10%).

The impacts of the Belgian aviation sector on global climate change is relatively small compared to other sectors or that of other countries, while regional climate impacts due to contrails, cirrus formation and change in the ozone concentration could have a large influence on the country because of the concentration of flights over the Belgian territory. A focus for Belgian policy makers could be to reduce the impacts from transit aviation, especially via operational measures targeting non-CO_2 effects.

D. Contribution of the project in a context of scientific support to a sustainable development policy

The ABC Impacts project scientific contributions supporting a sustainable development policy have taken multiple forms.

Concerning Belgian stakeholders and more specifically Belgian administrations, researchers participated actively as experts to the meetings of the "Ad hoc committee on bunker fuels – aviation and EU-ETS" of the CCIEP (national Coordination Committee on International Environmental Policies) – Greenhouse Effect working group, where the Belgian as well as the Flemish point of view concerning the inclusion of the aviation into the EU-ETS was prepared.

The research consortium organised also thematic workshops on "Aviation and offset programmes", "Non-CO_2 aviation climate impacts" and "Aviation scenarios and climate impacts" to which Belgian stakeholders as well as representatives from international organisations or research centres took part. Several specific co-operation actions followed these meetings as well as dedicated notes that were presented to Belgian and ICAO representatives, and discussed in more detail with members of the EU Parliament and Commission. ABC Impacts researchers have frequently interacted with the IPCC, in particular through the review of the AR4 and participation to the Plenaries of the WGI, WGII, and IPCC in 2007, contributing to improve the wording on aircraft induced cloudiness in the summary for policy makers.

ABC Impacts researchers participated also to several round-tables and scientific popularisation actions.

The project website (www.climate.be/abci) makes an extended glossary, different synthetic documents on the issues related to aviation and climate change, project publications, interesting references and links at everyone's disposal.

Finally, in order to assess the effectiveness of the identified policy options to reduce the total aviation climate impact, it was decided to use a multi-criteria analysis (MCA). A combination of the PROMETHEE&GAIA methodology and the Analytic Hierarchy Process (AHP) was carried out. The performance of the policy groups-alternatives were evaluated in relation to several appropriate criteria. The resultant ranking of possible alternatives is not intended to categorize the best one but to recommend an appropriate platform for future policy options compromises.

E. Keywords

Aviation ; Climate impacts ; Contrails ; Aviation induced cloudiness (AIC) ; Climate policy ; Mitigation ; Regional climate model ; Non-CO_2 climate effects.

1. INTRODUCTION

1.1. Climate stake and transport

Most important sources of anthropogenic GHG emissions are related to the combustion of fossil fuels and it is well known that transport is one the human activities resulting in the most important fossil fuel consumption. Transport amounts for a huge and increasing part of the energy-related GHG emissions (IPCC, 2007). While the general "Energy" category has slightly reduced its GHG emissions between 1990 and 2004 within the EEA area, the sub-category "Transport", taking into account all international transport, has increased its emissions by more than one third, with emissions from the international aviation registering by far the most important growth (+86%), especially in EU(15) countries (EEA, 2007). From 1990 to 2007 (EEA, 2009), international aviation GHG emissions rose in average by 4.5% per year for the EU(27).

1.2. Aviation, climate and climate policy

The aviation sector generates emissions having diverse impacts on climate. This diversity is caused by the fact that a great part of aviation emissions occur at high altitudes and interfere with the chemical balance between substances in the atmosphere, cumulating a variety of global and regional climate impacts:

- NO_x emissions play a role in the natural balances of atmospheric chemistry. At cruising altitudes they lead to a reduction of methane concentrations and a local increase of ozone concentrations;
- aerosol particles modify the radiation energy budget and may modify cloud properties by acting as cloud condensation nuclei or ice forming nucei. For example, soot heats the atmosphere locally by absorbing solar light and adds to the number of ice forming nuclei, and
- sulphur dioxide is oxidized to form sulphate (sulphuric acid) droplets which reflect solar light and modify could properties.
- water vapour is responsible together with aerosols and NO_x for the formation of contrails and cirrus clouds under specific meteorological conditions, which influence the local radiation energy budget.

As a consequence, the total climate impact of aviation is more important than the climate impact related to "traditional GHG" emissions only. Experts have evaluated that the total warming effect of aviation could reach 2 to 5 times the effect generated by aviation's CO_2 emissions only (IPCC, 1999; Sausen et al., 2005; IPCC, 2007; Lee et al., 2009).

Despite the previous considerations, the most important world-wide agreement on tackling climate change, the UNFCCC, does not take international transport such as aviation into account. This is mainly due to the fact that the emission allocation principle used in the Convention is based on the national territory where emissions occur, which is suitable for emissions from stationary installations or terrestrial transport modes such as road and rail transport but is not workable for emissions related to international transport modes like aviation and maritime transport (cf. most emissions occur above international territories like seas, oceans, etc. and are difficult to allocate to one or another country). The UNFCCC constitutional amendment, the Kyoto Protocol, which fixes quantitative emission reduction objectives for industrialised countries, did also not cover international aviation and maritime transport.

In the meantime, these transport sectors and especially international aviation have grown in such a proportion that aviation alone (including all its climate effects) may account for roughly 5-10% of the total anthropogenic contribution to climate change by 2050, and could have a much larger share if mitigation efforts are smaller in the aviation sector than in other sectors (IPCC, 2007, Marbaix et al., 2009). This trend can seriously undermine the effort realised by other sectors if not mitigated.

1.3. Objectives

The ABC Impacts project has been financed by the Belgian Public Planning Service (PPS) Science Policy within the framework of the research programme "Science for a Sustainable Development", research area "Climate". The main goals of the call for proposals were to reach a better understanding of the climate system and of the atmospheric processes and to support the preparation and evaluation of the climate policy.

In this context, the ABC Impacts project serves two main objectives: 1- to inform political decision-makers about the environmental, political and socio-economic implications for Belgium of integrating (or not) the international aviation transport sector into climate policy; 2- to be a tool for the preparation and assessment of Belgian climate policy, on the eve of the negotiations concerning the expansion of the European Emission Trading Scheme (EU-ETS) and the post-2012 phase of the Kyoto Protocol.

1.4. Teams

The consortium of research centres that has carried on the work is composed of the CEESE-ULB, ETEC-VUB, MOSI-VUB and ASTR-UCL. A brief description of each research centre is to find on the ABC Impacts webpage "About us" in the "Open section".

1.5. Content

This final report summarises the work carried out by the research consortium. After a summary of the followed methodology (Chapter 2), main results are presented concerning: the aviation market overview and forecasts (section 2.1), an aircraft emission inventory and technical emission reduction potentials (section 2.2), modelling of global and regional aviation climate impacts, the climate impact metric issue and flight climate impact calculators (section 2.3), climate policy tools, options to mitigate aviation climate impacts and description of the EU Directive 2008/101/EC that includes the aviation sector within the EU-ETS (section 2.4). A multi-criteria analysis (section 2.5) will compare different policy options taking into account main stakes coming from the previous sections and serve as an input for the development of scenarios (section 2.6). Finally, main conclusions and recommendations will be drawn up in section 2.7. An additional point (section 2.8) is dedicated to maritime transport and main comparison with aviation. Shipping has indeed many common points as regards the complexity of determining an adequate climate impact mitigation (global and regional effects) and allocation options, but differs strongly for several issues (e.g. regional climate impacts induce a cooling effect, the quality of emission and activity data is poorer).

Chapter 3 presents the research consortium actions to support Belgian policy makers as well as other national or international stakeholders to help them to better understand scientific work behind the issue of aviation climate impacts and analyse stakes related to mitigation policy options.

Chapter 4 describes the different dissemination flows that were used to diffuse and valorise ABC Impacts results such as the participation to the "Ad hoc committee on bunker fuels – aviation and the EU-ETS", the participation to "Offrem", the emissions inventory for off-road vehicles (including airport handling vehicles) of the Flemish Department of Environment, Nature and Energy (Leefmilieu, Natuur en Energie, ex-Aminal), the set-up of a project website (www.climate.be/abci), scientific publications and participations to national and international colloquia, the organisation of thematic workshops, scientific popularisation actions and networking.

Chapter 5 lists the numerous publications of the research consortium directly related to the work carried on in the ABC Impacts project.

Acknowledgments and References are to be found respectively in Chapters 6 and 7.

2. METHODOLOGY AND RESULTS

To achieve the objectives of the project, a multidisciplinary approach has been adopted.

On the basis of a literature review, a preliminary "state-of-the-art" has been carried out on the evolution of the climate policy, the emissions from aircraft, the evolution of the transport sector and specifically the aviation, the scenarios and assumptions as regards climate modelling.

In order to assess the evolution of aviation in the following years and to identify the characteristics of the different market segments (for the EU and for Belgium in particular), a market analysis has been achieved. This will be used to forecast the related aircraft emissions more in detail, as well as to assess the consequences of the integration of the aviation sector in climate policies on the environment, etc. The work carried out on this issue is summarized in section 2.1.

As regards the emission of the aviation sector, data have been collected from airports, Belgocontrol and Eurocontrol in order to build an emission inventory of aircraft landing on or taking off from a Belgian airport, as well as of overflights above the national territory. Moreover, the emission reduction potential from the aviation sector has been assessed, taking into account research and development regarding alternative fuels, new aircraft design, improved ATM, etc. The work carried out on this issue is summarized in section 2.2.

This data collection is of most importance for the climate modelling, mainly as regards the development of a specific model for assessing the regional climate impacts caused by aircraft. In the first phase, the existing model (JCM5) has been updated and completed with a specific module dedicated to the aviation sector. During the second phase of the project, a parameterization for representing contrails has been developed and implemented in the regional climate model CCLM (COSMO Model in Climate Mode) in order to assess the climate effects of aircraft induced cloudiness on the regional climate in Europe. The work performed on this issue is summarized in section 2.3.

About climate policy, its history has first been summarised highlighting the way transport, and especially the aviation sector, is concerned or not. An inventory of the main policy instruments having a direct or an indirect link with climate change has been performed. Instruments have been classified according to their characteristics (economic instrument, regulation, planning, etc.), described briefly and analysed from the point of view of the suitable competency level to implement them, and their relative environmental efficiency. Examples of their applications in the transport sector, specifically in aviation, have been given. The work has been completed by the follow-up of the current negotiations on the post-2012 UNFCCC-Kyoto scheme and the new EU directive including aviation into the EU-ETS. Different analyses have been carried out in order to assess the consequences and stakes related to several options discussed or proposed by EU member states or stakeholders (allocation principle, benchmarking method, specificities, etc.), as well as the potential interaction of this inclusion with other policies (e.g. post-2012 negotiations, EU-ETS review, etc.). The work carried out on this issue is summarised in the ABC Impacts Final report phase I as well as in section 2.4. It is important to note however that a non-negligible part of the work took the form of brief analyses and advices presented during the regular meetings of the "Ad hoc committee on bunker fuels – aviation and the EU-ETS" and is not summarised in this report (cf. most discussions are now out of date with the adoption of the EU Directive including the aviation sector into the EU-ETS (EU, 2008)).

The multi-criteria analysis is used to synthesize the comparison between the different policy options to tackle climate impacts from aircraft and to rank them according to their effectiveness in fulfilling each of the selected criteria. This method offers the opportunity to select the most appropriate "option" according to one specific criterion or to build a complete policy mix according to the complementary characteristics of the different options included. The methodology and the work performed are summarized in section 2.5.

According to results from the former points, different scenarios concerning aviation developments as well as its related climate impacting emissions and total climate impact will be drawn in section 2.6.

Finally, the conclusions and recommendations in section 2.7 synthesise the most important results from the former sections.

A specific section has been added focussing on maritime transport climate impacts in section 2.8.

2.1. Market overview and market forecasts of the aviation sector

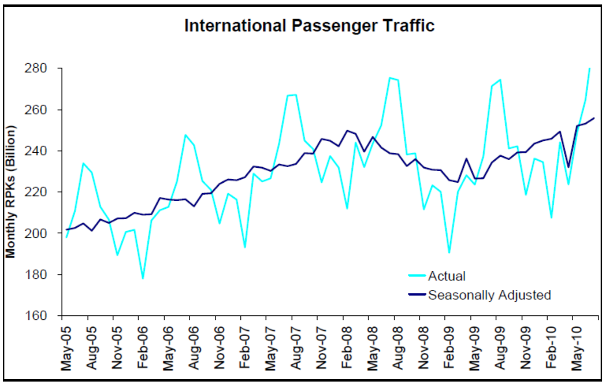
2.1.1. Market overview

Between 1995 and 2007 total volume of freight transport increased by 38% in tonne-kilometers (tkm) and total volume of passenger transport increased by 22,3% in passenger-kilometers (pkm) in the EU-27 (European Commission, 2009b). Both air freight and air passenger transport showed the highest average annual growth rates (AAGR) over the period 1995-2007, namely 4,5% and 3,7%, respectively, much above the AAGR values for all transport modes (1,7% and 2,7%, respectively). Note that freight transport by air is very limited in tonne-kilometers (tkm) compared to the other transport modes, but this type of transport increased by 55% between 1995 and 2007. In terms of passengers, air transport has become the second largest mode of transport in the EU-27, with an increase of 70,4% over the period 1995-2007.

Most recent data provided by IATA in their monthly Air Transport Market Analysis of July 2010 (IATA, 2010) shows that both the global air passenger and air freight transport sector are steadily recovering from the spectacular downturns in 2008 and

2009 caused by the financial and economic crisis. Pkm flown (RPKs) and air freight kilometres flown (FTKs) in July 2010 where already above pre-crisis levels of end 2007.

In air passenger travel markets, there was a very rapid phase of post-recession rebound from early 2009 until the end of 2009 when travel markets expanded at an annualized pace of 12% (Figure 1 left side). So far in 2010 (figures until July 2010), a slower growth phase has been evident, with an annualized pace of expansion closer to 8%. While slower than the 2009 rebound the travel market expansion in 2010 remains significantly above trend (6% pa) (IATA, 2010). The level of the global air travel market is now already back 3% above early 2008 levels. Had travel markets grown at trend during the subsequent period they would however have been 10% larger than evident in July 2010, which implies that just less than 2 years growth has been lost due to the economic downturn. This will only be regained if travel markets continue to grow at the pace of the first half of 2010 for a further 3 years, which seems unlikely given some of the pressures on economic growth emerging in regions like Europe.



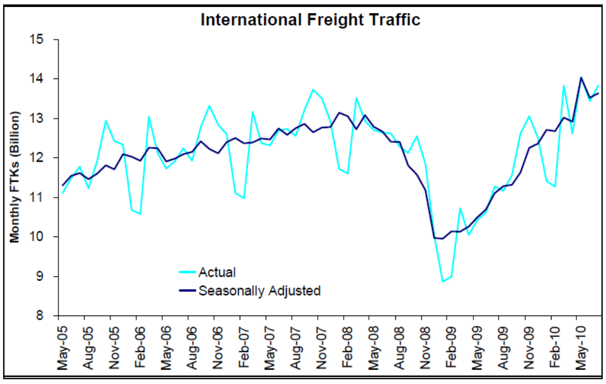


Figure 1: Global Monthly RPKs and FTKs of international air passenger traffic.
Source: IATA, 2010

Figure 1 (right side) shows a similar transition in expansion phase for the air freight market. From early 2009 until the last quarter of 2009, air freight markets were rebounding at the rapid annualized pace of 28%, but the slope of the seasonally adjusted FTKs became less steep in 2010 (ignoring the down in April and post-ash rebound in May) (IATA, 2010). During the first half of 2010, air freight market expansion slowed to an annualized pace of 17%. Month-to-month growth in July showed an annualized growth of 10%, which is still well above trend. Some further slowdown in air freight however should be expected according to IATA, due to the economic cycle which is moving into a different phase with business inventory rebuilding having come to an end, with more comfortable inventory-sales ratios regained (IATA, 2010).

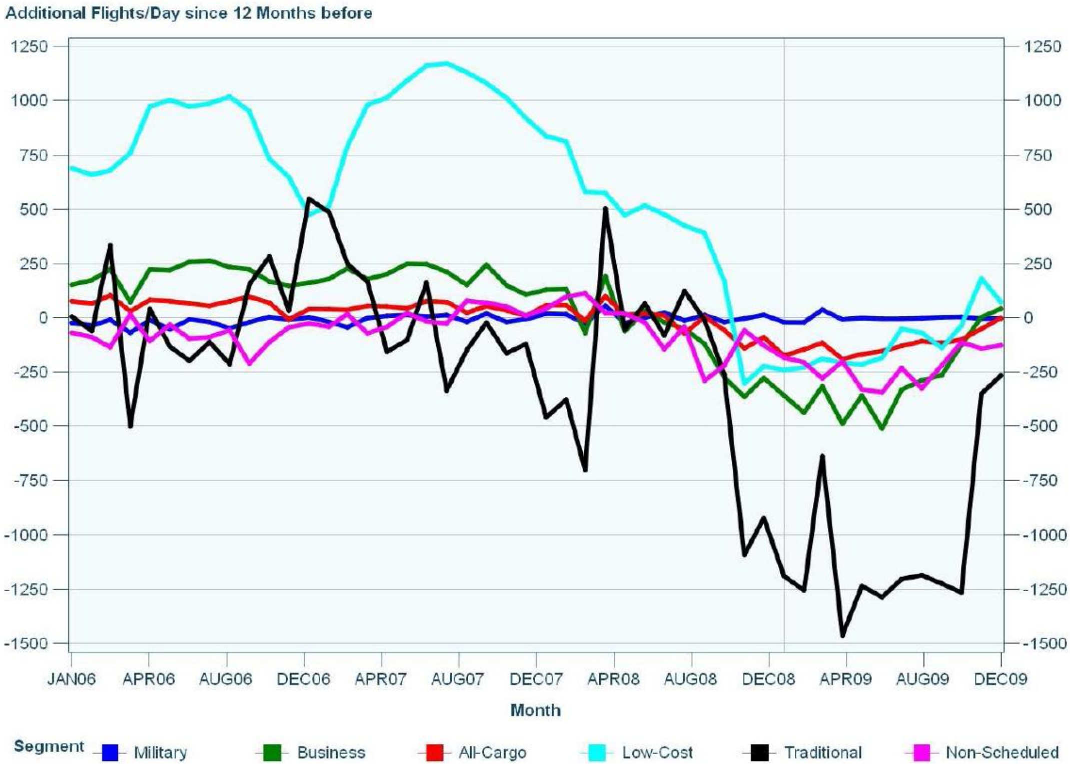


Figure 2: Year-to-year evolution of the different market segments in Europe.
Source: Eurocontrol, 2010b

There are however significant regional differences behind these figures. Specifically for Europe, growth figures are lagging behind worldwide averages. If we look at the market evolution in Europe during 2009, Figure 2 illustrates that almost all air market segments in Europe were still declining in 2009, including low-cost traffic, which had seen its first reduction in 15 years in November 2008. European segments started to grow on a year-to-year basis only at the end of 2009.

Recovery in Europe has thus been less strong than in the rest of the world and significantly below average. This lagging behind is also reflected in financial terms. Global airlines are expected to make $2,5 billion profits in 2010, nevertheless Europe is the only region where airlines are expected to make losses ($2,8 billion in 2010) partly explained by the Icelandic ash plume and the Greek crisis (Eurocontrol, 2010d), despite most recent figures from Eurocontrol showing European flights (IFR's) increased by 2,7% in June 2010 compared to the same month of 2009 (Eurocontrol, 2010e).

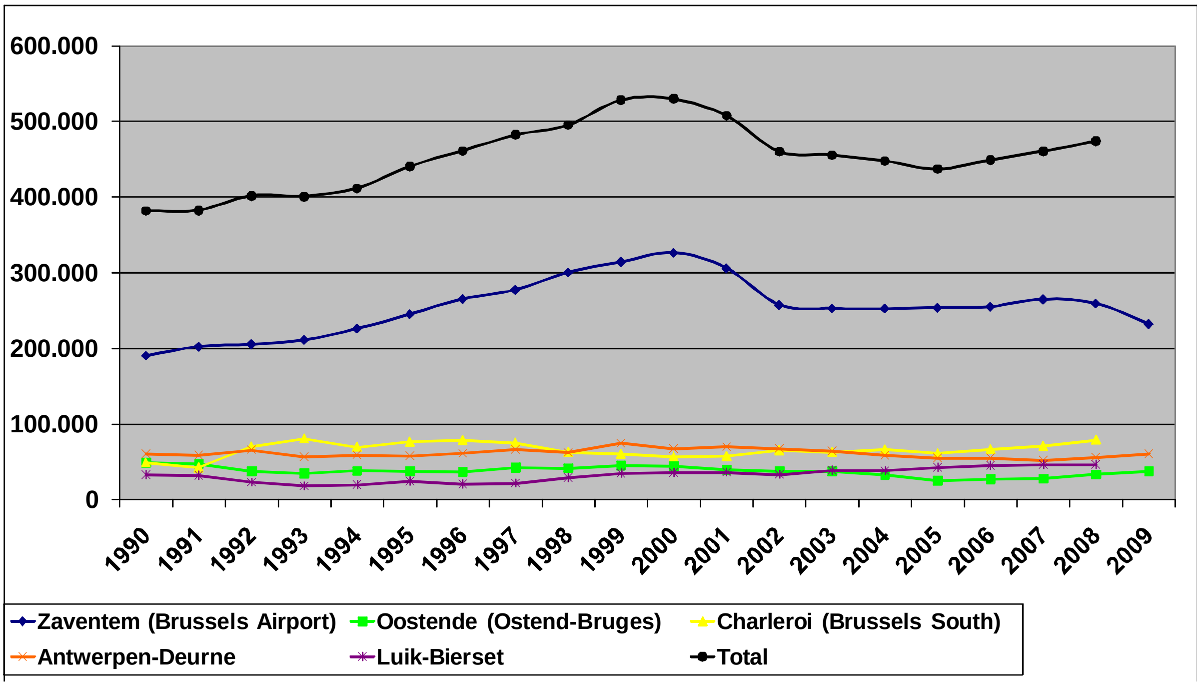


Figure 3: Number of IFR Movements at Belgian Airports (Landing and Take-Off)
Source: Own setup based on statistics provided by Federal Public Service Economy, 2010.

Figure 3 presents the evolution of the number of instrument flight rules (IFR) movements at the five main Belgian airports (with only partial figures for 2009). Since the economic downturn only came to full force in the second half of 2008, the total number of movements still increased over the whole year 2008. For 2009 however, a significant overall decrease is expected, which seems to be confirmed by the partial figures for 2009. For Brussels Airport, the number of IFR Movements in 2009 decreased with 10,5% compared to 2008. Brussels Airport, the largest Belgian airport, never fully recovered from the bankruptcy of the national flag carrier Sabena and of Brussels-based airliner "Citybird" in 2001. The decision of DHL in 2004 to move its centre of operations from Brussels Airport to Leipzig was another important factor, severely impacting cargo figures for the airport. There is some hope that the acquisition of SN Brussels Airlines by Lufthansa could change the tide for Brussels Airport, but this remains to be seen.

2.1.2. Market forecasts

Often simple, smooth growth curves are seen in air traffic forecasts that could encourage users of these forecasts to plan simplistic, one-size-fits-all solutions. These curves could mislead into believing that air traffic is a homogeneous mass swelling at 3-4% per year.

In reality however, air traffic demand is far from homogeneous, and its growth is far from uniform or guaranteed, as can be seen in Figure 4 which shows the dips in growth related to the oil crisis in the 70's and 80's, the recovery in the following years, the drop after the September 11th 2001 attacks and the restoration of growth thereafter (Eurocontrol, 2008).

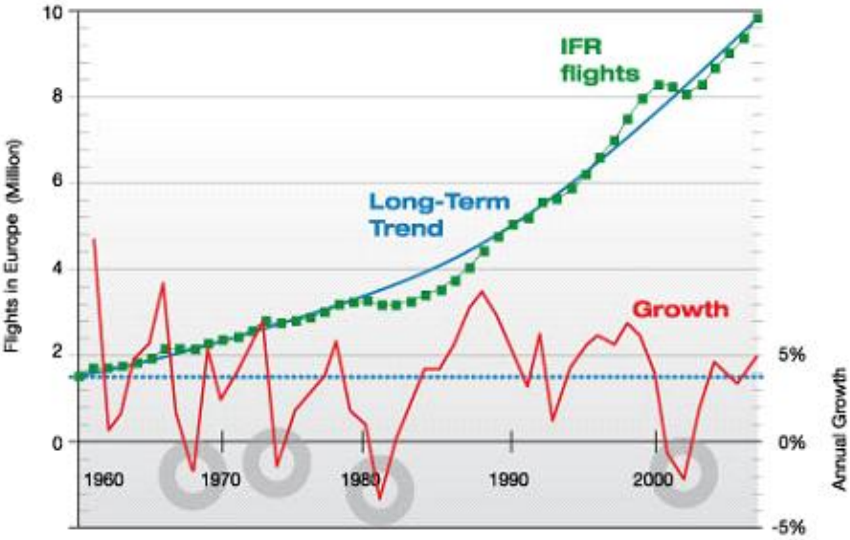


Figure 4: Growth in European air traffic during the last decades: non-uniform growth. Source: Eurocontrol, 2008

Global forecasts

The following global air traffic forecasts are based on long-term prognoses of Boeing for the period 2010-2029 (Boeing, 2010) and Airbus for the period 2009-2028 (Airbus, 2009). Boeing forecasts a demand for 30.900 new aircraft between 2010 and 2029 (Boeing, 2010) (compared to 29.000 between 2009 and 2028 in its previous forecast (Boeing, 2009)). The world fleet is expected to increase from 18.890 in 2009 to 36.300 by 2029 (Boeing, 2010) (up from 35.600 by 2028 in its previous forecast (Boeing, 2009)). Airbus expects the world fleet to increase from 15.750 in 2009 to 32.000 in 2028 (Airbus, 2009).

Key indicators resulting from the Boeing prognoses for the period 2009-2029 are represented in **Figure 5**, taking into account the dramatic drop due to the economic crisis in 2009. Airbus states that air travel expressed in RPK's has doubled every 15 years in the past and will do so in the next 15 years (Airbus, 2009). It is however important to note that prognoses from airplane manufacturers can be expected to be rather high, so these prognoses should be approached accordingly.

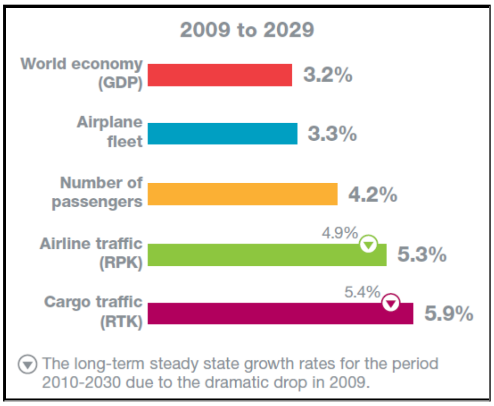


Figure 5: Key indicators for the period 2009-2028
Source: Boeing, 2009

European forecasts

Short (up to 2 years), Medium (up to 7 years) and Long-Term (up to 2030) Forecasts for Europe are provided by the Air Traffic Statistics and Forecasts Service (STATFOR) of Eurocontrol. They provide figures for IFR movements in the Eurocontrol Statistical Reference Area (ESRA). Given their recent nature, the short and medium term forecasts of traffic growth provided by STATFOR are strongly affected by recent economic events.

- *Medium-term forecasts (MTF)*

In the most recent MTF, Europe is forecast to have 11,5 million IFR flights in 2016, 22% more than in 2009. The recent economic downturn results in four 'lost' years of growth, which implies that the 2008 annual peak in flights will not be passed until 2012. Ignoring the leap-year effect in 2012, after weak growth in 2010 the traffic growth for Europe is expected to remain fairly stable at around 3% per year from 2011, which is below the long-term historical average of 3,8%-4%. In percentage terms, traffic growth will be stronger for most of the States in Eastern Europe (Figure 6). However, in terms of number of additional flights, the main contributors are expected to be Turkey and the busiest States of Western Europe (France, Germany, and Italy).

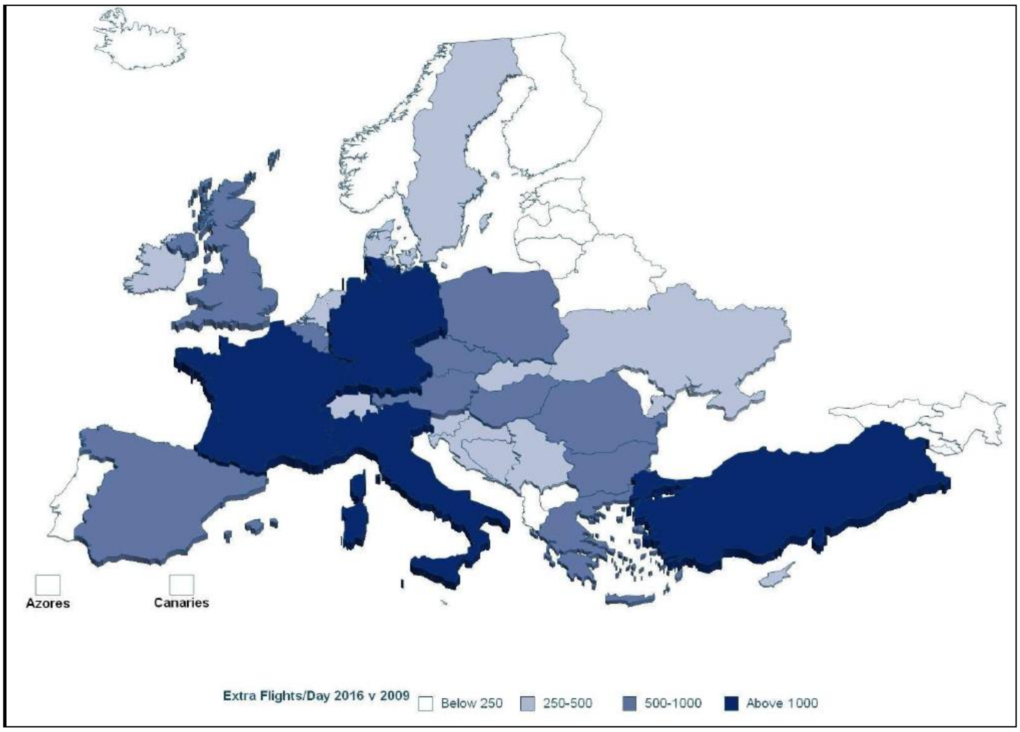


Figure 6: Number of additional movements per day for each State (2016 v 2009) (ESRA). Source: Eurocontrol, 2010b

- *Long-term forecasts (LTF)*

Eurocontrol publishes a LTF report every 2 years, making projections up to 20 years in the future, taking into account factors related to passenger demand, economic growth, prices, air network structure and fleet composition (Eurocontrol, 2008). The last LTF was published in November 2008 (the new forecast to be publicised in 2010 is not yet available) and is therefore outdated, given the fact that the traffic situation and the medium-term outlook changed significantly in the meantime due to the worldwide economic downturn.

