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Lower NO_x at Higher Altitudes

Policies to Reduce the Climate Impact of Aviation NO_x Emission

Report

Delft, October 2008

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Publication Data

Bibliographical data:
Jasper Faber, Dan Greenwood, David Lee, Michael Mann, Pablo Mendes de Leon, Dagmar Nelissen, Bethan Owen, Malcolm Ralph, John Tilston, André van Velzen, Gerdien van de Vreede
Lower NO_x at Higher Altitudes
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Aviation / Nitrogen oxide / Development / History / Science / Technology / Regulation

Publication number: 08.7536.32

CE Delft-publications are available from www.ce.nl.

Commissioned by: European Commission, DG Energy and Transport under contract TREN/07/F3/S07.78699.
Further information on this study can be obtained from the contact person Jasper Faber.

This report is printed on 100% recycled paper.

Preface

This report has been prepared for the European Commission, DG Energy and Transport under contract TREN/07/F3/S07.78699. Ronny Rohart was the responsible project officer.

During the project, the authors have benefitted from comments from stakeholders and experts. A full list is included in Appendix J. We express our gratitude to all the stakeholders who so generously gave their time, consideration and expert help. Any mistakes are, of course, only attributable to the authors.

The authors

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Short summary

This report sets out to design and evaluate policy instruments that address the climate impact of aviation NO_x emissions. It is well established scientifically that cruise NO_x emissions cause a significant part of the current total climate impact of aviation. At present, LTO NO_x emissions are controlled but cruise NO_x emissions are not, and they grow roughly at the same pace as air traffic.

After a review of the scientific literature, a comprehensive overview of NO_x formation and control technologies and the environmental trade-offs, and an elaborate policy analysis, this report concludes that it will take around three to five years to provide robust scientific input for potential policy instruments that are both well founded in scientific evidence and provide the right incentives to reduce emissions both in the short term and in the long term. The two main issues that will have to be resolved before such an instrument can be developed are:

- Establish a value for a policy-relevant metric for aviation NO_x climate impact, such as a GWP for NO_x.
- Either establish a way to model cruise NO_x emissions or quantify the relationship between LTO and cruise emissions in a sufficiently robust way.

Both issues should be capable of being resolved in three to five years, given sufficient study. In the meantime, the analysis perfomed for this report shows that the policy instruments that could be introduced would either have very limited environmental impacts but a solid scientific foundation, or a questionable scientific basis but a significant impact.

An **LTO NO_x charge**, introduced at European airports would primarily be a local air quality instrument, reducing NO_x emissions in the vicinity of airports. It would have a very small co-benefit on NO_x emissions at altitude. However, it may be perceived as an inequitable climate policy instrument, as the short haul flights that have a low contribution to the climate impact will pay most of the charge. It would be feasible to implement technically and legally.

An **LTO NO_x charge with a distance factor** would need a good policy instrument to reduce the climate impact of NO_x. Before it can be implemented, however, there needs to be a thorough assessment of the relationship between LTO and cruise emissions. A methodology already exists for the determination of this relationship but it is only applicable to current technology engines since it is empirical, and a more physically-based relationship would be required for this policy application so that future technologies could be robustly modelled. Moreover, it needs a well founded basis for the level of the charge, i.e. a value of the GWP of aviation NO_x. The legal basis for the instrument could be strengthened if international agreement could be reached on this value. New engine technology may lead to the breakdown of the existing relationship between LTO and cruise emissions. If this would occur, the environmental impacts of the charge could be reduced.

A **cruise NO_x charge** would be the best instrument to address cruise NO_x emissions, but it cannot be currently implemented since cruise NO_x emissions can neither be monitored nor modelled by a widely accepted method using publicly available data although manufacturers do possess the necessary information. Moreover, it needs a value for the GWP of NO_x.

Inclusion of **aviation NO_x emissions in the EU ETS** would need the determination of a method to calculate NO_x emissions. One obvious candidate for such a method would be based on the product of LTO NO_x emissions and distance. Moreover, the GWP of aviation NO_x would need to be established. The main advantage of this policy instrument would be that it would give the right incentive to minimise the combined climate impacts of CO_2 and NO_x emissions in engine design.

An **increased stringency of LTO NO_x standards** would reduce cruise NO_x emissions for future technology engines as long as the current relationship between LTO and cruise emissions holds. However, this is by no means a certainty. Standards have a solid legal basis. However, as they would need to be established internationally it is questionable whether the standards would meet EU expectations.

A **precautionary emissions multiplier** in the EU ETS could be readily implemented. Its legal basis would not differ much from the legal basis for the inclusion of aviation in the EU ETS. However, there is currently no scientific consensus for the value of an emissions multiplier, nor the method by which it is calculated. Furthermore, an emissions multiplier would increase the incentive to reduce CO_2 emissions, and since there is a potential trade-off between CO_2 and NO_x in future engine design, it may lead to NO_x emissions that are higher than they would have been without the multiplier. (Note that an emissions multiplier is not necessarily exclusively the most well known and discussed ‘multiplier’, the Radiative Forcing Index (RFI), which is in fact not an *emissions* multiplier at all.)

The **environmental impacts** of most economic instruments are comparable, i.e. in the range of reducing NO_x emissions by 3-5% relative to the baseline in 2020 if the levels of the charges reflect damage costs. The only exception is the LTO NO_x charge, which would have very small environmental impacts. Of course, the impacts of standards would depend on the stringency increase and the impacts of economic instruments would depend on the level of the charges imposed. Since most impacts of economic instruments on emissions arise from reduced demand rather than by technological changes, revenue neutral charges would have significantly lower impacts.

The **cost effectiveness** of all financial instruments is in the same range of € 1 to € 2 per kg of NO_x reduced. The main cost item here is welfare costs. In contrast, the main cost item of standards is resource costs. Therefore, the cost-effectiveness should not be directly compared. The cost-effectiveness of a 10% stringency increase would be € 10 - € 25 per kg of NO_x reduced, depending on the fuel penalty of meeting the standard.

Summary

This report sets out to design and evaluate policy instruments to address the climate impact of aviation NO_x emissions. It does so within the context of the proposal to include aviation in the EU ETS. In the proposal, the European Commission stated that 'by the end of 2008, the Commission will put forward a proposal to address the nitrogen oxide emissions from aviation after a thorough impact assessment'.

Before designing and evaluating policy instruments, this report has conducted a thorough review of the scientific evidence, NO_x formation and control technologies, and the regulatory framework regarding aviation NO_x emissions. This section summarises these reviews first before turning to the policy instrument design and evaluation.

Review of the scientific evidence

There is robust scientific evidence that NO_x emissions from the current aviation fleet contribute to global warming. Aviation NO_x emissions at cruise altitudes result in an enhancement of ozone (O_3) in the upper troposphere and lower stratosphere (UT/LS) and the destruction of a small amount of ambient methane (CH_4), of the order of approximately 1-2% of the background concentrations. The enhancement of O_3 results in climate warming, whereas the reduction in CH_4 is a cooling effect.

The contribution is significant and stronger in the northern hemisphere. Sausen et al. (2005) estimate the radiative forcing (a proxy measure of the additional amount of heat trapped in the atmosphere due to aviation - RF) for O_3 to be 21.9 mW/m^2 and an RF for CH_4 of -10.4 mW/m^2 for 2000 traffic. This estimate used updated emissions of NO_x from aviation for 2000. For comparison, CO_2 emissions from aviation have an RF of 25.3 mW/m^2 for 2000 traffic. Because O_3 has a much shorter lifetime than CH_4, the warming effects of O_3 are confined to areas with much aviation (i.e. the northern hemisphere) whereas the cooling effects of CH4 decay are global. As a result, the combined O_3+CH_4 forcing is positive in the Northern Hemisphere and negative in the Southern Hemisphere.

However, there is no agreement on the value of a policy-relevant metric to relate the climate impact of NO_x to the impact of other compounds. The RF metric used above to compare the climate impact of NO_x to CO_2 is a backward looking metric. It measures the forcing from the CO_2 built up in the atmosphere due to aviation emissions, for example. A policy-relevant metric is the global warming potential. This metric shows the integrated RF from a marginal additional emission of a unit mass of emissions (as a pulse) relative to that of CO_2. Thus, it is a measure for the *additional* global warming due to an *additional* emission. GWP is the measure used in the Kyoto Protocol to relate the climate impacts of regulated gases to the impact of CO_2. Although it is possible to calculate a GWP for aviation NO_x, results of these calculations are just beginning to be published in the scientific literature. Currently, there are few reported values and these diverge strongly.

A concerted effort may yield a GWP value of aviation NO_x in about three years. What is needed is a mobilisation of the international scientific community and a coordinated set of experiments performed so that a robust, consensus analysis of aviation NO_x GWPs can be undertaken. The outcome cannot be predicted of such a hypothetical study, but all things being equal, if such a study were performed, it is likely to take of the order 3 years. If, however, such a coordinated effort were to produce diverse results it is not possible to predict how long resolution would take. Clearly, such a coordinated experiment should be undertaken as a top priority to formulate a robust policy metric for aviation NO_x emissions.

Review of NO_x inventories and NO_x regulation.

Aviation emitted an estimated 1.7 to 2.5 Tg NO_x (as NO_2) per year around 2000. This report estimates that emissions within, and on flights to and from the EU accounted for 42% of these emissions in 2000.

Emissions are forecast to increase considerably in the future. Up to 2020, emissions are forecast to double relative to 2000 levels. By 2050, depending on the scenario chosen, emissions could have increased sixfold. If the environmental impacts of the inclusion of aviation in the EU ETS are taken into account, as well as the full benefits of the single European sky, and if one assumes that the voluntary research targets of ACARE are met and if they result in the introduction of new aircraft and engine types in the fleet, emissions could be 6 to 9% lower than the baseline in 2020. Under the same most optimistic scenario, emissions could be around 50% lower in 2050 relative to a sixfold increase in the baseline.

LTO NO_x emissions of jet engines are regulated and more stringent standards have been introduced repeatedly. LTO NO_x emissions of jet engines (with the exception of the smallest engines) are regulated by global standards, set by ICAO. Standards are expressed in Dp/Foo, i.e. mass of NO_x emitted per kN of thrust at maximum static sea level thrust. The standards allow engines with a higher pressure ratio (generally larger engines) to emit relatively more NO_x. Turboprops and other engine types are not regulated. All regulated engines have certified values of emissions which are public. For many non-regulated engines, LTO NO_x emission characteristics are known.

Despite more stringent LTO NO_x standards, there has been little progress in the reduction of NO_x emissions per seat kilometre offered. Although engines and aircraft differ in fuel efficiency and $EINO_x$ (mass of NO_x emissions per unit mass of fuel), and despite increasingly stringent standards, the general historical trend of NO_x emissions per seat kilometre has been flat in the last decades. The reason appears to be that aircraft and engines have become more fuel efficient, partially because of higher pressure and by-pass ratios in the engine. Because of the increase in pressure ratio, $EINO_x$ has increased as permitted under the ICAO standards. The combination of the downward trend in fuel use per seat kilometre and the upward trend in $EINO_x$ has resulted in an almost constant mass NO_x per seat kilometre.

Review of NO_x formation and control technologies

For current technology engines, lower LTO NO_x emissions result in lower NO_x emissions in cruise. More precisely, if the modification of an engine results in an LTO NO_x increase then it is expected that Cruise NO_x would move similarly. Likewise, if two engines are compared and one has lower LTO NO_x, then most probably it would also have lower cruise NO_x.

For future technology engines, the correspondence between LTO NO_x emissions and cruise NO_x emissions may break down. While today there is a reasonable correlation between LTO NO_x:Altitude NO_x future technologies such as lean burn staged combustors and open rotor engines hold the potential for significant change to this relationship. These future technologies will need to be monitored to ensure the relationship holds or is, if necessary, adjusted.

NO_x emissions cannot be monitored in situ but modelling of emissions is possible in principle. The method considered most accurate is the P3T3 method which relies on proprietary details of engine pressures and temperatures. There are also (at least) two alternative simplified methods which are commonly-used, known as the DLR and Boeing 2 fuel flow methods with the latter being approved by ICAO CAEP. These methods are thought to be reasonably accurate once the fuel flow is known and could in principle use openly available fuel flow model outputs. The accuracy of fuel flow model outputs is less widely accepted, particularly for new aircraft types.

There is a good correlation between modelled cruise NO_x emissions and LTO NO_x emissions times a distance factor. As a consequence, it could be possible in principle to use publicly available data on LTO NO_x emissions to approximate cruise NO_x emissions.

Policy instruments to reduce the climate impact of aviation NO_x emissions

Drawing on a long list of 15 policy options, six have been selected for further design and analysis after a broad evaluation and stakeholder consultation. These are:

1. An LTO NO_x charge.
2. An LTO NO_x charge with a distance factor.
3. A cruise NO_x charge.
4. Including aviation NO_x allowances in the EU ETS.
5. ICAO LTO NO_x emission standards.
6. A precautionary emissions multiplier on CO_2 allowances in the EU ETS.

1 An LTO NO_x charge

An LTO NO_x charge primarily targets local air quality. Its impact on cruise emissions and hence on the climate impact of aviation NO_x are a co-benefit. The basis of the charge would be the mass of standardised LTO NO_x emissions calculated according to ECAC/ERLIG method. The level of the charge per kg of NO_x would be set at the LAQ damage costs of NO_x, in line with established EU policy to internalise external costs, and would thus vary in different Member States. The charge would be levied on aircraft operators by all EU airports, in order to align the geographical scope with the scope of the EU ETS. Revenue neutrality, if desired, could be achieved by a simultaneous introduction of the charge and a reduction of landing fees. The charge would be collected by airport operators and would be levied on aircraft operators. The charge would be feasible to implement and is unlikely to raise legal issues, as similar charges are already levied on a number of EU airports.

An LTO NO_x charge based on estimates of LAQ damage costs would reduce aviation NO_x emissions by up to 0.5% relative to the baseline. At least until 2020, the largest impact would be from reduced demand. Consequently, a revenue neutral charge would hardly impact emissions. Emissions on short haul flights would be reduced more than emissions on long haul flights, even though the latter contribute considerably more to climate change.

An LTO NO_x charge would incentivise engine manufacturers to reduce LTO NO_x emissions. This incentive would be stronger for smaller engines which are generally fitted to regional or single aisle aircraft. In the long run, provided that for smaller engines the correspondence between LTO NO_x emissions and cruise NO_x emissions remains intact, this incentive could result in new engines and aircraft with lower LTO and cruise NO_x emissions.

2 LTO NO_x charge with a distance factor

An LTO NO_x charge with a distance factor would target cruise NO_x emissions and hence its climate impact indirectly. This is because there is a correlation between cruise NO_x and LTO NO_x times distance. The basis for the charge would be the mass of LTO NO_x emissions calculated according to ECAC/ERLIG method and the great circle distance between the airport of departure and the airport of destination. The level of the charge would be related to the climate damage costs of NO_x, taken to be the GWP of NO_x times the average cost of emission allowances in the EU ETS. The charge would be multiplied by a co-efficient of correlation between LTO NO_x times distance and cruise NO_x. This factor depends on the fleet and would need to be updated every number of years. It can be calculated with relative ease, provided that a dedicated workgroup is established.

The administration of such a charge could be entrusted to EUROCONTROL, as this organisation has the arrangements in place to calculate the charge and bill the aircraft operators. These are the same arrangements as for the collection of route charges. In this case, the collection of the charges would need to be based on a separate legal basis, e.g. a new agreement between the EU and EUROCONTROL. If the charge would raise revenue, EUROCONTROL could reimburse the funds raised to the EU Member States based on, for example, revenue tonne kilometres to and from airports in these Member States. If the charge would be implemented in a revenue neutral way, EUROCONTROL could reimburse the revenue on the basis of MTOW.km. Effectively, the charge would thus become an incentive to reduce the quotient of mass of LTO NO_x per unit of MTOW.

An LTO NO_x charge with a distance factor could reduce aviation NO_x emissions by up to 3.1% in 2020. The impacts vary from 0% for a revenue neutral charge or a charge with a low estimate of NO_x GWP to 3.1% for a revenue raising charge using a high estimate of NO_x GWP. At this timeframe, the impacts are mainly due to a reduction in demand. In contrast to the LTO NO_x charge without a distance factor, the charge with a distance factor reduces NO_x on long haul flights more than NO_x on short and medium haul flights. This is because the combined effect of higher emissions for large aircraft and longer flights.

As with an LTO NO_x charge, this charge would incentivise engine manufacturers to reduce LTO NO_x emissions. In this case, this incentive would be stronger for larger engines. In the long run, provided that the correspondence between LTO NO_x emissions and cruise NO_x emissions remains intact, this incentive could result in new engines and aircraft with lower LTO and cruise NO_x emissions.

3 Cruise NO_x charge

A cruise NO_x charge would be directly aimed at cruise NO_x emissions and thus the climate impact of aviation NO_x. However this advantage is partly lost because cruise emissions cannot be measured in situ and need to be modelled.