Belgium/Luxembourg zone forecasts

Given the fact that international aviation is a global business, the global economic downturn also had a deep impact on the activity in the Belgium/Luxembourg zone. As for smaller countries in Europe, most of the traffic in the Belgium/Luxembourg zone is due to overflights. The location of Belgium in the middle of the so-called FLAP zone (Frankfurt-London-Amsterdam-Paris) is critical in this respect. This zone includes four of the five busiest airports (or airport clusters) in Europe both in terms of passengers and in terms of movements.

Detail of the annual traffic in terms of IFR movements and the growth rates in the Belgium/Luxembourg zone for the period 2005-2016 (Table I:) are provided in the Medium-Term Forecast 2010 (Eurocontrol, 2010c).

This overview confirms the high proportion of overflights in the Belgium/Luxembourg airspace: 64,5% of all IFR movements in 2009.

Table I: Annual traffic and growth rates in Belgium/Luxembourg zone 2005-2016

	IFR Movements (x 1000)												
	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	
Internal	7	7	7	8	8	8	8	9	9	9	9	10	
Arr/Dep	365	369	384	383	355	358	366	378	388	399	409	421	
Overflight	636	680	709	717	658	661	680	702	721	741	760	780	
Total	**1007**	**1056**	**1100**	**1108**	**1020**	**1027**	**1055**	**1090**	**1118**	**1149**	**1179**	**1210**	
	Annual Growth (%)												
	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**AAGR 2016/2009**
Internal		0,4	0,9	20	-3,8	3,3	4,2	3,6	2,9	3,1	3,1	3,2	**4,0**
Arr/Dep		1,3	4,0	-0,4	-7,3	0,9	2,4	3,2	2,5	2,8	2,7	2,7	**2,5**
Overflight		7,0	4,3	1,1	-8,2	0,5	3,4	2,9	3,3	2,6	2,8	2,6	**2,5**
Total		**4,9**	**4,2**	**0,7**	**-7,9**	**0,7**	**2,7**	**3,3**	**2,6**	**2,8**	**2,6**	**2,6**	**2,5**

Source: Based on Eurocontrol, 2010c

Of course the economic growth and the demand for air travel is only one of the parameters influencing the extent of the climate impact of the sector. In the next sections, we will discuss the innovative technologies and operations which could also have an influence on this impact.

2.2. Technical considerations, emissions model and comparison with different transportation modes

Emissions from the aviation sector can cover a great range of activities according to what is considered as part of the sector or not. Although some attention has been paid to the emissions related to the transport to/from airports, as well as to emissions occurring as a consequence of handling operations and ground support, the main focus of the ABC Impacts project is on emissions related to aircraft operations (flights).

The following points present the emissions related to aircraft and their main characteristics, the potential emission reductions in the aviation sector and the emission database gathered by the project for the emission and climate modelling.

2.2.1. Aircraft emissions and energy efficiency

Introduction

Anthropogenic radiative forcing (or global warming caused by human activities) is mainly caused by CO_2 emissions (IPCC, 2001). Therefore, although some integrated approach over the different GHGs is necessary, it also seems sensible to pay some special attention to this greenhouse gas. Moreover getting an overview of the CO_2 emissions helps to get a better insight in the energy efficiency of different sectors and transport modes. When looking at the different sectors it appears that in 2004, transport activities were responsible for 23% of the worldwide GHG emissions (IPCC, 2007). At the same time the share of transport in a growing total of worldwide CO_2 emissions is expected to increase in the coming decades (Morcheoine, 2005).

Air transport, which was responsible for 12,1% of the GHG emissions of the transport sector in the EU in 2006, and road transport are the two main drivers for the growth in energy consumption (and its related CO_2 emissions) in the transport in the EU, as well as in Belgium (Figure 7). This situation is predicted to stay like that at least in the short to medium term (Festraets et al., 2007).

Even if some exploratory flights are being performed with different kinds of alternative fuels, currently, aircraft usually burn 100% fossil fuels (e.g. aviation gasoline, Jet A-1 fuel) and produce noise as well as different pollutants that are either intrinsically related to combustion processes of any carbon based fuel (CO_2, H_2O), either related to fuel composition (SO_x, NO_x) and/or to the "quality" of the combustion process (NO_x, HC, CO, PM,).

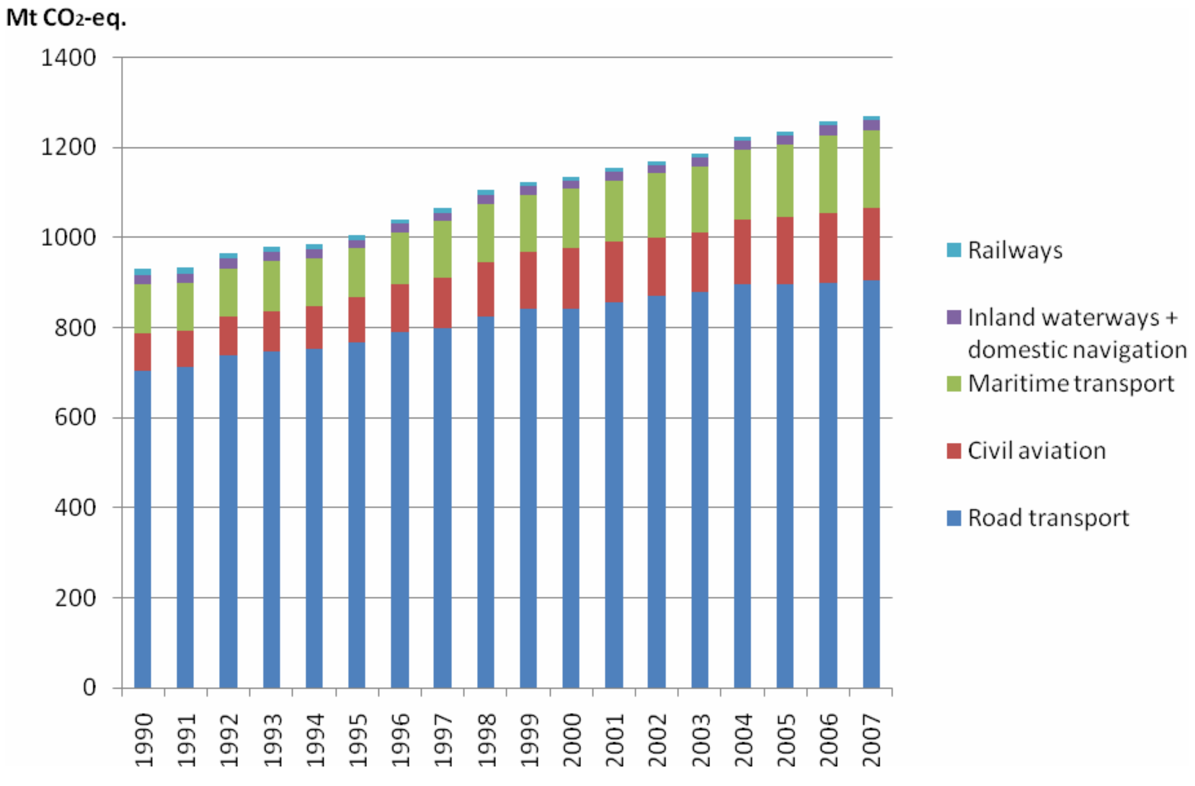


Figure 7: Evolution of the CO_2 emissions per transport mode (Mt CO_2).
Source: based on the statistical pocket book of the EU commission.

As will be made clear in the next sections, the total contribution of the aviation sector to climate change is actually higher than its CO_2 impacts alone. As a consequence, the relative share of aviation's contribution within transport related climate impacts is higher than its share of CO_2, which is depicted in Figure 7. Those pollutants all imply specific impacts on the environment including climate change (Table II:).

Until further progress is obtained in the development of alternative fuels for aviation use, the authors will consider that all of the fuel used in aviation consists of fossil fuel.

Given the fact that combustion conditions (e.g. temperature, atmospheric pressure, etc.) and fuel consumption change according to the engine power developed during each phase of the flight (e.g. taxi, take-off, cruise, etc.), the spreading of the emissions is not homogeneous through the different flight phases. The power setting of the engines during the LTO phase for example will result in higher NO_x, CO and unburned hydrocarbons (due to a less "complete" combustion) emissions as compared to the power settings used during the cruise phase. Emissions of CO_2 and SO_x are proportional to the amount of fuel burned (idem for SO_x emissions since they depend on the sulphur content in the burned fuel). The total distance flown, the fuel composition, the aircraft type and engine characteristics (e.g. technology, fuel efficiency, etc.) are the crucial influencing parameters to take into account when calculating those emissions.

Table II: Environmental impacts of different pollutants from fossil fuel combustion

Pollutant	Environmental impacts
CO_2	**Greenhouse gas (Role in climate change : global warming)**
CO	Toxic gas (impacts on living beings, a.o. health impacts)
NO_x	. Irritant gas (impacts on living beings (e.g. respiratory diseases)) . Role in the acidification and eutrophication of ecosystems . Role in the formation of tropospheric ozone (emissions at low altitude) . **Role in climate change (emissions at higher altitudes result in CH_4 depletion and ozone production)**
PM10 and PM2.5	. Impacts on living beings (e.g. respiratory disease) . **Role in climate change (influence on cloud formation and cloud properties when emittedssions at higher altitudes)**
SO_x	. Impacts on living beings (e.g. respiratory disease) . Role in the acidification of ecosystems . **Role in climate change (emissions at higher altitudes)**
HC / VOC	. Impacts on living beings (e.g. respiratory disease) and ecosystems . Indicator of the quality of the combustion and energy efficiency

As regards aircraft, jet fuel has a relatively low sulphur content (typically 0,05% by mass) compared to fuels for maritime or road transport for example. This factor results in relatively low SO_x emissions compared to other transport modes.

Although these emissions should not be neglected by policy makers in the context of air quality policies, this work focuses on climate change and does not discuss the other aspects.

Energy efficiency

Figure 8 illustrates the difference in energy efficiency for different flight distances covered by a typical long-haul jet airliner (B747-400). It clearly appears that the length of a mission influences the energy efficiency of the aircraft. Until a given threshold mission distance, tThe longer the mission is, the higher the energy efficiency is (expressed in kg of Jet-A1 fuelkerosene consumption per km). This is due to the high amounts of energy needed to lift the plane during take-off and climb of the aircraft, as well as to the fuel use during the landing phase of the flight. These parts of the flight are very energy intensive and do not implyinvolve the covering of large distances. Consequently they have a negative influence on the overall energy efficiency of the flight. From the threshold distance mentioned before (i.e. more or less 4.500 km in the case of the B747-400), where an optimum energy efficiency is obtained, the energy efficiency declines again: the weight of the additional fuel needed to perform the trip starts to deteriorate the energy efficiency during the first part of the flight (as more weight equals more energy consumption).

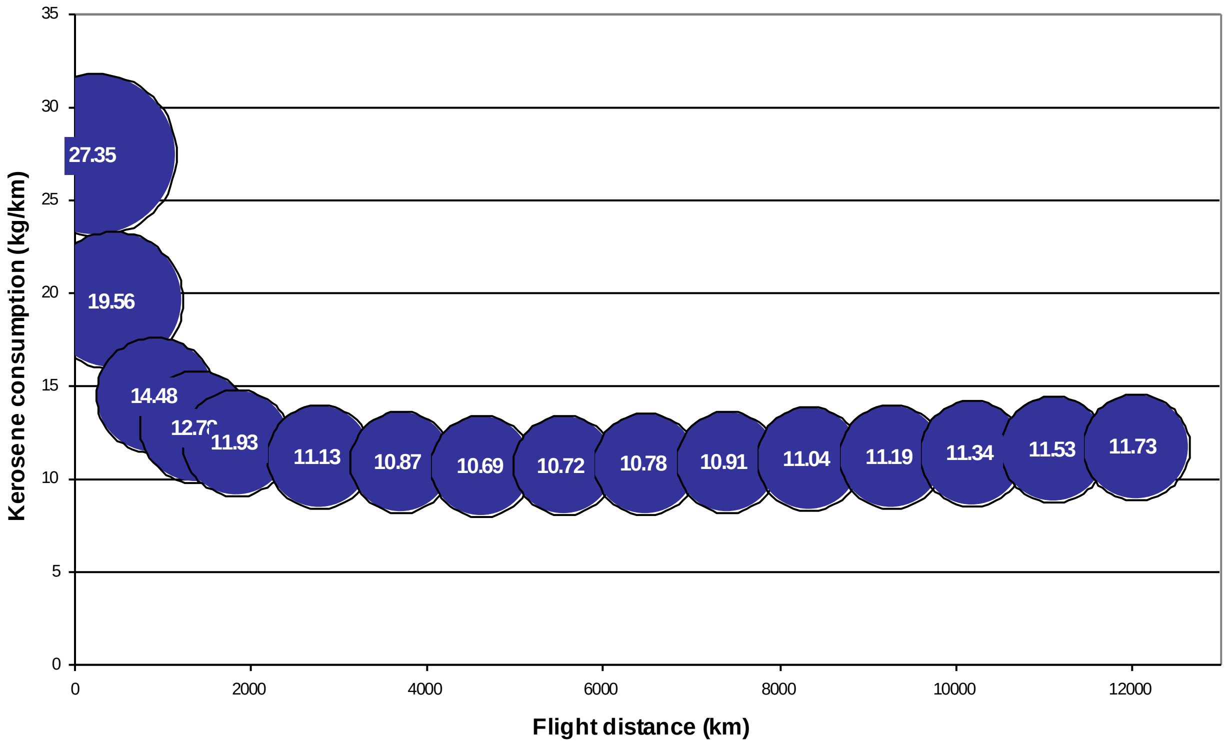


Figure 8 : Total fuel use of a B747 400 for different flight distances (radius of bubble represents consumption in kg/km). Source: based on EMEP/CORINAIR, 2006.

Figure 8 demonstrates very clearly the low efficiency of typical jet aircraft when used over short distances. The exact length of these short distances varies depending on the aircraft and is typically less than 1.500-2.000 km for the B747-400, but less than 700-800 for the medium-haul B737-400). Within the aviation sector, the influence of the higher energy consumption during the LTO cycle can be reduced when using turbopropellor aircraft, which are more fuel-efficient, especially during the LTO part of the flight. The reduced influence of the LTO cycle results in higher energy efficiencies for the short flight distances as compared to the previous types of aircraft. More generally, Figure 8 indicates that relatively easy gains regarding energy efficiency in air transport can be achieved through the shift from short-range flights towards less energy-intensive, but competitive transport modes such as, for example, high-speed trains.

Emissions

CO_2 emissions being directly related to the fuel consumption and the effects of CO_2 emissions being independent of the place (or altitude where they occur), the remarks concerning fuel use which were presented in the previous paragraphs are valid for CO_2 emissions as well. This implies high CO_2 emissions in high fuel consumption conditions and vice versa.

In a combustion process, NO_x emissions are influenced by three main factors: fuel composition (nitrogen content), combustion conditions (temperature, time passed in the combustion chamber) or prompt formation of NO_x (due to CH-radicals attacking N_2 molecules in the flame area). For an aircraft, NO_x emissions depend mainly on the engine technology and related combustion conditions. As regards one specific aircraft burning fuel, total NO_x emissions are mainly depending on the flight distance. This means they increase slightly less than proportionally with the flight distance. Basically, they show a similar profile to the CO_2 emissions profile detailed in the previous figure.

CO and HC (unburned hydrocarbons) are principally generated due to imperfect fuel combustion during the LTO phase. Even for longer missions, the bulk of the CO and HC emissions take place during the LTO phase. Those emissions are mainly a concern for local air quality issues and local environmental impacts around airports and have no significant impact on climate as compared to the other emissions of aircraft, such as CO_2, NO_x, water vapour, etc.

2.2.2. Activity database and emission calculations: evolution of the different kinds of emissions in the Belgian airspace

To perform a calculation of aviation emissions that is as precise as possible, it is essential to start from the most accurate available data concerning the activities in the Belgian sky. Like in many countries, the air traffic management operator owns the most reliable and exhaustive flight data. In this case, collaboration was sought with Belgocontrol. The consortium annually obtained extensive databases containing origin/destination data, aircraft types, flight distances etc. for all flights that passed through the Belgian airspace (including overflights). The data were provided in "database file" or "dbf" format and were sorted and transformed to enable the calculation of the emissions. The consortium also obtained some data but as some inconsistencies seemed to remain in the database, it was decided to proceed uniquely with the Belgocontrol data.

The emission data were calculated according to the following procedure:

1. organization of data;
2. allocation of the type aircraft;
3. calculation of the total distances covered per type aircraft;
4. calculation of the emissions related to the aircraft operating from the different airports;
5. calculation of the emissions and fuel consumption through the Corinair methodology (the fuel use and emissions per km are determined through linear regression of the Corinair data);
6. calculation of the emissions related to the aircraft from the different airports (this report shows only the aggregated data).

The evolution of the emissions in the Belgian airspace is depending on the type of aircraft used and on the magnitude of the activities both locally in Belgium as in the surrounding countries (as these activities often imply additional overflights).

Evolution of the fuel consumption, CO_2 and H_2O emissions

In this section the terms "LTO flights" will be used as opposed to "Overflights". This term stands for the operations including a landing and/or take-off on a Belgian airport or airfield (in other terms, the "local activities"). Overflights are flights passing through the Belgian airspace without landing or taking-off in a Belgian airport or airfield.

Concerning local activities, Figure 9 shows the evolution of fuel consumption and of its directly related combustion products (CO_2 and H_2O). Consequently, these three evolve in parallel, thus the conclusions that can be drawn from them are qualitatively similar. Following the reduced activities after the 9/11 attacks and the Sabena/Citybird bankruptcies (in 2001), a substantial reduction in fuel consumption appears in 2002. After this, the fuel consumption remained more or less stable during four years (2002-2005) and increased in 2006 and 2007. Traffic stabilized in 2008, which resulted in fuel consumption and CO_2 emission levels originating from the LTO flights in Belgium below the 2000 and 2001 figures. Due to reduced traffic as a result of the recent economic crisis, the emissions were approximately 7,3% lower in 2009 than in 2008.

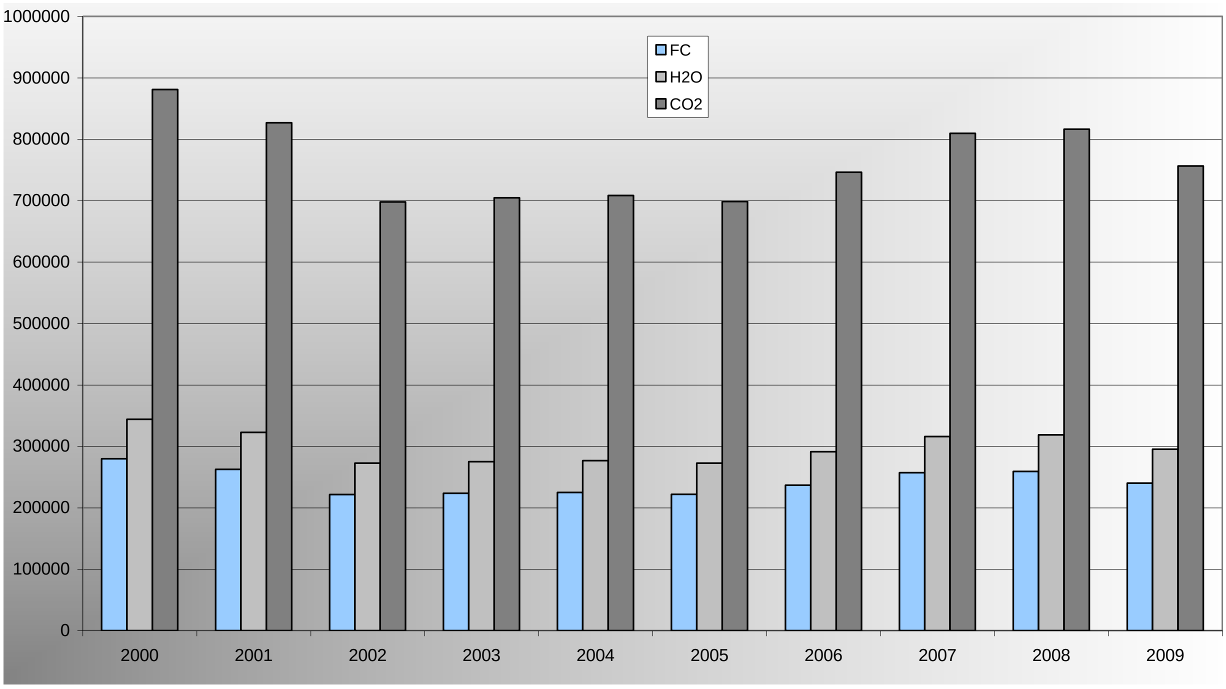


Figure 9: Fuel consumption and intrinsically related emissions of LTO flights in Belgium (tonnes / year). Source: based on data from Belgocontrol

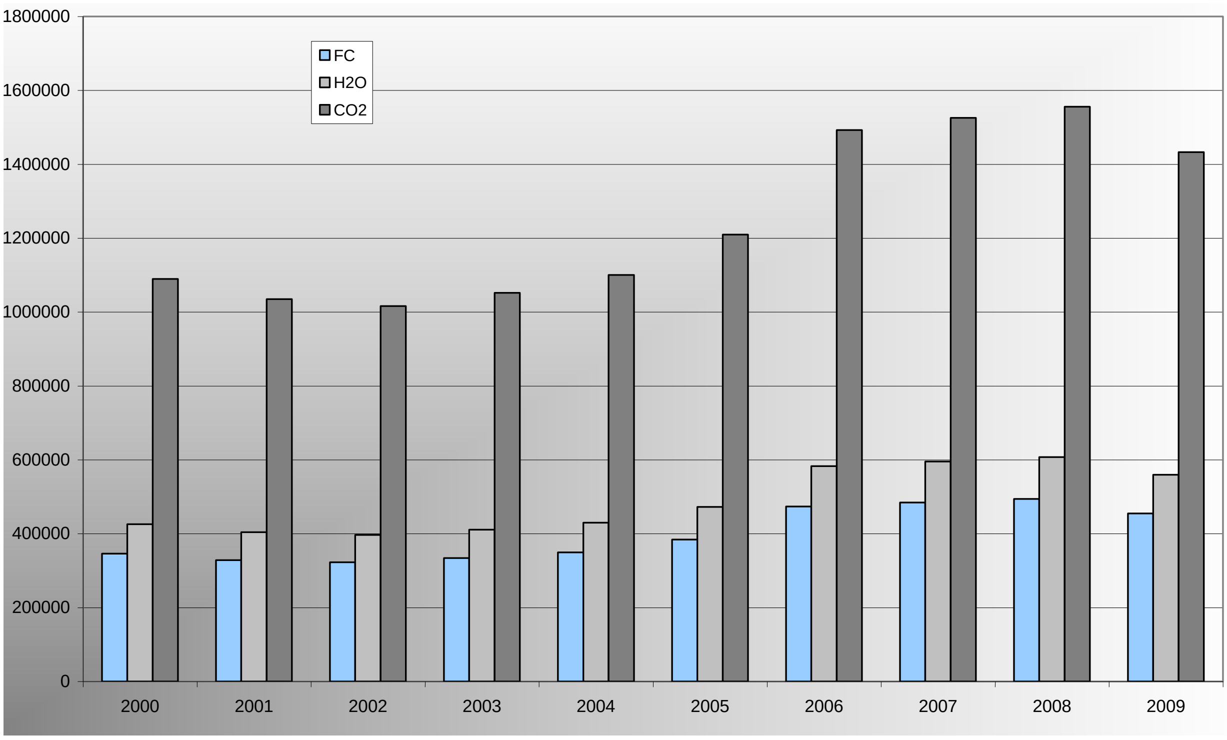


Figure 10: Fuel consumption and intrinsically related emissions of overflights above Belgium (tonnes / year). Source: based on data from Belgocontrol

As shown in Figure 10, the fuel consumption of the overflights decreased after 9/11/2001 as well. However, the recovery of these activities between 2002 and 2006 occurred much faster than for the local Belgian activities.

This is largely due to the fact that the effect of the 9/11 attacks mainly had an influence that was limited in time, while the bankruptcies of Sabena and Citybird have had a more structural effect on the local activities. The year 2007 is the first during which the growth of fuel consumption was higher for the LTO flights in Belgium than for the growth of the fuel consumption during overflights of the country. In 2008 it was not the case any more and again the overflights grew faster than the local Belgian activities. The economic crisis resulted in a reduction of the CO_2 emissions due to overflights of approximately 7,9% from 2008 to 2009.

When comparing both figures, it appears that the scales of the fuel consumptions are very different for the overflights and the LTO flights. Even including the comparatively high amounts of fuel used during the take-off and climb phases of the flights, the fuel consumption of the overflights within the Belgian airspace is approximately twice as high as the fuel consumption of the local activities.

This is due to two aspects: 1) overflights are more numerous than LTO flights, and 2) aircrafts only flying over Belgium are in average larger than those landing / taking off in the country.

2.2.3. Evaluation of different current and future aircraft technologies

Technology improvements play a crucial role in the reduction of the climate impact of aviation. Egelhofer et al., (2007) have calculated that between 1995 and 2005, the replacement of the world aircraft fleet allowed a reduction of the fuel consumption (and its consequent CO_2 emissions) by 6 to 7%, as compared to a hypothetical unchanged 1995-type fleet throughout that period.

However, cautiousness is required, as the highly interdependent implications of aviation on the different aspects of the environment (noise, climate, air quality, etc.) include gaps and uncertainties which might lead to undesirable consequences on one aspect when intending to tackle issues related to another aspect (trade-offs). For example, one might increase noise emissions while trying to reduce fuel consumption.

Current aircraft technologies

Early engines used in aircraft were similar to the ones used in automobiles. During the following decades, large improvements were performed in aviation engines and fuels. A lot of this progress was driven by military interests, both in Europe and North America. Primarily, the goal was to reach ever more power and reliability, while not increasing the engine's weight and size proportionally. The aim for increased power resulted in the development of specialized engines and fuels (aviation gasoline), until in the 1940s, the turbine engine provided even more power.

These turbine engines used kerosene (which is also used for wick lamps), until kerosene was eventually replaced by specialized aviation turbine fuels (or jet fuels). (Bacha J. et al., 2000)

Modern aircraft typically use Jet A-1 fuel, which is a mixture of many different hydrocarbons. The use of a liquid petroleum fuel such as Jet A-1 is due to advantages such as a high energy density per unit of volume compared to gases as well as easier handling and distribution as compared to solid fuels (Bacha J. et al., 2000). Although the implementation of alternative fuels can bring some modifications to the emission levels of the gas turbines used on most of the current aircraft, within the current aviation Jet fuels, there are little opportunities to reduce the emissions through fuel modifications, with an exception for sulphur emissions. Most of the emission levels are determined through the design of the combustion chamber.

Propeller engines, such as the Fokker 50 for example, are up to 20% more efficient than turbojet engines at low altitudes and airspeeds (Bacha J. et al., 2000). However, the main drawback of this type of aircraft is their lower speed, which is typically around half the speed of jet aircraft.

Nowadays, almost all commercial aircraft are equipped with *turbofan* engines, which use a turbojet as a core, but have a large fan, mounted in front of the compressor section. The basic principle of generating thrust with this type of engine is through a dual-circuit engine with a cold additional bypass flow. The fan, just like the compressors, is driven by a turbine and acts like a propeller. It pushes the air to create thrust. The bulk of the thrust, which is needed to 'push' the aircraft forward, is provided by the cold bypass. During the last years, the manufacturers have been trying to increase the mass flow of cold air, while reducing the jet speed. Hereby, the bypass ratio (BPR) is increased, which should improve the engines' propulsion efficiency (Wouters R., 2009). Turbofan engines are also quieter than turbojet engines, as the bypass air partially buffers the noise of the hot exhaust gases (Bacha J. et al., 2000).

Although today's jets are just as efficient as the latest piston engines (Peters & Middel, 2007), the current subsonic jet aircraft are approximately 75% more fuel efficient per pkm than 40 to 50 years ago (adapted from Macintosh and Wallace, 2009). The majority of this progress was achieved through engine improvements. The rest was obtained through enhanced airframe design (Macintosh and Wallace, 2009). Reductions of fuel consumption result in reduced CO_2 emissions, which is beneficial as regards climate. However, as mentioned in the previous chapter, the reduction in CO_2 and other emissions produced by an aircraft do not necessarily reduce the total impact that aircraft has on climate. Moreover, as Eurocontrol estimates that aircraft manufactured in 2015 will be 5,4% more fuel efficient than the similar-sized aircraft produced in 2004, this means that if an estimated 30% of the fleet is replaced by then, a similarly sized worldwide fleet would result in an emissions reduction of only 1,6% (Eurocontrol, 2006a). This shows that, even when not considering potential non-CO_2 trade-offs, the expected fuel efficiency improvements as such will not be sufficient to reduce aviation's impact on climate. Alternative fuels, such as agro-fuels and Fischer-Tropsch fuels are sometimes putne of the options put forward to reduce this impact. These are described in the next section.

Alternative fuels

Year on year, the efficiencies of the current technologies are improved. However, more radical technological improvements in aircraft design are sometimes presented as having the potential tocould result in faster and more significantleapfrog emission reductions if implemented. Some of the potential improvements of aircraft design, as well as airport and ATM operations are described in more detail below.

In the previous paragraphs, the main focus was on the conceivable means to reduce the impact of aviation through an improvement of its energy efficiency. This is obviously one of the solutions. However, another potential way to do so is to switch to alternative fuels.

- *Agro-fuels*

One of the potentially low-carbon alternative fuel types are agro-fuels. Many governments are stimulating the use of agro-fuels to reduce their dependency on imported energy sources, to support rural development and to try to reduce the climate impact of the transport sector. Nevertheless, a lot of criticism has been expressed over the alleged sustainability and financial viability of (the current) agro-fuels (Van Overmeire S., 2009).