Implementation of a cruise NO_x charge would require building a database to calculate cruise NO_x emissions per aircraft-engine combination and flight distance. The accuracy of calculations using publicly available data would be 10 to 15% when compared to more sophisticated calculations using proprietary data. With these calculations, a database could be established with cruise NO_x emissions per aircraft type over a range of distances. Each flight under the system could be assigned with a value of NO_x emissions from the database. A charge could be levied based on the emissions and their climate damage costs.

The administration of a cruise NO_x charge could be organised in the same way as an LTO NO_x charge with a distance factor. EUROCONTROL could be charged with collecting the charges and possibly reimbursing them in a revenue neutral scheme along the same lines as an LTO NO_x charge with a distance factor.

A cruise NO_x charge could reduce aviation NO_x emissions by up to 2.8% in 2020. The impacts vary from 0% for a revenue neutral charge or a charge with a low estimate of NO_x GWP to 2.8% for a revenue raising charge using a high estimate of NO_x GWP. At this timeframe, the impacts are mainly due to a reduction in demand. The cruise charge reduces NO_x on long haul flights more than NO_x on short and medium haul flights. This is because the combined effect of higher emissions for large aircraft and longer flights.

In contrast to LTO NO_x charges, this charge would incentivise engine manufacturers to reduce cruise NO_x emissions. As the charge is directly based on cruise emissions (assuming that these can be calculated accurately), the cruise NO_x charge would have the same environmental impacts whether or not the current the correspondence between LTO NO_x emissions and cruise NO_x emissions remains intact.

4 Including NO_x allowances in the EU ETS

Requiring aircraft operators to surrender NO_x allowances in the EU ETS for their emissions would target cruise NO_x emissions and hence its climate impact indirectly. The amount of NO_x for which allowances have to be surrendered can be calculated for each flight with the same formula as the LTO NO_x charge with a distance factor. The value of NO_x allowances would be related to the value of CO_2 allowances by the GWP of NO_x. In this way, there would be full fungibility between aviation NO_x allowances and aviation CO_2 allowances.

The administration of the inclusion of aviation NO_x emissions in the EU ETS would be identical to the administration of the inclusion of aviation CO_2 emissions. The only additional requirement would be the establishment of a baseline. A historical baseline can be calculated for every year for which detailed flight data are available, using the same formula that will be established for calculating NO_x emissions of flights.

Inclusion of aviation NO_x emissions in the EU ETS could reduce aviation NO_x emissions by up to 2.8% in 2020. The impacts depend on the allocation method. With full auctioning, the environmental impact would be highest; with updated benchmarking, it could be considerably lower depending on the baseline and emission growth.

As with LTO NO_x charges with a distance factor or cruise NO_x charges, inclusion in the EU ETS would incentivise engine manufacturers to reduce cruise NO_x emissions. The risk of a negative design trade-off between CO_2 and NO_x emissions would be absent, as the value of reducing emissions for both is related by their climate impact as expressed in GWP.

5 ICAO LTO NO_x emission standards

ICAO LTO NO_x emission standards have been the predominant instrument to reduce LTO NO_x emissions for decades. ICAO has regulated LTO NO_x of large jet engines since 1986. Standards have been progressively tightened, about every 6 years since the mid 1990's; the most recent standards became effective as of 1 January 2008. An EU NO_x standard could in principle be implemented and enforced by EASA, but there is a serious risk of competition distortions in the event of an EU standard exceeding ICAO standards.

The relation between LTO NO_x standards and cruise emissions is complex. Although there is a correlation between LTO NO_x and cruise NO_x for current engines, increased stringencies have not reduced cruise emissions per seat kilometre. The main reason is that standards allow engines with higher pressure ratios to emit more NO_x per unit of thrust. Engines with higher pressure ratios have better fuel efficiency performance, so there have been strong incentives to increase pressure ratios, resulting in higher absolute NO_x emissions. Furthermore, for new engine technologies, the current relation between LTO NO_x and cruise NO_x may break down. This would render LTO NO_x emission standards an unsuitable instrument to control the climate impact of aviation NO_x emissions in the absence of continuous review.

Depending on the level to be agreed by international consensus in CAEP, increased stringency of standards could reduce aviation NO_x emissions by 2.3 to 5.2% in 2020. These results are based on the assumption that the current relation between LTO and cruise emissions remains intact. Of course, the impacts depend on the outcome of international political negotiation processes.

6 Precautionary emissions multiplier

A robust value for an emissions multiplier cannot be proposed, based on the current scientific evidence. A commonly proposed metric to base the multiplier on, RFI, is unsuitable as it is a backward looking metric and does not assess the climate impact of an additional amount of emissions.

A precautionary emissions multiplier would give the wrong incentive to technological development without some signal of an intended future revision that addresses NO_x directly. In engine design, there is a trade-off between CO_2 and NO_x. Therefore, increasing the incentive to reduce CO_2 emissions may lead to NO_x emissions that are higher than they would have been without the multiplier. Of course, this would only result in higher NO_x emissions in the long run as new engines are introduced into the fleet.

A precautionary emissions multiplier can be readily implemented, as it shares most of the design features of the inclusion of aviation in the EU ETS.

The precautionary emissions multiplier could reduce aviation NO_x emissions by 4.7% in 2020 maximally. The impacts vary from 0.3% for an emission multiplier of 1.1 to 4.7% for a value of 2.0. The impacts are mainly due to a reduction in demand and to a further reduction of fuel burn.

Overall conclusion

In conclusion, this report demonstrates that it will take three to five years to design policy instruments that are both well founded in scientific evidence and provide the right incentives to reduce emissions both in the short term and in the long term. The two main issues that will have to be resolved before such an instrument can be developed are:

- Establish a value for a policy-relevant metric for aviation NO_x climate impact, such as a GWP for NO_x.
- Either establish a way to model cruise NO_x emissions or establish the correlation coefficient between LTO and cruise emissions.

Both issues should be capable of being resolved in three to five years. In the meantime, the policy instruments that could be introduced would either have very limited environmental impacts but a solid scientific foundation, or a questionable scientific basis but a significant impact.

1 Introduction

1.1 Background to this study

In December 2006, the European Commission published a proposal to ‘include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community’ (COM2006(818)final). According to this proposal, aircraft operators will have to surrender CO_2 emission allowances for each tonne of CO_2 they emit within the scope of the system. If this proposal is adopted, aircraft operators would have an incentive to reduce CO_2 emissions on top of the incentive to reduce fuel burn exercised by the costs of fuel.

It is well understood that the climate impacts of aviation are not caused by CO_2 alone (IPCC, 1999). NO_x emissions have an indirect impact as they lead to the formation of ozone, which is a greenhouse gas, and the destruction of a small amount of ambient methane, also a greenhouse gas. The overall result is that more heat is kept in the atmosphere, contributing to global warming. For this reason, the Commission is considering policy measures aimed at a further reduction of NO_x emissions.

Moreover, in engine design, there may be a trade-off between CO_2 and NO_x emissions. Within limits, an engine can provide a certain thrust with lower fuel burn (lower CO_2 emissions) but higher NO_x emissions, or vice versa. As CO_2 emissions will become more costly to the customers of engine manufacturers because of aviation’s inclusion in the EU ETS, they could respond by aiming their research even more towards fuel efficiency. Some of the gains in fuel efficiency could perhaps be made at the expense of higher NO_x emissions. If this would be the case, the inclusion of aviation’s CO_2 in the EU ETS therefore carries the risk that reductions in CO_2 emissions will be partially offset by higher NO_x emissions.

One of the ways to prevent a negative trade-off from occurring would be to incentivise engine manufacturers or aircraft operators to lower NO_x emissions of engines. This can be done in a number of ways, using economic or regulatory instruments, by subsidising research, et cetera.

It is for this reason that the Commission has announced in its proposal that ‘by the end of 2008, the Commission will put forward a proposal to address the nitrogen oxide emissions from aviation after a thorough impact assessment’.

To prepare for this proposal and the impact assessment, the Commission retained the services of a consortium led by CE Delft to study to identify and evaluate European measures to reduce emissions of nitrogen oxides from aircraft. The current document is the final report of this study.

1.2 Policy Background

Although there is currently no policy that addresses the *climate impact* of aviation NO_x emissions, policies exist with regard to NO_x emissions during the landing and take-off (LTO) phase of flight, and their related local air quality impact. Section 1.2.1 summarises EU policy within the ICAO/CAEP framework and Section 1.2.2 describes EU policy with regards to local air quality and climate.

1.2.1 ICAO

It is broadly Community policy to work within the ICAO/CAEP[1] framework wherever possible.

Since 1986, ICAO policy and action in the field of NO_x has focussed upon stringency - setting certification standards for LTO NO_x applicable to engines newly certificated after (future) implementation dates. Current standards, the so-called CAEP/6 standards, apply to engines for which type certification is issued from 2008. CAEP/8 is currently discussing whether the standards would be set at more stringent levels in the future.

ICAO also gives considerable attention to keeping medium and long term technology goals under expert review, and established the (LTO) Exhaust Emissions Data Bank maintained by the UK CAA. Formal ICAO guidance has been issued on operational opportunities for aircraft operators to minimise fuel use and reduce GHG emissions. Indeed CAEP has looked at all the categories of flanking approaches complementing stringency (research-oriented, voluntary, operational and economic), which are developed in this report.

Overall, therefore, although work within ICAO has brought increasing NO_x stringency and this may well continue, the European Community has noted that these measures in themselves are insufficient to offset the growth of the environmental impact of air transport, both historically and forecast.

1.2.2 European Commission

The Commission has legislated on local air quality (LAQ), Directive 1999/30/EC[2] being particularly relevant in this context, as it has spurred several airports in Europe to impose LTO related charges as elements of holistic action plans to improve LAQ. In 2008, the EU has adopted a new directive on air quality, 2008/50/EC[3].

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[1] International Civil Aviation Organization/Committee on Aviation Environmental Protection.

[2] Council Directive 1999/30/EC of 22 April 1999 relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air.

[3] DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on ambient air quality and cleaner air for Europe.

At the cruise level, the Commission declared unequivocally in 2005[4] that despite the complex contrariness of the climatic effects of NO_x (ozone production and methane reduction) 'the net result is that the ozone dominates the methane effect, thus warming the Earth'. That Communication went on to recognise the need to study potential trade-offs between CO_2 and other emissions. It also suggested that once aviation were brought into the EU ETS[5] either a multiplier would have to be employed to allow for non-CO_2 emissions, or ancillary instruments (such as NO_x related airport charges) would be needed.

The current Proposal[6] to bring aviation into the EU ETS from 2011 or 2012 is limited to CO_2 emissions but provides that 'to address other gases, by the end of 2008, the Commission will put forward a proposal to address the nitrogen oxide emissions from aviation after a thorough impact assessment'. This study was commissioned to contribute to that assessment.

1.3 Outline of the study

This study comprises seven, partially overlapping stages (see Figure 1). The first two stages reviewed current and future NO_x emissions and measures currently being taken or planned to limit them, while at the same time identifying options for further measures that the EU could take. The review was mostly be based on existing literature. The identification of further measures involved extensive stakeholder consultation.

Based on the review, and on the experience of the consortium members, with input from stakeholders, all the options identified in the second stage were broadly evaluated in terms of costs, benefits and legal situation. Based on this evaluation, the consultants selected five policies for further design and study in agreement with the Commission.

The consultants have designed the five selected options and evaluated their cost-effectiveness, the advantages and disadvantages. As part of this process, the legal situation of each option has been thoroughly analysed.

Stage seven concludes the project by compiling the results of the project in a final report.

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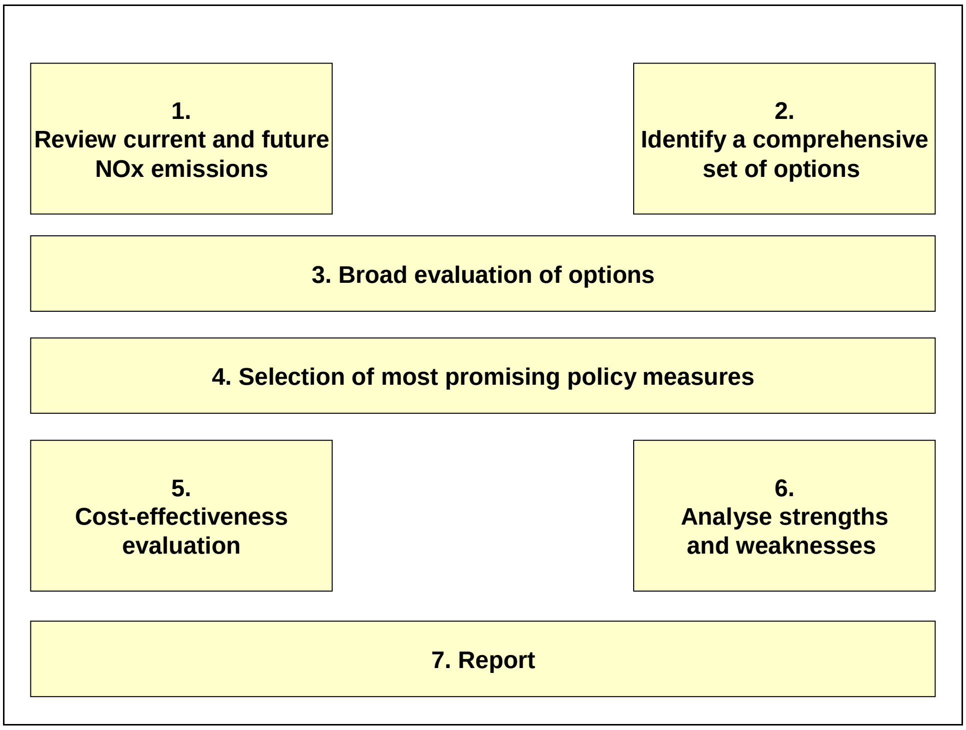
[4] Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions : Reducing the climate change impact of aviation (COM/2005/0459 final).

[5] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowances trading within the Community and amending Council Directive 96/61/EC. Directive 2003/87/EC was in turn amended by Directive 2004/101/EC to incorporate Kyoto mechanisms.

[6] Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community (COM/2006/0818 final, and subsequent documentation chronicling the continuing progress of the Proposal at htp://ec.europa.eu/environment/climat/aviation_en.htm.

Figure 1 Graphic presentation of project execution



1.4 Outline of the report

This report comprises a concise main report and a large number of Appendices with more detail. The main report sets out to define the problem of the climate impact of aviation's NO_x emissions in Chapter 2. Chapter 3 discusses possible policy objectives. The scientific evidence of the climate impact of NO_x is summarized in Chapter 4 and the relevant engine technology issues in Chapter 5. The selection and design of policy instruments to meet these objectives are in Chapter 6. Chapter 7 evaluates the policy options, and Chapter 8 compares them with each other. Conclusions are in Chapter 9.

The report has nine Appendices. Appendix A reviews current and future NO_x emissions and develops a baseline for the assessment of stringency options. Appendix B elaborates on the selection of policy options as summarized in Chapter 6, while Appendix C elaborates on the design of the selected options. Appendices D and E analyse the impacts of market based instruments and standards respectively. A legal analysis is presented in Appendix F. Appendix G is on the route charges collected by Eurcontrol, while Appendix H presents an analysis of the coefficient of correlation between LTO NO_x and cruise NO_x emissions. Finally, Appendix J describes the stakeholder consultation process.

2 Problem definition

2.1 What is the issue or problem that may require action?

The climate impact of aviation is caused by a range of emissions and physical disturbances of the atmosphere (IPCC, 1999; Sausen et al., 2005). One of the main climate impacts in terms of radiative forcing (RF) is caused by emissions of nitrogen oxides (NO_x).

Aviation NO_x emissions lead to the formation of ozone, which is a greenhouse gas, and the destruction of a small amount of ambient methane, also a greenhouse gas. The overall result is that to date, more heat is kept in the atmosphere, contributing to global warming. Whilst the global mean forcings from aviation NO_x-impacted ozone and methane appear to partially cancel, such a simple conclusion is not valid (IPCC, 1999). There is evidence that suggests that an imbalanced forcing from ozone at altitude in the northern hemisphere may result in greater warming than if that same forcing had been distributed across both hemispheres, a pattern which mirrors the the distribution of aviation NO_x emissions.

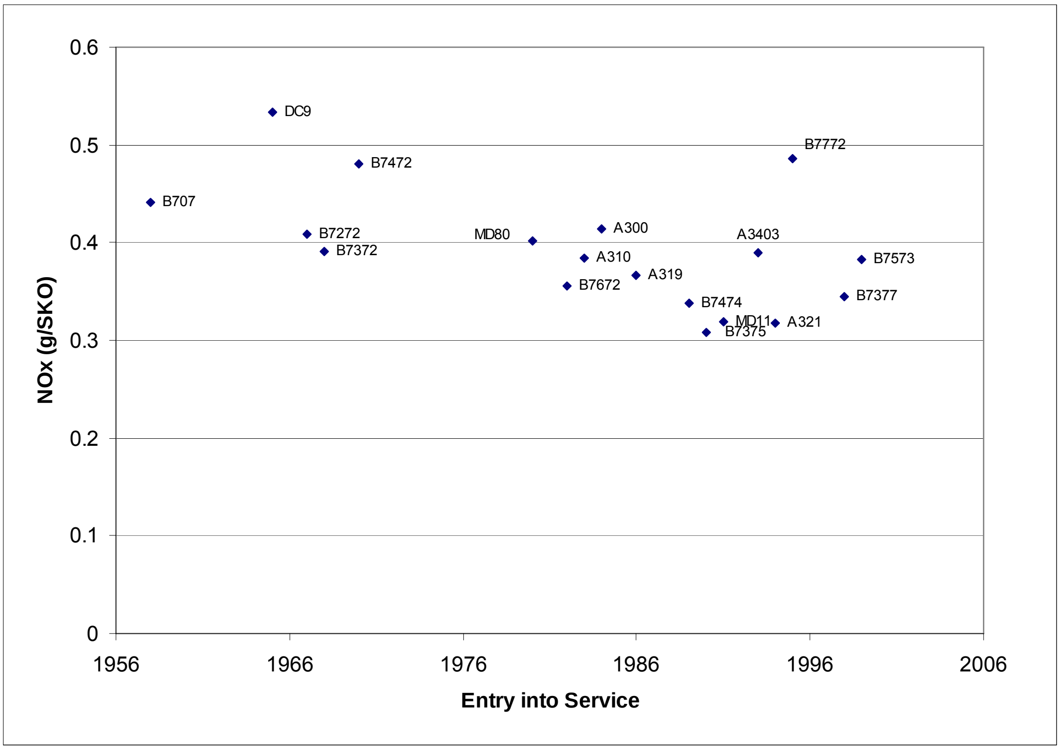
Sausen et al. (2005) estimated the positive RF of NO_x induced ozone to be 21.9 mW/m^2 and the resulting negative methane forcing to be -10.4 mW/m^2.

2.2 What are the underlying drivers of the problem?

The main driver of the increase in the climate impact of aviation NO_x emissions is the growth of aviation activity.

In recent decades, there have been significant improvements to aircraft engines, resulting in lower emissions of NO_x per unit of thrust at constant pressure ratios. These improvements have in part been driven by the expectation of increasingly stringent standards for NO_x emissions in the LTO phase. ICAO has repeatedly set tighter standards since 1986. Since for current engine and combustor designs a reduction in LTO NO_x corresponds to a reduction in cruise NO_x, total NO_x emissions have decreased, relative to a situation without standards or technological advances in NO_x emissions. However, due to the metric in which the standards are expressed and due to the strong commercial pressure to improve fuel efficiency of engines, pressure ratios have indeed increased. This increase has offset some of the technological gains and resulted in a rather flat historical trend in NO_x emissions per SKO, as can be seen from Figure 2.

Figure 2 Historical trend of NO_x emissions per seat kilometre offered (SKO) versus year of entry into service (EIS)



Source: Appendix A.

Furthermore, new engine and combustor designs may lead to the breakdown of the relationship between LTO NO_x emissions and cruise NO_x emissions (ICAO, 2007). If these designs are incorporated in the fleet, total cruise NO_x emissions may go either way despite increases in stringency for LTO NO_x emissions.

In engine design, there is a fundamental physical trade-off between fuel efficiency (and hence CO_2 emissions) and NO_x emissions. This is because increasing pressure ratios result in higher temperatures and pressures at the combustor inlet, making NO_x formation more optimal. With current high fuel prices and the forthcoming inclusion of aviation in the EU ETS there is an even higher incentive to reduce fuel burn and CO_2 emissions. This may incentivise the exploitation of the $NO_x : CO_2$ trade-off in new engines.

2.3 How would the problem evolve, all things being equal?

As demand for aviation is forecast to rise in the next decades, aviation's emissions of NO_x will increase and so will the climate impact of NO_x emissions. This report's forecast, based on the FESG2002 scenario, are that emissions on flights to and from the EU will have doubled in 2020 relative to 2000 levels. By 2050, depending on the scenario chosen, emissions could have increased sixfold. These forecasts assume that all new aircraft that enter the fleet from 2008 comply with CAEP 6 standards. All other assumptions are based on FESG demand and fleet rollover forecasts.

In reality, there are some developments that could limit the growth in aviation NO_x emissions relative to the baseline:

- The inclusion of aviation in the EU ETS is expected to induce a reduction in demand relative to the baseline. This report estimates that the impact of ETS in 2020 will amount to a reduction in NO_x of 2.5 to 4.9% in 2020 depending on the price of allowances (€ 20 - € 40) and under the assumption that either all allowances are auctioned or all costs are passed on to consumers (see Appendix D).
- The implementation of the Single European Sky (SES) will reduce detours from optimal flight tracks. In line with the Impact Assessment for the Inclusion of Aviation in the EU ETS (CE, 2007)[7], this report assumes that detours on flights to and from EU airports will reduce by 7% in 2020[8]. Reductions in NO_x emissions will then be roughly proportional. However, aviation being a competitive industry, cost reductions that would be achieved as a result of SES would be passed on to customers and the lower prices would induce an increase in demand. This report estimates that 30 to 40% of the environmental gains of SES could be offset by increased demand (see Appendix D).
- Engine and airframe manufacturers are aiming their research towards goals that would significantly reduce LTO NO_x. In Europe, research goals have been stated by the Advisory Council for Aeronautics Research in Europe (ACARE). On a global scale, CAEP has adopted the conclusion that the leading edge of LTO NO_x control technologies is likely to lie about 45% below current (CAEP/6) standards by the year 2016 and at about 60% below in 2026. All these goals are non-binding research targets. If these goals were to be met, and if the technology also proved to be commercially viable, aircraft with significantly lower LTO NO_x emissions would gradually be introduced into the fleet. If these goals were met with technologies that would not only reduce LTO NO_x emissions but also cruise NO_x emissions - an assumption that is by no means certain - then adoption would result in a decrease in aviation NO_x emissions. However, since the number of new aircraft that meet these goals in 2020 will be limited, and the number of these aircraft in the fleet will be even smaller, no significant gains from these developments can be expected in 2020. By 2050, gains would maximally amount to 50%.

Emission forecasts are presented graphically in Figure 3.

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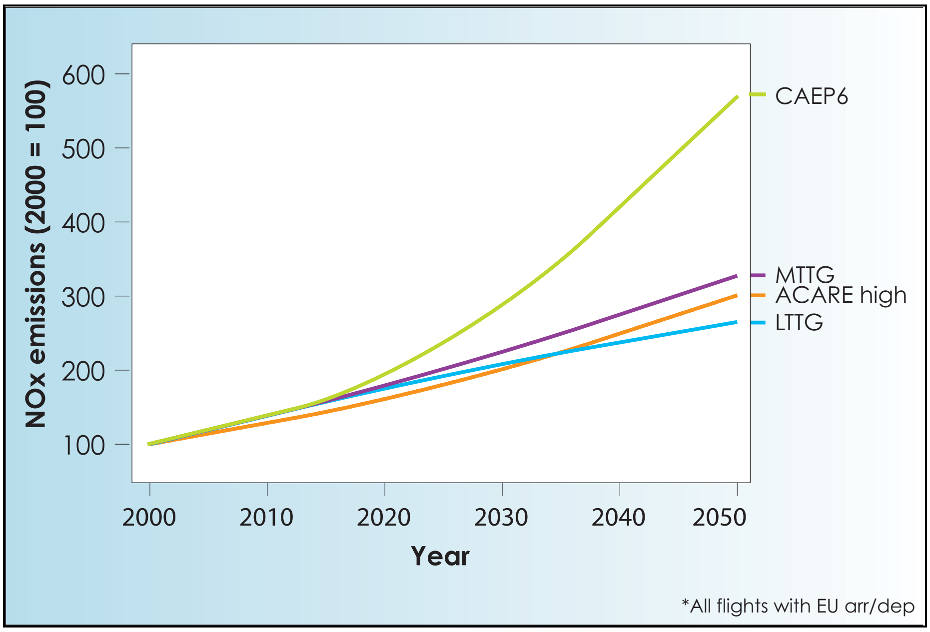
[7] Technical Assistance for the IA of inclusion of aviation in the EU ETS. CE et al., January 2007.

[8] *SESAR Definition Phase - Milestone Deliverable 5* mentions a 10% reduction in fuel use per flight due to ATM improvements (SESAR Consortium, 2008). The document is not clear on the geographical scope of this achievement. However, it is likely that the geographical scope is the European airspace. If so, the 7% on all flights as assumed in the Impact Assessment for the Inclusion of Aviation in the EU ETS (CE, 2007) and in this report is probably an overestimate.

Figure 3 Forecast emissions under various technology scenarios



Source: Appendix A.

In summary, assuming the maximum environmental impacts of ETS, SES and CAEP Long Term Technology Goals (LTTG), emissions in 2020 could be up to 9-12% lower than the baseline without any policies which predicts a doubling over 2000 levels. However, if cost decreases associated with SES would be passed on, emissions would be reduced by 6-9% relative to the baseline. By 2050, emissions could be limited to a threefold rise in 2050 relative to a sixfold increase in the baseline. However, if the voluntary goals would not be met, or if some of the technologies would not prove to be commercially viable, or if they would not result in corresponding decreases in cruise NO_x, these gains would not be made.

3 Objectives

The proposal to include aviation in the EU ETS (COM(2006)818) contains the following preamble, which is the basis for the present study:

> Aviation has an impact on the global climate through releases of carbon dioxide, nitrogen oxides, water vapour and sulphate and soot particles. The Intergovernmental Panel on Climate Change has estimated that the total impact of aviation currently is two to four times higher than the effect of its past carbon dioxide emissions alone. Recent Community research indicates that the total impact of aviation could be around two times higher than the impact of carbon dioxide alone. However, none of these estimates takes into account the highly uncertain cirrus cloud effects. In accordance with Article 174(2) of the Treaty, Community environment policy must be based on the precautionary principle and therefore all impacts of aviation should be addressed to the extent possible. Pending scientific progress to identify suitable metrics for comparing the different impacts, a pragmatic and precautionary approach is required. Emissions of nitrogen oxides will be addressed in other legislation to be presented by the Commission (Preamble 12).

The summary preceding the proposal states that:

> To address other gases, by the end of 2008, the Commission will put forward a proposal to address the nitrogen oxide emissions from aviation after a thorough impact assessment.

NO_x emissions have impacts on both local air quality and climate. The above quotation from the proposal indicates that the climate impacts are relevant here.

It is also clear that the policy should ‘address’ emissions of nitrogen oxide. This, of course, could mean several things:

- First, one could argue that ‘addressing’ aviation NO_x emissions simply means to limit or reduce the emissions. Since the preamble specifically refers to ‘other legislation to be presented by the Commission’, we take this to mean limiting or reducing NO_x emissions relative to a baseline that includes the policies already being implemented or already being incorporated in legislation.
- Second, since the Green Paper on fair and efficient pricing (1995), and the White Paper on efficient use of Infrastructure, the European Transport Policy 2010 (2001), it is a stated aim of EU policy to internalise the external costs of transport. This has been restated in EC overall transport strategy (Time to decide, 2001) and the midterm review (Keep Europe moving, 2006). A policy that addresses NO_x emissions could therefore have the objective to internalise the external costs of aviation NO_x emissions, or put differently, internalise the climate damage caused by aviation NO_x emissions.

- Third, in the stakeholder consultations prior to the formulation of the proposal to include aviation in the EU ETS, attention has been given to policies to address the non-CO_2 climate impacts of aviation (EC, 2006[9]). One of the arguments that many stakeholders used against using a multiplier was that in engine design, there is a trade-off between CO_2 and NO_x emissions. A policy instrument that just targets CO_2 may run the risk of causing the exploitation of this trade-off to the extent that the climate impact of aviation deteriorates. This argument could be used to define the objective of the policy as to limit the growth rate of NO_x emissions to the growth rate of CO_2 emissions after the inclusion of aviation in the EU ETS. In technical terms, the aim of the policy would be to ensure that the emission index of NO_x ($EINO_x$, the mass of NO_x emitted per unit of mass of fuel burned) will not increase.

For the purpose of this report, we have chosen to evaluate the policy proposals on the basis of the objective being defined as to limit or reduce the mass of aviation NO_x emissions relative to a baseline that includes policies already being implemented or legislated.

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[9] European Climate Change Programme II (ECCP II), Aviation Working Group, Final report, 2006.

4 Climate impacts of aviation NO_x emissions

4.1 Introduction

Global aviation emissions of NO_x amounted to approximately 2 to 2.5 Tg (NO_x as NO_2) per year in 2000, according to various estimates (Gauss et al., 2006; Eyers et al., 2005; Kim et al., 2007).
According to the IPCC (1999) report, '*Aviation and the Global Atmosphere*', and many other studies, aviation NO_x emissions at cruise altitudes result in an enhancement of ozone (O_3) in the upper troposphere and lower stratosphere (UT/LS) and the destruction of a small amount of ambient methane (CH_4), of the order of approximately 1-2% of the background concentrations (IPCC, 1999).
The enhancement of O_3 results in climate warming, whereas the reduction in CH_4 is a cooling effect. These effects are usually assessed in terms of changes in global mean radiative forcing (RF) because of the linear relationship between a change in global mean RF and a global mean surface temperature response.

In this Chapter the following are addressed:
- How aviation NO_x impacts upon climate.
- How these impacts are assessed.
- Whether aviation NO_x impacts can be related to those from CO_2. And,
- Whether an aviation NO_x GWP can currently be recommended for usage as a means to cost aviation NO_x emissions.

4.2 How do the climate impacts of aviation NO_x emissions come about?

Aviation NO_x is well known to affect the tropospheric O_3 budget, which is coupled to the CH_4 budget.

The formation of tropospheric ozone is a very complex process and whilst some of the details are incompletely understood (particularly some of the production processes from non-methane hydrocarbons and the modification to O_3 budgets by clouds), the main features of it are reasonably well understood (e.g. Seinfeld and Pandis, 1998; Wayne 2000) and are outlined as follows.

Ozone is constantly being formed and photolysed in the cycle:

[1] $$O(^3P) + O_2 + M \longrightarrow O_3 + M$$

[2] $$O_3 \xrightarrow{h\nu} O(^3P) + O_2$$

where $O(^3P)$ is atomic oxygen in the ground state formed from the photodissociation of O_2 (mostly in the stratosphere > 16 km) where the wavelength of the incoming radiation is < 243 nm and M represents a third body. This system is perturbed in the troposphere and lower stratosphere by the presence of CO, CH_4 and other non-methane hydrocarbons (NMHCs). Carbon monoxide from natural and man-made sources reacts with the hydroxyl radical to form the hydroperoxy radical HO_2:

[3] $$OH + CO \longrightarrow H + CO_2$$

[4] $$H + O_2 + M \longrightarrow HO_2 + M$$

This HO_2 may then react with NO to form NO_2 which is subsequently photolysed to reform NO, and produce $O(^3P)$, which may then participate in reaction [1]:

[5] $$HO_2 + NO \longrightarrow NO_2 + OH$$

[6] $$NO_2 \xrightarrow{h\nu} NO + O(^3P)$$

Methane and other NMHC's may also contribute to the formation of HO_2:

[7] $$CH_4 + OH \longrightarrow CH_3 + H_2O$$

[8] $$CH_3 + O_2 + M \longrightarrow CH_3O_2 + M$$
$$CH_3O_2 + NO \longrightarrow CH_3O + NO_2$$

[9] $$CH_3O + O_2 \longrightarrow HCHO + HO_2$$

and then reacting as in equation [5]. NMHCs can also participate as in [7] to [9], where, by convention, the NMHC is designated 'RH', taking the place of CH_4 and its derivative species above. The formaldehyde (HCHO) thus formed can also react with OH to form HO_2 and its photolysis products contribute towards HO_2 formation:

[10] $$HCHO + OH(+O_2) \longrightarrow HO_2 + H_2O + CO$$

[11] $$HCHO \xrightarrow{h\nu} {}^{2}\!/_{3}H_2 + CO$$

and,

[12] $$HCHO + 2O_2 \xrightarrow{h\nu} {}^{1}\!/_{3}2HO_2 + CO$$

Ozone is lost from the system, either by dry deposition at the earth's surface, or by chemical destruction, principally from photolysis to form $O(^1D)$ (the electronically exited state of atomic oxygen) which reacts with water vapour to form OH, this reaction being the principal source of OH in the atmosphere:

[13] $$O_3 \xrightarrow{h\nu} O(^1D) + O_2$$

[14] $$O(^1D) + H_2O \longrightarrow OH + OH$$

two other major routes of chemical destruction of O_3 are reaction with OH and HO_2

[15] $$O_3 + OH \longrightarrow HO_2 + O_2$$

[16] $$O_3 + HO_2 \longrightarrow OH + 2O_2$$

However, any injection of NO competes for the HO_2 and therefore reduces the rate of loss of O_3 by HO_x ($OH + HO_2$). Evidently, any NO_x present in the chemical system acts as a catalyst for O_3 production. Nitric oxide also reacts with O_3 to form NO_2, but since the NO_2 is photolysed during the day, no net formation of O_3 results on the time-scale of ~1 day except in polar winters. The catalysis is terminated when NO_x is removed from the system which can occur either in the day by reaction with OH:

[17] $$NO_2 + OH + M \longrightarrow HNO_3 + M$$

or by night to form HNO_3 which is absorbed on existing aerosol:

[18] $$NO_2 + O_3 \longrightarrow NO_3 + O_2$$

[19] $$NO_3 + NO_2 \longrightarrow N_2O_5$$

[20] $$N_2O_5 + H_2O \longrightarrow 2HNO_3$$

However, NO_2 may be regenerated by photolysis of HNO_3:

[21] $$HNO_3 \xrightarrow{h\nu} NO_2 + OH$$

or by reaction with OH,

[22] $$HNO_3 + OH \longrightarrow H_2O + NO_3$$

and subsequent photolysis of NO_3,

[23] $$NO_3 \xrightarrow{h\nu} NO + O_2$$

or:

[24] $$NO_3 \xrightarrow{h\nu} NO_2 + O(^3P)$$

The role of HO_x is critical; the pathways of OH and HO_2 generation having been given in (n). In addition, however, acetone ($(CH_3)_2CO$), hydrogen peroxide (H_2O_2) and other peroxides may provide additional sources of HO_x (Wennberg et al., 1998). Peroxy radicals are removed from the system by three main pathways:

[25] $HO_2 + HO_2 \xrightarrow{M} H_2O_2 + O_2$

[26] $\underline{OH + H_2O_2 \longrightarrow H_2O + HO_2}$

[27] $\text{Net}: OH + HO_2 \longrightarrow H_2O + O_2$

[28] $OH + NO_2 \xrightarrow{M} HNO_3$

[29] $\underline{OH + HNO_3 \longrightarrow H_2O + NO_3}$

[30] $\text{Net}: OH + NO_2 \longrightarrow H_2O + NO_3$

[31] $HO_2 + NO_2 \xrightarrow{M} HNO_4$

[32] $\underline{OH + HNO_4 \longrightarrow H_2O + NO_2 + O_2}$

[33] $\text{Net}: OH + HO_2 \longrightarrow H_2O + O_2$

It has also been known for some time that NO_x emissions result in a reduction of ambient CH_4. Emissions of NO_x result in enhanced concentrations of the hydroxyl radical, OH.