Even if the relatively small number of fuelling points and vehicles involved result in a potentially more simple adoption of such fuels for aviation compared to other sectors, such as road transport (Hupe J., 2009), alternative jet fuels have to meet all the required safety and reliability standards of the aviation industry. Although the aviation sector has currently no commercially viable alternative for Jet-A1 fuel, a significant R&D effort is being put into the development of agro-fuels and some of the results are showing potential (GIACC-ICAO, 2009). Some airlines even performed test flights with blend-in agro-fuels (e.g. Air France-KLM performed some test flights with fuels originating from algae, while Virgin Atlantic performed some tests with agro-fuels coming from babassu and coconut oil). After some criticism on the alleged sustainability of these fuels, it seems the sector is currently mainly interested in the use of algae based agro-fuels. (Lane J., 2008).

In any case, to meet the criteria for sustainability, agro-fuels for aviation - just like other agro-fuels for transport or for energy production – should not compete (directly or indirectly) with food crops, should not stress the water resources and should not result in the waste of valuable land for example. In 2006-2007 for instance, it was estimated that agro-fuels were responsible for approximately half of the increase in demand for major food crops such as corn, wheat and soy bean (IMF, 2008). Obviously, their net CO_2 balance should also be better than the CO_2 balance of fossil jet fuels on a complete well-to-wing basis (Roetger T., 2009 and Hemmings B., 2009).

Although previous considerations indicate that there is still a lot of discussion going on to determine if (some of the) agro-fuels are really sustainable, let us assume that the CO_2 balance of a given agro-fuel is better than for conventional jet fuels and that it can be blended in the fuel tank with some conventional fossil jet fuel.

Using a fuel with slightly higher hydrogen content than Jet-A fuels and with a potentially lower energy content will have an influence on the water contents of the exhaust. Nevertheless, as the exhaust consists mainly of an excess of by-pass air, the overall composition of this exhaust gases will be only slightly different.

As a summary, it can be said that agro-fuels, although some of them might reduce the CO_2 emission balance of the aviation activities, are not yet available on a large scale (Roetger T., 2009) and are likely to slightly increase the non-CO_2 climate effect of aircraft. The precise extent of this increase is depending on the fuel used, but should be calculated and should be taken into account before claiming any beneficial effect of an agro-fuel on climate compared to conventional jet fuel.

Despite the efforts of the industry to develop (sustainable) alternative jet agro-fuels and the promising perspectives of some of the investigated agro-fuels, it is likely that it will take decades before jet fuels are replaced in a significant way (> 20%). Moreover, andit is unclear how sustainable these fuels will be overallway in the next several years (GIACC-ICAO, 2009).

- *Fischer-Tropsch fuels*

Fischer-Tropsch fuels are usually (natural) gas-to-liquid (GTL) or coal-to-liquid (CTL) fuels. Just like for some agro-fuels, some "Fischer-Tropsch fuels" can be used as a drop-in solution with the current fuels in any proportion. This allows to keep on using the same fuelling infrastructure, while requiring no or a very little amount of adaptations to the aircraft themselves. While these fuels present the advantage to be actual drop-in solutions and to reduce the dependency of airlines on fossil oil through diversification of the energy sources, they are still based on fossil energy sources (natural gas or coal) and do not reduce the climate impact of the industry (Maurice L., 2009). On the contrary, the impact tend to increase due to the energy demand of the refining and liquefaction process of the fuel, although carbon capture and storage could be considered. According to some, reductions of the life cycle GHG emissions of Fischer-Tropsch fuels can be obtained by replacing gas or coal by biogas or biomass as a source for the fuels. The latter, are sometimes called biomass-to-liquid fuels (Fonta P., 2009). A test flight with an Airbus A380 using GTL fuel has successfully been performed in 2008.

- *Cryogen fuels: hydrogen as a main energy carrier*

Liquid Hydrogen (LH_2) is sometimes put forward as a potential, long-term energy-carrier for transport in general and for aviation in particular (Ponater M. et al., 2006). Some small, limited-capacity aircraft using hydrogen in a combustion engine or in a fuel cell (such as the DLR-H2 and Boeing's adapted Dimona) have been presented for both manned and unmanned air vehicles (Dahl G. & Suttrop F., 1998 and Boeing, 2008). This so-called cryoplane technology shows the advantage of leading to no direct CO_2 emissions and to no particle emissions. The NO_x emissions would not be completely eliminated. However thanks to the extended possibility to use lean fuel burning (Wouters R., 2009b), the NO_x emission index can be expected to be lower than for conventional Jet engines.

Disadvantages of hydrogen powered aircraft however, are that these aircraft currently need oversized fuel tanks and of present reduced performances (regarding size, capacity, range, etc.) as compared to conventional aircraft.

Also, although most of the emissions of these aircraft would be reduced when compared to conventional aircraft, in the specific context of aviation and climate, the use of cryogen fuels instead of Jet A1 would also increase the frequency of contrail formation for similar air traffic intensity. This is due to the fact that the threshold temperature increases with the hydrogen content in the fuel and that for the same energy content, liquid hydrogen driven engines emit 2,5 times more water vapour than engines using conventional aviation fuel. For this reason, such aircraft would cause contrails over a larger range of altitudes than Jet-A1 powered aircraft (Schumann U., 1996). It has been estimated that the potential contrail cover would be increased by approximately 30% if all aircraft were powered by liquid hydrogen instead of Jet A-1 fuel (Marquart S. et al., 2005). However, it is possible that the direct climate impact may not be very different. That is to say that the cleaner exhaust emits fewer particles, resulting in a lower availability for them to form ice particles. This means that the contrails would show a lower optical thickness should cryogenic fuels be used instead of Jet-A1 (Svensson F. et al., 2004).

Finally, if wanting to claim hydrogen as a clean fuel, some attention must be paid to the production pathway of hydrogen, which can be produced from renewable energy sources (for example through electrolysis), but is currently mostly produced through steam methane reformation (thus consuming fossil energy sources) (Royal Belgian Academy Council of Applied Science, 2006).

Future airframe design

Currently built aircraft present some adaptations for increased energy efficiency. However, a significant number of the currently used aircraft were developed years or decades ago and results in a delay between the development of the technology/design and its implementation. Consequently, not all of the aircraft present in the current fleets are equipped with the most up-to-date technologies. The most relevant and recent developments concerning airframe design are summarized below. The fuel and emissions savings obtained through new airframe and engine designs vary depending on the aircraft they are applied to, as well as on the scale of the adaptation. Therefore it is not always possible to provide absolute figures for the individual technologies/designs.

- *Wingtip devices*

To reduce the drag of aircraft, and more specifically the drag of the wings, wingtip devices were designed. The two most current wingtip devices are "winglets" or "raked wingtips". Both of them are used to reduce the turbulence, and consequently the drag of the wings, hereby reducing fuel consumption.

- *Open-rotor or unducted fan*

The current engines are expected to evolve towards the Intercooled Recuperated Aeroengine (IRA), which is an engine equipped with an exhaust gas heat exchanger. With this system, fuel savings of up to 10% are possible on long-haul flights (Wouters R., 2009a). However, more radical changes can be expected in the medium term, as several engine developers are working on open-rotor or unducted fan (UDF) engines. The concept is not new though, as it traces back to the 1970's, but it was abandoned for a while due to engineering problems. These engines are fitted with several rows of propellers, which rotate in different directions and stick out at different angles, hereby giving the aircraft a greater trust. The UDF or open-rotor engines' much higher BPR than conventional turbofan engines reduces fuel use by up to 30%. Some of the drawbacks are that this technology leads to reduced speeds for the aircraft as well as to increased noise levels (Aerospace technology, 2008). Therefore, it could be assumed that currently, open-rotor aircraft would be an appropriate alternative technology to reduce the climate footprint of short- and medium-haul flights principally. Rolls-Royce, for example is working on an adapted open-rotor design, as the massive fan of open-rotor engines wouldn't fit under the wings of the current aircraft like the current engines do. Therefore most of the current or past prototypes of aircraft with UDF fitted them in the back of the aircraft, above the tail wings.

- *Adapted operation design*

When aircraft are designed, the developers aim at certain characteristics that need to be met by the aircraft. These characteristics include range, cruise speed, etc. Designing aircraft for a shorter maximum range can significantly reduce the weight of the aircraft. Moreover, as for shorter-haul flights, slower cruising speeds are not a real issue, these limited speeds imply less powerful engines (thanks to a more limited drag at slow speeds) and consequently less fuel consumption and emissions for the aircraft.

- *Reduced weight materials*

Aircraft design also offers possibilities regarding reductions of weight through material substitution. For instance, the new A380 already contained 25m% of composite materials, while the yet to be put in service Airbus A350 will contain 53m% of these materials. Boeing also intends to replace (part of) the aluminium casting of its B 787 Dreamliner by carbon fibre (Aerospace technology, 2008).

While new materials allow weight reductions, it is also possible to consider structural weight reductions by implementing new aircraft designs. This is illustrated in the section about blended wing-body aircraft.

Finally, another possibility to reduce the weight of aircraft is to replace the heavier hydraulic or mechanical control systems by a lighter all-electric control system (fly-by-wire) or by an all glass fiber control system (fly-by-light).

- *Improved aerodynamic design*

Since a long time, aerospace engineers tried to reduce the drag of the aircraft. Currently, laminar components/laminar flow technology, smooth surfaces and computational fluid dynamics allow to improve aerodynamic design and to reduce fuel consumption. One of the currently used techniques, not applied originally on aircraft, is the use of variable camber wings. This type of wings reduces drag (or improves aerodynamics) by adapting the camber of the wings optimally to the different flight phases.

- *Other future designs*

In the short term, investigations are expected to focus on how to improve the fuel efficiency of conventional aircraft configurations. In that context, next to efforts to improve engine efficiency, efforts are mainly made to reduce air resistance and to reduce weight. While the propeller drives can reach savings of up to 20%, the laminar flow might result in savings of up to 15% and the design and materials choice is estimated to be able to account for between 5 and 10% reductions in fuel consumptions (Junghanns J. & Klein C., 2009).

Although some of the previous descriptions concerning (alternative) fuels and technologies are quite drastic, some more groundbreaking concepts have been presented over the last years or even decades. Most of them did not make it (yet) as a full commercial product. Nevertheless, many prototypes or concepts present some interesting aspects and ideas. Some of them are illustrated below.

Long-term R&D projects

- *Electrically propelled aircraft*

Although the technology of electrically propelled aircraft is far from being mature for commercialization in airline operation, some prototypes and one-seaters have been developed and presented in recent years (Enerzine, 2009a and 2009b).

The UK-based company Yuneec for example, developed a fully electric two-seater called E430. The first test flights were performed in June 2009 and the commercialization of this aircraft is expected in 2010.

Another is the "Solar Impulse", which aims to demonstrate a fully solar-powered flight. However, this type of aircraft is still far from market maturity. Nevertheless, this kind of inititiative helps to gather knowledge on how to reduce weight and energy consumption as well as on the possibilities to change the energy carrier of aircraft.

Electric propulsion presents the advantage of not causing any direct emissions during the flight. Moreover, electricity could be produced from renewable energy sources (wind/solar), which means that, theoretically it would be possible to fly without any (CO_2 and non-CO_2) climate impacts of the current aircraft (except maybe for aerodynamically induced contrails; Kärcher et al., 2009). This technology also shows some potential to reduce air quality and noise issues around airports.

- *Blended wing-body and flying wings*

While flying wing designs do not have a separate body structure, and have the shape of one big single wing, blended wing-body designs merely have a flattened (though distinct) body. This body produces a significant part of the lift to keep the aircraft flying, while some distinct, separate wings are softly blended into the body of the aircraft. At the same time, the shape helps to increase the payload in the centre body portion of the aircraft (Nasa, 2003).

Both Airbus and Boeing are looking into the blended wing-body (BWB) concept. NASA and industry studies suggest that a large BWB commercial aircraft could result in 20% less fuel consumption per pkm at subsonic speeds. However, although this concept is already used for military aircraft, it will require a lot of engineering, time and investment before becoming reality as a commercial airliner.

2.2.4. Optimized operational measures

Airport facilities

Aircraft are obviously using energy and emitting most GHGs when they fly, but also cause the emission of GHGs when they are in operation on the ground. Aircraft are equipped with auxiliary power units (APU) to provide energy for non-propulsion purposes. This includes starting the main turbines as well as providing the pneumatic and electric power to run the heating and ventilation systems before starting the main engines.

Some airports are equipped with ground-based power units (GPUs), which allow the energy supply of aircraft without the need to use their on-board APUs. Not only, can this approach reduce the consumption of energy up to 6 times, but it also helps to reduce air quality issues around airports (Morris K., 2006). Moreover, as the aircraft are connected to the airport's electric grid, they also use the same electricity, which opens the perspective of renewable energy use.

Although hydrogen is not yet a mature technology for the main energy supply of commercial aircraft, when airports are not equipped with GPU systems, hydrogen might show environmental and/or commercial relevance for APU applications. For instance, a fuel cell could replace the auxiliary turbines. This would imply that the main turbines would exclusively handle flight performance and would operate in the load conditions in which they genuinely use the energy in the most efficient way. Moreover, the avoidance of auxiliary turbines would reduce noise, vibrations and local (mainly NO_x) pollution around airports.

Another way to reduce the energy consumption and emissions in the vicinity of airports is through the use of an efficient refuelling system. In Brussels airport for example, the fuel is supplied directly through pipelines from the refineries of the port of Antwerp (NATO pipeline). This hydrant refuelling system avoids the circulation of numerous refuelling trucks between the airport and the refinery (Flight global, 1993), hereby reducing the well-to-wing emissions of the aircraft.

Air traffic management (ATM)

Apart from the technology used to power the aircraft and the facilities used on the airports themselves, it is important to optimize the use of the airspace. The most important way to do this is through an optimization of the ATM system. This would reduce undesired detours and holding patterns of aircraft above congested airports, hereby reducing the flight times and distances. As a consequence, the emissions and energy consumption could be reduced as well.

The high number of countries in a relatively small area such as Europe leads to complex and less than optimal trajectories for aircraft operating in European skies.

As demand in air transport strongly increased in recent years, the limits of the capacity of the current ATM system in Europe are appearing, Therefore a more efficient air transport is a must and this the reason why SESAR programme, has been launched. The aims of SESAR are to restructure national airspaces with a consolidated air traffic service provision (reduce fragmentation) and to modernise the ATM system by 2020.

One of the goals of SESAR is to ensure a more sustainable air transport development in Europe in a safe and efficient manner. The key targets of the programme are: a) increasing the capacity by a factor of three; b) improving safety by a factor of ten; c) reducing by 10 % the environmental impact per flight and finally d) cutting ATM costs by half (Redeborn, 2007).

Ideally, improved ATM system could allow avoidance of ice supersaturated air masses as to limit AIC. In that case, a balance should be made between potentially increased fuel consumption and avoided non-CO_2 impacts.

Continuous Descent Approach (CDA)

Although CDA was already identified in 1970's, it is not generally applied. Depending on the type of aircraft, this approach method can result in the saving of up to 400kg of fuel per flight. Moreover, CDA has been identified as an appropriate low-noise procedure approach (Morris K., 2006).

Importantly, when implementing measures to improve energy efficiency, one must bear in mind that potential trade-offs exist between different issues. For example, requiring the use of preferential runways or flight routes for noise reduction might increase fuel consumption. Towing aircraft to runways can induce safety concerns. Also, ultimately, as far as aircraft design is concerned, numerous complex trade-offs exist between noise, fuel consumption/CO_2 emissions, local air quality/NO_x emissions, odours/unburned HC emissions, etc. This should be taken into consideration before making any final policy decision.

Technical and operational mitigation options

An assessment of alternative fuels, alternative technologies and alternative operational measures was performed and can be found in their full version in (Matheys, 2010). The take-home messages for these three categories of measures are provided individually below:

- *Alternative fuels*

Measures designed to promote alternative fuel use (especially agrofuels) in aviation should consider potential changes in land-use which might occur to cultivate the feedstock.

Although near-term prospects for alternative jet fuels are limited, several types of alternative jet fuels show a potential to reduce the impact of the sector on climate in the mid- to long-term. Next to the issue of the potential competition for land-use with food crops in the case of agro-fuels, the viability of the alternative fuels depend on their certification for jet fuel use, on the development of low-cost, renewable feedstocks and on (the absence) of other, more attractive, potential applications competing (from an energy-efficiency or economic point of view) for the use of these fuels (Hilleman et al., 2009).

A number of criterions are to be considered if wanting to quickly implement alternative fuels:

- compatibility with the current fuelling systems (most crucial criterion)
- maturity of the production technology (including process scale-up and market compatible prices)
- production potential of the fuel in the next decade (potential resource constraints)

To enable the stakeholders to evaluate the level of development the different types of fuel have reached, the concept of "*Fuel Readiness Level"* has been suggested (ICAO Environment Section, 2009). This approach could provide a global framework to evaluate the maturity of a fuel univocally on a worldwide scale.

The previous remarks mainly concern physical limitations. However, to provide a competitive, commercial product, production costs need to be considered as well.

Three alternative fuels may be available in commercial quantities in the next decade:

- Venezuelan VHOs and Canadian tar sands (highest potential however they would result in increased GHGs).
- FT fuels produced from coal, from a mix of coal and biomass or from natural gas (depending on the rate of construction of commercial plants and preferably combined with CCS).
- HRJ fuels produced from renewable (bio) oils (depending on the availability and prices of the feedstock)

Roughly, these three types of fuels currently result in WTW GHG emissions which are higher than conventional Jet A-1 fuel. Consequently, from a climate point of view, these fuels are not recommendable, except maybe in some specific cases for the renewable HRJ fuels.

Some of the considered fuels might show some greater benefits if used for other applications than aviation. For example, none of the analysed fuels (Unconventional petroleum, GtL FT fuels, CtL FT fuels, alcohols, renewable oils, hydrogen) show a higher interest for application in aviation than in road transport for example (Hilleman et al., 2009).

The production of alternative fuels for aviation theoretically leads to a lower demand and price pressure (compared to a situation without alternative fuels) on all of the petroleum products, not only on conventional aviation fuels. Inversely, the use of alternative fuels for other purposes also induces a reduction of demand for the conventional products, which in turn is beneficial to the aviation sector.

Alcohols (ethanol/butanol), although potentially promising for road transport, should be discarded for use in aviation applications. This is due to several factors: reduced energy density leading to reduced performance of the aircraft (lower range, lower energy efficiency due to higher payload), high vapour pressure causing problems for high-altitude flights and safe handling of the fuel. Alcohols thus seem much more appropriate for use in ground transportation applications or even more so for electricity production.

Further research is needed to fully understand the relationship between fuel composition (sulphur content, aromatic content, hydrogen-carbon ratio, etc) on the one hand and PM emissions on the other hand. *In fine*, this could allow optimisation of fuel composition in order to reduce PM emissions, hereby reducing the impact of the sector on both air quality and climate.

Because data are currently not easily comparable, it seems recommendable to implement a standardised way to quantify the WTW GHG emissions of different fuels to allow a more objective comparison of the numerous alternatives currently under development (Hilleman et al., 2009). This standardised approach would not only be useful to assess the actual environmental benefit of the different fuels, but also to integrate them coherently in mechanisms such as the EU-ETS or other emission related schemes (ICAO Environment Section, 2009).

Table III: Overview of the strengths and weaknesses of the main alternative fuel families for aviation. The different parameters are rated on a scale ranging from very positive (+++) to very negative (---).

Parameters	***Gas and Coal to Liquid***	***Agro-fuels***	***Liquefied Hydrogen***
Compatibility with current system	+++	+	---
Cost	+	0	---
Potential climate benefit	--	+	+
Large-Scale availability / production capacity in the near-future (2020)	++	+	---
Potential side effects on climate compared to conventional aviation fuel (risk)	-	0	--
Potential side effects on other environmental compartments compared to conventional aviation fuel (risk)	+	--	++

Table III illustrates that none of the alternative fuels for aviation shows a homogeneously positive (or even neutral) balance as compared to the current aviation fuel (Jet A-1). Therefore, while underlining the need to maintain research and development efforts in alternative fuels in general, it may be legitimate to wonder if pushing for the specific use of these alternative fuels in aviation makes sense from an environmental point of view. As the advantages of using these alternative fuels in aviation are generally lower than for other applications (such as power generation and road or maritime transport) and the potential negative side effects are more important, it seems that forcing the above mentioned fuels into one or another application (for instance: aviation) might result in significant diseconomies and could reduce progress towards an overall reduction of GHG emissions/climate impacts (Hilleman et al., 2009). Obviously, this does not mean that R&D efforts (on energy efficiency and/or improved operations) specifically meant for the aviation sector should not be maintained or reinforced. These will be discussed in the next section.

The main driver towards the use of alternative fuels for aviation will be the price of oil products on the international markets. If the goal (of the aviation sector) is to maintain energy prices at a moderate level, the strategy of choice should be to increase energy efficiency and to promote alternative fuels, not only in aviation but in all sectors depending on oil products. The followed logic is that a saved barrel has the same impact on price levels as a barrel displaced to alternative fuels (a reduction in demand for conventional fuels), be it in aviation or in any other sector. From an economic point of view, the production and use of every barrel of alternative fuel (in any application whatsoever) reduces the demand and attenuates the upwards price pressure on conventional fuel for aviation applications.

Overall, if the use of alternative fuels is to be encouraged by governments, it should thus not specifically be encouraged for an application in the aviation sector. Based on an individual environmental analysis per alternative fuel, the development of the fuels considered to have a positive environmental balance should be stimulated in a more general way as it seems none of them show greater environmental benefits for aviation than for other applications.

- *Alternative technologies*

By 2025, new technologies could result in a potential improvement of 20 to 35% of the efficiency of currently produced aircraft. Drag could be reduced by fuselage coatings and adjustable wings. At the same time, engines running at higher temperatures and pressures as well as geared engines, which optimise the speeds of the different components of the turbine, could reduce fuel consumption. Moreover, open-rotor designs could result in some efficiency improvements comparable to the ones of turboprops while maintaining more attractive operating speeds (Bullis, 2009).

Table IV provides an overview of the strengths and weaknesses of the different alternatives described in this section.

When considering technology improvements for aircraft, one crucial commercial/practical aspect has to be kept in mind. Aircraft have a lifetime of over 20 years. The improvement of environmental performances of a fleet/the worldwide fleet will show a significant delay compared to the first entry into service of an aircraft with a new technology. Taking technology development into consideration as well, this means that an aircraft fleet at any particular date in time is mainly composed of aircraft using a technology developed 30 to 35 years earlier (Carlier et al., 2005).

Table IV: Strengths and weaknesses of the main alternative state-of-the-art technologies for aviation. The different parameters are rated on a scale ranging from very positive (+++) to very negative (---).

Parameters	***Wing tip devices***	***Open rotor***	***Adapted operation design***	***Reduced weight materials***	***Variable camber wing***	***Improved aero-dynamic design***
Potential climate benefit	+	+ +	+ +	+ +	+	+
Compatibility with current system	+ + +	+ + +	+ (some routes might have to be reallocated)	+ + +	+ + +	+ + +
Cost	+ + +	–	---	--	0	--
Retrofit possible	Yes	No	No	No	No	Yes (Riblets, laminar nacelles) No (laminar wings)
Large-Scale availability / production capacity in the near-future (2020)	+ + +	+	+	+ +	+ + +	+
Potential side effects on climate compared to current situation (risk)	+	+ +	+ + + (no side-effects expected)	+ +	+	+
Potential side effects on other environmental compartments compared to current situation (risk)	+ + + (none)	- (potential increased noise)	- (potential extra LTO on longer routes)	+ + + (none)	+ + + (none)	+ + + (none)
Estimated fuel savings	1-2%	10%-20%	8-14%	10-20%	Marginal Most aircraft already equipped	Riblets (1-2%) Laminar nacelles (1%) Laminar wings (10-20%)

- *Alternative operational measures*

Table V provides an overview of some key features of some suggested operational measures. Some other operational measures, such as point-to-point operations (Often used by low-cost operators as opposed to the hub-and-spoke systems of national flag carriers. Although larger aircraft are more efficient in principle, the added space and comfort potentially lead to lower energy efficiency), formation flights, or tankering are sometimes proposed to reduce the climate impact of the sector (Eyers, 2010). However, these are not discussed here because of their marginal or sometimes even uncertain benefits.

Table V: Overview of the strengths and weaknesses of the main measures regarding optimisation of the aviation operational system. The different parameters are rated on a scale ranging from very positive (+++) to very negative (---).

Parameters	***Airport facilities (GPU, etc.)***	***SESAR***	***RVSM***	***CDA***	***Meteorological navigation***
Potential climate benefit	+	++	+	+	+++
Compatibility with current system	+++	+	+++	0	-
Cost	+	--	++	+	--
Time needed for implementation	+++	-	++	+	---
Potential side effects on other environmental compartments (non-climate)	++	0	+	++	0

The main advantages of the optimisation of the operational measures are that most of them do not require actual technology development work or fleet replacement. Moreover, they potentially improve the environmental performance of important numbers of aircraft at the same time. The most important drawback however, is that from an organisational point of view, some of these measures imply significant efforts, sometimes including the prerequisite of international or even global agreements before implementation.

Importantly, it needs to be kept in mind that RVSM and SESAR are measures primarily aiming at increasing the efficiency and capacity of the airspace. Also, while they might have a reduced climate impact as a result when assuming identical traffic flows, increased capacity could also induce increased demand, increased traffic and ultimately increased climate impacts.

2.3. Climate impacts from the aviation sector

One of the characteristics of aviation compared to other modes of transport is that an important fraction of the emissions that are relevant for climate occur at high altitude. A second characteristic concerns the geographical location of aviation climate impacts: aircrafts contribute to global warming and cause other local/regional climate impacts.

Total climate impact from aviation is more important than the climate impact from CO_2 only and has to be qualified according to the time horizon considered.

2.3.1. Impacts of aviation on climate

Due to the incomplete combustion of fuel, aircraft emit in addition to carbon dioxide (CO_2) and water vapour (H_2O), nitrogen oxides (NO_x), unburned hydrocarbons, carbon monoxide (CO), soot and sulphur dioxide (see IPCC, 1999 and section 2.3.1). These emissions have impacts on climate, environment and human health.

Given the fact that CO_2 molecules have a long lifetime, they accumulate and are mixed homogeneously in the atmosphere, where they absorb long-wave radiation emitted towards space by the surfaceand radiate part of it back to the ground, then increasing the surface temperature. The perturbation of the radiative (i.e. energy) balance at the top of the troposphere is referred to as radiative forcing (RF). In the case of CO_2 emitted by aviation this forcing causes a global warming estimated to + 0,028 Wm^{-2} (+0,015 to +0,041 Wm^{-2}) in 2005 (Lee et al., 2009b).

NO_x molecules emitted by the engines catalyse different chemical reactions that exist between ozone and methane present in the atmosphere. Model studies have shown that at this altitude the nitrogen oxides induce a short-term (less than a week) increase in ozone concentrations and a longer-term (around 11 years) decrease in methane and ozone concentrations (Stevenson et al., 2004). As both of these gases have a greenhouse effect, this induces in 2005 a positive RF of +0,026 Wm^{-2} (+0,008 to +0,082 Wm^{-2}) for the short term ozone increase and a negative one of -0,013 Wm^{-2} (-0,002 to -0,076 Wm^{-2}) for the methane reduction.

The total RF of NO_x in 2005 is estimated by Lee et al., 2009 to be +0,014 Wm^{-2} (+0,004 to +0,016 Wm^{-2}). As the lifetime of ozone is shorter than the typical mixing time of the atmosphere, the changes in ozone concentrations are larger in the Northern hemisphere and at high altitudes where most of the global traffic is concentrated. The altitude of emissions also has an influence on the perturbation of ozone concentrations (IPCC, 1999).

Figure 11 shows the radiative forcing of ozone for the base-case, normalized to CO_2 emissions, and the changes if there would be a shift of flight altitudes. It can be seen that the higher the typical flight altitude, the stronger the (average) impact (based on Fichter et al., 2005).

Aircraft flying around the tropopause have a direct and an indirect impact on global cloudiness. The direct impact is due to contrails, which represent artificially induced cirrus clouds that form under certain meteorological conditions in the plume of airliners.

Additionally, aerosols emitted at high altitudes may serve as condensation nuclei and hence result in a general increase in cirrus clouds that develop in the air mass. A cirrus cloud with different properties may have a different impact on radiation, resulting in an indirect effect of the aircraft exhaust substances on climate.