[34] $NO + HO_2 \longrightarrow NO_2 + OH$

The O_3 increase associated with NO_x emissions is accompanied by a shift in the concentrations of HO_2 to OH. The increased OH concentrations from aircraft NO_x emissions then result in a reduction in CO concentrations from the reactions

[35] $OH + CO \longrightarrow H + CO_2$

[36] $H + O_2 + M \longrightarrow HO_2 + M$

The lifetime of CO is of the order months, so that decreased CO concentrations from increased OH may spread from cruise altitudes down to lower altitudes and latitudes (bearing in mind that most NO_x emissions from aircraft occur at 8-12 km in northern mid-latitudes). Much of the CH_4 oxidation in the troposphere occurs at tropical and sub-tropical latitudes and because CO levels are reduced, OH is higher (CO being a sink for OH) and as a result, more CH_4 is oxidised, reducing CH_4 concentrations:

[37] $OH + CH_4 \longrightarrow CH_3 + H_2O$

Thus, as CH_4 concentrations are reduced as a result of aircraft NO_x emissions, the RF effect from ambient CH_4 is reduced, such that a negative RF from CH_4 can be attributed to NO_x emissions from aviation.

4.3 How can aviation NO_x impacts be assessed?

There are many examples in the literature of calculations of the impact of aviation NO_x emissions on the tropospheric O_3 and CH_4 budgets, some of which were reviewed by IPCC (1999), and others have subsequently been made.

Most of these studies have examined the impacts of some estimation of aviation NO_x emissions for a particular historical year or some projection on tropospheric chemistry. In doing so, only the O_3 perturbation can be calculated to an equilibrium response. For CH_4, multi-decadal integrations would have to be made to calculate the equilibrium response which would be computationally expensive, which is why an estimation of the change in CH_4 lifetime is parameterized (see Fuglesvedt et al., 1999).

Once the chemical perturbation arising from aviation NO_x emissions is calculated, the usual next step is to calculate the RF arising from these changes. This is often done with off-line radiative transfer codes (see Prather et al., 1999).

In the IPCC (1999) assessment, the RFs of O_3 and CH_4 arising from aviation NO_x emissions for 1992 traffic were calculated, which resulted in global mean RFs from O_3 of 23 mW/m^2 and a negative RF from CH_4 reduction of -14 mW/m^2.

Similarly, Sausen et al. (2005) calculated an RF for O_3 of 21.9 mW/m^2 and for CH_4 of -10.4 mW/m^2 for 2000 traffic. This estimate used updated emissions of NO_x from aviation for 2000. The absolute forcings were smaller than was found by the IPCC (1999) relative to emissions, this was thought to be the result of improved models of global atmospheric chemistry and transport. Of more significance was the changed ratio of O_3/CH_4 RFs, -1.6 for IPCC and -2.1 for Sausen et al. (2005). The CH_4 reduction was smaller in later studies, possibly as a result of less numerically diffusive models arising from improvements in spatial and vertical resolution.

For the IPCC's (1999) calculations, it was concluded that the positive RF from O_3 outweighed the negative RF from CH_4 reduction. However, the IPCC was careful to note that the situation is potentially more complex than implied by simple subtraction of the CH_4 RF from the O_3 RF:

> *'The NO_x driven perturbations to O_3 and CH_4 produce RFs (+0.023 and -0.014 W m^{-2}, respectively) that are of similar magnitude and in part cancel. However, the latitudinal imbalance from these two perturbations do not cancel: the combined O_3+CH_4 forcing is positive in the Northern Hemisphere and negative in the Southern Hemisphere. The response of the climate system to such geographically non-homogeneous forcing is*

> *unknown. At least regional differences can be expected, and there may even be differences in the global mean response.'* (IPCC, 1999, Chapter 6).

There is more recent evidence that geographical distribution of aviation-like forcings is of importance. Stuber et al. (2005) who found that an O_3 forcing in the Northern Hemisphere lower stratosphere resulted in a larger climate sensitivity by a factor 2 over a uniform CO_2 forcing.

It is important to understand what the calculations presented by IPCC (1999) and Sausen et al. (2005) were intended to do: the question essentially was '*what are the radiative impacts from present-day aircraft NO_x emissions?*'

The usage of a Global Warming Potential (GWP) implies an entirely different question, i.e. '*what is the integrated RF from a marginal additional emission of a unit mass of emissions (as a pulse) relative to that of CO_2 over some given timeframe?*'

There is currently no sound scientific metric to compare the size of the non-CO_2 climate impacts of aviation with the climate impacts of aviation's CO_2 *emissions*. Previously, some commentators have suggested using the Radiative Forcing Index (RFI; some of total forcings divided by the CO_2 forcing) for aviation, but CE et al. (2005) argued that this is not a suitable metric for policy purposes. Since then, Forster et al. (2006) and the IPCC (2007) have also stated that the RFI should not be used as an emissions index to account for non-CO_2 effects.

The main drawback of the usage of the RFI in this fashion is that it is based on the accumulation of historical emissions of CO_2 in the atmosphere. Thus it captures the contribution of aviation to climate change, to date, from CO_2. Thus, there is no unique value of an RFI since it depends entirely on the historical growth rate of emissions and, like RF, it is a partially 'backward-looking' metric (the CO_2 term). Applying this in a policy context would seem like punishing a sector for past behaviour, which cannot be changed, rather than encouraging changes in the future. Also, RFI cannot be related to the common metric used in climate policy i.e. the Global Warming Potential (indexed to a 100 year time horizon).

CE et al. (2005) evaluated a number of other potential metrics for a multiplier but concluded that none were suitable. Most potentially suitable forward-looking metrics are still in the research domain and currently being assessed and evaluated, i.e the Global Temperature Potential (GTP) (Shine et al., 2005), a modification to this for aviation, the Global Temperature Index (GTI) (CE et al., 2005) or the Emissions Weighting Factor (EWF[10]) (Forster et al., 2006; Corrigendum 2007). What they all suffer from is the uncertainty in underlying integrated RFs over a fixed time horizon from ozone and methane (Fuglestvedt et al., 2008). This is a function of the complexity of the responses in a physicochemical system of a pulse or sustained NO_x emissions.

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[10] Actually, Forster et al.'s 'Emissions Weighting Factor' is simply a GWP.

The scientific basis for a 'multiplier' on CO_2 emissions is embedded in the Kyoto Protocol with GWPs. At present, too much uncertainty remains over the value of an aviation NO_x GWP to recommend a value for policy purposes. However, given the clear evidence that aviation has positive RF impacts on climate in addition to those from the impacts of its CO_2 emissions, it could be argued that the precautionary principle should be invoked to justify a multiplier.

In the following section, the means by which marginal emissions of NO_x might be related to corresponding CO_2 emissions is examined.

4.4 How can aviation NO_x impacts be related to those of CO_2?

The conventional way in which the radiative impacts of one climate forcing agent are related to those of CO_2 is by the usage of the GWP.

The GWP is the ratio of the radiative efficiency per emitted unit of a forcing agent, integrated over some time horizon to that of CO_2 (by convention). Or, more formally;

[1] $$GWP_x = \frac{\int_0^{TH} a_x[x(t)]dt}{\int_0^{TH} a_r[r(t)]dt}$$

where *TH* is the time horizon over which the calculation is made, a_x is the radiative efficiency arising from a unit increase in atmospheric abundance of the substance (x) in question (in W m^{-2} kg^{-1}), [x(t)] is the time-dependent decay in the abundance of the instantaneous release of the substance, and r refers to the reference substance in the denominator.

GWPs are generally most suitable for long-lived gases such as CH_4, N_2O and the halocarbons. The time horizon chosen is arbitrary: however, it should be realised that different values for GWPs arise from the use of different time horizons.

An absolute GWP (AGWP) may also be formulated, which is essentially the nominator of equation [1], which can be expressed as:

[2] $$AGWP^x(TH) = \int_0^{TH} A_x \exp(-{}^{t}\!/_{\alpha_x})dt = A_x\alpha_x[1-\exp(-{}^{TH}\!/_{\alpha_x})]$$

for a gas x, where A_x is the radiative forcing per kg, α_x is the lifetime, and *TH* is the time horizon.

In some respects, the AGWP is more straightforward for examining aviation NO_x effects on O_3 and CH_4 as the units can be reduced to W m^{-2} yr, i.e. the integrated RF over a selected TH and the relativity to the CO_2 AGWP ignored.

The above metrics are usually in the form of *pulse* GWPs and AGWPs. It is also possible to formulate GWPs with sustained (constant) emissions.

As outlined by CE Delft et al. (2005), the application of GWPs to aviation NO_x emission has been scientifically contentious because of the nature of NO_x emission effects on O_3 – it is short-lived and spatially variable in magnitude.

In the IPCC (1999) report, the usage of an aviation NO_x GWP was rejected on the grounds that it '*has flaws that make its use questionable for aviation emissions*' and that '*there is a basic impossibility of defining a GWP for aircraft* NO_x'. The basis of the latter statement was that the O_3 production per unit NO_x varies in time and space because of complex non-linear atmospheric chemistry that depends on background concentrations of both NO_x from other sources, and other chemical species.

Others, however, have taken quite a different stance, using the GWP as a convenient metric to compare different NO_x effects for both surface and aviation sources, e.g. Johnson and Derwent (1996), Derwent et al. (2001); Wild et al. (2001), Stevenson et al. (2004), Berntsen et al. (2005), Forster et al. (2006), Derwent et al. (2007). Whilst this list is not comprehensive, these are the most cited works in the literature. Of these seven studies, four originate from one research group.

IPCC recently summarized GWPs arising from four of these studies (Forster et al., 2007), which is reproduced in Table 1 below.

Table 1 GWPs for O_3 and CH_4 from NO_x emissions for a 100 year time horizon (adapted from Forster et al., 2006)

Study/NO_x source	GWP CH_4	GWP O_3	GWP Net
Derwent et al. (2001) NH surface $NO_x^{a,b}$	-24	11	-12
Derwent et al. (2001) SH surface $NO_x^{a,b}$	-64	33	-31
Wild et al. (2001) industrial NO_x	-44	32	-12
Berntsen et al. (2005) surface NO_x, Asia	-31 to -42^c	55 to 70^c	25 to 29^c
Berntsen et al. (2005) surface NO_x, Europe	-8.6 to -11^c	8.1 to 12.7	-2.7 to +4.1^c
Derwent et al. (2001) aircraft $NO_x^{a,b}$	-145	246	100
Wild et al. (2001) aircraft NO_x	-210	340	130
Köhler et al. (2008) aircraft NO_x ^{d}	-70	82	12
Stevenson et al. (2004) aircraft NO_x	-159	155	-3

Notes:

[a] Corrected values as described in Stevenson et al. (2004).

[b] For January pulse emissions.

[c] Range from two 3D chemical transport models and two radiative transfer models.

[d] Köhler et al. (2008) did not present GWPs but this was calculated by Fuglestvedt et al. (2008, submitted).

As can be seen from Table 1, for surface emissions of NO_x, there is poor agreement on a net GWP, even to its sign. For aviation emissions of NO_x, the results of Derwent et al. (2001) and Wild et al. (2001) are similar, at 100 and 130. However, Stevenson et al.'s (2004) results (using the same model as that of Derwent et al., 2001) calculates a small *negative* net GWP of -3. Köhler et al.

(2008) have also recently calculated NO_x impacts, and the resultant GWPs were presented by Fuglestvedt et al. (2008 submitted), with a net GWP of 12 for a time horizon of 100 years.

It is also possible to modify the GWP to include the concept of efficacy of forcings (e.g. Joshi et al., 2003; Hansen et al., 2005). This is the ratio of the climate sensitivity of an individual forcing agent to that of CO_2. Calculations and investigations of climate efficacies of individual forcings, and effects, are in their infancy. Some efficacies of aviation forcings do exist for O_3, CH_4 (as modified by aviation NO_x emissions), e.g. Ponater et al. (2006). Using Ponater et al.'s (2006) efficacies of 1.37 and 1.18 for O_3 and CH_4, respectively, the GWPs in Table 1 may be modified.

The Stevenson et al. (2004) results warrant some examination as they are so dissimilar to the other two studies cited by the IPCC (Forster et al., 2007).

Stevenson et al. (2004) used a NO_x emission 'signal' 10 times greater in magnitude than actual aviation NO_x emissions as a pulse. The reason for a magnified emission was stated as '*to produce a large signal in the model, but also to remain within reasonably realistic bounds for atmospheric concentrations of* NO_x' (Stevenson et al., 2004, section 5.1). The large NO_x signal will have produced a large perturbation of OH, which is ultimately responsible for CH_4 destruction, reaction of CH_4 with OH being the main sink (destruction) term for CH_4 (see section 4.2). Moreover, the O_3 production chemistry has a tendency to saturate at high NO_x conditions. Thus, Stevenson et al.'s (2004) caution over interpretation of their results is well made: '*..we should introduce a note of caution when considering the results presented here, especially in absolute radiative forcing terms*'.
More recently, the same research group has published further results on RF from NO_x emissions (Derwent et al., 2007). In this paper, they examine pulse emissions of NO_x and cite a *positive* net GWP for aviation NO_x emissions.

It is clear that the magnitude and sign of the net GWP from aviation NO_x is dependent upon the model used, the experimental design and in addition, the time-horizon considered.

It was necessary to adopt some numerical values of GWPs for cost modelling. Like Forster et al. (2007) we do not adopt a best estimate but rather a range. It is our view that whilst such a large range exists with only a few values available, a 'best estimate' is inappropriate. The range that we adopt is 1-130 and a range modified by efficacies results in net GWPs of 25-220. We have not adopted the absolute value of -3 from Stevenson et al. (2004) for this analysis whilst uncertainty remains over the validity of the value, given the artificially magnified emissions. Thus, a conservative lower value of GWP of 1 was adopted.

Additionally problematic is the *interpretation* of the above model experiments. They all use pulse emissions (as do all Kyoto-based GWP calculations). Pulse emissions allow one to look at the effect of an additional unit mass and provide a convenient aid to understanding atmospheric processes.

However, in the real world, individual isolated pulses are not occurring. Nor are sustained emissions (effectively, repeated equal emission pulses). For aviation, emissions of various species are increasing such that the results of pulse experiments should not be over-interpreted. What they principally do is allow an examination of *decay responses* in terms of magnitude and time, and are instructive about what may ultimately happen to the climate on cessation of these emissions.

4.5 Can an aviation NO_x GWP be used as a basis for policies?

Essentially, it is possible, in principle, to use a net GWP from aviation NO_x (the sum of O_3 and CH_4 integrated RFs) for policy development. A policy that targets the climate impact of NO_x emissions from aviation should be consistent with other climate policies and thus have an approach consistent with the use of a GWP, as in the Kyoto Protocol. However, the current situation concerning the GWP of aviation NO_x emissions precludes such an approach at the moment.

Currently, if one accepts a time-horizon of 100 years, for compatibility with the Kyoto Protocol, there are relatively few modelling studies upon which one can base an aviation NO_x GWP. The results are rather variable, and in one case negative in sign, although this result is peculiar in the sense that a large pulse was utilized (10 times normal emissions). This made the results less easy to interpret since the large NO_x signal will have produced a large OH enhancement, which is the principal sink term for CH_4.

One can only conclude that the state of the science in terms of producing a robust GWP for aviation NO_x emissions is immature, and an aviation NO_x GWP cannot be recommended for current policy applications at this point in time. Essentially, only two modelling groups have been examining this aspect and they have produced rather diverse results.

Therefore, what is needed is a mobilization of the international scientific community who have such models at their disposal and a coordinated set of experiments performed so that a robust, consensus analysis of aviation NO_x GWPs can be undertaken. The outcome of such a hypothetical study cannot be predicted, but all things being equal, if such a study were performed, it would be likely to take about 3 years. If, however, such a coordinated effort were to produce diverse results it is not possible to predict how long resolution would take.

Clearly, such a coordinated experiment should be undertaken as a top priority to formulate a robust policy metric for aviation NO_x emissions.

4.6 Conclusions

- Under current estimations of global aviation NO_x emissions, the positive O_3 RF response is larger than the negative CH_4 response, by a ratio of 2, in absolute terms. Thus, aviation NO_x emissions are currently resulting in climate warming.
- Modelling experiments with pulses of NO_x emissions allow atmospheric processes to be understood. Methane has a much longer lifetime than O_3, so it takes much longer for the atmosphere to come back to equilibrium from a pulse perturbation in terms of the negative CH_4 forcing. Thus, it is possible that the combined integrated O_3 and CH_4 RF can be either positive or negative, depending upon the experimental design and the model used.
- Isolated pulses are not occurring in the real world, and as such, pulses are a hypothetical device to aid understanding of the responses of the atmosphere. Most pulse studies of aviation NO_x imply that the net integrated RF is positive from O_3 and CH_4 responses.
- GWPs for aviation NO_x have been derived in a very limited number of studies, essentially from only three modelling groups. There is poor agreement on the magnitude, with one result being slightly negative. The study which gives a negative GWP is an outlier, with all other studies providing a positive GWP.
- At this point in time, the science is too immature to recommend an aviation NO_x GWP for usage in policy and it is recommended that an international study using a variety of suitable models is coordinated to determine the sign and magnitude of an aviation NO_x GWP.

5 Engine technology issues

This Chapter describes the key technical issues and outcomes that it has been necessary to cover in pursuit of this study. The major headings are as follows:

5.1 The combustor within the aero-engine.
5.2 Products of combustion.
5.3 ICAO CAEP LTO NO_x Standards Stringency.
5.4 ICAO-CAEP 2007 Medium (10 year) and Long Term (20 year) LTO NOx Goals.
5.5 Fundamentals of NO_x formation.
5.6 Engine NO_x control strategies.
5.7 Trade-offs involved in reducing NO_x emissions.
5.8 LTO NO_x versus Cruise NO_x.

5.1 The combustor within the aero-engine

NO_x produced by aero-engines is formed in the combustor. The combustor is at the heart of the turbo-fan (and turbo-prop) engine and it must work reliably at all engine settings and in all weather conditions. There is no back-up system other than attempted re-lighting in flight - if the altitude permits. Therefore safety must remain the top priority and can never be compromised.

Nonetheless, there have been several examples where the pursuit of reduced NO_x has resulted in unacceptable levels of combustor flame stability and/or the tendency to ‘flame out’. When attempting to control NO_x production through the development of new combustor designs flame stability is often one of the key challenges and one that rules out many potential technologies. Very high levels of combustor burning efficiency are also required and any fall-off will cause an increase in CO_2 as well as some other pollutants.

Furthermore, in striving for NO_x reductions, additional complexity is being introduced in to the combustor. In addition to safety, several other requirements are already placed on the combustor designer and Figure 4 below which is taken from ICAO CAEP’s NO_x Long Term Technology Goals Report[11] provides a good summary of the key requirements.

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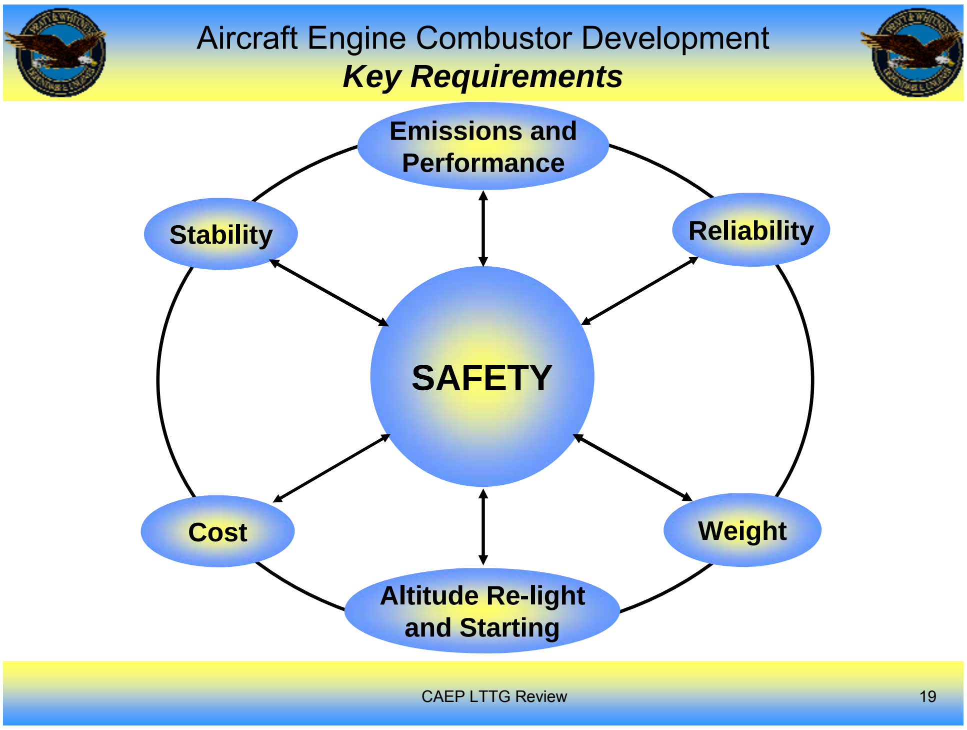
[11] ICAO CAEP 7 Report of the Independent Experts to the Long Term Technology Task Group on the 2006 LTTG NO_x Reviewand the Establishment of Medium and Long Term Technology Goals for NO_x.

Figure 4 Aero-engine combuster key requirements



Aircraft Engine Combustor Development
Key Requirements

SAFETY

Emissions and Performance

Reliability

Weight

Altitude Re-light and Starting

Cost

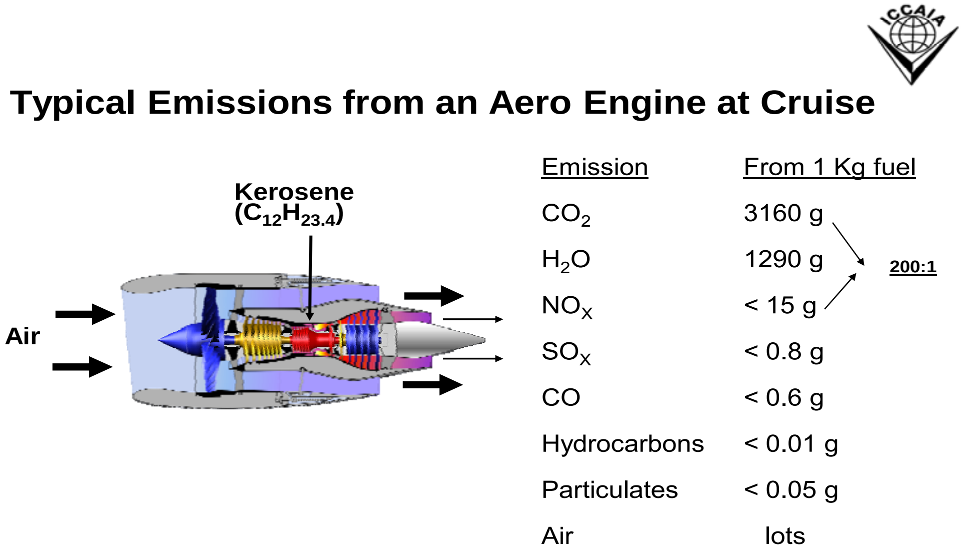
Stability

CAEP LTTG Review 19

5.2 Products of combustion

Aero-engine products of combustion roughly comprise 70% CO_2, a little under 30% H_2O, and less than 1% each of CO, NO_x, SO_x, VOCs, particulates and other trace emissions including Hazardous Air Pollutants (HAPs). Figure 5 is an industry (ICCAIA) portrayal and illustrates typical values for these emissions at the cruise condition. Currently international ICAO limits exist for CO, Smoke, unburnt hydrocarbons (UHC) and NO_x. Sulphur is controlled through fuel standards. H_2O and CO_2 are directly related to the fuel burn and the engine design and duty and are uncontrolled other than by commercial and performance pressures.

Figure 5 Typical Aero-engine Mass Emissions at the Cruise Condition


Typical Emissions from an Aero Engine at Cruise

Emission	From 1 Kg fuel
CO_2	3160 g
H_2O	1290 g
NO_X	< 15 g
SO_X	< 0.8 g
CO	< 0.6 g
Hydrocarbons	< 0.01 g
Particulates	< 0.05 g
Air	lots

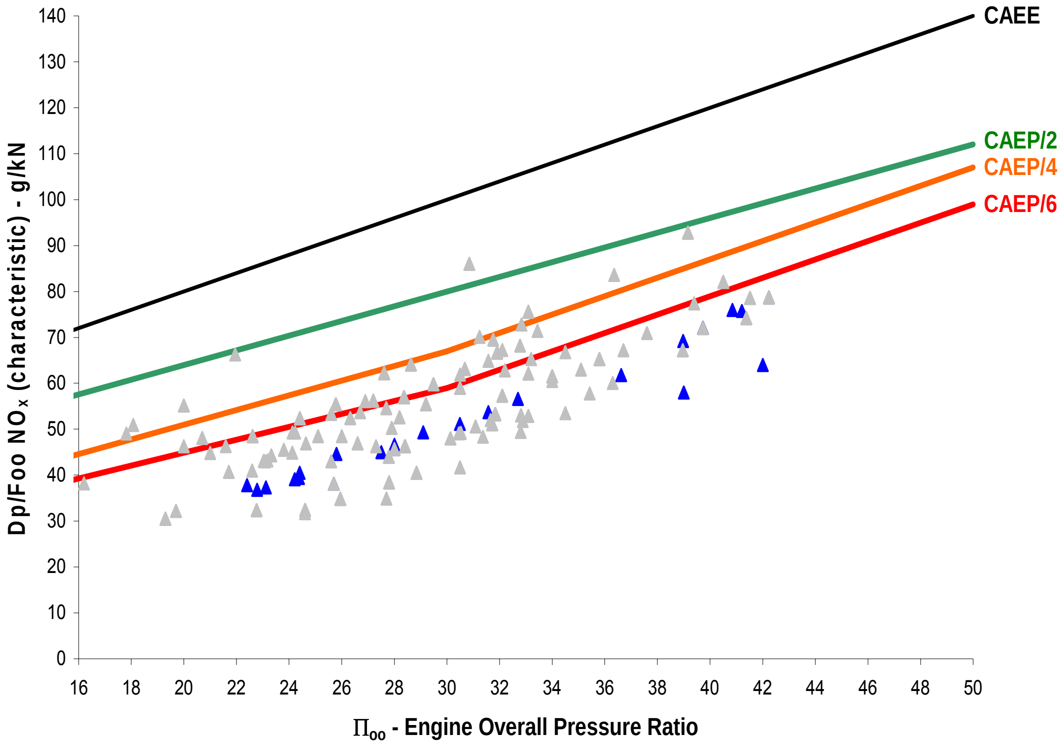
Note: This study team's analysis of Cruise $EINO_x$ indicates a range of between about 8 to < 25 as compared with 15g/Kg shown above.

5.3 ICAO CAEP LTO NO_x Standards Stringency

The regulation of LTO NO_x through ICAO first became effective in 1986 (CAEE). No further tightening came in to force for ten years until 1996 (CAEP2) when a 20% reduction was made against the CAEE standard. Since then further reductions have been made at shorter time and smaller reduction intervals: CAEP4 with an effective date of 2004 -16% versus CAEP2; CAEP6 effective date 2008 -12% below CAEP4. Until CAEP4 the standard was a simple straight line of permitted NO_x rising with increasing overall engine pressure ratio (OPR), however, from CAEP 4 onwards an increased slope kink in this line appeared at OPR 30 which permitted higher OPR engines to produce more NO_x than would have been the case with a straight line. Also at CAEP6 the slope of the line was reduced somewhat for engines below OPR 30. These regulations apply for engines rated above 26.7kN (6,000 lbs thrust) though for engines up to 89kN (20,000 lbs thrust) some 'small engine' relief is available.

The LTO NO_x metric used for all of these ICAO standards was Dp/F_{oo} which is defined as the mass of emissions produced (Dp) during a static sea level ($_{oo}$)engine test for a simulated idealized LTO (landing and take-off cycle) normalised against maximum engine thrust (F_{oo}). Figure 6 below shows these various ICAO NO_x standards together with non-attributed in-production engine data from the databank also highlighting the more recently certificated engines.

Figure 6 Progression of ICAO NO_x certification standards together with engine; data points - recent certifications are highlighted



It can be seen from Figure 6 that significant reductions in ICAO certificated NO_x levels have already been promulgated. Overall, from 1986 through to the 2008 requirement, at OPR 30, the permitted level has reduced by about 40% from the initial level though this reduction is somewhat less at higher OPR levels due to the ‘kink’ in the curve introduced in CAEP4.

Despite these significant increases in the stringency of ICAO standards, because higher OPR engines are permitted to produce more NO_x, and because of fleet growth and slow fleet rollover, it is not necessarily the case that total fleet NO_x has been reduced. Had OPR remained at the 1986 level (and in the absence of growth) absolute NO_x levels would have fallen as a result of the subsequent NO_x reduction technologies. However, OPR increases were employed to achieve substantial improvements in fuel burn i.e. CO_2 reduction.

NO_x production at the higher OPRs was, of course, reduced by the technical improvements to always fall below the stringency lines. However the absolute emissions increased due to the general increase in OPR. The reductions required by ICAO would have needed to be much greater to have produced an absolute reduction at the high OPRs employed.

These ICAO certification limits apply only to newly certificated types and with industry standard production lives of 15+ years for most aircraft types coupled with the even longer in-service lives of 30+ years for passenger aircraft and about 45 years for freight types, total fleet NO_x is slow to respond to a change in the stringency of the NO_x standard. This is illustrated by ICAO's FESG finding that 60% of passenger aircraft were still in service at 30 years of age![12] - and this factor of long service life is in addition to the continuing production of engines certificated to an earlier standard stringency.

The incorporation within these ICAO standards of a slope against OPR was in response to the characteristic for the mass of NO_x emitted to increase along with increasing OPR (and temperature). This characteristic is discussed more fully below in Section 5.5. These higher pressures and temperatures have been used in a drive to improve fuel efficiency through improvements in thermal and cycle efficiency. The CAEP 4 kink was introduced in recognition of the fuel efficiency benefits of encouraging high OPR engines and also because of the even steeper NO_x rises that are a feature of 'throttle push' engines - variants designed to operate over a range of increasing thrusts developed from a base engine.

A significant fact is that these ICAO stringency increases were adopted only after the latest engines had been certificated and therefore demonstrated to be below the proposed new standard. Thus these ICAO standards were not technology forcing though importantly they have prevented regression by subsequent later engine types.

When designing new products, particularly the first of a new family of engines, manufacturers will design in a NO_x compliance margin to guard against any shortfall in NO_x control performance and to meet customers' expectations of proofing against future increases in stringency. Moreover, several stakeholders have argued that their research has been oriented by the expectation that standards would be tightened. As a result, for future engine designs, manufacturers aim not only for compliance with standards, but for exceeding the standards by at least the next anticipated stringency increase. These margins are evident from the most recent certifications, where most new engines were certificated at between 5 to 20% below CAEP6.

There has been discussion in ICAO for very many years of the possible development of a recognised metric and method for identifying the mass of NO_x emitted while an aircraft is at cruise. Thus far this work has not yielded an agreed approach. Section 5.8 below provides a discussion about using LTO based NO_x for Cruise NO_x estimation.