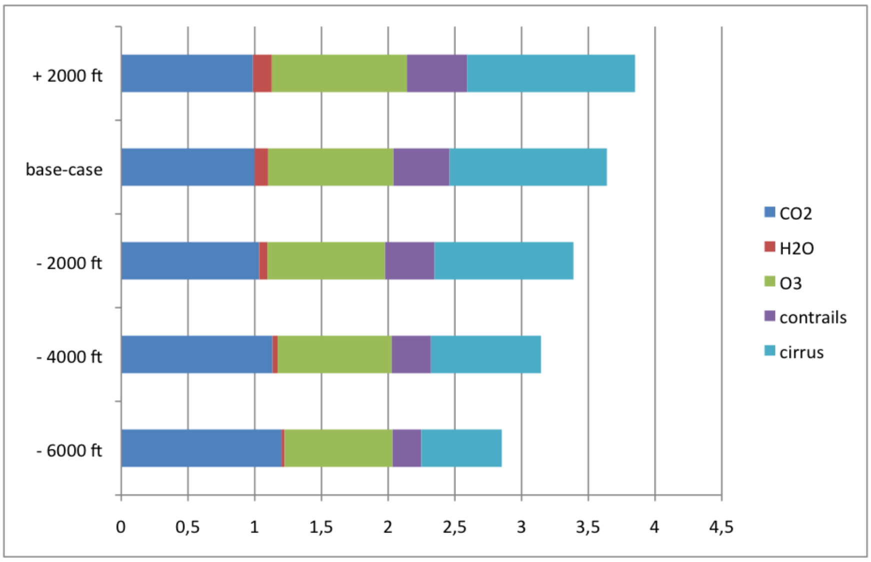


Figure 11: Relative climate impact of CO_2, H_2O, aircraft induced O_3, linear contrails and induced cirrus clouds as a function of flight attitude. The CO_2 radiative forcing in the base-case (current fleet) is used as reference (1).
Source: based on Fichter et al. (2005) and Lee et al. (2009)

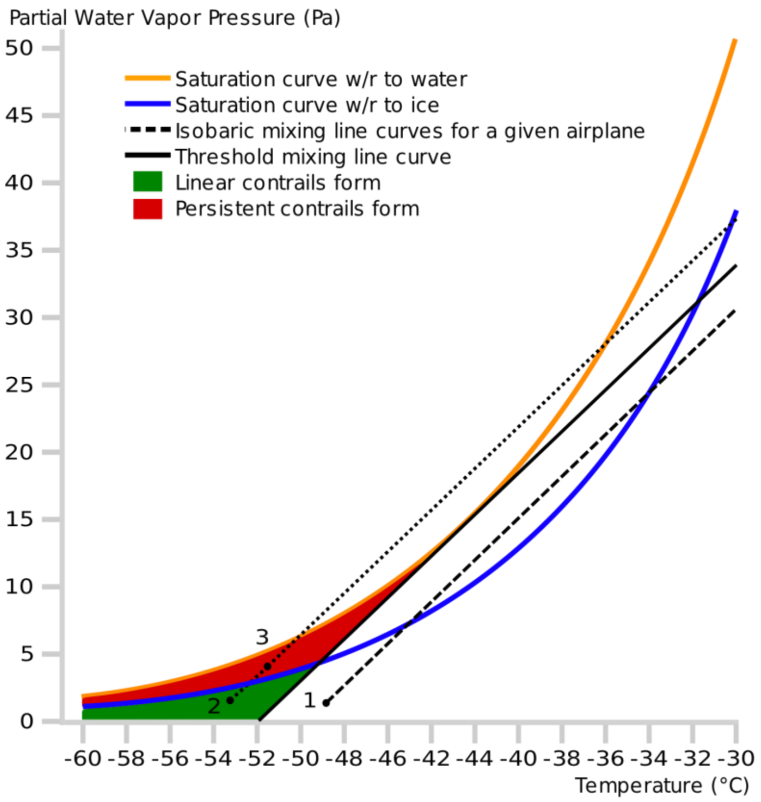


Figure 12: Schematic representation of the Schmidt-Appleman criteria for the formation of linear and persistent contrails. The blue line indicates the water saturation line as a function of temperature (in °C) and partial water vapour pressure (in Pa).The blue line indicates the ice saturation line. The green area indicates the range of ambient conditions for which linear contrails can be formed without persisting, and the red area, in which the air is supersaturated, indicates the ambient conditions for which persistent contrails can be formed and persist.

Figure 12 shows the so-called Schmidt-Appleman criteria (Schumann, 2000), that allow to determine if contrails are being formed, and if they are persistent. In the graph, the orange line represents the saturation pressure curve with respect to water, whereas the blue curve is the saturation pressure with respect to ice.

The mixing lines that connect the engine exhaust conditions (very high temperature and high partial water vapour pressure) with the ambient conditions are close to isobaric (constant pressure). Therefore, they follow a linear evolution in this graph, with a slope depending on the emission index of water vapour and on the heat emitted by the engine. As the heat emitted depends on the overall efficiency of the engine, it implies that the slope of the curve in Figure 12 is steeper for a more efficient airplane and that more regions are hence prone to form contrails. This shows an important trade-off that is existing between fuel (and thus CO_2) efficiency and non-CO_2 climate impacts (in this case due to contrails).

For a given engine, all the mixing lines that lay below the black line in Figure 12 do not exceed the water saturation, while it would be needed to trigger the condensation of water droplets which subsequently form ice crystals in the young contrail.

Once these initial ice-crystals are formed, additional water vapour sublimates on these crystals if the ambient air is ice-supersaturated (red region in Figure 12.). If this is not the case, the ice crystals begin to sublimate once the mixing line has crossed the ice-saturation curve (green region in Figure 12).

Figure 13 shows the relative importance of radiative forcing (RF) from carbon dioxide emitted by the fleet in 2005 to the total RF of the fleet (base case, from Lee et al., 2009). In a study by Fichter et al. (2005), it has been shown that, for the current fleet, a systematic shift of the altitude will have an impact on the RF of the non-CO_2 agents. In the figure the RF of CO_2 in the base case is normalized to a value of 1. Cases with an upward shift by 2.000 ft and a downwards shift by 2.000, 4.000 and 6.000 ft have been analyzed. Figure 13 shows that, although the emissions of carbon dioxide are increasing when the cruising altitude is reduced (due to increasing air density and thus drag on the airframe), the total RF is decreasing.

Since the report of IPCC on the aviation and the global atmosphere (IPCC,1999), scientific understanding on contrails has progressed and the RF of contrails has been revised to a much lower value (approximately 3 times less, Lee et al., 2009a). However, the forcing from aircraft induced cloudiness is estimated to be much larger. While no best-guess was provided in IPCC (1999), Lee et al. (2009a) provide a best guess of 33 mWm^{-2} (12,5 to 86,7 mWm^{-2}) for AIC, leading to a total RF of aviation in 2005 of 78 mWm^{-2} (38 to 139 mWm^{-2}) (Figure 13).

Respectively 15,1 and 42,3% of this forcing is due to linear contrails and AIC, and only 35,9% to carbon dioxide, thus showing the importance of cirrus cloud production by the aviation sector. Whereas CO_2 emitted by aviation accounts for 1,6% (0,8 to 2,3%) of the total anthropogenic RF, the total aviation RF (with AIC) accounts for 4,9% (2,0 to 14%) of the total RF.

However, these figures only show one dimension of the problem, as they give values for the global radiative forcing. But due to the inhomogeneous distribution of aircraft traffic over the globe and due to a very short lifetime of AIC, the local forcings are much higher.

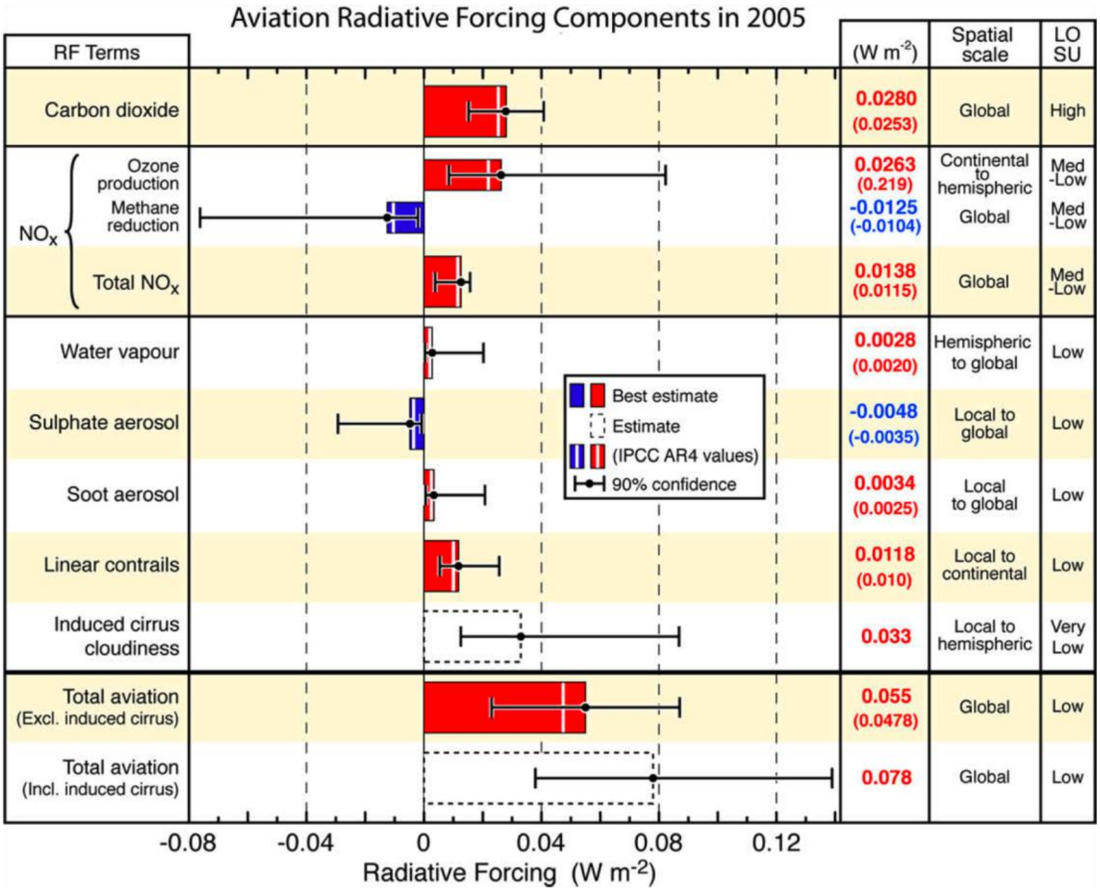


Figure 13: Radiative forcing components from global aviation as evaluated from preindustrial times until 2005. Bars represent updated best estimates or an estimate in the case of aircraft-induced cirrus cloudiness (AIC). IPCC AR4 values are indicated by the white lines in the bars as reported by Forster et al. (2007a). Numerical values are given on the right for both IPCC AR4 (in parentheses) and updated values. Error bars represent the 90% likelihood range for each estimate. The geographic spatial scale of the radiative forcing from each component and the level of scientific understanding (LOSU) are also shown on the right (Lee et al., 2009).

Figure 14 gives an estimation of the local radiative forcing, of linear contrails and AIC averaged over Europe and Belgium. These calculations only take into account the difference of density of air traffic over these regions. Moreover the different colours of the bars in Figure 14 show the forcing of these additional clouds that is due to flights taking-off and/or landing in the considered region and those overflying it.

The regional radiative forcing from aviation over Europe is estimated to be ± 500 mWm^{-2}, with only 0,7% of this forcing being due to planes overflying Europe (most planes travelling over Europe are landing or tacking in the continent). The flight density over Belgium is one of the highest in the world (Eyers et al, 2004) and we can see that the local forcing of AIC is of the order of 1 Wm^{-2} with only 5% being due to planes taking-off or landing in Belgium. This value is of the same order of magnitude as the 1,6 Wm^{-2} given by IPCC (2007) for the global forcing of anthropogenic CO_2.

This does however not imply that the climate impacts will be comparable, as we are comparing a local to a global forcing and the atmosphere will distribute elsewhere some of the effects of this strong local forcing.

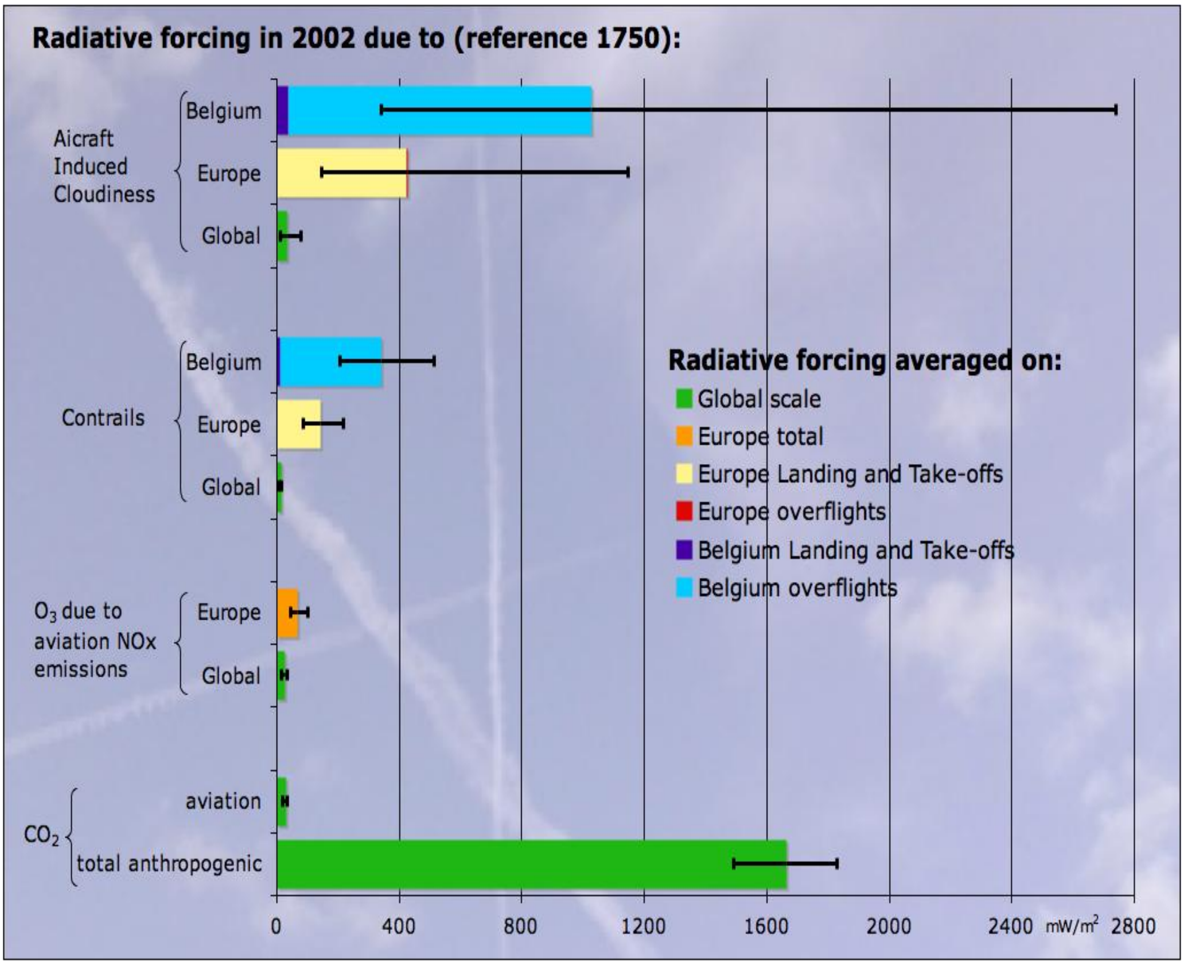


Figure 14: Relative importance of radiative forcing induced by the aviation sector (CO_2, O_3, contrails and AIC) in the year 2002 as well as radiative forcing of CO_2 from all anthropogenic sources. Where applicable, the radiative forcing is averaged on different regions and a distinction is made between planes landing and taking off in the region of interest and those overflying it. (Meyer et al., 2008)

Another important aspect that can influence these findings is the altitude where the emissions occur. Airplanes are currently flying at an altitude where most supersaturated regions are present. A change in altitude could reduce the RF of contrails and AIC.

2.3.2. Modelling the global impacts of aviation on climate (interactive model)

Method

To investigate the implications of aviation on climate stabilisation, we use the Java Climate Model (JCM, available on www.climate.be/abci → Open Section - Impacts Calculation), an "integrated assessment" model that was designed to facilitate the interactive exploration of scenarios, taking different stabilisation objectives into account. The originality of JCM is that users can see an instant response to adjusting parameters, and thereby explore sensitivities of scenario projections to diverse options and uncertainties. The climate and carbon cycle components consist in relatively simple (but non-linear) models with sets of parameters based on results from more complex models.

New modules providing aviation emissions scenarios and radiative forcing calculation were added in the framework of this project, and recently updated to include the latest scenarios made available. Baseline scenarios for aviation are taken from IPCC (1999), the CONSAVE project (Berghof et. al 2005), and the FAST scenarios (Owen and Lee, 2006 ; see also IPCC 2007b).

The radiative forcing changes due to aviation are calculated on the basis of IPCC (1999) adjusted to the more recent TRADEOFF data (Sausen et.al, 2005) for CO_2, O_3, CH_4, sulphate and carbon aerosols, water vapour, linear contrails and cirrus. "Efficacy" factors that adjust the relative global warming effect of gases according to the distribution of their forcing can optionally be applied. The aviation forcing feeds into the rest of JCM to calculate the effect on global temperature, sea-level, etc., enabling exploration of the sensitivity to diverse scenarios and uncertainties. Some aspects of the model outside the aviation modules were also improved during the second part of the project, in particular by updating historical socio-economic data and future projections and providing a solution for the problem of discontinuities between (updated) history and (existing) future projections. A new version of the model was released in early 2009 (see www.climate.be/jcm). The model is also available on version management server (SVN), for collaboration between developers.

Is mitigating aviation emissions important for climate stabilisation?

As it is an interactive model, with many adjustable parameters, JCM can be used for many experiments. As a practical example and useful discussion in itself, we summarise the application of the model to an evaluation of how important aviation impacts mitigation is in the context of climate stabilisation (see Marbaix et al., 2009).

The model is used in the "temperature stabilisation" mode: it internally adjusts the mitigation of future emissions for all sectors together by an iterative process so that the global mean temperature stabilizes at a fixed level from a given year on.

In this example, we select 2°C (above pre-industrial level) starting in 2100 (2°C is the EU policy objective for climate stabilisation, and is broadly consistent with studies on "causes for concern" regarding climate impacts, but there would be arguments for long-term stabilisation at a lower level).

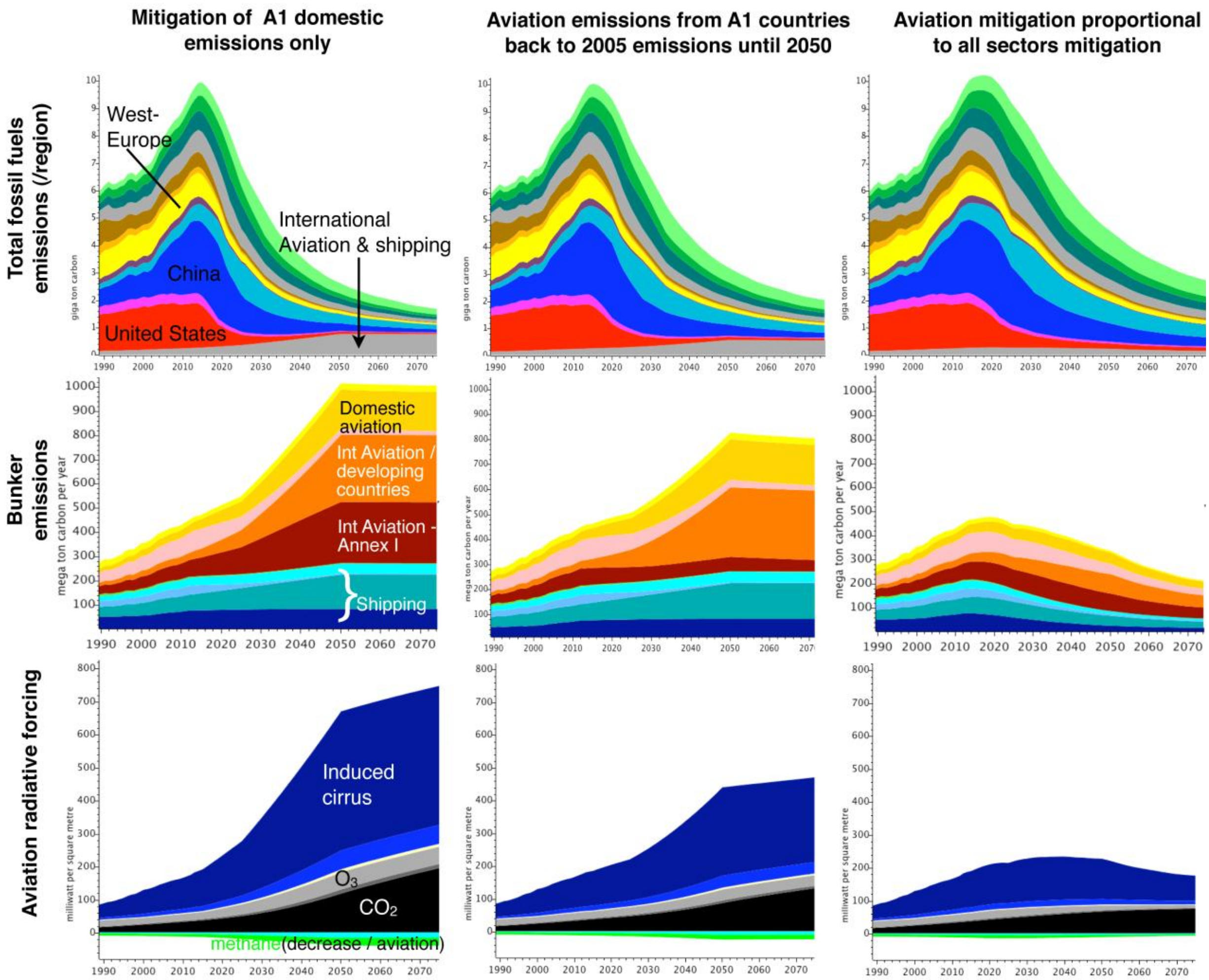


Figure 15: Illustration of the consequences of mitigation in the aviation sector on emissions available to other sectors given a global constrain (2°C stabilisation). First line: fossil fuel emissions, carbon dioxide only (GtC); second line: aviation and shipping emissions (MtC); third line: radiative forcing (mW/m^2). In the first column, aviation emissions follow a baseline (non-mitigation) scenario with relatively high emissions (FAST-A1).

An example of results is shown on Figure 15 for the FAST A1 scenario. The first column relates to the "continuation of existing policy": in the aviation sector, mitigation is required only for domestic flights within Annex I countries. For aviation in these countries, the same emission reductions are imposed as for all other sectors (constrained by the 2°C stabilisation), i.e.:

$$\frac{(CO_2^{\text{aviation A1}})_{\text{mitigated}}}{(CO_2^{\text{aviation A1}})_{\text{baseline}}} = \frac{(CO_2^{\text{all sectors}})_{\text{mitigated}}}{(CO_2^{\text{all sectors}})_{\text{baseline}}}$$

In this example the baseline is IPCC SRES A1B scenario. As most aviation scenarios were not defined after 2050, we use constant emissions thereafter. In this scenario without mitigation of international aviation, emissions are growing substantially. As the stabilisation temperature objective (2°C limit) is maintained, the emission budget available to other sectors is very small, and even the total "permitted" CO_2 emissions becomes small, due to the fact that there are very significant non-CO_2 emissions, in particular due to the aircraft induced cloudiness (section 2.3.1).

The two remaining columns present example mitigation scenarios applied on the aviation sector. They are based on simple hypotheses aiming at exploring the consequences of mitigation in the aviation sector (or lack of it) on the remaining emission space for the other sectors, within the selected global temperature change limit.

In the second column, only emissions from flights starting and/or ending in an UNFCCC Annex I country (A1) are reduced. The rule is that these emissions comes back to the 2005 level in a few years after 2013, remain at that level until 2050, then decrease at a rate of 1%/year. As shown by the second line of graphics, total aviation emissions are significantly reduced. As baseline aviation emissions were large, resulting in a tight constraint on emissions from other sectors, the limited aviation mitigation has large impacts on these other sectors. The third column is an example of large mitigation of all bunker emissions from all countries: aviation emissions are reduced in the same proportion from their baseline as global (all sectors) emissions are reduced from their baseline.

Table VI: Reduction of CO_2 emissions from all sectors except aviation in 2050 in % of the corresponding 1990 emissions (including land-use change)

	IPCC		FAST		CONSAVE	
	Fa2	Fe1	A1	B2	ULS	DtE
Mitigation of emissions within A1 countries only	55	70	82	68	73	-
A1 emissions back to 2005 emissions until 2050	50	60	69	59	63	
Same as above + all aviation -1%/year after 2050	47	56	63	54	58	53
Aviation mitigation proportional to other sectors	35	39	43	38	40	

Table VI: summarizes the main results, showing 2050 emission reduction for all sectors except aviation in % of 1990 emissions. All scenarios (in columns) except the last one are non-mitigation scenarios (no climate policy for aviation). We add mitigation hypotheses (shown in rows) as explained above.

There is one additional intermediate scenario, in which this mitigation is again applied on international flights involving Annex I countries only until 2050, but in addition, both A1 and non-A1 reduce their emissions by 1%/year after 2050.

The main result is that mitigation restricted to emissions from flights within UNFCCC Annex 1 countries (following Kyoto Protocol commitments) would imply very large emission reduction in other sectors: from -55 to -82% of 1990 emissions, in order to have roughly 50% chances that global warming remains below 2°C from pre-industrial (for a best estimate climate sensitivity and other mean parameters: uncertainty in climate parameters can be explored interactively with the model). This "business as usual" (BAU) scenario does not take into account the recent inclusion of international aviation from/to/within Europe in the EU-ETS, which may lead to significant changes in the direction of the mitigation scenarios discussed below, but with a magnitude that is still hard to estimate at present: in the ETS, the reduction may concentrate on other sectors, even outside the EU. The change may thus remain limited, in particular as long as only CO_2 emissions are considered, underestimating the climate impact of aviation as compared to other sectors.

When larger mitigation is applied on aviation, the burden on other sectors becomes more bearable: for example, in the high emission baseline FAST A1, the other sectors can only emit 18% of their 1990 emissions, but when reducing emissions from A1 countries, and then progressively all emissions (3rd case), the other sectors can still emit 37% of their 1990 emissions. The CONSAVE-DtE ("Down to Earth") scenario is another example of mitigation, also showing smaller mitigation efforts in non-aviation sectors than in the "existing policy" cases.

Avoiding large increases in the aviation emissions is thus an important component of mitigation to achieve climate stabilisation at a low level (see also Alice Bows & Kevin Anderson, 2008).

2.3.3. Regional climate modelling

Model Description

The regional climate model CCLM was selected for this project. It is based on the numerical weather production model COSMO (formerly LM, see Steppeler et al., 2003) used operationally amongst others by the German Weather Serviced (DWD). An overview of the climate version can be found in Will et al. (2009).

The model configuration is similar to the configuration used for the consortia runs of the CLM-Community: The model version is 3.14 with 0,2° horizontal resolution and 40 vertical levels on a rotated longitude-latitude grid (140x160 grid points). The domain covers entire Europe, spanning form Iceland to Northern Greece and from Southern Spain to the Northern Tip of the Scandinavian Peninsula.

At its lateral boundaries the model is forced by NCEP re-analysis (meteorological) data (Kistler et al. 2001) and the model is run for the year 2005. A two-category and one-moment ice-microphysics is used in the model, with prognostic cloud ice and water vapour mixing-ratios (Doms et al., 2005).

Parameterisation of AIC in CCLM

Due to a resolution of about 20km the model is not capable of capturing processes that are happening at lower spatial scales in the plume of an aircraft. That is why the results of the LES simulation by Lewellen and Lewellen (2001) are introduced in the microphysics of the model if the Appleman-Schmidt temperature criterion is fulfilled and if the air is ice-supersaturated (i.e. if persistent contrails are forming). Lewellen and Lewellen (2001) have shown that the importance of the ice super saturation is an order of magnitude higher than is the type of airplane. In the present approach, the values given by Lewellen and Lewellen (2001) are linearly interpolated for the different super-saturations, and fixed parameters representing the overall airplane fleet are used.

As the values for the amount of ice formed when Appleman-Schmidt criteria are fulfilled are given per flown kilometre, they are multiplied by the distance flown in the corresponding grid box. The introduction of the additional ice due to aviation in the microphysics of the model permits a coherent treatment of the evolution and advection of AIC with natural cirrus clouds and it permits the growth of contrails into cirrus clouds.

Runs with homogeneous flight distribution

In order to analyze the differences in the potential to form contrails in different regions, a first experiment has been made in which an airplane has been assumed to fly in every grid box at every time step. The results thus give us an appreciation of the potential additional cirrus cloud cover due to aviation.

Figure 16 gives the additional high cloud cover (above 8km) in the run with the contrail parameterization as compared to a control run where this parameterization was not used, averaged for 2005. The impact on the high clouds shows substancial local increases of the cover (up to 5%); this is similar to a recent study done with a GCM that includes the transformation of contrails into cirrus clouds (Burkhardt et al., 2008). This, as well as a comparison of the magnitude of the direct output of the parameterisation (contrail ice) and the additional ice formed after going through the microphysics scheme of the model, strongly suggests that the model can simulate the transition from contrails to cirrus clouds. It is also interesting to note that although airplanes are assumed to fly at every altitude in this run contrails are formed mainly between 8 to 12km (altitude at which Appleman-Schmidt criteria is the most often fulfilled).

The increase is higher around the Mediterranean coast and the Scandinavian Peninsula, whereas the North Sea shows a rather low potential to form contrails. In mid-latitude Europe, the model shows a high potential over the South of the British Isles, the Channel and the Benelux, whereas Central France and large parts of Germany have a lower potential.

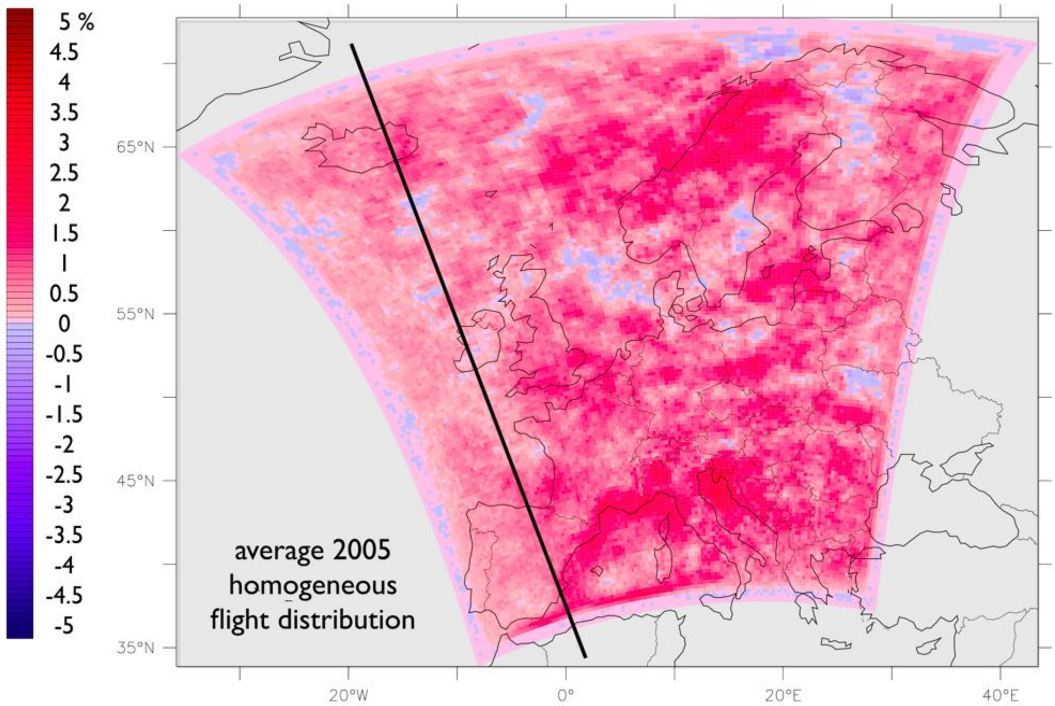


Figure 16: Difference of the high cloud cover (in % of coverage) between a run with potential contrails and the reference run.

Concerning the seasonal cycle, the potential AIC cover is highest in winter, a result which is consistent with the fact that very low temperatures favour supersaturation, and lowest in June. The diurnal cycle shows a peak around midday in the annual average. This peak may be related to the onset of convection around this time and can also been seen in the summer average of the diurnal cycle. The predominance of convection with warmer temperatures can also explain the inhomogeneous distribution of the potential cover from April to August.

Runs with real flight distribution

One run has been done where the flight distribution over Europe is based on data from the AERO2k database (Eyers et al., 2004). This database gives the flown distance1 for 2002 on a grid by 1° x 1° and 500 ft vertical resolution. Therefore, we had to downscale the data to the higher resolution (0.2° x 0.2°) model grid (values were uniformly distributed in a way that the sum of distances remains unchanged).

Figure 17 shows us the additional high cloud cover (above 8km) in this case based on real flight distribution. A comparison with Figure 16 shows that the pattern is now much contrasted, and in particular over Northern Europe the modelled AIC is much smaller, which is due to a reduced flight density over this area, compared to Central Europe.

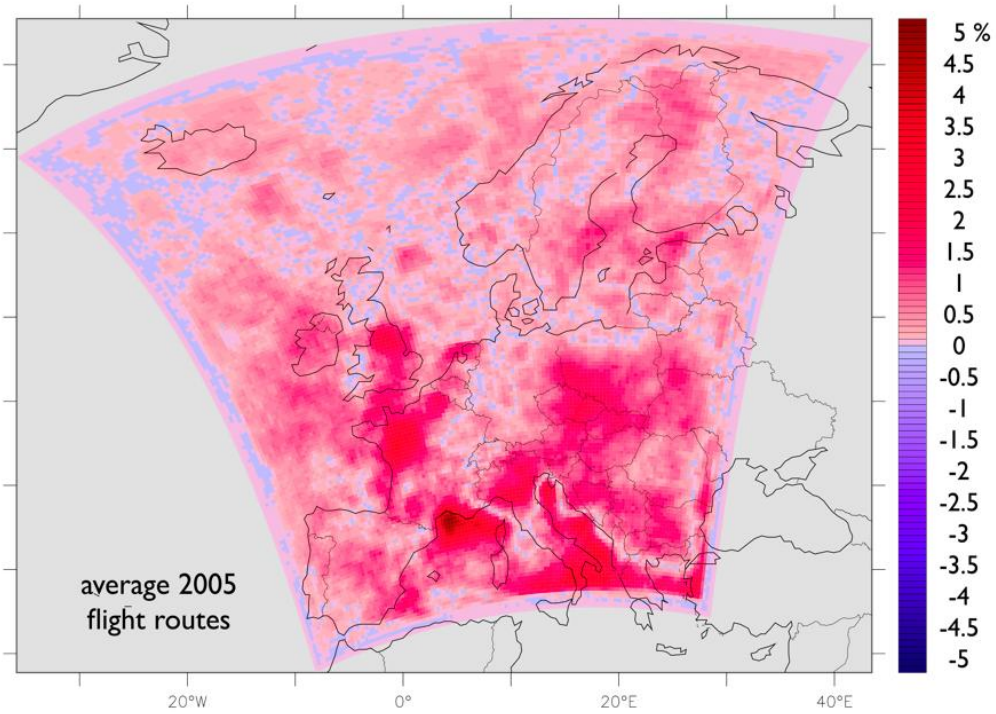


Figure 17: Difference of the high cloud cover between a run with contrails and the reference run (in % of coverage, average over 2005). The distribution of flight movements is based on AERO2k (Eyers et al., 2002).

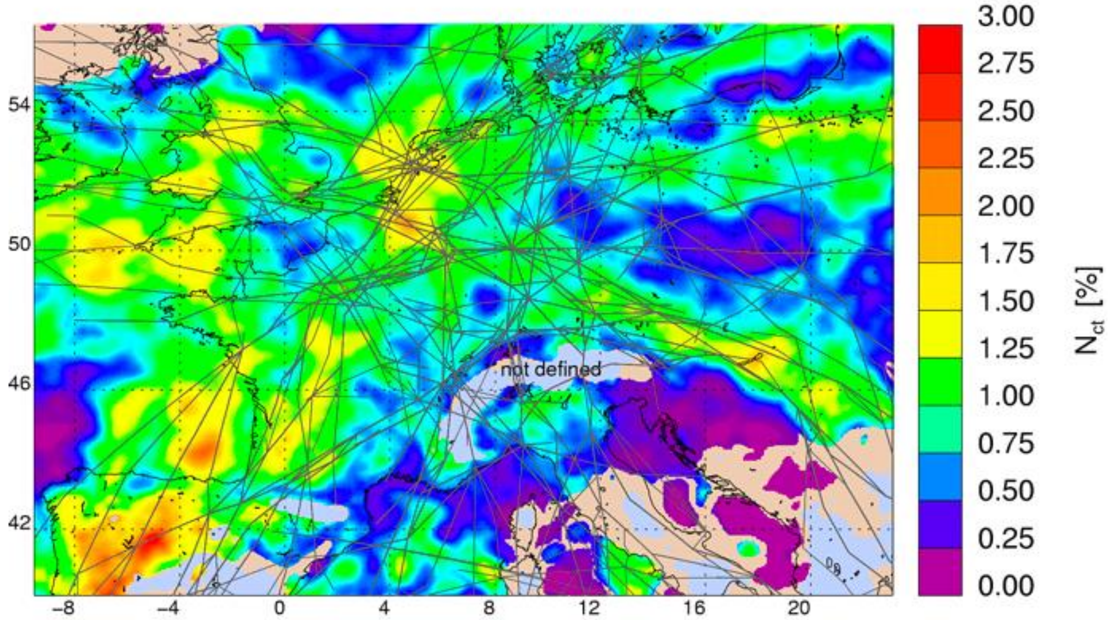


Figure 18: Observation of linear contrail coverage from satellite observations from Meyer et al. (2002).

Figure 18 gives the observed coverage of linear contrails averaged over 2000-2005 as inferred from satellite observations by Meyer et al. (2002). We can first see that this coverage is much lower compared to the AIC given by CCLM, which is as expected (because the observed values do not represent the full AIC). A comparison shows that the model is capable of capturing some important patterns such as the high cover over Western France and the lower cover over Eastern France. Also the higher cover over the Benelux and the lower cover over Germany are captured. However the high increase over Spain is absent in the model which may be due to the proximity of the boundary data, which do not represent super saturation.

2.3.4. Metrics of climate impacts – comparing impacts from CO_2 and other causes for mitigation purposes

The impact of aviation on climate comes from several effects (see previous sections) that perturb the radiative balance of the Earth, resulting in a net warming. To compare climate forcing agents from different sources, with different magnitudes and life-times, it is useful to have a single "indicator of climate impact", commonly called "metric". This is particularly the case for cap-and-trade systems, which need an indicator to express target(s) that ultimately rate climate-impacting agents in monetary terms.

For aviation, there is an additional difficulty because the impact on cloudiness is not simply proportionall to the amount of an emitted gas (even water vapor). To estimate the total impacts from aviation, a simple solution is to use a "multiplier" – a coefficient that multiplies CO_2 emissions to include other effects. Until recently, much of the debate around the value of this multiplier has focused on the "Radiative Forcing Index" (RFI), introduced by the IPCC (1999). It is defined as the ratio of the total radiative forcing to that from CO_2 emissions alone. However, it was not supposed to be used as a way to "aggregate" effects, i.e. as a "metric" that provides a common unit for all emissions. In its last report (IPCC, 2007, AR4 WG1, chap 2, page 215), the IPCC notes that the RFI "should not be used as an emission metric since it does not account for the different residence times of different forcing agents". This has also been confirmed in the expert meeting on metrics organised by the IPCC in 2009 (IPCC, 2009). Practical uses of the RFI assume that the radiative forcings are computed for a given year taking into account *the accumulation* of emissions from a given sector *prior to the reference year;* while this method includes some consideration for residence times, it does not relate to impacts in the future and is thus not appropriate to deal with the consequences of present emissions.

Global warming potential

The reference unit in the context of cap-and-trade systems such as the EU-ETS is the "equivalent carbon dioxide".

Based on IPCC-AR4, in the context of emissions, equivalent CO_2 is defined as the amount of carbon dioxide emission that would cause the same total radiative forcing, integrated over a given time horizon, as an emitted amount of the considered (well mixed) greenhouse gas(es). In simple words, it is an amount of CO_2 that would have roughly the same impact on climate as that of the considered gas (or other climate forcing agents). The equivalent CO_2 is obtained by multiplying the amount of emitted gas by its Global Warming Potential (GWP).

Equivalent CO_2 and GWPs are focusing on long term, global average effects: they are indicators of the effects on the climate over a given period, which is 100 years in the Kyoto Protocol. The IPCC definition also reminds that it is made to measure global average effects, as it says that it is to be applied on "well mixed gases", that is, gases that stay in the atmosphere long enough to reach an homogenous repartition over the planet. It is clear that equivalent CO_2 cannot take full account of all aviation effects, since most of the non-CO_2 effects are very short term – e.g. cirrus clouds produced by planes can only last days, with primary effects concentrated near the location (at least latitude) of emission. As it is a long term global average, equivalent CO_2 cannot describe such regional differences. Stronger changes in some regions, or a tendency to cause faster climate change compared to CO_2, could cause more damage if it is caused by the short-lived processes due to planes than with the "equivalent" amount of real CO_2.

Therefore, a GWP-based CO_2 equivalent is not a comprehensive measure of impacts on climate. However GWP counts all climate forcing agents in a consistent way (average effect, over 100 years). It seems logical that any aggregated measure of the very different effects of short-lived and long-lived emissions would be unable to measure their possible consequences in a comprehensive manner, in particular because the difference between short and long term effects will depend on the future path of global emissions for all sectors. The detail of the "value" of contrails vs. CO_2 warming potentials is not defined a priori without knowing these future emissions. A frequent misunderstanding is that the key issue is a lack of scientific knowledge: in fact there are fundamental limitations to the use of an aggregated measure of climate warming (or damages) potential. Research may help in making sound choices, but there is already enough understanding of aviation impacts to conclude that aviation is having more effects on climate than those from CO_2 alone.

While the use of equivalent CO_2 is debatable especially for the short term effects, its use in a cap-and-trade system may possibly be supplemented by regulations concerning the short-term effects. This would be particularly justified in Europe, as these effects are regional and particularly large over most of the continent.

Global temperature potential compared to GWP

Other aggregate measures of non-CO_2 effects have been proposed, in particular the global temperature potential (GTP). GTP is defined as the ratio between the global mean surface temperature change at a given future time horizon following an emission of the considered compound relative to the reference gas (e.g. CO_2) (IPCC, 2007, 2.10.4). The GTP metric has the potential advantage over GWP that it is more directly related to surface temperature change (it may include "efficacies" that relates radiative forcing to temperature changes). The considered emission can be a "pulse" at the beginning of the period or an emission sustained throughout the period. While the GWP is an integral quantity over the time horizon (climate forcing at the beginning of the period), the GTP uses the temperature change at the end of the selected period: radiative forcing closer to the end contributes relatively more. As noted by Forster et al. (2006), there is a near equivalence between the GTP for sustained emission changes and the GWP (defined for a pulse emission). In the context of trading, the requirement is to count the effects of present emissions, so that the focus is on the "pulse" variant of the GTP metric. As only temperature changes at the end of the period are counted, effects at the beginning of the period will only be seen through feedbacks and inertia in the climate system, so that gases that have short lifetimes will be weighted less with GTP than with GWP. It is thus possible that the GWP offers a more balanced measure of the impacts of short and long lived emissions.

As there are different types of agents that have impacts on climate, involving very different time scales (from days to centuries), no single metric can measure all aspects of impacts; in addition, impacts of a given agent are dependent upon the future emissions of other agents. Hence any single metric is a compromise. In conclusion, while there is scope for more research regarding measures of impacts of climate altering atmospheric emissions (metrics), the GWP metric currently used in international agreements is valuable. Its replacement would require careful assessment of potential new measures or improvements.

What do we know about multiplier values and uncertainties?

Following the above discussion, we focus on GWP as a measure of non-CO_2 impacts compared to those from CO_2. It is a consistent metric, and it has the advantage that it is already used in the Kyoto protocol and other carbon trading such as the EU-ETS (we provide a more detailed discussion on the use of a multiplier in connection with the EU-ETS in Ferrone and Marbaix, 2009). As explained above, it approximately represents the total average climate impact over a given period divided by that of CO_2 alone.

While climate policy focuses on the 100 years time average, we also computed the multiplier for a 20 years average to illustrate the fact that focusing on shorter term impacts results in larger impacts of non-CO_2 (mostly short term) agents compared to CO_2, which means higher multiplier values. The resulting multiplier values are reported in Table VII: , including all important effects: NO_x (ozone and methane effects), contrails and induced cirrus. We updated these figures during the course of the project, and this version of the table is based on the latest radiative forcing estimates from the literature, taking uncertainty into account (Lee et al., 2009a and Forster et al., 2006).

Table VII: Multiplier estimates based on the GWP metric, for 20 and 100 years integration. The uncertainty ranges are indicative, as these cannot be strictly interpreted as a confidence intervals due to approximations in the combination of the climate forcing factors; this is particularly important for the 3 left columns (% contribution), which remain rough estimates.

	Components of non CO_2 impacts as fraction of the total *non CO_2 impacts*			**Multiplier (all impacts)**		
	NO_x	**contrails**	**cirrus**	**low**	**best estimate**	**high**
20 years	3 to 6 %	22 to 28 %	66 to 75%	2,6	4,1	7,5
100 years	-1 to +7 %	19 to 30%	64 to 69 %	**1,5**	**2**	**3**

Following the current scientific understanding, contrails and their evolution into cirrus clouds clearly plays a more important role for climate than the NO_x emissions, justifying the extended analysis of aircraft induced cloudiness that is done inside this project (in particular for section 2.3.3).

Additional effect of carbon feedback

The multiplier values from Table VII: take into account all the major effects that have been discussed in the literature. However, they are still conservative estimates as at least one significant effect was not taken into account: the short term warming due to non-CO_2 effects leads to an additional positive feedback in the carbon cycle that converts this short-term forcing into a long-term effect.

The soil respiration and the atmosphere-ocean chemistry are both dependent on the temperature. An augmentation of this temperature will lead to an increased concentration of CO_2 in the atmosphere, thus leading to more warming and giving a positive feedback on the increase of temperature.

An investigation of this effect with the JCM model (section 2.3.3) showed that this feedback effect adds an additional 21% to the cirrus+contrail forcing (Ferrone and Marbaix, 2009). Compared to the uncertainty of the forcing, this number seems relatively small but it converts the short-term pulse forcing into a long-term effect (this "indirect" aviation CO_2 is an extra 30% on top of "direct" aviation CO_2 emissions).

Therefore, even when considering only long term effects, this should be taken into consideration. This additional forcing is also much less sensitive to the time-horizon considered than the total aviation forcing is, since it only involves CO_2 (rather than a mix of other agents with short- and long- term impacts which need to be converted to a common unit). Hence, its relative importance is less dependent on a methodological choice involving a value judgment.

2.3.5. Flight impacts calculators

This section provides an overview of parameters influencing the climate impact that can be allocated to individual passengers and should consequently be considered as much as possible in aviation climate impact calculators.

Non-CO_2 emissions

As was described in detail in the previous chapters, the influence of aviation on climate is not limited to CO_2 emissions. Nevertheless, since CO_2 is the agent whose impact has the highest level of scientific understanding, many climate impact calculators limit themselves to the calculation of the CO_2 emissions a passenger is responsible for. One of the ways used to circumvent this limitation is to implement a multiplier. Usually this multiplier is invariable and is based on the CO_2 emissions of the aircraft.

Ideally however, a multiplier should be variable and should be based on the location in which the aircraft is operated, as well as on the type of aircraft (and engine) used. In the long-term, it might become important to specify the kind of fuel used to operate the aircraft, as the composition of the fuel can have an important influence on the non-CO_2 climate impacts of aircraft.

Several air calculators use dimensionless multipliers between 2 and 4 to account for the non-CO_2 climate impact of aviation. These multipliers are usually based on the RFI for aviation that was estimated to be 2,7 with an uncertainty of +/- 1,5 by the IPCC. However, as explained in the previous sections, RFI is not an appropriate metric to calculate personal air travel climate impacts.

Deviation from the Great Circle Distance

When operating a flight between two airports, an aircraft does usually not fly exactly as the crow flies. This is due to the complexity of the national and international airspaces. For example, some areas are restricted due to exclusive military operation. Moreover, aircraft have to operate along pre-existing corridors which are not always the shortest/most efficient flight route between two points.

Possibility to provide the specific parameters of a given flight

- *Choosing the aircraft*

Many of the calculators do not allow the user to specify the aircraft used to perform his/her trip, but use an "average" emission level for any flight. This average emission level is often based on the fuel consumption of one common aircraft or on the average fuel consumption of a limited number of commonly used-aircraft.

However, as the different aircraft present some significantly different fuel consumption and emission levels, it is advisable to allow the user to select the exact aircraft he or she is flying. If this aircraft is not included in the database an aircraft that comes as close as possible to the real aircraft (regarding capacity, age, technology, range, etc.) should be offered to the user.

- *Integrating transfers or stop-overs*

When travelling by air, it's not uncommon to have to perform a transfer or a stop-over. When calculating the impact of a trip on climate, it is of foremost importance to mention their existence when they occur. This is not only due to the additional distance that is covered by the passenger (as the transfer airport will probably not be located exactly on the flight-route). It is also a result of one or more additional LTO phases (and thus an increase in emissions and energy consumption). Finally, a change of aircraft often involves a different aircraft type on the legs of the trip, which also has an influence on the climate footprint of the passengers.

- *Integrating the chosen flight class and/or the occupancy rate*

The number of passengers in a given aircraft strongly influences the individual contribution of the passengers. Also, the selected travel class plays an important role. This parameter is essential in determining the emissions a passenger is responsible for. First and business class seats take more space and result in fewer passengers for a given available seating area aboard an aircraft.

New calculator - Aviactor

Aside from the scientific uncertainties described in the previous sections, the main choice determining the results of climate impact calculations related to aviation emissions is the chosen time horizon (TH), as explained in section 2.3.4. Quite generally, one could state that a 20-years TH (or shorter) results in the dominance of the short-lived GHG emissions in the climate impact, while a TH of 100 years results in more weight on CO_2 impacts which then represent about half of the total impact on climate (hence the multiplier should be set at 2 for this TH).

Selecting a TH of 100 years implies that short-lived effects are "diluted" over a long period, ignoring the fact that in practice they result in a large contribution to climate change right after the flight (e.g. for induced cloudiness, the effect is concentrated on a few days, except for feedback effects explained in section 2.3.4). Therefore, the consideration of a time horizon of 20 years seems useful, yet this is mostly a value-based decision. It should be noted that a TH of 100 years is used within the Kyoto Protocol first commitment period, and that in the context of a cap-and-trade system, using various TH would likely cause compatibility issues and might be confusing. However, when calculators are used in the framework of emission offsetting, different TH may be considered.

To extend the possibilities of the existing calculators, a new tool called Aviactor (Aviation Climate impact Calculator) was developed and is available at: www.aviactor.net. One of the added values of this tool is that it allows the user to calculate his/her climatic impact, including an assessment of the non-CO_2 impacts.

When wanting to calculate his/her climatic impact, the user selects a number of parameters:

- airport of departure and airport of arrival: These airports can be selected from a pre-established database. If the airport(s) the user is looking for is not included in this list, the user will be able to fill out the longitude and latitude of the airport(s) through the database tool.
- type of aircraft used to travel: The interface also includes a pre-established list of aircraft. If the user does not know which type of aircraft he/she is flying, type (aggregated data from the most common aircraft) can be selected by the user.

Typically, the layout and load factor of an aircraft influences the passenger's individual impact. If the aircraft selected by the user offers different flight classes the emissions to be allocated to the different flight classes are displayed. Next to the class in which the passenger flies, the occupancy rate of the aircraft is also considered in the allocation of the climate impact.

Assumptions underlying the new calculator

To increase revenue, many passenger aircraft carry some cargo (belly load). Therefore, it could be argued that part of the emissions should be allocated to this cargo. The calculator allocates a fraction of the emissions to the cargo in function of the type of aircraft (narrow-body or wide-body for example).

Aviactor calculates the Great Circle Distance (GCD) between the airport of departure and the airport of arrival, and includes some deviations from the GCD as a function of the total length of the trip.

The emission factors used in the calculating tool developed here are taken from the EMEP Corinair methodology.

The program includes a database of the capacity and range of most aircraft currently used by commercial airlines performing passenger transport. These capacities are used to calculate the fraction of the impact to be allocated to the user of the interface. The ranges stored in the database are used to check if the trip suggested by the user is possible or not. Should it be longer than the maximum range of the specified aircraft, the calculation of the emissions and of the climate impact are performed, but a message draws the attention of the user to the unlikelihood of his or her request.

Database analyser

Another tool was developed to process databases containing numerous flights (for example for all the flights occurring in a country's air space) in an automated manner. Weaknesses of the currently provided databases are well known and are discussed in den Elzen et al. (2007). One of the main problems for many researchers is the reporting of non-scheduled traffic. The consortium could circumvent this problem by the use of the Belgocontrol data.

More detailed and extensive information concerning the new calculator can be found in Matheys, 2010.

2.4. Climate policy options

This section broaches the different potential/existing policy measures that could be used to tackle aviation climate impacts, as well as a brief overview of the current evolution in international agreements concerning the aviation sector and the mitigation of its climate impacts.

2.4.1. Potential/existing policy tools

An inventory of existing /potential policy tools to mitigate aviation climate impacts has been carried out. Each tool has been described briefly and analysed from the point of view of the suitable competency level to implement it as well as its relative environmental efficiency. Some examples of existing climate policy instruments in the transport sector (transport in general and aviation in particular if instrument exists or are discussed) have also been mentioned (see Final report phase I for more detail: www.climate.be/abci - Open Section - Project publications).

The following paragraphs summarise the main conclusions of the analysis performed during the project and serve as an input for the multi-criteria analysis (section 2.6) and the scenarios (section 2.7).

Raising public awareness

Several sociological studies (e.g. Cairns S. & Newson C., 2006) have indicated that raising public awareness was a key element in any successful environmental policy. It helps concerned actors to accept adopted measures more easily on the one hand and to act voluntarily by implementing some potential solutions on their own (e.g. voluntary/negotiated agreements/actions) on the other hand. The efficiency of such kind of measure depends not only on the confidence in and the credibility of the source and arguments put forward, but also on the clarity and simplicity of the message transmitted. As regards the effectiveness of the tool, the major challenge is to target the right groups and to induce a real change in their mentality and/or behaviour.

Voluntary agreements

OECD's reports (e.g. OECD, 2003) conclude that voluntary initiatives have in general both low environmental effectiveness and economic efficiency. In practice, they are generally combined with other policy measures playing the role of incentives or used as "raising public awareness" tool.

Concerning the particular example of voluntary offsetting in the aviation sector, the ABC Impacts workshop organised on the topic (www.climate.be/abci - Open Section - Project publications - Workshops) has concluded that some public regulations could improve the confidence in and the efficiency of such programmes by offering a harmonized framework of comparison and control as it exists for CDM or JI projects, and that generally non-CO_2 climate impacts were not taken into account in emission calculators from airlines. Concerning the improvement of emission calculators, a new calculator was developed and considers non-CO_2 aviation climate impacts as well as different parameters potentially having a significant influence on the emission calculation for a given flight (see section 2.3.5).

It is also important to note that, as far as local/regional environmental impacts are concerned, offset programmes (compensation by emissions reduction in another region and/or activity) will probably not compensate for all the environmental effects (e.g. some local effects of AIC or ozone destruction due to aircrafts; related effects such as noise, eutrophication or health impacts ; section 2.3.3).

Concerning future perspectives, even if the aviation sector is included in the EU-ETS and in the post-2012 UNFCCC scheme, offset programmes dedicated to the aviation sector will have a reason to exist. They are indeed great tools to raise public awareness (provided that emission calculations are made transparent and improved, among other things as regards non-CO_2 climate impacts, and that a certain level of harmonisation and control is provided for example through a EU label) and can cover the whole climate impact of a flight.

Research and development

As already explained in section 2.2, R&D on alternative fuels and aircraft design will potentially generate CO_2 emission reductions and/or regional climate impacts mitigation. However, the different trade-offs between aviation climate impacts (CO_2 versus non-CO_2) raise questions. Moreover, the emission reduction potential in the aviation sector compared to expected higher GHG emission reduction potentials in other sectors (cf. production of alternative fuels for example) requires a global overview to be sure that the total climate impact of the aviation sector will really be mitigated by those measures. In addition, considering that the sector is expected to grow after the recovery from the economic crisis (see section 2.1), the adopted technical or flight management measures will probably not be able to compensate for the emission increase generated by the traffic growth. R&D is therefore a necessary but not sufficient policy tool (Eyers, 2010).

Economic and financial tools

In our society, financial and economic tools are predominant especially as regards measures to tackle climate change. The UNFCCC, the Kyoto Protocol and the EU-ETS put market mechanisms forward as the most economic and efficient measure to mitigate GHG emissions. It is generally coupled with a "Command and control regulation" measure aiming at capping total emissions that will be traded on the market. Therefore, there is a need for detailed and accurate data on fuel consumption and/or emissions.

Recently, the aviation sector has been included into the EU-ETS. This new European directive (EU, 2008) is described in more detail hereafter (section 2.4.3).

Concerning the aviation sector, one of the most important issues with cap-and-trade systems is the scope of climate impacts that are covered (CO_2 only, CO_2 + NO_x, all aviation climate impacts), seeing that trade-offs (for example between global or regional climate impacts) could worsen the total aviation climate impact if not taken into account.

Again, it is important to keep in mind that more regional climate impacts can not be compensated for by emission reductions in other parts of the world (see section 2.3.3). However, to simplify the policy mix and to avoid counter-productive interactions between different policy tools (cf. potential trade-offs and loss in the general overview on aviation total climate impacts), it could be interesting, besides the adoption of specific measures to avoid for example aircraft induced cloudiness, to include CO_2 and non-CO_2 aviation climate impacts in a single market mechanism, such as the EU-ETS. More details concerning the use of a multiplier in this context are provided in section 2.3.4.

Besides this, different measures can be applied, not specifically to tackle aviation climate impacts but to avoid market distorsion and competitive advantages for the aviation sector compared to other transport modes: fuel taxation on Jet A-1 fuel, VAT on all air travel tickets, suppression of duty free sales on-board and in airport terminals, etc. These measures are not easy to implement (cf. concerning Jet A-1 fuel taxation, bilateral agreements have to be reviewed with all non-EU countries with which the EU shares air links) but could reduce the economic bias that artificially supports the demand for air transport).

Command and control regulation

As regards environmental policy, regulations can consist of: a limit on certain emissions (specific standards or global cap on emissions of a sector/country), setting a minimum level of efficiency (e.g. energy consumption, emission per produced unit), standard definitions of product composition (e.g. fuels), an access / activity restriction under certain circumstances, etc.

Fixing a cap on GHG emissions is the sole policy measure aiming at limiting the total volume of the emissions covered by the cap. Concerning the aviation sector and the climate change issue, the cap has to take non-CO_2 emissions into account to be able to tackle the total climate impact induced by aircraft. Otherwise, trade-offs could threaten the general objective of "stabilization of greenhouse gas concentrations in the *atmosphere* at a low enough level to prevent dangerous anthropogenic interference with the climate system" (UNFCCC) or of limiting the average global temperature increase to 2°C above the pre-industrialisation levels (European Parliament, 2007). Section 2.3.2 provides more details concerning the stakes between these stabilisation objectives on the one hand and the relationships with climate impacting emissions from aviation as well as from other sectors on the other hand.

2.4.2. International climate policy and aviation

Having the history of international climate policy agreements in mind (for more detail see: http://www.climate.be/abci - Open Section - Documentation), it is clear that mitigating GHG emissions from international transport was not the priority sector for the UNFCCC compared to industries, domestic transports, etc. for which emissions could easily be allocated to the country where they took place (cf. stationary sources or transport sources limited to a specific country). For international transport such as aviation, this allocation principle is completely inapplicable as such (cf. most emissions occur above international territories like seas, oceans, etc. and are difficult to allocate to one or another country). The sole request from the UNFCCC as regards international aviation, is that countries work in co-operation with ICAO to reduce their emissions, with no significant results so far.

The UNFCCC constitutional amendment, the Kyoto Protocol, fixes quantitative emission reduction objectives for industrialised countries (Annex I countries). Logically, it does neither cover international aviation, nor maritime transport emissions (the fuel consumed by international aviation and maritime transport is usually called "bunker fuel"). As far as the emissions of the international transport were insignificant compared to other sectors, it was easier to ignore them and try to implement measures targeting the major emitters. But presently, with its huge development (section 2.8) coupled to real emission reduction efforts in several targeted sectors of Annex I countries (one of the most important exceptions being the domestic transport sector that is still growing and is dramatically increasing its emissions), GHG emissions from international transport sectors are becoming a major barrier for successful stabilisation scenarios (section 2.3.2).

Therefore, the current negotiations concerning the design of a post-2012 UNFCCC scheme to succeed to the Kyoto Protocol consider among other things the way international aviation emissions could be taken into account. After several unsuccessful SBSTA (Subsidiary Body for Scientific and Technical Advice)'s attempts to allocate aviation emissions to countries, a sector-based approach as adopted in the EU Directive including aviation into the EU-ETS (EU, 2008 ; see section 2.4.3 for more detail) could be followed.

Besides this allocation issue, another problem arises from the scope of the UNFCCC scheme if it is extended to international aviation emissions. Indeed, agents targeted in the Protocol are 6 major anthropogenic GHGs (CO_2, CH_4, N_2O, PFCs, HFCs and SF_6) and do not include all aviation emissions impacting climate, like NO_x and aerosols.