Finally it should be noted that these (LTO based) ICAO NO_x certification standards have been applied only to turbo-jet and turbo-fan engines and not to turbo-propellers. Some more limited databanks do exist for turboprop LTO NO_x, for example, manufacturers have reported the corresponding data to Swedish Aeronautical Institute (FOI). FOI has published an interim database that, with the

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[12] Wickrama U. CAEP/5-IP/11, 8-17 January 2001, Montreal.

manufacturers consent, could be distributed to authorized parties. This database is currently used for inventory purposes and charging schemes at various airports.

5.4 ICAO-CAEP 2007 Medium (10 year) and Long Term (20 year) LTO NO_x Goals

In 2006 ICAO's CAEP commissioned a study from a small group of independent experts to establish long term technology goals (LTTGs) for LTO NO_x reduction technologies used in commercial aero-engines with the time periods to be considered being Medium Term (MT Goal 10 year) and Long Term (LT Goal 20 year). The Independent Experts were tasked with reviewing current NO_x performance; potential outcomes from current research programmes; longer term potential reductions and finally climate impact evidence.

The report of the Independent Experts[13] was presented to the CAEP 7 meeting in February 2007 and the findings were accepted. The declared MT and LT goals are shown below in Figure 4 which has been taken from the report to CAEP. This shows that both goals were expressed as bands with the MT 10 year band lying about 45% below the CAEP 6 standard (at OPR 30) and with the LT 20 year band at about 60% below CAEP 6.

It is immediately apparent that both LTTG Goal bands lie well below current standards and by a large margin as compared with the difference between successive changes to standards. In this connection it is particularly noteworthy that while ICAO standards, by and large, follow proven technical capability, in contrast these Goals were set at what was judged by the Independent Experts to be the likely leading edge of NO_x reduction capabilities at the two declared time periods. Note that when performance in the MT NO_x band has been achieved, NO_x production at the highest OPR will be lower than in the lowest OPRs of CAEP 6 and absolute NO_x reductions will have been achieved.

Figure 7 also includes the ACARE goals for NO_x plotted against the same basis and it can be seen that the assumed ACARE engine contribution to LTO NO_x reduction (by the year 2020) lies close to the bottom end of the MT (2016) Goal but above the LT 2026 Goal. It would appear, therefore, that these CAEP Goals and the ACARE NO_x goal are broadly in line with each other.

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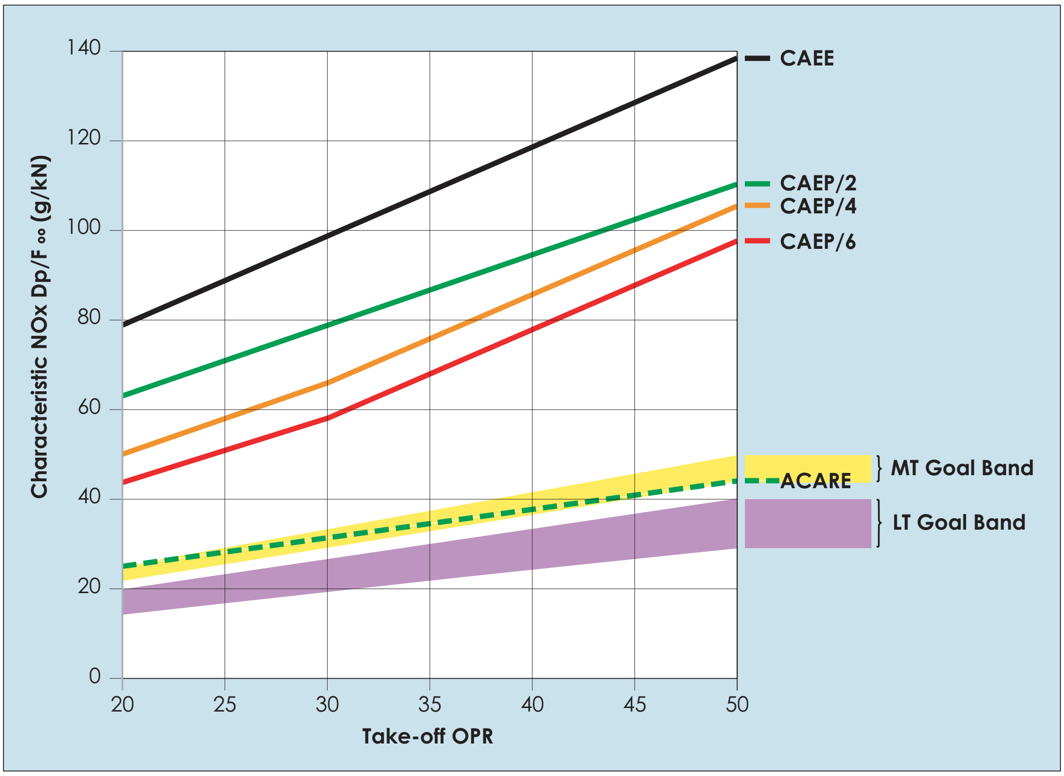
[13] Report of the Independent Experts to the Long Term Technology Task group on the 2006 LTTG NO_x Review and the Establishment of Medium and Long Term Technology Goals for NO_x – Proceedings ICAO CAEP 7 Montreal February 2007.

Figure 7 ICAO CAEP 7 Long Term Technology NO_x Goals shown alongside ICAO NO_x standards together with ACARE targets



5.5 Fundamentals of NO_x formation

The formation of nitrogen oxides in aircraft gas turbines

The formation of NO_x in aircraft engines can be via four different routes: the thermal route ('thermal NO_x'); the prompt route ('prompt NO_x'); the nitrous oxide route (N_2O) and the fuel-bound nitrogen route (Bowman, 1992). Of these the thermal route overwhelmingly dominates in aero gas turbines burning aviation kerosene.

Thermal NO_x arises from the thermal dissociation of nitrogen (N_2) and oxygen (O_2) molecules in combustion air. At high temperatures, N_2 and O_2 dissociate into their atomic states, N and O and react with N_2 and O_2 to form NO via the 'Zeldovich mechanism', whereby:

[1] $$N_2 + O \longrightarrow NO + N$$

[2] $$N + O_2 \longrightarrow NO + O$$

Rates of these reactions are dependent upon the stoichiometric[14] ratio (air to fuel ratio) in the primary combustion zone, flame temperature, system pressure and the time spent at the flame temperature (residence time or stay time). Therefore the NO_x formed is a function of $\exp^T \times P^n \times R$. Here T is the characteristic flame temperature and P is the combustor pressure. The exponent 'n' is typically ~0.5 but can approach zero in premixed lean flames. Residence time R at the highest temperatures will, typically, only be unit milli-seconds, by design, in order to compete with NO_x reaction rates that are very fast at high power conditions. Figure 8 illustrates the rate at which NO_x EI increases with pressure ratio in combustors that did not feature any (deliberate) NO_x reduction technology. Whilst the difficulty of making substantial reductions in NO_x at the high pressure and temperature conditions is evident it should also be true that any technology capable of producing such reductions should make even bigger percentage reductions at low power.

NO (nitric oxide) is the primary NO_x species produced in the flame. Subsequent reactions form NO_2, through the turbine, jet-pipe and in the environment. This further reaction is favoured by relatively low gas temperatures and by traces of unburned fuel and carbon monoxide. The range of possible temperature regimes, times and trace gas concentrations within the engine and near plume can result in conversions of NO to NO_2 ranging from almost none to levels in excess of 80%.

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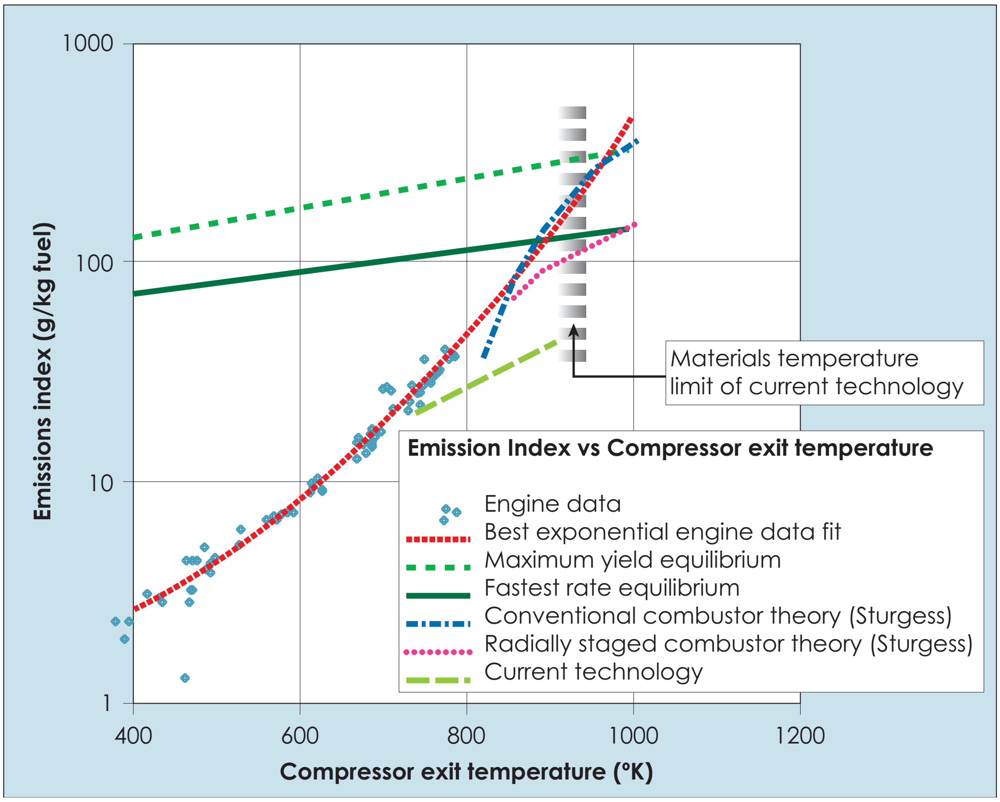
[14] In a fuel/air mixture at stoichiometric ratio = 1.0 all of the available fuel is exactly able to burn with all of the available oxygen. At higher values of the ratio all the oxygen would be used but there would be an excess of fuel in the combustion products. At lower values there would be an excess of oxygen remaining in the combustion products.

Figure 8 Relationships between NO_x EI and Pressure ratio[15]



5.6 Engine NO_x control strategies

Combustor designs

There are two, main, NO_x controlling combustion modes that could be applicable to gas turbines.

- Rich burn, Quick quench, Lean burn (RQL).
- Lean burn[16].

Each will be described below in more detail.

Various other successful NO_x reduction technologies such as 'catalytic combustion' 'flameless combustion', etc. have not proved suitable for aero engine use as a result of problems such as weight, size, stability, etc.

RQL Combustion

The familiar, traditional, combustor that dated from the origins of the gas turbine until the advent of emissions controls was, generally, a rich burn, quench, lean burn design. (Figure 9) It was natural, therefore, that work to reduce smoke, idling emissions and NO_x would start by making improvements to the existing design. The current RQL designs are very sophisticated versions of this original design which feature excellent control of fuel preparation, air/fuel ratios, internal

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[15] From LTTG Report.

[16] Lean Premixed Prevaporised combustion (LPP) which is not now considered practicable for liquid fuelled engines is also described here briefly.

aerodynamics and residence times. The most modern designs also owe much to the investment in Computational Fluid Dynamics (CFD) and combustion chemistry models that has been made over the last 30 years or so. In the RQL design the primary combustion zone of the combustor is operated richer than stoichiometric at take-off and climb, in a fairly narrow air/fuel ratio (AFR) band that avoids smoke formation whilst making little NO_x.

Figure 9 Schematic illustration of an RQL combuster

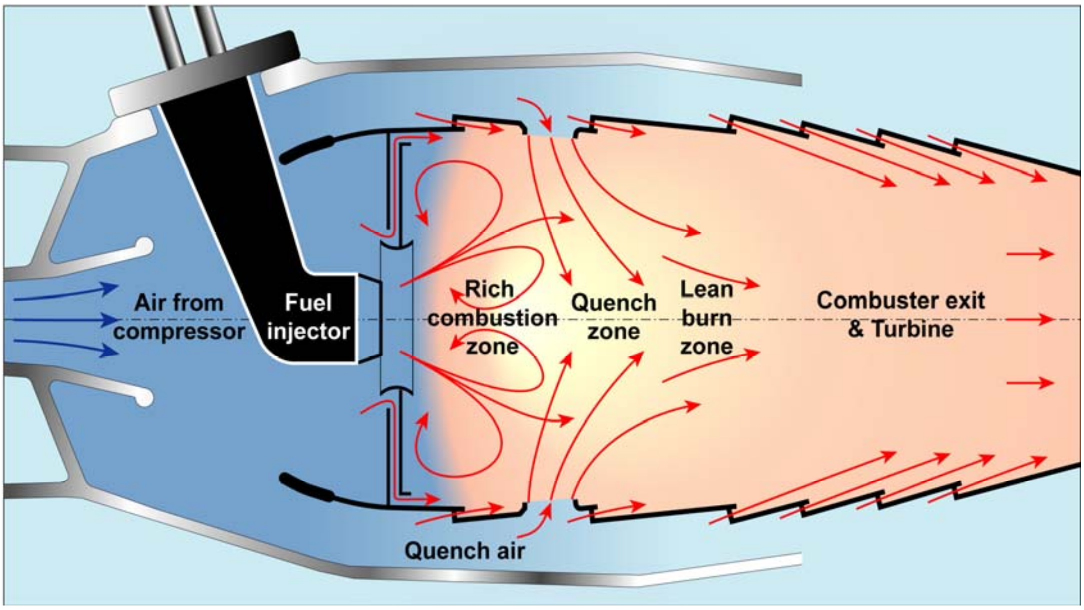
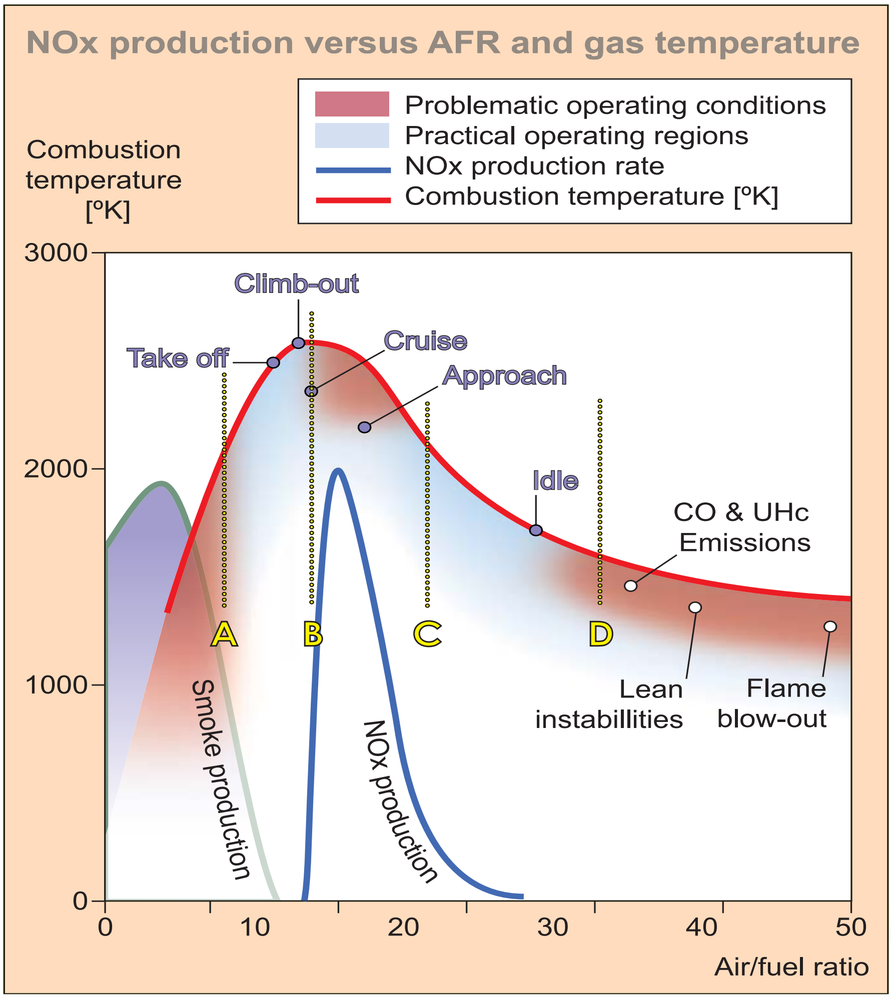


Figure 10 shows, schematically, the relationship between NO_x formation, flame temperature and AFR together with acceptable and unacceptable operating bands.