As a consequence, negotiations concerning the integration of international aviation in the post-2012 UNFCCC scheme will have to include debates on the extension (or not) of the scheme to non-Kyoto GHGs. It is important to note that several trade-offs exist between aviation CO_2 and non-CO_2 emission mitigation options (e.g. flying at a higher altitude reduces the fuel consumption and related CO_2 emissions but increases climate impacts from NO_x emissions, see section 2.4.1), which implies that tackling the CO_2 issue only could make aviation's total climate impact even worse if non-CO_2 aviation climate impacts are neglected.

2.4.3. EU Directive 2008/101/EC

Seeing the inertia of the negotiations to set up a global agreement, the EU decided to take the discussion a step further with the adoption of Directive 2008/101/EC (EU, 2008) including aviation activities into the EU-ETS.

Previously, EU-ETS covered only indirectly some emissions from the different transport sectors as refineries and power-generation have been included in the targeted sectors but not the direct emissions from fuel combustion for transportation purposes.

In January 2006, the European Commission officially presented a directive proposal to include the aviation sector into the EU-ETS (European Commission, 2006). As regards Belgium, discussions took place at the "Ad hoc committee on bunker fuels – aviation and the EU-ETS" (for more details, see the synthesis documents on the "Belgian institutions related to climate policy" and "Belgian climate policy mechanisms" on http://www.climate.be/abci - Open Section - Documentation), to which ABC Impacts researchers participated as experts (section 3.1.1).

After several months of negotiations with Member States, the Parliament, the Council and the European Commission, EU Directive 2008/101/EC (EU, 2008) was adopted in November 2008 and was officially published in January 2009.

Targeted activities

The Directive covers all flights (both intra- and extra-EU flights) landing or taking-off from an aerodrome situated in the territory of a Member Sate from the first January 2012 (detailed aviation activities targeted are listed in Annex I of the Directive).

Several exemptions have been introduced such as:

- aircraft not fulfilling the "de minimis" clause as regards MTOW (i.e. aircraft with an MTOW lower than 5.700 kg) are exempted. During the negotiations, proposals have been made to raise the limit to 20.000 kg which would have excluded a major part of the business aviation activities (aviation market segment with one of the most important growth rate these last decades, before the economic crisis, and with one of the lowest load factors);
- specific flights such as for security and medical reasons, training, military and humanitarian missions, etc. are exempted;
- aircraft operators not fulfilling the "de minimis" clause concerning the volume of activities (i.e. operating less than 243 flights per four-month period for three consecutive periods) or concerning the quantity of emissions (i.e. operating flights with total annual emissions < 10.000 t CO_2 per year) are exempted. This rule has been adopted to avoid "*disproportionate administrative burdens*" (EU, 2008, §18) compared to the low volume of activities concerned (+/- two one-way flights per day). According to some estimations realised for Belgian airports (Matheys et al., 2009), this clause concerns indeed a minor part of the activities and their related emissions.

- on a case by case analysis, flights coming from or going to a country having implemented measures "which have an environmental effect at least equivalent to that of this Directive to reduce climate impact of flights to the Community" (EU, 2008, §17) could be exempted. To avoid double regulation in such a case, the European scheme could be linked to other trading schemes or equivalent measures could be taken into account to adapt the implementation of this Directive.

Each Member State will be in charge of verifying and controlling emissions of aircraft operators issued with an operating licence in that Member State or "whose emissions in a base year are mostly attributable to that Member State" (EU, 2008, §26). As regards Belgium, the preliminary extended list includes 43 operators, 15 of which have a Belgian operating licence and 9 a licence from the USA (European Commission, 2009a).

The approach adopted by the EU directive is quite new compared to the work already carried out at the SBSTA-ICAO level because it gives up the idea of allocating aviation emissions to countries on the one hand and adopts a sector-based vision on the other hand. From then on, aircraft operators from third countries are covered by the directive, which is in line with the rule of non-discrimination between economic actors of a specific market but offends the sensibilities of countries where aviation plays a major economic role. Besides, reactions from third countries on the new directive were quite harsh, especially from countries having a large aviation market such as the USA or China. At its annual General Assembly in September 2007, these countries tried to make ICAO adopt a resolution condemning the enforcement of the directive to third country airlines excepted if a preliminary consent was obtained (Appendix L to ICAO's Resolution A36-22). With the formal reservation registered by the EU on this point (Council of the EU, 2007), the suggested text was made legally unenforceable. USA threatened however to combat the directive and currently three US airlines and IATA have introduced a claim at the Court of Justice of the European Communities saying that forcing non-EU airlines into the EU-ETS is illegal.

Targeted emissions

Non-CO_2 emissions are not addressed even if the Directive recognizes that aviation's total climate impact is more important than that from CO_2 emissions alone. This is in line with the EU-ETS already implemented for other sectors, addressing CO_2 only. It is explicitly mentioned that NO_x emissions will be tackled separately and, concerning AIC, only R&D, operational and technical measures are brought up.

The initial directive proposal (European Commission, 2006) included a fixed multiplier to take non-CO_2 aviation climate impacts into account.

The idea of this fixed multiplier has not been kept because of different arguments: scientific uncertainties on the magnitude of AIC climate impacts (mainly put forward by aviation sector-based associations), existence of trade-offs between CO_2 and non-CO_2 climate impacts that is not recognised in a fixed multiplier, etc. (section 2.4.4). Instead of suggesting a better way to include non-CO_2 climate impacts taking into account scientific certainties (e.g. the minimum AIC climate impacts), the issue has been eliminated from the Directive and relegated to the adoption of complementary measures.

Emission ceiling and allocation principles

The emission cap (E_{cap}) for the sector has been set for the moment at the average of annual aviation emissions between 2004 and 2006. In 2012, the total of the allowances allocated to aircraft operators will amount to 97% of the historical 2004-2006 average and afterwards to 95% multiplied by the number of years (N_y) in the period beginning in 2013. The general review of the EU-ETS (Directive 2003/87/EC) could adapt these percentages (P_R) in accordance with the adoption of new emission reduction objectives.

3% of the allowances (P_{SR}) will be set aside for a special reserve (for new entrants and fast-growing operators) and another 15% of the allowances will be auctioned (from 2013, this percentage P_A could be increased according to the review of the EU-ETS).

The other allowances will be allocated for free according to a specific benchmark.

From then on, each concerned aircraft operator will receive a number of free allowances (A_{Op}) for the period considered on the basis of the following calculation:

$$A_{Op} = E_{cap} \times N_y \times P_R \times (100\% - P_{SR} - P_A) \times \text{benchmark}$$

The benchmark refers to the tkm data registered by the operator during the reference year for the period (e.g. 2010 is the base year as regards the 2012 period) divided by the sum of the tkm data of all concerned operators in the same year. The tkm (= distance x payload) data are calculated by applying these rules (EU, 2008, Annex IV):

- distance of a flight = great circle distance between the aerodrome of departure and the aerodrome of arrival + 95 km;
- payload = total mass of freight, mail and passengers carried (for passengers, a default value of 100 kg per passenger and its checked baggage can be applied ; crew members are not considered as passengers).

This benchmark rewards best performances of aircraft operators. If the trajectory of the flight is optimised, it will approach the great circle distance (GCD) used in the calculation.

The fixed 95km added to the GCD have been negotiated probably to avoid penalising shorter distance flights for which the actual route could be by far longer than the GCD due, among other things, to congestions at busy airports (cf. the aircraft has to fly around the airport until it receives the authorisation to land). This problem, as well as an increased optimisation of the flight routes, could partially be solved by ATM improvements (see section 2.2). Concerning the payload, the use of the real weight, instead of MTOW or other capacity indicators, encourage aircraft operators to improve their load factor. However, some might be tempted to improve artificially their load factor during the base years (for example by selling air tickets at lower prices) to obtain more free allowances for the whole commitment period. This will represent a typical situation of the "Prisoner's dilemma" for aircraft operators (each operator may try to play at its advantage with no consideration for the overall market advantages).

Main comments on the new directive

Seeing that international aviation is not included in the Kyoto Protocol, aviation allowances will not be accepted outside the sector (EU, 2008, §27), so that the integration of aviation into the EU-ETS is made via a semi-open system. This raises the question of the interdependencies and the necessity of a coherent view between the different emission trading systems.

To avoid carbon leakage, it is necessary to find a solution to include aviation in the post-2012 UNFCCC scheme. Otherwise, a part of the expected emission reductions in the aviation sector triggered by the inclusion in the EU-ETS could partially be compensated for by higher emissions in the rest of the world (e.g. less energy efficient aircraft allocated to routes outside the EU).

In the absence of complementary policy measures to tackle non-CO_2 aviation climate impacts, the relationship between the allowance and the real climate impacts of the sector will not be equivalent between the aviation sector and other sectors covered by the EU-ETS. In the context of the EU-ETS review and the emission reduction objectives decided by the EU to limit the global temperature increase to 2°C above pre-industrialisation levels, it might be necessary to integrate non-CO_2 aviation climate impacts in the climate policy and even strengthen the CO_2 emission reduction objectives for aviation, otherwise, other sectors would have to make supplementary emission reduction efforts (section 2.3.2).

Moreover, the directive only mentions potential complementary policy measures to tackle NO_x emissions from the aviation sector while the ABC Impacts project demonstrates that as far as the aviation sector is concerned, aircraft induced cloudiness has a much more important role in generating climate impacts than NO_x emissions (section 2.3).

In this respect, a coherent policy mix avoiding trade-offs between separate measures is necessary to be able to mitigate the total aviation climate impact. Therefore, it could be simpler to include aviation non-CO_2 climate impacting emissions in the same policy tool than CO_2 emissions, i.e. the EU-ETS, through an improved multiplier for example (section 2.3.4).

2.5. Multicriteria analysis

2.5.1. Description

Different policy measures are available to reduce climate impacts from the aviation sector. In this study some policy options were identified. In order to assess the effectiveness of each of them, it was decided to use an evaluation methodology. In this study some policy options were identified.

Several methods can be employed for evaluations within the transport sector. But most of them imply a monetarisation of the different elements considered giving less room to subjective and qualitative aspects. A multi-criteria analysis (MCA) gives instead the possibility to overcome these constraints.

This is one of the main reasons why the MCA method has been chosen by the "ABC Impacts" project analysts. Furthermore, MCA techniques can be used to establish a list of a limited number of options for subsequent detailed appraisal; to rank them according to their effectiveness in fulfilling each selected criterion and finally to identify the most preferred one. A MCA offers also a support to the decision makers, allowing this way a more transparent decision process.

Most of the economical, industrial, financial or political decision problems are multicriteria (decisions to be made based on various criteria). Usually there is no perfect solution and no alternative is the best one on each criterion. Compromise solutions have to be considered. By applying a MCA it is possible to some extent to delineate an appropriate platform for future compromises.

2.5.2. Methodology

For this study the MCA called PROMETHEE&GAIA was applied, an MCA method developed by Brans (1982) and by Macharis, Brans and Mareschal (1998).

This approach allows a better capturing of the scientific knowledge and experience about the different criteria and alternatives gathered by the multi disciplinary ABC Impacts project research consortium. The performance of those policies groups-alternatives (Technology R&D/Investments, Operational efficiencies/Infrastructures and Market-based measures) could be evaluated in relation to several appropriate criteria (Climate performance, Feasibility, Large scale implementation, Socio-economic impact).

These criteria will be explained later on and a detailed description can be found in annex 1. After these two important steps, the selection of the best compromise alternatives was proposed.

The preparatory work followed different steps: 1° problem’s definition and the identification of the alternatives; 2° translation of the objectives into criteria (one or more indicators were constructed for each criterion); 3° quantification of the relative importance (weights) of each criterion (the preference intensity was expressed on a scale from 1 to 9).

Given the fact that indicators such as emissions reduction achieved or scores on an ordinal indicator such as high/medium/low for criteria are values difficult to express in quantitative terms, the definition of an “indicator qualitative scale” enabled the measurement of each alternative performance in terms of its contribution to the objectives.

A qualitative scale consists of a list of semantic values and a list of corresponding numerical values (Table VIII:). Each semantic value is associated to its corresponding numerical value, which is actually used for the computations. For this assessment a 1 to 9 points scale going from bad to excellent effectiveness has been applied (i.e. How effective is the policy option “alternative fuels” to contribute to reduce the “CO_2 emissions”).

Table VIII: 1 to 9 point(s) qualitative scale used in D-Sight

Semantic values	PROMETHEE values
Bad	1
Bad to Neutral	2
Neutral	3
Neutral to Good	4
Good	5
Good to Very good	6
Very good	7
Very good to Excellent	8
Excellent	9

By the Multi-criteria analysis it was possible to compare the different strategic alternatives, putting the decision-maker in the position to take his potential final decision. For each objective the elements with a clearly positive or negative impact on the sustainability of the considered alternatives were pointed out. The ranking of the various alternatives allowed specifying the strong and weak points of each of them. Thanks to the flexibility of this method it was possible to measure the stability of this ranking through a sensitivity analysis to see if the result significantly changes when the weights are changed.

PROMETHEE allows the user to directly exploit the data (alternatives and criteria) of the problem in this simple performance matrix (Table IX:). This matrix consists of aggregating each alternative contribution to the objectives, where a_1, a_2... a_i... a_n are n potential alternatives and f_1, f_2… f_j, f_k are k evaluation criteria. Each evaluation f_j (a_i) must be a real number (Brans and Mareschal, 1983).

Table IX: PROMETHEE performance matrix

	$f_1(.)$ $f_2(.)$ …… $f_j(.)$ …… $f_k(.)$
a_1	
a_2	
…	
a_i	$f_j(a_i)$
…	
a_n	

Source: Brans and Mareschal, 1983

The newly developed user-friendly PROMETHEE software D-Sight allowed to build up the matrix of the research consortium assessment. In addition, the data and the results of the multicriteria analysis can be visualised in a plane called GAIA (Geometrical Analysis for Interactive Aid). The information (k-criteria in a k-dimensional space) is projected on this plane on which the potentially conflicting character of the different criteria appears. The GAIA plane displays graphically the relative position of the alternatives in terms of contributions to the various criteria (Brans and Mareschal, 1994). PROMETHEE & GAIA calculate positive and negative preference flows for each alternative. The positive flow is expressing how much an alternative is dominating (power) the other ones. The negative flow is expressing how much it is dominated (weakness) by the other ones.

Based on these flows, the PROMETHEE I partial ranking is obtained (it does not compare conflicting alternatives). PROMETHEE II provides a complete ranking. It is based on the balance of the two preference flows.

It has to be noted that the two rankings are influenced by the weights allocated to the criteria. A special feature of D-SIGHT called The Walking Weights allowed to modify the weights (a sensitivity analysis tool) in an attempt to see if the alternative rankings results significantly changes when the weights are modified. In general this analysis is useful when the decision-maker has not established too rigidly determined weights.

Regarding the ABC Impacts - MCA, the performance matrix has consisted of qualitative scores considering the performance effectiveness of each alternative related to the identified objectives. Each criterion has a specific preference function used to compute the degree of preference associated to the best alternative in case of pairwise comparisons (Brans and Mareschal, 1994). Regarding this assessment the preference function 'usual shape' (basic type without any threshold) was applied.

2.5.3. The set up of the ABC Impacts - MCA

The policy measures have been grouped into three categories: 1- Technology R&D; 2- Operational Efficiency/Infrastructures; 3- Market-based Measures.

The criteria were grouped into four categories: 1- Climate performance; 2- Feasibility; 3- Large-scale Implementation; 4- Socio-economic Impact.

A description of each criterion group and criterion can be found in Annex 1 (ABC Impacts website > Open section > Project publication > Public reports).

In setting up the performance matrix, for several relations with ambiguity there has been a common agreement of the ABC consortium to set two different scores (high and low). Each score was justified by an appended comment (see Annex 2, ABC Impacts website > Open section > Project publication > Public reports). The weights were established by priority calculation of the Analytic Hierarchy Process (AHP) Expert Choice ComparionSuite pairwise comparisons software worked out by the ABC Impacts consortium and stakeholders.

Priority is a numerical value represented as a percentage of one. Priority is calculated from judgments entered for Pairwise comparisons. Local Priorities refer to the priorities calculated for a single level of objectives/criteria groups (Figure 19) or sub-objectives/sub-criteria (Figure 20) that are directly under an objective or sub-objective on the hierarchy.

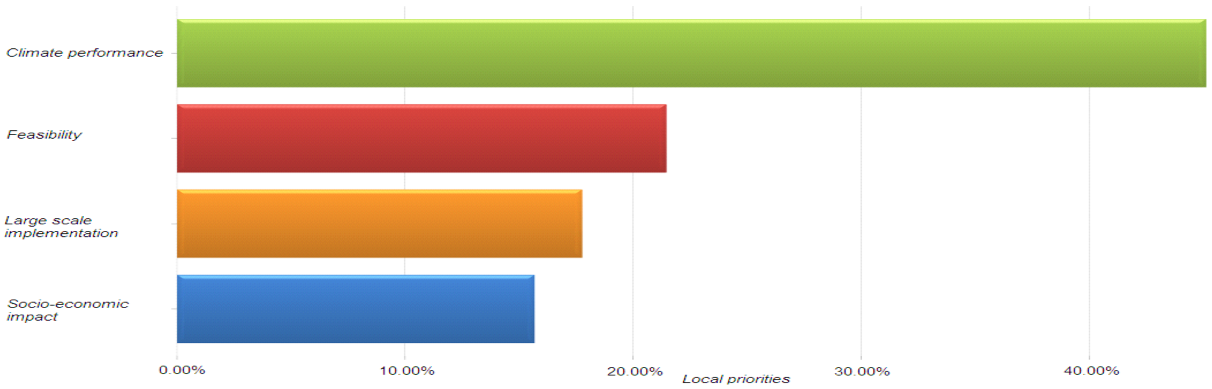


Figure 19: Local priorities calculated in Comparion for the criteria groups

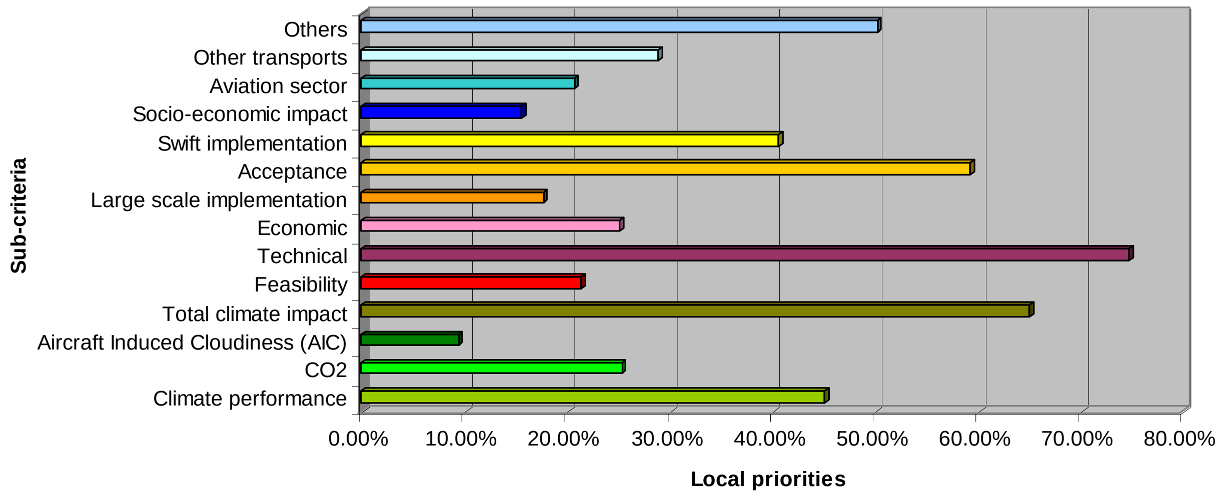


Figure 20: Local priorities calculated in Comparion for the sub-criteria

The priorities of each level objectives or sub-objectives always total one (Table X:).

Table X: Weights established by priority calculation of the AHP Comparion pairwise comparisons applied in D-Sight

Criteria group and subcriteria	Local priorities (weights)
Climate performance	**45,12%**
CO_2	25,40%
Aircraft Induced Cloudiness (AIC)	9,50%
Total Climate Impact	65,09%
Feasibility	**21,45%**
Technical	74,78%
Economic	25,22%
Large scale implementation	**17,76%**
Acceptance	59,32%
Swift Implementation	40,68%
Socio-economic impact	**15,67%**
Aviation Sector	20,78%
Other Transports Modes	28,95%
Others	50,26%

The AHP Comparion methodology consisted in:

- the pairwise comparisons of all criteria groups in relation to the goal, i.e.: Task: Consider "Policy options to reduce the total aviation climate impact":

  Which of the two objectives displayed, "Climate performance" and "Feasibility", is more important with respect to "Policy options to reduce the total aviation climate impact"?

- and of the pairwise comparisons of the sub-criteria in relation to each corresponding criteria-group, i.e.: Task: Consider "Climate performance:

  Which of the two objectives displayed, "CO_2" and "Aircraft induced cloudiness (AIC)", is more important with respect to "Climate performance"?

Those pairwise comparisons have been achieved by the ABC Impacts consortium as well as by the stakeholders and combined for the final results. Furthermore the ratings were used to select a predefined value to a single objective or alternative. Ratings are not used to compare two objectives or alternatives. A rating scale is used to define the values available for selection.

Additionally in Comparion, a measurement scale has been defined based on the PROMETHEE performance matrix high qualitative scores. For the ABC Impacts consortium the same effectiveness values were introduced, while the stakeholders provided their own judgements (Figure 21).

Rate each alternative with respect to 'Aircraft induced cloudiness (AIC)'.

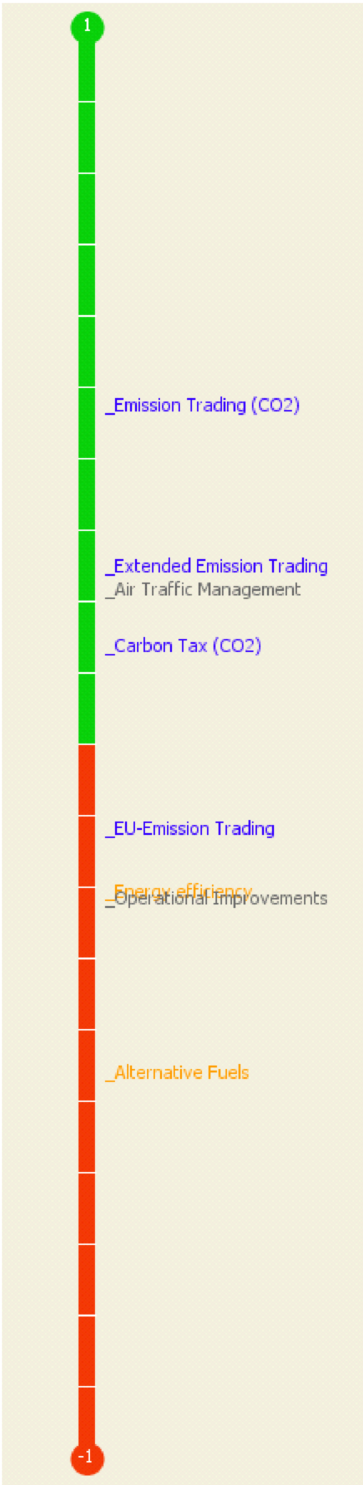
Energy efficiency	Bad (0%)
Alternative fuels	Neutral to good (38%)
Air traffic management	Very good (75%)
Operational improvements	Neutral (25%)
Carbon tax (CO2)	Neutral to good (38%)
Emission trading (CO2)	Neutral to good (38%)
Extended emission trading	Very good to excellent (88%)
EU-Emission trading	Neutral (25%)

Figure 21: Comparion measurement scale based on the PROMETHEE performance matrix scores

Afterwards, for each group of criteria (objectives) and the corresponding sub-criteria (sub-objectives), the weights prioritisation results were set up within the D-Sight application. Some of the matrix scores provided by the consortium did not consist of a fixed value, but rather of a range. To include these ranges, it has been decided to show the ranking once assuming the highest ends of the ranges, and once assuming the lowest ends of the ranges. The PROMETHEE II complete ranking Thermo tool represented for high and low (Figure 22 and 23) scores the following standings. It corresponds to the net flows scores of the alternatives. The green part of the thermometer is the positive part (e.g. values between 0 and 1) while the red part represents the negative values (between 0 and -1).

We see almost the same ranking for the high scores (left) as well for the low scores (right). This shows that the ranking is stable. With the low scores, emission trading schemes is clearly the most preferred and the other alternatives are on a distance away from each other. With high scores, emission trading schemes are still preferred but we see that the other alternatives are more grouped together, whereas "alternative fuels" are clearly at the other of the spectrum.

The ranking is noticeably influenced by the established weights attributed for all the criteria groups and each criterion. The walking weights application of D-Sight is a constructive tool for future research allowing to analyse the possible feedbacks of "objectives of the different stakeholders" (Figure 24).



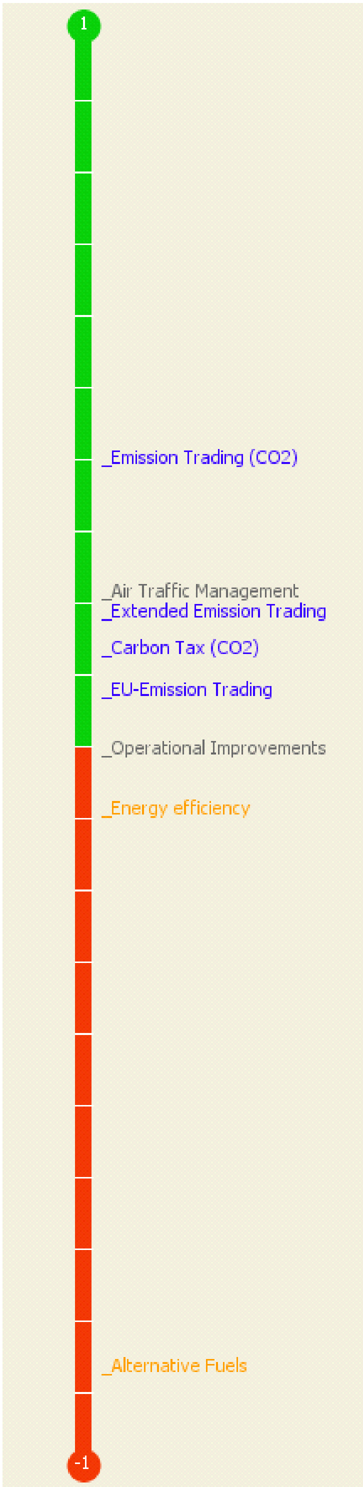


Figure 22 (left) and **Figure 23** (right): D-Sight Thermo tool for high scores and D-Sight Thermo tool for low scores

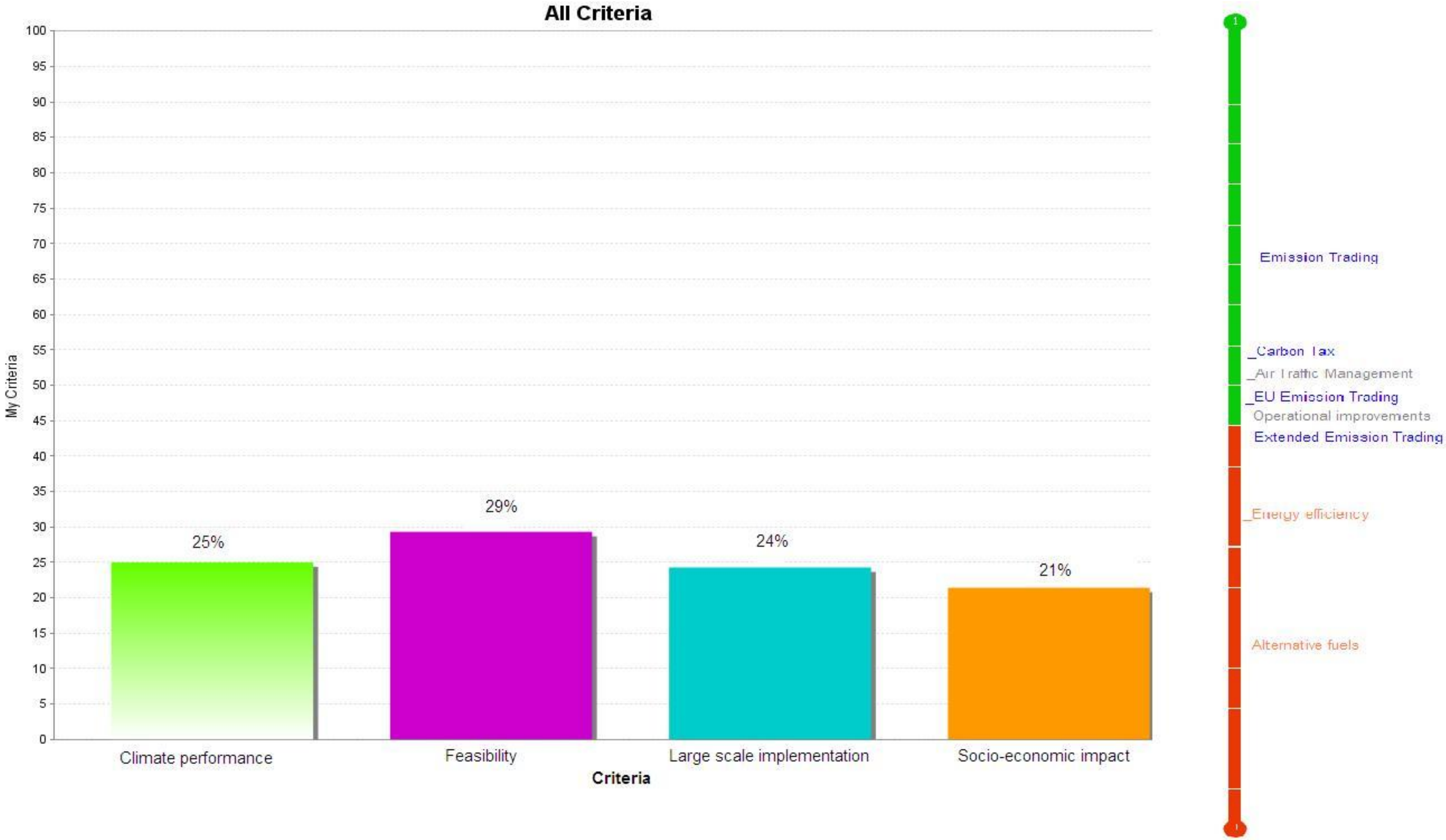


Figure 24: Walking weights application of D-Sight within the ABC-MCA

The AHP Comparion assessment showed the following (normalised) ranking of the considered alternatives (Figure 25).