Figure 10 NO$_x$ production versus AFR and gas temperature



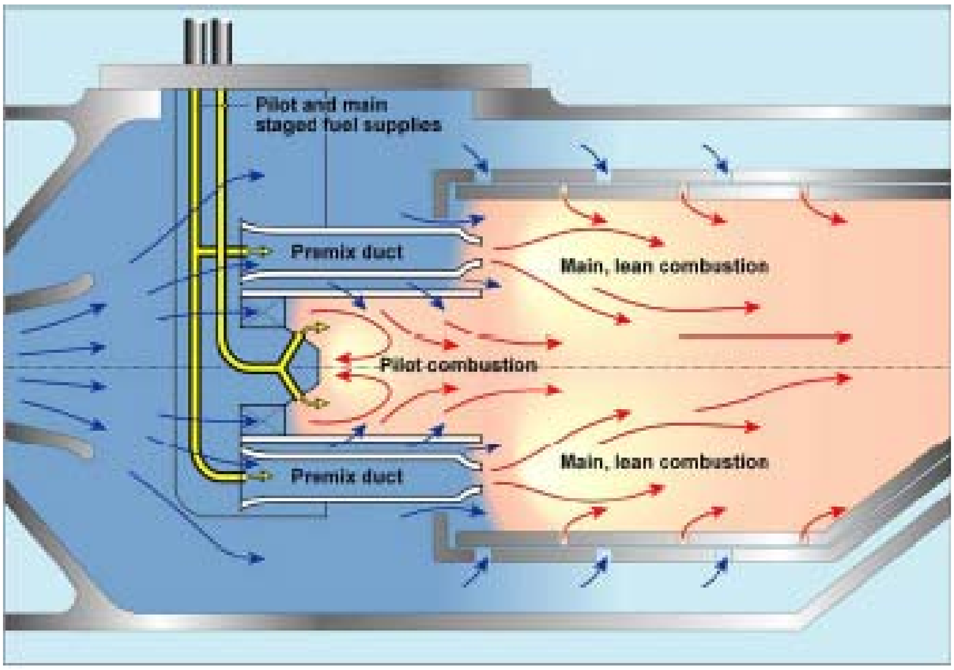
In Cruise and Approach the primary zone may operate in or close to the NO$_x$ production band. However because of the design features built in for LTO NO$_x$ reduction, – good fuel preparation, short residence time – and because the combustion air temperature and pressure are low NO$_x$ production at these conditions is also reduced. It should be expected that NO$_x$ reduction technology designed for the take-off and climb conditions (where NO$_x$ reduction is very challenging) would be at least as good at Cruise and Approach where, from a NO$_x$ reduction perspective, conditions are much more benign.

After the primary zone, additional air is injected into the combustor to dilute the part-burned rich combustion products from the A-B zone (Figure 10) to somewhere in the C-D band to complete burning. Clearly, the mixing of the air with the primary zone products must be very fast and uniform so that NO$_x$ production is minimized in passing through the B-C zone. Achieving this minimization is a considerable technical challenge because the NO$_x$ production rate is very fast and the aerodynamic mixing process (which is not naturally very fast) has to be designed to be as efficient as possible and comparably fast.

Lean burn Premixed Prevaporised combustors

LPP technology is illustrated conceptually in Figure 11.

Figure 11 Schematic illustration of an LPP combustor



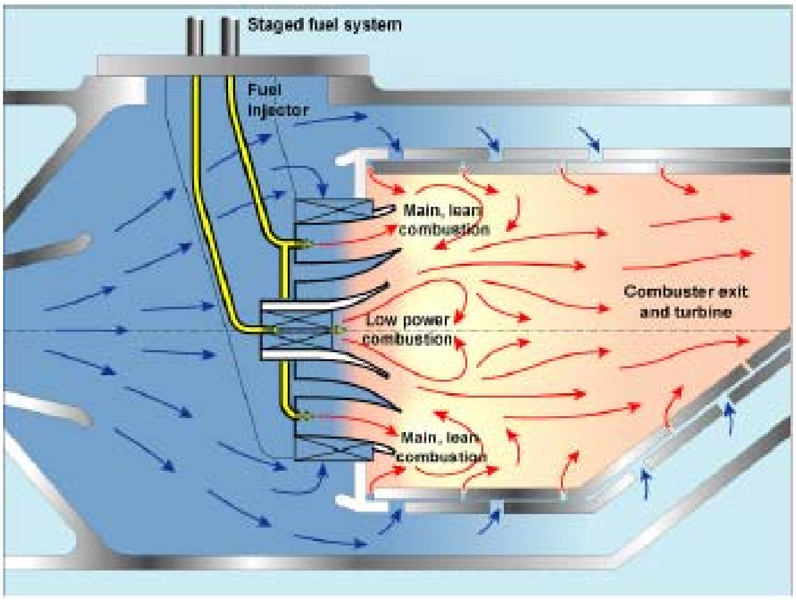
This technology aims to emulate gas fuelled combustion in that the fuel spray is perfectly mixed with an excess of air and evaporated before entry to the combustor. In principle the technique could produce very low NO_x emissions than are currently being achieved in gas fired power plant applications where weight, complexity and passenger safety are not problems. However, in spite of considerable research activity in the 1980s and ‘90s the technology was best by numerous problems that appear to be insurmountable. Although NO_x reductions of better than 90% were demonstrated (at reduced combustor pressures) it was necessary to use non-premixed pilot combustion in order to ensure the safe operation of the combustor. This reduced the gains to ~60% only. Overall there were huge operability and flight safety issues.

Lean Burn direct injection Combustors:

In spite of the large NO_x reductions that have been achieved by RQL technology, rising pressure ratios and combustion air temperature are increasing the difficulty of making further large improvements, especially for the larger, high pressure ratio engines. After the LPP research programmes, possibilities of lean combustion, direct injection (i.e. fuel sprays) were investigated in combustors featuring novel aerodynamics that allow separate combustion zones to co-exist in the same combustion space (Figure 12). These separate zones allow staging for high power and low power duty to be achieved in order to optimize the combustion process.

This design approach requires that a very high percentage (in the region of 40 to 50%) of the combustor air passes through the airspray fuel injector. Therefore the fuel injector tends to become large and complex with some issues of cost and weight and problems of overheating. Excellent performance in terms of fuel spray placement and quality is required of the atomizer in order that the spray should be as much vaporized and mixed with the airflow as possible prior to the flame.

Figure 12 Schematic illustration of a DLI combuster



From the results of experiments with circumferential staging in the past it might be expected that this technology would require much work to meet low power efficiency/emissions targets. Also because of the staging it cannot, automatically, be assumed that Cruise/LTO NO_x relationship will be retained. Rather, Cruise NO_x will have to be optimized separately in its own right. On the other hand because of the additional flexibility offered by the more complex fuel injection system and the staging there must be prospects of achieving better Cruise NO_x than the current RQL technology.

5.7 Trade-offs involved in reducing NO_x emissions

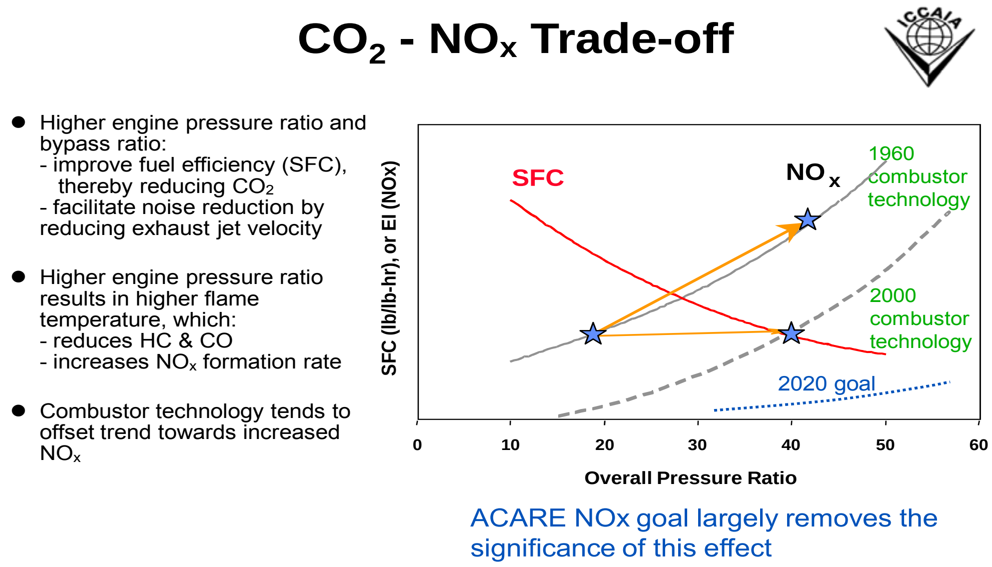
Engine design involves making trade-offs between many requirements. For the purposes of this study, the most important trade-offs at the engine level are those between CO_2 and NO_x, and the trade-off between NO_x and noise. It is important to recognise, however, that trade-offs occur not only at the engine level, but also at the aircraft level, where the pollutants are eventually emitted. At the level of the whole aircraft, trade-offs are broader than in the case of the engine alone.

5.7.1 CO_2 : NO_x Trade-offs at the engine level

With these two gaseous emissions in mind it is clear that for a fixed engine technology standard, if engine core temperatures and pressures are increased in pursuit of reduced fuel burn and CO_2, then all else being held equal, the mass of NO_x emitted will rise. Alternatively in the opposite direction, if engine core temperatures/pressures are reduced in order to reduce NO_x output then engine thermodynamic efficiency will be reduced and additional fuel will be burned in order to restore thrust.

However, in practice over time, reduced fuel burn and reduced NO_x production have both been achieved by pursuing concurrent fuel burn and NO_x reduction technologies. As long as further NO_x control technologies remain to be developed then improvements in both characteristics can continue though, if in the future NO_x control was to plateau, then trade-off may become a bigger factor. The ICAO LTTG NO_x goals study referred to above indicates that this plateau has not yet been reached nor is likely to be in the next ten years and possibly twenty years. Figure 13 produced by industry (ICCAIA) amply illustrates that both specific fuel consumption (SFC) and NO_x have been reduced over the past several decades and that future NO_x goals (ACARE is used here for illustration), if achieved, will result this happy situation continuing.

Figure 13 Illustration of CO_2 : NO_x Trade-off for varying combustor technology standards



CO_2 - NO_x Trade-off

- Higher engine pressure ratio and bypass ratio:
  - improve fuel efficiency (SFC), thereby reducing CO_2
  - facilitate noise reduction by reducing exhaust jet velocity
- Higher engine pressure ratio results in higher flame temperature, which:
  - reduces HC & CO
  - increases NO_x formation rate
- Combustor technology tends to offset trend towards increased NO_x

ACARE NOx goal largely removes the significance of this effect

5.7.2 To what extent could fuel efficiency (CO_2) improvements have been taken further in the absence of NO_x controls?

Given the significance of CO_2 emissions to climate change, the question remains to what extent even better fuel burn (CO_2 performance) may have been possible if NO_x controls were more relaxed. This study has sought to better establish the strength of this $NO_x : CO_2$ trade. To this end discussions have taken place with at least three major engine manufacturers and a breadth of comments have also been received from other stakeholders including several involved in the ICAO CAEP process.

The conclusion of this study is that improvements in SFC (CO_2) to date have been constrained more by materials' temperature limits, for example, turbine entry temperatures (TET) and consequent cooling issues than by the mechanisms employed to reduce NO_x. Thus far there has been little inhibition in CO_2 performance caused by the need to control NO_x other than in some cases where NO_x control mechanisms may have added some additional engine weight (though not significant at the scale of the whole aircraft).This might rise to perhaps 100 kg) in a future DLI combustor as a result of a more complex fuel control system and additional manifolds, etc. as well as some additional combustor complexity. Having said this, many of the modifications have turned out to have other value. For instance combustor traverse factor, smoke emissions, and wall cooling and computational methods have all benefitted from the enhanced research environment.

This finding that the pursuit of NO_x reduction technologies has had little effect on CO_2 cannot be altogether surprising given that, at least in the case of ICAO CAEP, any change in stringency demands proven technical feasibility and economic reasonableness. It is also supported by the fact that on-going CAEP studies on the cost-effectiveness of modifying non-compliant engines by fitting modern low NO_x combustor systems assume a CO_2 penalty of just 0 to 0.5%, with 0.25% being viewed as a reasonable single figure.

Arguably, the concentration on fuel burn reduction in the last 30 years allowed high OPR NO_x emissions to rise faster than the reduction technology could keep pace with. Although this is easier to see with hindsight, it does indicate the dangers of pursuing a single minded long term goal without periodic reviews to identify any perverse or linked effects.

5.7.3 Therefore can $NO_x : CO_2$ Trade-offs be ignored for future regulations?

The short answer is no! As was described in Section 5.7.1, at the fundamental level there is an inverse link between the production of CO_2 and NO_x. If the thermal efficiency of an engine core is raised through higher core pressures and temperatures (increasing fuel efficiency/reducing CO_2), and all else is held equal, there will be a resulting rise in the mass of NO_x emitted. This might be referred to as the $NO_x : CO_2$ seesaw with, on the one side, NO_x regulations and standards bearing down on NO_x as against fuel price and payload/range pressures bearing down on CO_2.

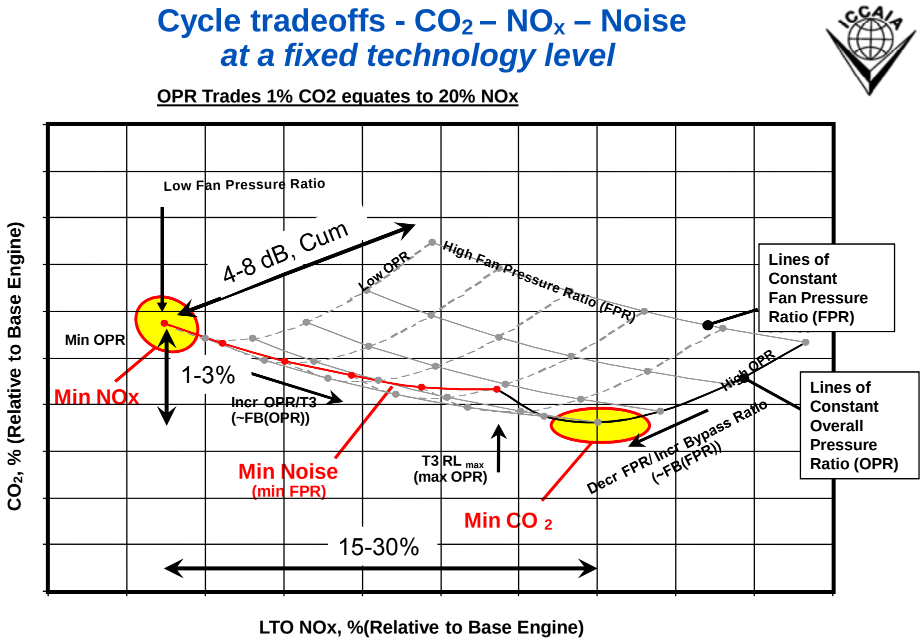
Therefore, at a given technology standard, if pressure builds on CO_2 reduction then NO_x will tend to rise, and conversely, if heavy pressure is exerted to reduce NO_x then CO_2 production will tend to rise. However, Section 5.7.1 also described that over time both of these emissions have been reduced concurrently and that this was due to improving NO_x control technologies coming on stream coupled with the emergence of higher OPR engines (as well as higher by-pass ratio). However, this success is slightly overstated as it must be borne in mind that engines with higher OPRs are permitted to produce more NO_x under the slope in the ICAO NO_x standards – see Figure 6.

With current high fuel prices and the forthcoming inclusion of aviation in the EU ETS there is an even higher incentive to reduce fuel burn and CO_2 emissions. This may result in the exploitation of the NO_x : CO_2 trade-off in new engines to the point where reduced climate impacts resulting from the inclusion of aviation in the ETS may be partly offset by increasing NO_x emissions.This situation would tend to the view that both CO_2 and NO_x need to be borne down on to avoid either one being adversely affected by pressures otherwise applied solely on the other.

Interestingly, given the presence of ICAO NO_x standards, which it has already been described inhibit backsliding on NO_x, this would appear to mean that, other than utilising the ICAO permitted NO_x vs. OPR slope, in extreme circumstances there is greater potential for a degradation in CO_2 performance rather than for CO_2 pressure to degrade NO_x performance.

Figure 14 below has been provided by ICCAIA and is similar to one incorporated into the ICAO LTTG Report. This shows that for a given technology standard minimising CO_2 may be adversely affected at the level of between 1 to 3% against a reduction of between 15 to 30% improvement in NO_x. If a single figure were to be chosen then the gearing might be summarised as 2% CO_2 penalty for a 20% NO_x improvement. The corresponding figure taken from the LTTG report would be a 2% CO_2 penalty for a 22% NO_x improvement – i.e. broadly similar. Trade off at these relatively high levels has been taken to indicate the dangers of forcing the pace on the regulation of NO_x, through such as standards, ahead of the availability of viable NO_x reduction technologies which, when available, permit both CO_2 and NO_x to be reduced.