Figure 25: Comparion assessment normalised ranking of the alternatives

This figure shows the overall score of the alternatives taking all the criteria into account. We see that emission trading is very clearly highest ranked with 100% of the possible score it could get. It is followed by energy efficiency (score of 96,03%) and then the others which have almost the same scores.

The corresponding performance analysis reports a dynamic example of changing a priority (climate performance from 45,12% to 20,33% for example) and the related impact of one objective on the other objectives and on the alternatives (Figure 26 and Figure 27).

For each of the alternatives (scenarios) we get a coloured line, indicating the performance of that alternative on the 4 criteria and the overall score we get at the right vertical axis. The weight of the criteria is represented by the bleu bar within the criterion bars. Within the first figure the weight of climate performance is 45,12% and in the second figure we decrease that to 20,33%. The weights of the other criteria are increasing accordinally. At the overall axis at the right hand side we can see what this change in weight is causing to the overall ranking. The first three alternatives are not changing in the ranking. The extended emission trading scheme falls however from a fourth to the last place. This is because it scores very well on the criterion that we changed. On the other hand, operational improvements would become more important.

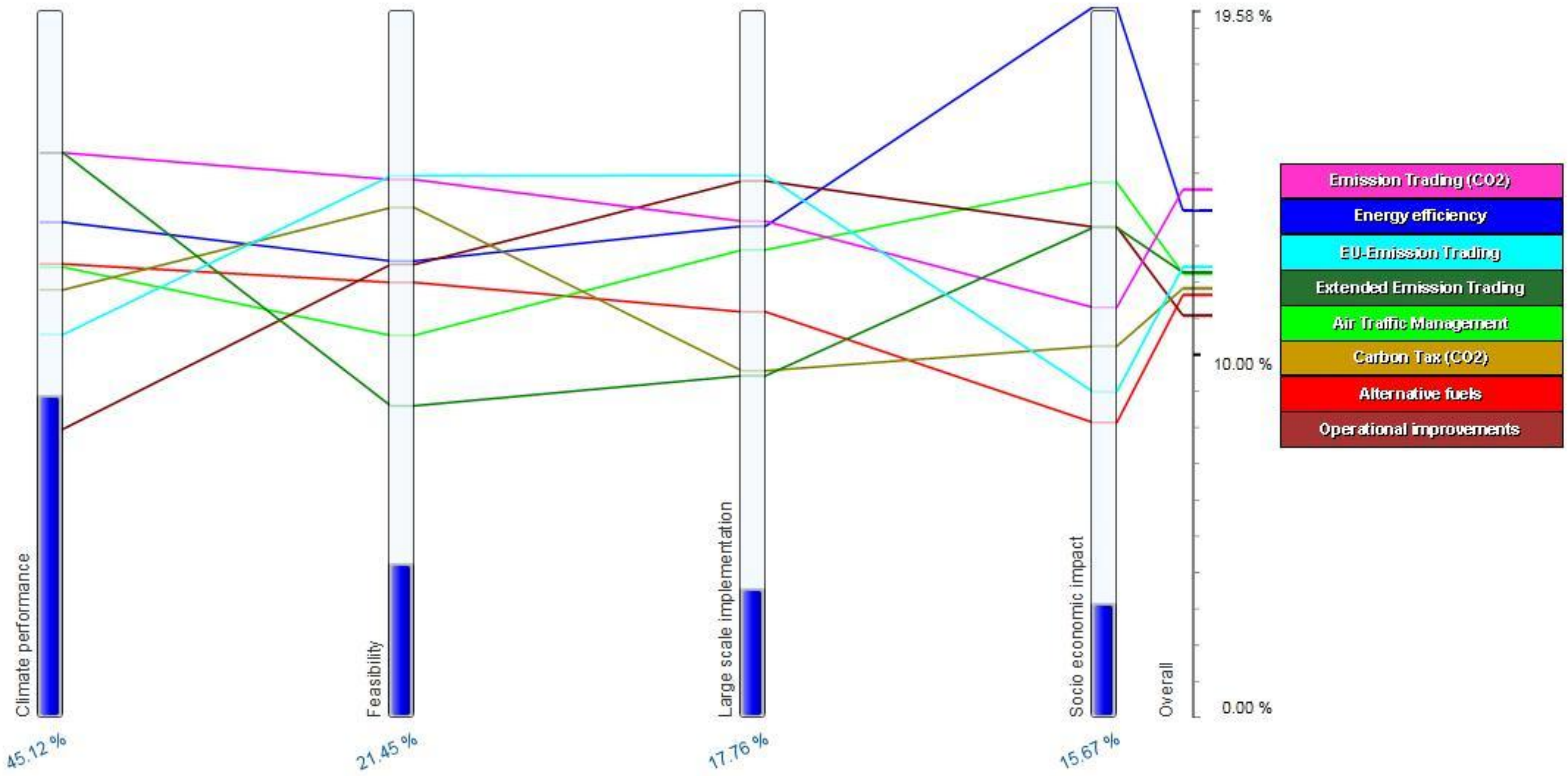


Figure 26: Performance analysis with the original objective priorities

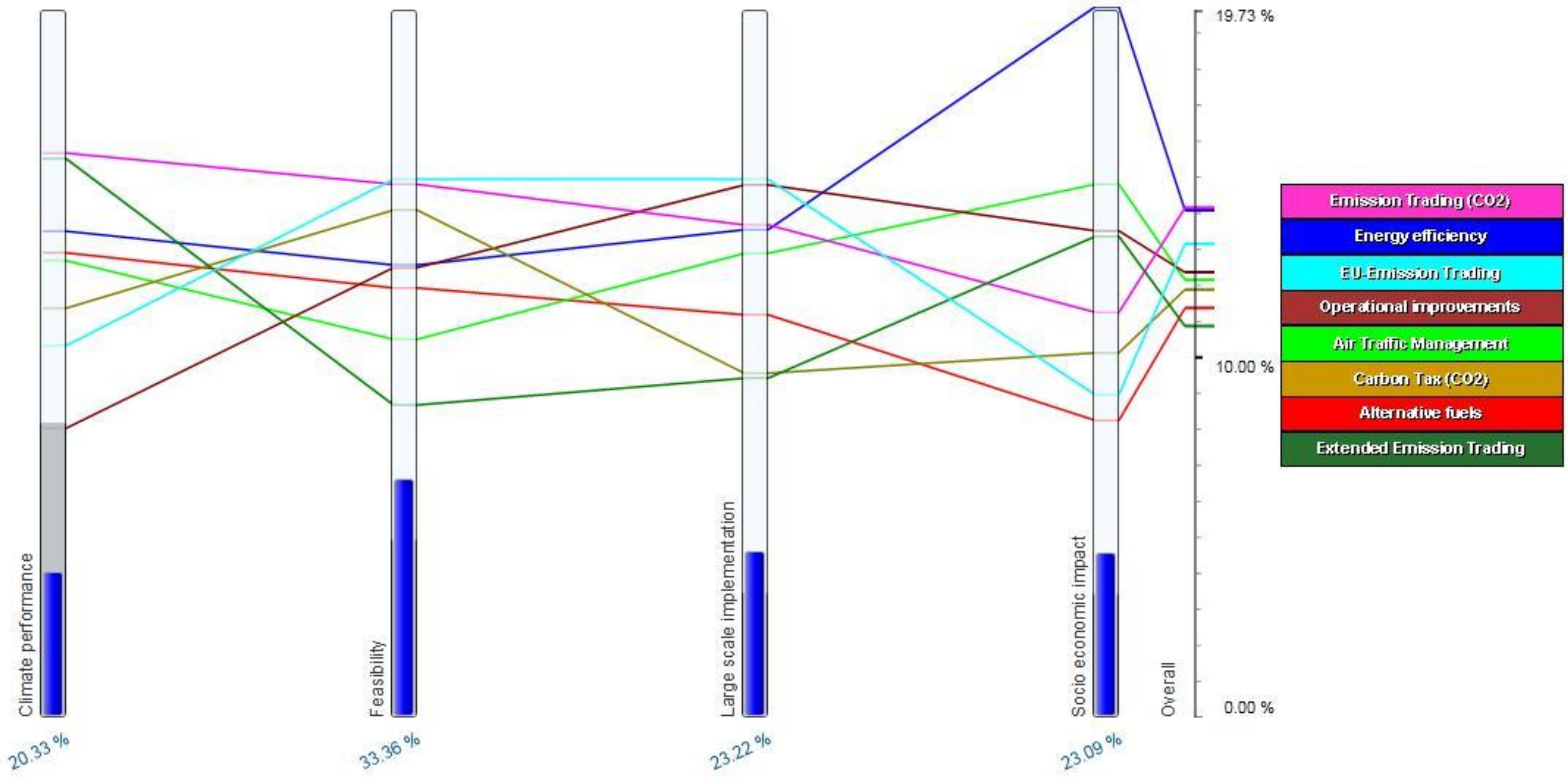


Figure 27: Performance analysis of the impact changing the priority for an objective

2.5.4. Conclusions

By applying a multi-criteria analysis as evaluation tool it is possible to some extent to delineate an appropriate platform for future policy options compromises. The user-friendly D-SIGHT allowed to use qualitative scales instead of the default numerical scale for the criteria values. The software application has shown to be a valuable tool related to a complex decision problem on behalf of climate change policy support.

The outcome of the MCA gives a ranking of the different policy measures and shows which measure scores best for the aggregation of all the criteria. Based on this ranking, it can also be seen which policy measures are the best for the different criteria. But more importantly, the analysis clearly indicates the advantages and disadvantages of the different measures which are available for policy makers to reduce the climate impact of aviation on climate. It is furthermore possible to apply a sensitivity analysis to look how consistent the measure is if the weight of a criterion is changed.

Regarding the D-Sight application the policy options ranked within the high scores application as top 3: Emission Trading (CO_2), Extended Emission Trading and Air Traffic Management (ATM). Besides, the low scores provided: Emission Trading (CO_2), Air Traffic Management (ATM) and Carbon tax (CO_2).

Concerning the Comparion outcome the policy options ranked on the first 3 positions are: Emission Trading (CO_2), Energy Efficiency and EU-Emission Trading.

The analysis shows that emission trading is always coming out on top of the evaluation process. Air Traffic Management (ATM), Extended Emission Trading, Carbon tax and Energy Efficiency can be also counted on the top 5 of policy options that can be implemented.

A policy package of the top ABC-MCA assessment out coming measures is often better than the environmental effectiveness of the implementation of a single policy option, as no single policy option can simultaneously offer a reasonable level of flexibility in minimizing the costs of its implementation and provide a significant reduction of the total climate impact.

Considering the first three ranking policy options, the reduction of CO_2 seems best controlled within an ETS. There is no incentive to reduce AIC, but a reduced demand leads to less AIC formation. Moreover more efficient airplanes produce additional contrails and may contribute to reduce the flow. Emission ceiling and the increase in AIC and decrease in CO_2 w/r to baseline may balance in the long term. There is no technology requested and a lot of experience gained already with existing schemes.

Concerning the economic feasibility there is no investment needed, but a follow-up system must be implemented and there is no economic payback for the sector. It offers many options to minimise costs, funds raised need to be invested in a proper way to minimize the impact on economy and it can only be outstanding on the long term.

The large scale implementation acceptance can be expected to induce an overall increase in financial burden for customer. But it seems more fair (and complex to understand), so less protest is to be expected. There will be a better acceptance level because flexible and cost minimisation and a market implies winners and losers (companies created after the quota distribution), but many groups will accept.

An ET is technically easy to implement. Practically, more difficult because of the need for a global agreement even if still many difficulties to agree world-wide but more and more stakeholders are in favour considering the example of the EU and due to experience with ET the implementation should be quite swift.

It will probably increase the cost for the aviation sector, but efficiency is rewarded depending on the price level and the airline performances and it puts airlines worldwide on the same level.

An Extended Emission Trading (non CO_2) measure will lead to a reduction for the total impact. No economic investment is needed, but a follow-up system must be implemented furthermore there is no economic payback for the sector, it offers many options to minimise costs but costs will be higher than without non-CO_2 and the funds raised need to be invested in a proper way to minimize the impact on the economy and it can only be an excellent measure on the long term.

It will be expected to induce an overall increase in financial burden for customers. But it seems more fair (and complex to understand), so less protest should to be expected. Anyhow there is still much reluctance from the aviation sector and politicians to consider non-CO_2 impacts but more and more stakeholders are in favour of a consideration of the total climate impacts. Additionally there could be an increased cost for the aviation sector and it might lead to supplementary fuel use if AIC has to be avoided.

The Air Traffic Management (ATM) measure should result in reduced CO_2 emissions for all aircraft, in particular in Europe the introduction of direct routes might reduce CO_2 emissions, but low compared to the total and expected growth within the EU and the USA.

Regarding the AIC climate performance it should result in reduced AIC (as less km are going to be flown), so a full reduction potential and it could help to reduce the overall non-CO_2 climate impact and if contrail avoidance is taken into account, it can strongly reduce the AIC RF.

This options is already identified and a lot of investments and proof of concept done, however it needs further refinement, in particular for contrail forecasting.

It will require some relatively limited investment (partly from governments), major investments needed in R&D and additional infrastructure and can only be excellent on the long term. It will reduce other costs related to consumption, congestion, etc.

There will be no particular risky socio-economic impact for the aviation sector: increased efficiency, lower costs, reduce travel time, fuel consumption and related air pollution.

Considering Energy efficiency (airframe design, engines, materials), even if ranked at the second class within the combined stakeholder-consortium Comparion assessment, for the ABC experts it is directly linked to CO_2 emissions, the low fleet turn over and it depends on R&D investments. It is quite efficient for a single plane, but it will not countercoup the high growth of the sector.

The AIC climate performance has a potential increase in contrail formation when efficiency of engines is increased, trade-offs: more efficient airplanes produce more contrails and more efficient engines produce contrails for a broader range of temperatures.

The economic feasibility depends on the level of adaptation of the aircraft (retrofit or not), but a energy efficiency is always an economic incentive (sometimes not sufficient, but still) and depends on regulations and policy incentive, the investments made for newer technology will be rapidly counteracted by fuel savings and can be good on the long term if there are significant test results for a large scale implementation.

2.6. Scenarios development and links with the MCA

Trying to estimate how the aviation sector will develop in the coming years and decades is a very difficult exercice. Indeed, many internal (airline cost structure, technological and operational improvements, etc.) and external (e.g. evolution of societies and demography, evolution of the word-wide economy and GDP of each country, behavioural changes of consumers, etc.) parameters have to be projected, with often great uncertainties, and then combined. The specific combination of assumed parameters evolutions leads to potential development scenarios for the sector.

Projecting future emissions of the sector adds another step to the exercice by anticipating how aviation development will be translated in terms of emissions (cf. it depends on technological evolutions, characteristics of the fleet composition and management, policy measures adopted, etc.). Therefore, several projects have been dedicated totally or partially to this large and time-consuming task (e.g. Eurocontrol forecasts, CONSAVE 2050, IPCC/SRES, ACARE/ASTERA, etc.).

Whatever the projections made in those projects, the more distant the time horizon studied, the greater the discrepancy between final values according to the different scenarios (cf. Figure 28 illustrating results from different CO_2 aviation emission scenarios compared to the expected evolution of total anthopogenic CO_2 emissions).

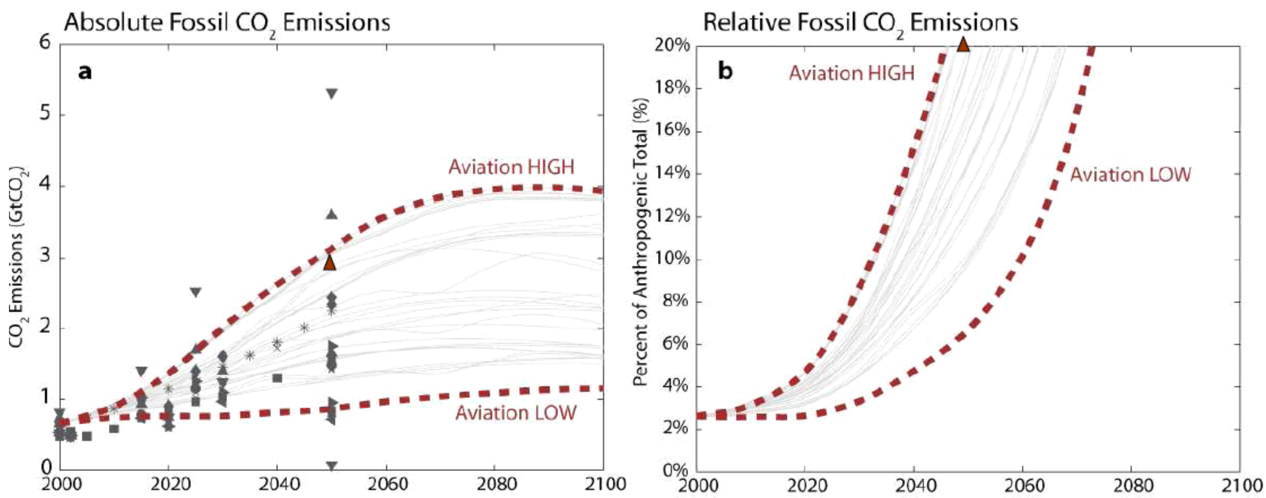


Figure 28: Projected aviation fuel emissions to 2050 (Lee et al. (2009) in Eyers, 2010)

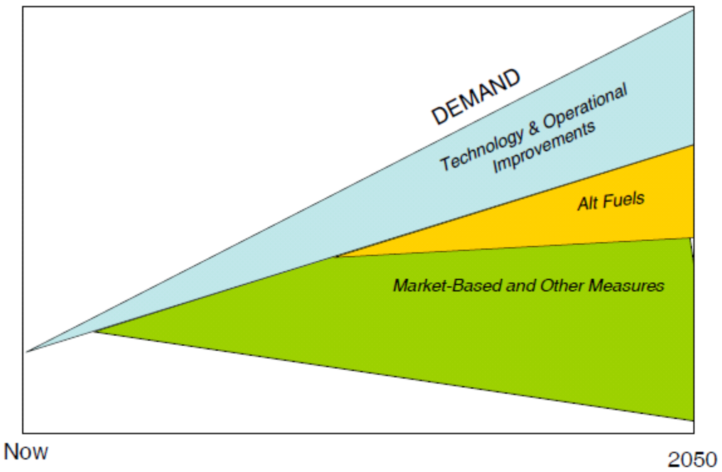


Figure 29: Mitigation potentials of aviation climate impact for the three main categories of policy options (Eyers, 2010)

In spite of the important uncertainties and assumptions leading to such discrepancy, it is known for sure that, compared to different global GHG emission reduction scenarios, even freezing international aviation emissions to the 1990 level will not be sufficient to let some space for other sectors around 2050. Hence aviation emissions definitively have to be reduced for limiting global warming to a "satisfactory" level.

Given that, all in all, technological solutions could reduce by 2030 aviation CO_2 emissions by a maximal intervalle of 25% to 65% (with radical changes), according to the socio-economic and political context, a policy mix including regulations, market-based instruments and/or other measures (among others measures aiming at limiting/curbing growth in demand) will be necessary to mitigate aviation total climate impacts (Figure 29).

One approach with scenarios is to set a target and to analyse how the current development trend and expected technological progress are compatible with the objective. The multi-criteria analysis can be used in this context by ranking the different policy options according to their potential effectiveness to reach a selected goal (e.g. reduction of the total aviation climate impact by x% within next decade) and to identify the synergies/complementarities between different policy options in order to set a coherent and efficient policy mix.

Another approach with scenarios, adopted for example in the CONSAVE 2050 European project (Berghof et al., 2005), consists in predetermining (quantitative or qualitative) values for a set of socio-economic and environmental indictors in order to build different and contrasted general development scenarios for the society (in the CONSAVE 2050 project, four scenarios (Table XI) were selected and called respectively "Unlimited sky", "Regulatory Push & Pull", "Fractured World" and "Down to Earth").

For each CONSAVE selected scenario, specific assumptions are made concerning the development of the aviation sector and related policy instruments. Growth factors differ significantly according to the scenario adopted and according to the region analysed due to the combination of assumptions.

Table XI: Assumptions made for the aviation sector in the four CONSAVE 2050 selected scenarios (based on Berghof, 2005, p7)

Assumptions for 2020/2050	Unlimited Sky	Regulotary Push & Pull	Fractured World	Down to Earth
Aircraft technology	New very large aircraft available	Idem + hydrogen powered ac	Different standards	Introduction of hydrogen powered ac
Air transport supply & demand	Very high increase	High increase	Low growth in international flights	Decrease
Airport & ATM capacity	Constraints	Capacity regulated	Depending to regions	No constraints but low profitability
Aviation costs	Lower specific costs	Lower specific costs	Higher (security & standards)	Higher specific costs

In this case, the multi-criteria analysis could help identifying set of policy options that are more suitable in a specific expected context to mitigate total aviation climate impact or that will help reaching the desired development scenario.

2.7. Main conclusions and recommendations

From both the Belgian and global points of view, ignoring non-CO_2 aviation climate impacts will reduce climate policy measures effectiveness and could even worsen aviation climate impacts (cf. several trades-offs).

From the global point of view, if the objective is to stabilise global warming at +2°C, it implies that aviation has to reduce its total climate impact in order to avoid impeding other sectors' development too much. As technological development will not be sufficient to compensate for expected aviation growth, market-based and regulatory measures will have to be adopted to complete the current climate policy mix and help reducing aviation total climate impact.

Moreover, concerning non-CO_2 aviation climate impacts, it has to be considered that AIC is quite substancial and has a greater climate impact than NO_x (AIC from aviation has a RF impact at the local/regional scale of the same order of magnitude as that of total anthropogenic CO_2).

From the Belgian point of view, it is important to take into account climate impacts due to overflights (mainly AIC) along with the impacts from national LTOs and to put the emphasis on operational measures and modal shift (mainly for intra-EU travels) in order to reduce AIC formation .

2.7.1. Technical and operational mitigation options

Through important innovative adaptations the aviation sector succeeded in implementing significant reductions of the emissions (CO_2, H_2O, Soot, CO, SO_x, NO_x, etc.) and fuel consumption of individual aircrafts. However, these improvements (fuel consumption decreases by 0,5% - 2% per year) are smaller than the high growth rate of the sector (average of 6,4% per year between 1991 and 2005). In the future, several improvements (implementation of synthetic fuels or agro-fuels, aircraft design and engine improvements, etc.) as well as some radical changes in the long-term (like the use of hydrogen as a fuel for aircraft) can be expected. Moreover, some specific management changes (improved ATM, RVSM, CDA, etc.) might reduce the impact of aviation on climate by more than 10% without the need for new technologies to be implemented onboard and without the delay that is necessary for fleet renewal when new technologies are implemented.

However, these evolutions alone do not appear sufficient to reduce climate impacts from the aviation sector enough to be consistent with scenarios avoiding global warming above 2°C from pre-industrialisation levels. Therefore, complementary climate policy measures are necessary to mitigate future aviation climate impacting emissions.

2.7.2. Modelling aviation climate impacts

Aviation impacts on climate are much more significant at the local/regional scale than on global average due to short term non-CO_2 effects and intense regional air traffic (the radiative forcing due to aviation is estimated to 78 mW/m^2 on global average (for the year 2005), to 400 mW/m^2 over Europe (in 2002), and to 1 W/m^2 over Belgium). The largest impact of aviation on climate, outside that from CO_2 in the long term, is likely to be that from induced cirrus clouds.

The regional climate model selected for this project is CCLM (COSMO Model in Climate Mode, Will et al. (2009)). The horizontal resolution is 20km to enable simulations long enough for climate impact analysis covering the whole of Europe. As the processes occurring in the plume of aircraft are taking place at much finer scales, these are parameterised (using ice-supersaturation simulated by the model as a key input). Ice amounts computed from this parameterisation are then introduced in the cloud microphysics scheme of the model.

Test simulations were first made by assuming a homogeneous spatial distribution of flights, providing results that appear coherent and consistent with other studies. The potential AIC cover is larger in winter than in summer, resulting from the more frequent occurrence of super saturation in winter. To date, a single run has been done with an actual flight distribution over Europe, based on the AERO2k database (Eyers et al., 2004). The initial comparison with satellite data is promising, and more simulations and analyses of results will be done before the end of this project.

2.7.3. Metrics of impact on climate and inclusion of aviation in cap-and-trade systems

Our research confirms that impacts on climate from causes other than carbon dioxide, and specifically those from aircraft induced cloudiness, are non-negligible and likely to be substantial. Therefore, these need to be taken into account in mitigation objectives and related legislation, which is currently not the case. We included aviation impacts on climate and reference future scenarios in an interactive global climate model, and made it available on the internet (www.climate.be/jcm), enabling users to experiment with hypotheses regarding scenarios, uncertain climate parameters, and choices such as time-horizon. Our own analysis with this tool shows that to achieve a relatively ambitious mitigation target (such as limiting temperature increase from the pre-industrial to 2°C), it is very likely that the net emissions and climate impact from aviation will need to be much lower than in BAU scenarios. In the absence of efforts in the aviation sector, such a global target would imply that emissions from other sectors fall to very low levels within the next decades.

Non-CO_2 effects must also be taken into account to reflect the effective climate impact of aviation transport when comparing or adding it to the impacts from other sectors, such as in the EU-ETS. Failing to do so would result in emission reduction units from aviation that would have a higher effect on climate than units from another sector. Taking the geographical situation of the country into consideration, this is an aspect of potential new regulations that should receive special attention from Belgian policy makers. This aspect should also be taken into account when trying to inform the general public about aviation and climate change. Therefore, it is essential to include it in offset calculators for example.

The difficulties associated with attributing a weight to non-CO_2 impact from aviation, i.e. defining a metric for these effects, may have given the impression that uncertainties are so large that no reliable numbers can be provided to policymakers. However, we conclude that current knowledge is sufficient to provide estimates of aviation impacts on climate in spite of remaining uncertainties, with the caveat that metrics of non-CO_2 impacts have a fundamental limitation that will probably always require a compromise: a choice regarding the relative weight of short and long term effects (from days to centuries) must be done. In line with the recent expert meeting of the IPCC on metrics (IPCC, 2009), we currently recommend the use of Greenhouse Warming Potentials (GWP) to express the climate impacts of aviation in terms of CO_2 amounts having a comparable effect on climate, with a 100-years time horizon to match the choice done in the Kyoto Protocol.

Once GWP is selected as a climate impact metric, a remaining issue is that the uncertainty is still significant (roughly a factor of 2 or 3 between the low and high end of the 90% confidence interval). However, in the specific case of a trading system, we suggest that there is a rationale to simply select the best-guess value, as selecting the high estimate would not represent a more cautious approach – it would be more likely to overestimate the "climate value" of reduction units in the aviation sector as compared to other sectors. Based on the current literature, the simplest solution that we may advise is to use a multiplier of CO_2 emissions (based on GWP) equal to or slightly above 2 (cf. conclusions of the ABC Impacts workshop on "Aviation and offset programmes"). Similar values have been proposed for a long time, and although this should remain revisable as research progresses, it is now more supported by research then before.

However, a fixed value for all flights is not fully satisfying, as the actual impact may differ for each flight and specific measures (e.g. flight management to mitigate persistent contrails) may reduce the non-CO_2 impacts but slightly increase fuel consumption (and thus CO_2 emissions). We discussed variable multipliers and similar measures in a note to policymakers (Ferrone and Marbaix, 2009).

A complementary approach may be to have specific legislation for certain non-CO_2 impacts (as the EU is planning for NO_x). However, this does not eliminate the issue of trade-offs that may exist (e.g. techniques that reduce non-CO_2 impacts at the expense of more CO_2 emissions: in some cases, regulation outside the CO_2 cap-and-trade may also result in more CO_2 emissions).

2.7.4. Belgium and aviation climate impacts

The Belgian aviation market has a very specific position within Europe due to its geographical situation; in the middle of the so-called FLAP area which is delimited by four of the five main airports of Europe: Frankfurt, London, Amsterdam and Paris. This also implies that the number of overflights is already considerable through Belgian airspace and could become even more important due to the sector growth and potential route adaptations (according to Statfor-Eurocontrol, the adoption of shorter routes could increase overflights above the Belgian territory by 10%).

On the one hand the impacts of the Belgian aviation sector on global climate change is relatively small compared to other sectors or other countries but on the other hand regional climate impacts due to contrails, cirrus formation and change in the ozone concentration could have a large influence on the country because of the concentration of flights over the Belgian territory. A focus for Belgian policy makers could be to reduce the impacts from transit aviation (overflights), especially via operational measures targeting non-CO_2 gases.

2.8. What about international maritime transport?

2.8.1. Introduction

In 2005, international maritime transport (which does not include military and fishing vessels) represented 2,8% of total anthropogenic CO_2 emissions (Buhaug et al., 2009).

Shipping has several issues in common with the aviation sector as regards its growth expectation and its climate impacts.

As for international aviation, shipping registered a huge development these last years but is not covered by the UNFCCC, nor included in the Kyoto Protocol. The same argument is put forward to explain this, i.e. most emissions occur outside national territories and are therefore not easily attributable to countries.

Moreover, non-CO_2 climate impacts are significant and induce specific and more regional effects (cf. impacts of ship tracks).

However, the specificities of the maritime transport sector (atmospheric pollution in coastal zones, various activity data, numerous ports and routes, emission location, poor quality data and statistics available, etc.) make it even more difficult than for aviation to find an adequate policy option to mitigate its total and long term climate impacts.

2.8.2. Market characteristics and evolution

According to UNCTAD, more than 80% of world trade is transported by ships. In addition, the maritime transport sector has registered an annual growth rate of +4,6% (tkm/year) between 1986 and 2006 (mainly cargo and tankers). Growth has been particularly high since 2000 (+5,2% on a yearly average from 2002 to 2007, Eyring et al., 2009).

Cargo represents 50% of the maritime fleet (including fishing) but 89% of total gross tonnage transported by ships (Buhaug et al., 2009) and 77% of the main engine (mostly diesel engines) power installed in the fleet (Eyring et al., 2009). Transport of refrigerated goods (usually HCFC-22 installations, wich has a limited impact on the ozone layer but a huge GWP) in countainers has sharply increased these last years.

Many ships are operating under a flag of convenience in countries such as Panama or Liberia (Buhaug et al., 2009) even if major trading nations are the USA, Germany, China, etc. Traffic is estimated to occur by 80% in the Northern Hemisphere (32% Atlantic, 29% Pacific, 14% Indian Ocean, 5% Mediterranean (Eyring et al., 2009)). Asianwaters registered the most significant growth in shipping activities.

According to the four IPCC SRES scenarios until 2050, ship traffic demand will outweight GDP growth, showing that a significant effort will be needed to mitigate or offset future shipping emissions (Eyring et al., 2009).

2.8.3. Emission inventories

Main ship emissions are due to fuel combustion (exhaust gas), refrigerants and release of VOC related to crude oil transport (tankers). Besides climate impacts, these emissions, more specifically NO_x and SO_x (marine fuels are rather heavy and rich in sulphur), released by ships cause many other environmental damages such as acidification, impacts on human health in coastal zones and on ecosystems, etc.

Emission inventories are carried out on the basis of a "top-down" (e.g. from national fuel sale statistics) or "bottom-up" approach (e.g. emissions for each specific ship categories according to activity data) which result in relatively different results (Eyring at al., 2009).

To illustrate this in pratical terms, the two Belspo's projects on maritime emissions in Belgium, ECOSONOS (Maes F. et al., 2007) and MOPSEA (Gommers A. et al., 2007), adopting each one of the approaches, gave results differing so significantly that a comparison exercice has been carried out to understand more in detail the major parameters explaining such a huge gap between both emission estimations. Beside some divergences in the scope of the studies (type of vessels, activities and stages of navigation taken into account), the lack in or low quality/harmonisation of several statistics (total km travelled, emission per ship km, activity data, etc.) were pointed out as a major explanatory factor.

As a consequence, it is seems to be more difficult to determine a CO_2 emission ceiling as it has be the case for the aviation sector for its inclusion into the EU-ETS, and to evaluate accurately the emission reduction potentials of the sector or its total climate impact.

According to Eyring et al., 2009 best estimates, oceangoing shipping emitted around 780 Tg of CO_2 in 2000, which represents 2,7% of all anthropogenic CO_2 emissions that year and is comparable to the emissions of the aviation sector. For NO_x, SO_x and PM, average results reached respectively 5,4 Tg (3 to 10 Tg), 5,5 Tg (3 to 10 Tg) and 1,4 Tg (0,4 to 3,4 Tg). Refrigerant emissions are expected to be lower than 3.000 t per year (Devotta et al., 2006 in Eyring et al., 2009) and to reduce their climate impact in the future thanks to the enforcement of the Montreal Protocol's objectives.

Due to high growth perspectives, it is however expected that the environmental benefits of NO_x and SO_x mitigation measures would be significantly counteract.

2.8.4. Climate impacts of shipping and mitigation potential

Contrarily to aviation, shipping emissions occur at low altitude. Contrary to road transport, they take place mostly in relatively pristine air zone above oceans and seas (the marine boundary layer). This zone is in contact with the large heat capacity of water and has efficient mixing processes which give her a spatial and temporal homogeneity in temperature. Moreover, the marine boundary layer (MBL) is frequently covered with clouds.

NO_x emissions of ships interfere with the ambient air of the MBL and induce more OH^-, directly by reaction with HO_2 and indirectly by generating ozone. SO_x are oxidised to sulphate which increases the oxidation of dimethyl sulphide (released by phytoplankton) to partly form sulphate aerosols. Sulphate aerosols play a huge role as condensation nuclei (cf. ship tracks where droplet concentration is increased by a factor of 2 and droplet size are reduced by 50%) and change clouds reflectivity in the MBL (Eyring et al., 2009).

Therefore, climate impacts of maritime transport are specific: on the short term, shipping has a cooling effect (Figure 30) but on a longer term (+/- 50 years), the disappearance of regional cooling effect (due to aerosol induced cloudiness) makes that CO_2 accumulation in the atmosphere dominates the RF balance and causes a global warming effect (on the basis of GTP ; Eyring et al., 2009).

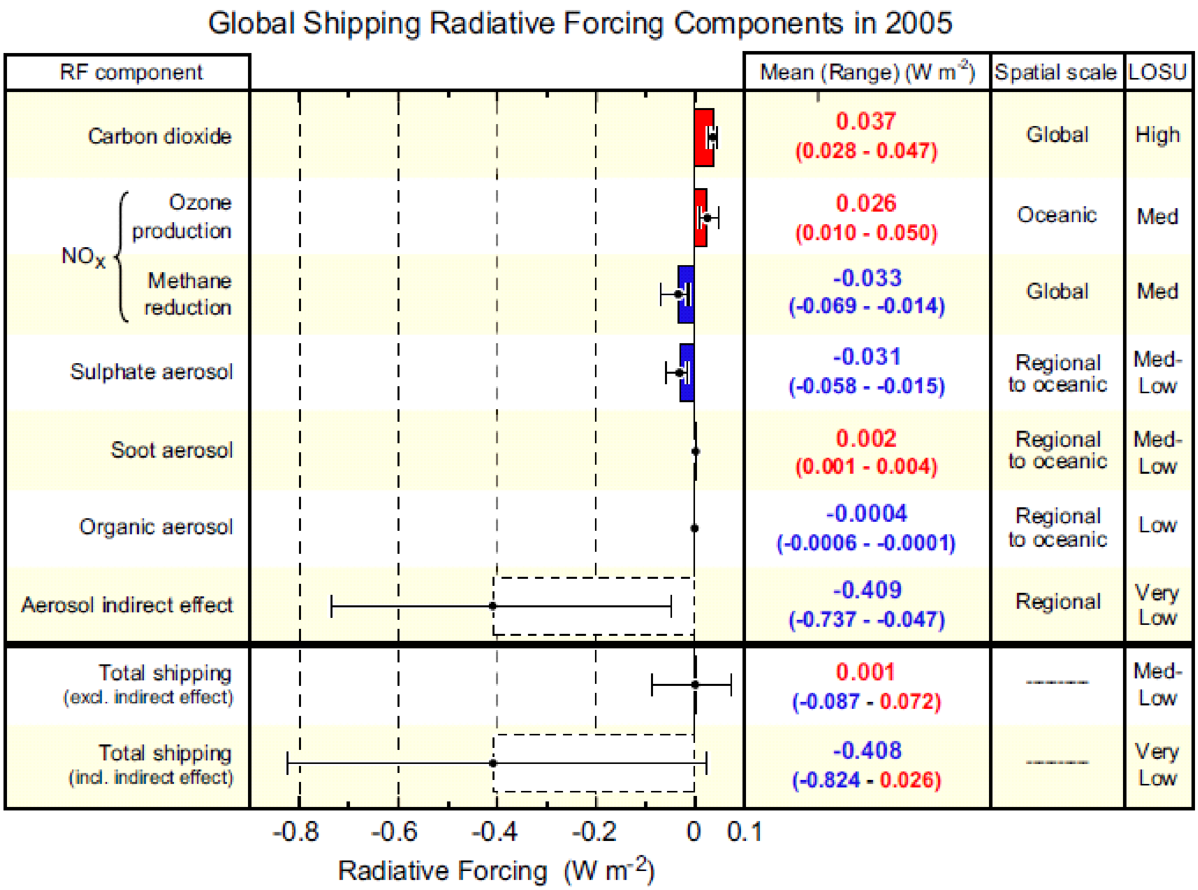


Figure 30: Global average annual mean radiative forcing (RF) and literature ranges due to emissions from oceangoing shipping in Wm^{-2} for 2000 (upper panel) and for 2005 (lower panel). The boxes show the mean of the lower and upper estimate reported in the literature and the whiskers show the range of literature values given by the highest and lowest estimate. The typical geographical extent (spatial scale) of the RF and the level of scientific understanding (LOSU) is given in addition. The RF contributions with very low LOSU are displayed in dashed lines. Source: Eyring at al., 2009

It has to be noted that because of the adoption of new standards to reduce NO_x emissions (cf. IMO, Annex IV of the Marpol Convention, and new EPA standards) and sulphur content of marine fuels, the present-day cooling effect of shipping due to altered clouds will probably be lowered in the future (Eyring et al., 2009).

Another important issue concerns the indirect climate effect due to the release of black carbon from ships exhaust gasses on snow. This impact is not taken into account in the previous evaluation of shipping climate impact (Figure 30) but this could be a potentially important warming effect.

Beside this, the localised negative RFs due to shipping results in potential change in the precipitation patterns (cf. altered properties of the clouds, Buhaug et al., 2009).

Finally, global warming could influence shipping climate impact due to the opening of Artic routes, which could reduce fuel consumption for several trips through the adoption of more direct routes on the one hand, but could enhance the disturbing effect of black carbon on snow on the other hand. Black carbon / soot deposition could futhermore become a great danger for the highly vulnerable environment of that area (Flanner et al., 2009 in Eyring et al., 2009).

2.8.5. Mitigation potential

Globally, adapted ship design could reduce energy consumption by 10 to 50% for new ships and improvements in ship operation could offer better energy efficiency for the whole fleet from 10 to 50%. The combined effect of both measures is expected to reach 25 to 75% reduction in CO_2 emissions compared to a BAU scenario. Some more challenging technological options are conceivable such as using wind and solar energies (on the longer term) or using alternative fuels (not so easy because loss of power expected). (Buhaug et al., 2009)

It has to be taken into account that reduction of NO_x and SO_x emissions in the following years due to new emission and fuel content standards will probably weaken the short- to medium-term cooling effect compared to former BAU scenario and that the mitigation effort of climate warming emissions will have to be even greater (Eyring et al., 2009).

However, despite these improvements, as it is the case for aviation, significant effort will be needed to stabilise the total climate impact from shipping and ongoing technological solutions will not be satisfactory to reach this goal alone (cf. otherwise by 2050 shipping emissions will reach 12 to 18% of the total permissible global CO_2 emissions in the WRE450 stabilisation scenario, Buhaug et al., 2009).

2.8.6. Policy options

IMO is sharply in favour of using two efficiency indexes in the climate policy measures to be applied to the maritime transport sector: the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operational Indicator (EEOI). The first one would be to be used essentially for new ships, while the second one takes into account operational improvements and could then be useful for the whole fleet. The sole cost-effective solutions to mitigate CO_2 emissions from the sector would be a mandatory limit on those indexes. However, EEDI concerns only new ships, which reduces its environmental effectiveness, and using EEOI is technically challenging to establish and update baselines and to set targets (Buhaug et al., 2009).

Two other instruments would be more practical, cost-effective and stronger incentives for better ship design and operational improvements: the Maritime Emission Trading Scheme (METS) and the International Compensation Fund for GHG Emissions from Ships (ICF) financed by a levy on marine bunkers. Concerning the ICF, IMO's report states that "part of the environmental effect of the ICF depends on decisions about the share of funds that will be spent on buying emission allowances from other sectors" (Buhaug et al., 2009).

At the EU level, the Commission is analysing the options to include the maritime transport sector into the EU-ETS, as it has already been the case for aviation, but the finalisation of the proposal takes much more time than expected.

2.8.7. Conclusions

International maritime transport climate impacts need to be tackled too and quite rapidly if we want to have a chance to fulfil the objective of the "stabilisation scenario" without putting disproportionate pressure on the other sectors.

Technical and operational options will indeed not be sufficient given the strong growth in activities. Market-based options have to be adopted to stabilise and reduce the climate impacts of the sector.

Besides, it has to be kept in mind that new standards on NO_x emissions and sulphur content of marine fuels will have an influence on the climate impacts of the sector. This has to be taken into account in the design of mitigation policy options and in the emission scenarios used for modelling future climate impacts.

Moreover, potential changes due to global warming could have a direct influence on the location of ship emissions (e.g. opening of Northern Sea Route, Artic more accessible, sea level rise, etc.) and makes worse indirect environmental and climate impacts of the sector: "*Increased air pollution and deposition in the Arctic is of particular concern because of the high vulnerability, and in the case of soot deposition as a climate feedback mechanism* (Flanner et al., 2007 in Eyring et al., 2009)." Soot deposition on snow covered areas modifies the solar radiation reflexion and absorption, causing a net warming effect.

In brief, modal shift in favour of the maritime transport will not solve the climate issue of transport if nothing is done to mitigate the climate impacts of this sector too.

3. POLICY SUPPORT

The policy support took place via different channels such as the "Ad hoc committee on bunker fuels – aviation and EU-ETS", many face-to-face contacts with members of the administration or European and International organisations, the participation to the Belgian stakeholders dialogue process and the thematic workshops organised by the research consortium.

3.1. Project scientific support to Belgian administrations

3.1.1. Ad hoc committee on bunker fuels

As experts, researchers of the ABC Impacts project participated on the "Ad hoc committee on bunker fuels – aviation and EU-ETS" meetings of the CCIEP – Greenhouse Effect working group where the Belgian as well as the Flemish point of view concerning the European emission trading system was prepared. Research teams have advised and informed the "Ad hoc committee" in due time and with a complete overview of all aspects related to the topic: statistics, economic and market aspects, emissions and technologies, climate impacts, scope of the proposal for Belgium, stakes of the different points to be discussed (e.g. : stake related to the adoption of a 5.700 kg or 20.000 kg limit, pros and cons of different benchmark methods and of member states' proposals, consequences related to the selection of a fixed weight per passenger, consequences related to the addition of a fixed number of kilometres to the great circle distance, consequences of creating a reserve, scientific explanation of non-CO_2 climate impacts, pros and cons of the introduction of a multiplier for non-CO_2 emissions, interconnections of the proposal with other on-going negotiations like the EU-ETS review or ICAO's work, leaving open the possibility to include non-CO_2 gases in a later step, etc.). Comments and remarks were also provided on scientific documentation supplied by the European Commission.

3.1.2. Vlaamse Milieu Maatschappij

Regular contacts with the Flemish Environmental Agency (Vlaamse Milieu Maatschappij), through to the users' committee and through informal meetings, have allowed synergies with people working on aviation emission inventories on daily basis. Moreover this allows validation of the used methodology to obtain a coherent and comparable output with the different actors in the country.

3.1.3. CEMAR

The project CEMAR, Connecting Employment and Mobility in Airport Regions, of the province of Flemish Brabant was supported with advice. It concerns a European project within the planning period of 2007 – 2013 in the program of Interreg IV B.

3.2. Project scientific support to international institutions

Some meetings and discussions were organized with members the DG Environment of the European Commission (in particular Philip Good and Rasa Sceponaviciute), as well as with P. Liese, member of the European Parliament. In particular there have been discussions on how to include non-CO_2 effects of aviation into the EU-ETS, and led to the publication of a note about a multiplier based on the GWP followed by a note that describes a variable multiplier (whose value depends on the actual climate impact of a flight) that might give an incentive to airlines to avoid areas where persistent contrails are formed.

Input to the Belgian submission for the governmental review process of the 4th assessment report (AR4) of the IPCC, for the three working groups reports as well as for the synthesis report. Related to aviation it has been suggested in figure SPM.2 in WG1 report, which is also included as figure 2.4 in the synthesis report, to specify linear contrails, as the raditatve forcing of AIC is not included in the associated graph (section 2.3.1 for details). Members of ASTR-UCL participated actively at the following plenaries: 10th session of WGI (29 January to 1 February 2007) in Paris, France ; 8th session of WGII (2-5 April 2007) in Brussels, Belgium ; 27th session of IPCC (12-17 November 2007) in Valencia, Spain. Researchers from the project also contributed to inform the EU delegation at the UNFCCC COP 14 (Poznan, 2008) on the issue of metrics.

3.3. Project scientific support to other stakeholders

Multiple exchanges, scientific support and co-operations occurred with NGO's and market actors (Belgocontrol, EBAA, ICAO, etc.) took place during the project (section 4.6). Besides, regular users' committees involving national and international stakeholders were organized in parallel with related workshops assessing specific sub-topics of the aviation and climate issue (section 4.4). The consortium was also asked as an expert/reviewer to provide comments and remarks concerning a document about aviation and climate change ("Les Limites du Ciel") published by Inter-Environnement Wallonie.

4. DISSEMINATION AND VALORISATION

Thanks to ABC Impacts, several researchers have been trained on the topic of climate impacts in general and those from the aviation sector in particular. Moreover, two PhD thesis directly related to the project will be defended soon.

Results and recommendations stated in this report, as well as complementary analyses, have been valorised and disseminated by the ABC research consortium to the scientific community and to Belgian stakeholders (administrations, NGOs, sector-based associations or companies), as well as to international institutions such as the EU, EBAA, Eurocontrol, ICAO, and the UNFCCC /IPCC through:

4.1. Participation to the ad hoc committee "bunker fuels – aviation and climate policy" meetings

See section 3.1 for more detail

4.2. Website

A project website has been set up (http://www.climate.be/abci) with a section open to every body and a secured section for the use of the research consortium (intranet).

The home page contents a description of the project and the tasks, as well as the announcement of new topics available on the website. The "Open Section" consists in a description of the research consortium, an extended glossary and various synthesis documents, the different project publications, interesting references and links on the topic of "aviation and climate change", and a page dedicated to calculation tools such as the JCM5 climate model developed by ASTR with a specific module dedicated to the aviation global climate impact.

4.3. Publications and participations to scientific colloquia/conferences

ABC Impacts researchers participated to numerous scientific meetings such as for example: Climate Change Congress, Copenhagen, Denmark (10/03/2009-12/03/2009) ; CLM Working Group meetings 2009, Langen, Germany, (13/03/2009) ; Fifth International Symposium on Non-CO2 Greenhouse Gases (NCGG-5) in Wageningen, The Netherlands, (30/06/2209 - 03/07/2009) ; Meteoclim: PhD Symposium 2009, Louvain-la-Neuve, Belgium (28/01/2009) (organized by Andrew Ferrone and one session chaired by Andrew Ferrone) ; ETTAP Environment and Transport in different contexts Conference 16-18 February 2009, Ghardaia ; Climate Change workshop at VITO, Mol, Belgium (15/10/2008) ; ECAC/EC conference: Meeting the environmental challenge, Geneva, Switzerland (28/10/2008 and 29/10/2008) ; Quantify summer school, Athens, Greece (10/09/2007 – 21/09/2007) ; First Belgium Meteoclim symposium, Leuven, Belgium (10/10/2007) ; First European Air and Space (CEAS) conference. Berlin (10-13 September 2007) ; BIVEC-GIBET Transport Research Day 2007 Rotterdam. 3rd April 2007 ; Conference, The Next 50 years in Transport, Christchurch New Zealand 25-27 July 2007 ; International Summer School: Aviation Weather and the Atmosphere, Braunschweig, Germany (21/08/2006 – 01/09/2006).

They provided also a lot of presentations and publications, which are detailed further in this report (chapter 5).

4.4. Users' committee meetings and related workshops

Beside the scientific support to decision-makers, the project has also benefited from the collaboration with users' committee members by being kept informed very quickly about all developments on the issue and about main stakeholders' positions. Users' committee members have transmitted interesting reports or information and have helped the research team to find contact persons within the aviation sector. Some points of view concerning flight data or emission calculations have been discussed more in detail in specific meetings with some members of the users' committee. Thanks to this committee, the ABC Impacts consortium was invited as expert to the "Ad hoc committee on bunker fuels – aviation and the EU-ETS" (section 4.1).

During the committee meetings, methodology, results and discussion points were presented and debated with the members. Different specific workshops took place in the meantime to analyse more in detail some topical issues such as voluntary offset programmes, non-CO_2 aviation climate impacts, etc. Minutes of the workshops and related presentations are at every one disposal on the ABC Impacts website (www.climate.be/abci - Open Section – Project publications).

4.5. Scientific popularization actions

Researchers and promoters participated to various scientific popularization actions such as round-tables, media actions or book reviewing.

4.5.1. Participation to roundtables

Researchers have participated in different events aiming at explaining the main stakes between aviation and climate change or climate policies. For example, in the context of the BEST (Board of European Students in Technology) Summer School on Aviation held in Brussels in July of 2007, a class of the students originating from a variety of European countries were taught on Aviation and Environment/Climate Change. At the round-tables "Commission nuisances aériennes" of the CdH (January 2007, Brussels), "Transport aérien et changement climatique" of IEW (November 2007, Namur) and "Conférence de Nouvel An: aviation et changement climatique" of Ecolo (January 2008, Grez-Doiceau), a synthesis of the topic was presented to representatives of political parties, NGOs, citizens, etc. ABC Impacts researchers took part to the debates after the presentations. On the Wetenschapsbeurs Lucerna college 2009 "Een beter milieu begint bij jezelf" (Brussels 8-9 May 2009), the ABC Impacts project was presented to some secondary school students to whom.the influence of air travel on climate was explained to.

On the "Nuit des chercheurs/Nacht van de onderzoekers 2007" (Brussels 28 September 2007), the ABC Impacts project was presented with a poster, while the general public could discuss the main focus of the project with the researchers.

4.5.2. Participation to media actions (radio or TV broadcasts, press articles)

ABC Impacts researchers and promoters co-operated / participated actively to different media scientific popularization actions (chapter 5, section 5.4 for more detail), and to the scientific reviewing of the document "Les limites du ciel" (Courbe P., 2008) that aims at explaining to citizen aviation climate impacts and main related stakes, as well as the position of the NGO on these topics.

4.6. Networking

4.6.1. Scientists working on emission or climate modelling

Concerning climate modelling, contacts were established with the CLM user group (especially with Andreas Will from BTU Cottbus and Burkhard Rockel from GKSS in Geesthacht, Germany). Moreover there have been contacts established with Ulrich Schumann at DLR and we are planning to broaden these contacts to other research at DLR. On the other side we have also contacts with a research group at CERFACS in Toulouse, lead by Daniel Cariolle, who are working on developing a parameterization of contrails to be used in climate models.

Contacts have been held with a member of the TREMOVE project (Bart Van Herbruggen, TMLeuven) in order to get a better understanding of this well-known transport and environment model. Other co-workers from TMLeuven whom the consortium has had some contacts with are: Griet De Ceuster, Kris Vanherle and Eef Delhaye.

4.6.2. European and Belgian administrations and NGOs

Regular contacts and meetings have taken place between ABC Impacts researchers and several European and Belgian administrations or NGOs (e.g. concerning the emission inventory, policy support and advice, information, etc.)

4.6.3. Sector-based associations

Very good relations have been established with Belgocontrol, Eurocontrol Headquarters and Eurocontrol Experimental Centre for obtaining the necessary data, getting access to the used forecasting models as well as to establish in joint cooperation with these actors a way to predict future emissions based on the combining of the market forecast models and the emission model Pagoda.

The research team held several meetings with colleagues from different departments from Eurocontrol (David Marsh, Brussels – Headquarters ; Frank Jelinek, Brétigny-sur-Orge - Experimental Center ; Patrick Tasker, Brussels – Headquarters ; Stefano Mancini, Brussels – Headquarters ; Ted Elliff, Brétigny-sur-Orge - Experimental Center ; Roger Jerram, Brétigny-sur-Orge – Experimental Center). The contacts with these different persons were useful to get access to the state-of-the-art emission factors, emission modelling tools and databases.

Frequent contacts were held with Mr. Guy Verluyten from the Belgian Air Traffic Management Services (Belgocontrol). This allowed obtaining an excellent overview of the aviation activities in Belgium, as well as the best possible insight in the overflights of the territory.

Some contacts with Mr. André Clodong (EBAA / Ecomundo) took place. In this context, some application to review Eurocontrol's data gathering methodology for the aviation part of the extended EU-ETS was submitted.

During the visit of the MOCA (section 4.3) in Montreal, Andrew Ferrone also visited the Environmental Unit of ICAO and presented the work done on regional climate model within the ABC Impacts project as well as the project itself to the persons present (the public was very interested in our findings in particular our discussions of the inclusion of non-CO_2 effects in an emissions trading scheme). It was also asked that the ABC Impacts consortium should have a look at the ICAO CO_2 emissions calculator and give suggestions how to improve it. Andrew Ferrone was invited to contribute to new environmental report of ICAO which is planned to be published.

5. PUBLICATIONS RELATED TO THE PROJECT

5.1. Peer reviewed articles/presentations/posters (scientific publications or colloquia)

Ferrone A., Marbaix P., Matthews B., van Ypersele J.-P. (2009), Regional climate modeling of aircraft induced cloudiness, oral presentation at the Fifth International Symposium on Non-CO_2 Greenhouse Gases (NCGG-5) in Wageningen, The Netherlands, June 30 to July 3, 2009

Ferrone A., Marbaix P., van Ypersele J.-P. (2009), Simulation of aircraft induced cloudiness in the regional climate model, oral or poster presentation at the 2nd International Conference on Transport, Atmosphere and Climate Aachen, Germany and Maastricht, The Netherlands, 22-25 June 2009.

Ferrone A., Marbaix P., van Ypersele J.-P., Lescroart R. (2009), Parameterization of aircraft induced cloudiness in the regional climate model CCLM, poster presentation at the MOCA 2009, Montreal, Canada, 19 – 24 June 2009.

Ferrone A., Marbaix P., Matthews B., Lescroart R., van Ypersele J.-P. (2009), A parameterization of aircraft induced cloudiness in the CLM regional climate model, oral presentation at the 2nd Lund Regional-scale Climate Modelling Workshop: 21st Century Challenges in Regional-scale Climate Modelling, Lund, Sweden, 4-8 May 2009.

Ferrone A., Marbaix P., Matthews B., van Ypersele J.-P., Lescroart R. (2009), Condensation trails in the regional climate model CCLM, poster presentation at the IARU International Scientific Congress on Climate Change, Copenhagen, Denmark, 10 – 12 March 2009.

Ferrone A., Marbaix P., Matthews B., van Ypersele J.-P., Lescroart R. (2009), Condensation trails in the regional climate model CCLM, poster presentation at the COSMO/CLM Seminar, Langen, Germany, 9 – 11 March 2009.

Ferrone A., van Ypersele J.-P. (2009), Aircraft induced cloudiness in the regional climate model CCLM, oral presentation at the Meteolclim PhD symposium 2009 at UCL in Louvain-la-Neuve, 28 January 2009

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Matheys J. (2010). Analysis of the CO2 and non-CO2 Climate Impacts of Aviation: Recommendations and Tools for Mitigation, Doctoral thesis, Vrije Universiteit Brussel, Brussels, Belgium.

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Matheys J., Boureima F-S., Sergeant N., Timmermans J-M., Van Mierlo J. (2009), The influence of the "de minimis" clause of the European Emissions Trading Scheme on CO_2 emissions of flights between developing countries and Belgium, Transportation Research Part A, (Submitted).

Matheys J., Rogolle C., Sergeant N., Timmermans J-M., Rombaut H., Van Mierlo J. (2008), Analysis and improvement of "The Last Mile" to and from the national airport as part of the mobility policy in the Brussels urban area, Conference on Urban Transport – Malta.

Festraets T., Macharis C., Matheys J., Van Mierlo J. (2007), Aviation and climate change in Belgium, Congress paper for the Next 50 years in transport, Christchurch, New-Zeeland, 25 to 27 July 2007, 25 p.

Festraets T., Macharis C., Matheys J., Van Mierlo J., Meyer S. (2007), Aviation and the Belgian climate policy: integration options and impacts, Congress paper for the Nectar Conference 2007, Porto, Portugal, 9 to 12 May 2007, 15 p

Festraets T., Matheys J., Macharis C., Van Mierlo J. (2007), Implications for short distance aviation in Europe induced by a restrictive government policy, Congress paper for the Transport Research Day 2007 of BIVEC – GIBET, Rotterdam, Nederland, 3 April 2007, pp. 433-454.

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Meyer S. (2006), Poster for the Transport and Environment Conference (INRETS, Reims 12-14/06/2006) and the TAC conference (Oxford 26-29/06/2006): http://dev.ulb.ac.be/ceese/ABC_Impacts/documents_abc/Poster.pdf

5.2. Other scientific publications / presentations

Ferrone A. and P. Marbaix (2009), A note on how to take into account the aircraft induced cloudiness in the EU-ETS. (Available on www.climate.be/abci - Open Section - Project publications - Notes to the stakeholders)

Ferrone A., J.-P. van Ypersele (2008), An overview of the significance of climate change and the importance of controlling emissions from all sectors including aviation, ECAC/EC conference : Meeting the environmental challenge, Geneva, Switzerland (28/10/2008), oral communication (note: Representing J.-P. van Ypersele for an opening IPCC presentation)

Matheys J., Festraets T. (2008), Co-authors of the focus report and the background documents of MIRA-T 2007 of the Flemish Government (Vlaamse Milieumaatschappij) for the part concerning Transportation (aviation).

Meyer S. (2008), *Aviation et changement climatique*, New Year conference of Ecolo on the 25th of January 2008, Grez-Doiceau.

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Matheys J. (2007), Teaching of the Aviation and Environment/Climate Change class on the BEST Summer School on Aviation, July 2007, Brussels.

Meyer S. (2007), *Perspectives du transport aérien: impacts environnementaux, évolution et réponses*, presentation at the Inter Environnement Wallonie round-table on the aviation and climate change, on the 20th of November 2007, Namur.

Meyer S. (2007), Presentation of the ABC Impacts project at the kick-off meeting organised by BELSPO on the 26th and 27th of March 2007.

Meyer S. (2007), *Aperçu des pollutions atmosphériques liées au transport aérien – Impacts climatiques*, presentation at the round-table "Commission Nuisances aériennes du CEPESS" on the 12th of January 2007, Brussels.

5.3. ABC Impacts publications

The following publications are available on the ABC Impacts website (www.climate.be/abci - Open Section - Project publications): Final report phase II (September 2010) and Final report phase I (April 2008) ; minutes and presentations of the three ABC workshops ; note on the inclusion of non-CO_2 effects of aviation in the ETS (August 2008) ; various synthetic documents for scientific popularisation of the project ; leaflet ABC Impacts (November 2006).

Members of the research consortium took part in different television/radio programmes or press articles on the topic of aviation and climate change: Le Vif / L'Express (14/05/10), participation du consortium à l'élaboration du Dossier spécial sur l'aviation ; Radio Contact (14/03/07), *Les infos (5.30PM ; 6.30PM)*, J. Matheys ; De Morgen (04/07/07), *Het cijfer : 2.800 ton CO_2-uitstoot ;* RTBF (21/08/06), *Journal Télévisé (1.30 PM)*, Pr. J-P. van Ypersele ; RTL-TVI (20/08/06), *Journal Télévisé (1 PM)*, Pr. J-P. van Ypersele ; De Standaard (19-20/08/06), *Vorsers gaan effect van luchtvaart op klimaat na ;* Le Soir (18/08/06), *Un nuage aérien qui inquiète.*

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Finally, we would like to underline our appreciation to all of the participants to the workshops and users' committees. They provided us with some priceless feed-back. The interaction with the participants has always been constructive and very instructive.

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