Figure 14 Example carpet plot of engine cycle trade offs - CO_2/NO_x/Noise



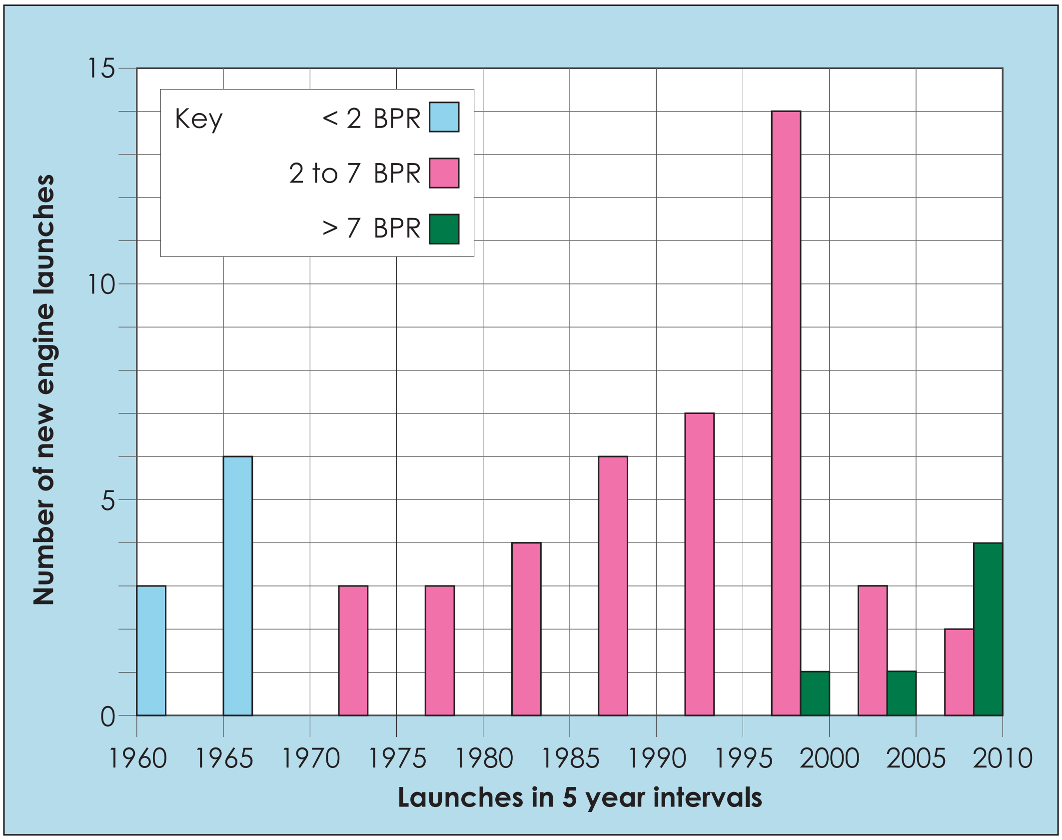
5.7.4 The Impact of Future Engine Technologies on CO_2 : NO_x Trade-off

Since the development some 40+ years ago of the Turbo-fan engine from the first generation of pure jet engines their progress has been characterised by two key trends, that of increasing by-pass ratio (BPR) and of overall pressure ratio (OPR). Both of these trends have been driven by the requirement for improved fuel burn – and reduced noise. Improved fuel burn has been achieved through improved propulsive efficiency provided by the front fan coupled with improvements in thermal efficiency achieved by making the (reducing sized) engine core work harder. Since the introduction of the by-pass engine these increases in BPR and OPR can be considered to have been gradual and progressive – evolutionary rather than revolutionary.

By-pass ratio has progressively increased

The numerical value of BPR reflects the proportion of the total air moved by the front fan of engine as compared with the proportion passing through the hot core of the engine (compressor, combustor and turbine) and which itself drives the front fan. Over the 40 years or so since the introduction of by-pass engines, values of BPR have risen from around 1 (i.e. equal flows through the fan and the core) to the highest values today of around 10:1 where approximately 1 part of the air passes through the core for every 10 passing through the front low pressure fan. Engine diameter increases with BPR in order for the fan to pull sufficient quantities of air. Figure 15 below illustrates the trend in BPR. Due to several competing factors related to aircraft mission, engine performance and physical size, the highest BPR engines tend to be on long haul wide-bodied aircraft whereas modern engines powering today's narrow-bodied fleet have maximum BPRs of around 5 or 6.

Figure 15 Long term trend in engine by-pass ratio



Future trend in BPR – possibilities for more radical change

As described above the past several decades have been characterised by a steady rise in BPR within the constraints of what might be termed conventional turbo-fan engines. However, there are today at least some possibilities for more radical change and recent very large rises in fuel price have certainly renewed interest in concepts that have been gently simmering for a considerable period of time. Two notable examples are the geared turbo-fan engine (GTF) and the open rotor (sometimes also called the propfan) engine.

Taking these in turn:

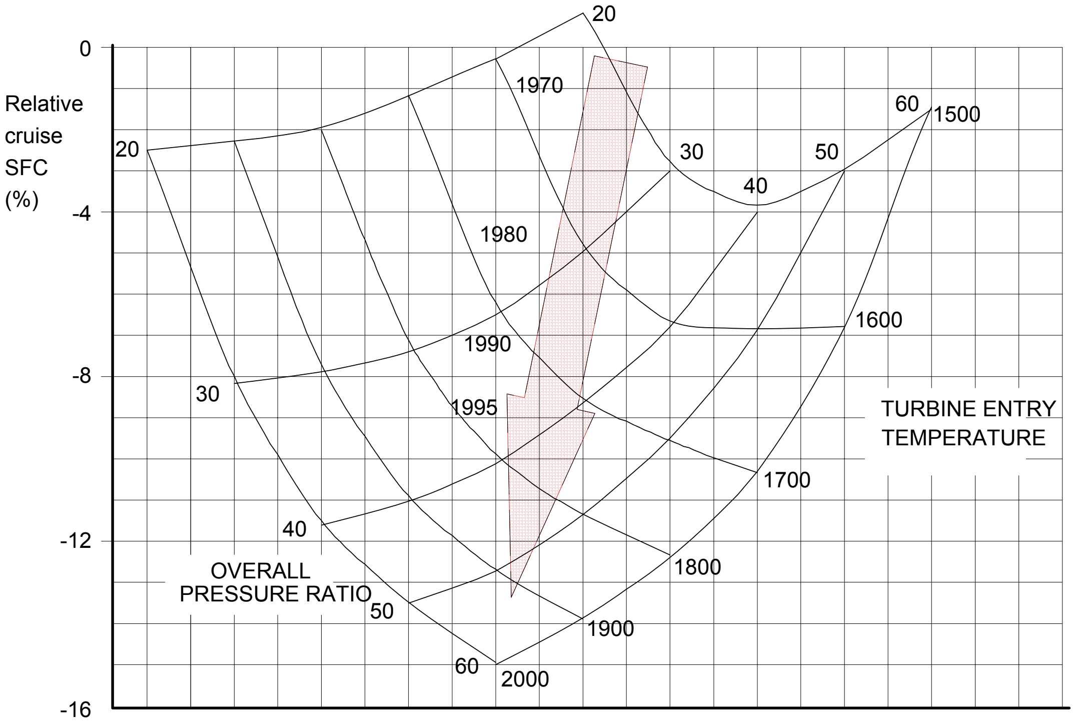
The essential difference between the GTF as compared with a conventional turbo-fan engine is the addition of a gearbox between the front fan and the turbine driving the fan. This will permit the BPR for engines for narrow-bodied aircraft to rise from around the present day value of 5 or 6, it is claimed, to a value around 10 to 12 (i.e. as good as today's best wide-bodied aircraft engine). The GTF is currently being designed around applications requiring up to around 30,000 lbs of thrust (nominally single aisle 150 seaters). In principle higher thrust GTF engines for wide-bodied aircraft might in time be envisaged though issues will arise related to gearbox weight and design for such high powers. As is intrinsically the case with increasing BPR, GTF engine diameter will be larger but in other respects outwardly it will have the appearance of a conventional turbo-fan engine.

The open rotor or propfan engine concept. Unlike the GTF, the open rotor will be strikingly different to today's turbofan arrangement. Its most striking feature will be that the fan case will have been removed and the fan itself replaced by immediately apparent large swept propeller-like blades. At the simple concept level the open rotor can be thought of as a turbo-fan where the BPR has risen to very high levels (several tens) and the cowl has therefore grown to an impossible diameter (weight and drag) and therefore has been dispensed with. In many senses this concept is closer to the turbo-propeller but with the swept blades enabling speeds and cruise altitudes closer to turbo-fans. It is likely such engines will employ a contra-rotating pair of blades. An apparent limitation will be maximum thrust size as even a mid thrust size engine suitable for 150 seaters will be likely to have a diameter close to 4 metres. There will be challenges related to en-route noise and engine placement but with anticipated significant fuel efficiency benefits. Considering NO_x, such will be the propulsive and core cycle characteristics that changes to NO_x production may be quite complex and it seems likely that changes to NO_x production may go in opposing directions at different stages of the flight envelope.

Overall Pressure Ratio has progressively increased

Coupled with increasing BPR, relatively, engine cores have reduced in size and been made to work harder as evidenced by the rising OPR trend. This has led to higher engine core working pressures and temperatures resulting in increases in engine thermal efficiency. Figure 16 illustrates this trend over time. OPRs have risen progressively to highest values today of 40+: 1 where today materials' temperature limits and limitations in cooling and modelling methods have slowed OPR growth.

Figure 16 Long term trend in engine OPR, TET, and cruise SFC



Future trend in OPR - possibilities for more radical change

In today's climate it may be hard to believe but it is less than 5 years ago that jet fuel was priced at less than one a US dollar a gallon, today it is above three dollars. The materials temperature limits discussed above require costly and complex solutions to help to encourage further increases in OPR (and temperature). At lower fuel prices the balance lay more towards favouring greater reliability and longer component life rather than in pushing very hard at the OPR limitations. At today's fuel prices, however, the balance has moved considerably further towards justifying attempts to move significantly further on OPR though this implies more complexity, for example, the use of intercoolers. This will also put further pressure on NO_x control technologies which may require their own step changes and certainly so if either the ACARE goals or CAEP's LTTG goals are to be realised – see Figure 7.

5.7.5 CO_2 : NO_x Trade-off at the whole aircraft level

At the engine level the trade-off between NO_x and CO_2 is contained within the thermodynamics and combustion chemistry of the engine itself. At the level of the whole aircraft this issue becomes yet more complicated as both aerodynamic and structural efficiencies also come in to play. For example, as has already been evident above when considering ICAO certification trends, it is perfectly possible (indeed not unusual) for an engine with improved efficiency through higher OPR to exhibit reduced fuel burn (reduced CO_2) but increased certification LTO NO_x. When this engine is then coupled with an airframe this airframe itself may have improvements in aerodynamic efficiency (lift/drag) and/or improvements in structural efficiency (reduced weight).

These airframe improvements combined will, for the same payload & range mission, result in a somewhat lighter airframe due to (somewhat) smaller wings and engines, having the effect of reducing fuel burn in flight and also of reducing the required thrust and therefore engine size or throttle setting. Such may be the scale of these reductions that the original higher NO_x production of the higher OPR engine may be more than offset by reductions in NO_x production resulting from savings due to these other factors.

In EI terms (Emissions Index – grams NO produced per kg of fuel burned), such a situation would result in an engine with a higher $EINO_x$ being fitted to a more efficient airframe with the overall result that at the level of the whole-aircraft, $EINO_x$ (or mass of NO_x produced per seat km) is reduced as compared with an aircraft/engine combination of a previous generation. The following sequence of three figures taken from Appendix A.2.6, demonstrate exactly this outturn. Working through these, Figure 17 shows a trend of increasing whole aircraft EI NO_x (g NO_x/kg Fuel) against entry into service date. Figure 18 illustrates the improvement in fuel efficiency with time due to a combination of both aircraft and engine improvements. When these two trends operate together Figure 19 shows the resulting fairly flat trend in mass of NO_x/SKO (seat kilometre offered) emitted with the growth in $EINO_x$ being almost exactly balanced by fuel efficiency improvements.

The ACARE goals, and even more CAEP's own Medium Term and Long Term NO_x technology goals, indicate that there is every prospect of further significant improvements in NO_x reduction technologies. If these LTTG Goals are achieved, coupled with potential fuel burn improvements, then on a per SKO basis significant reductions in mass NO_x emitted, even at high OPRs, may be achievable.

Figure 17 Whole aircraft EINO$_x$ versus Entry into Service Data - FAST 2000 Model

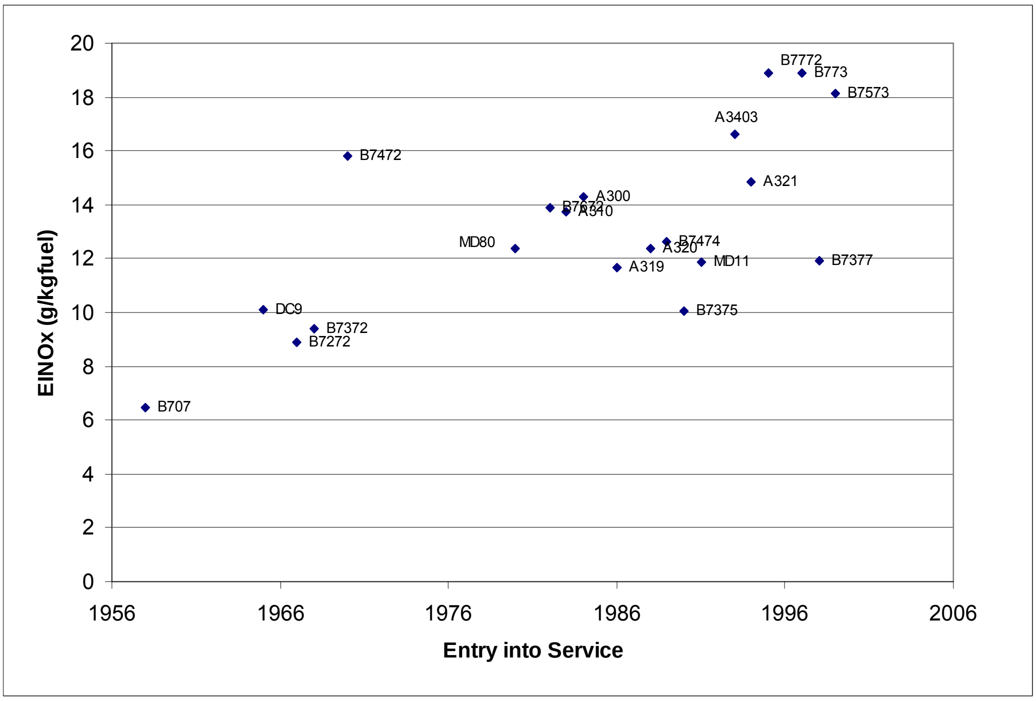


Figure 18 The rate of fuel efficiency improvement versus entry into service date - FAST 2000 model

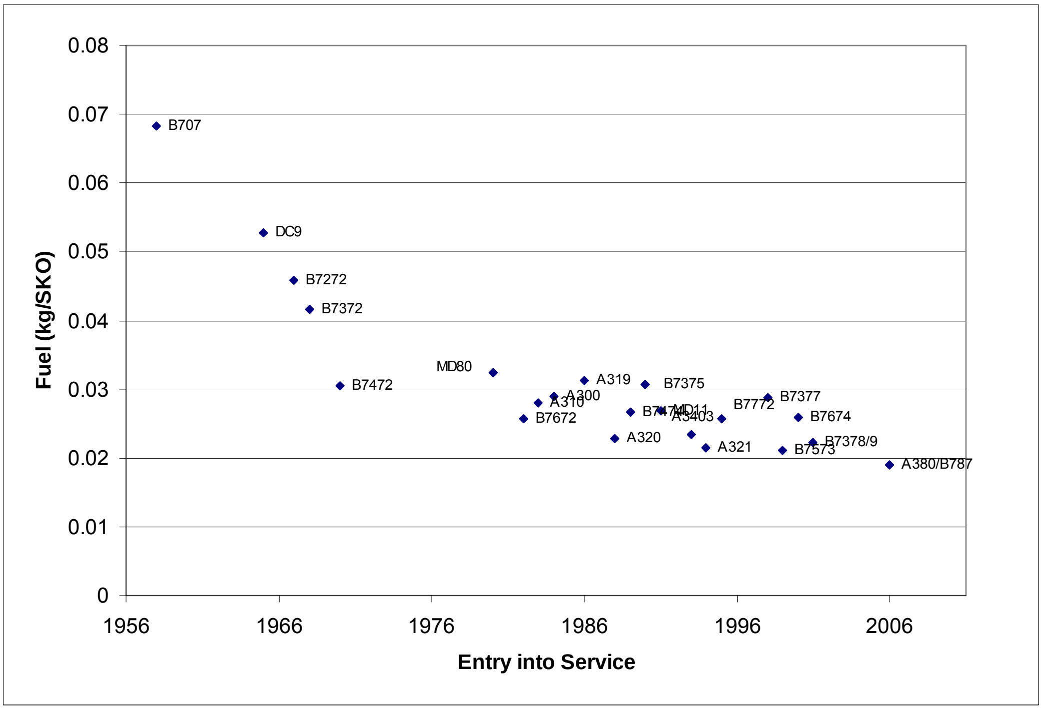
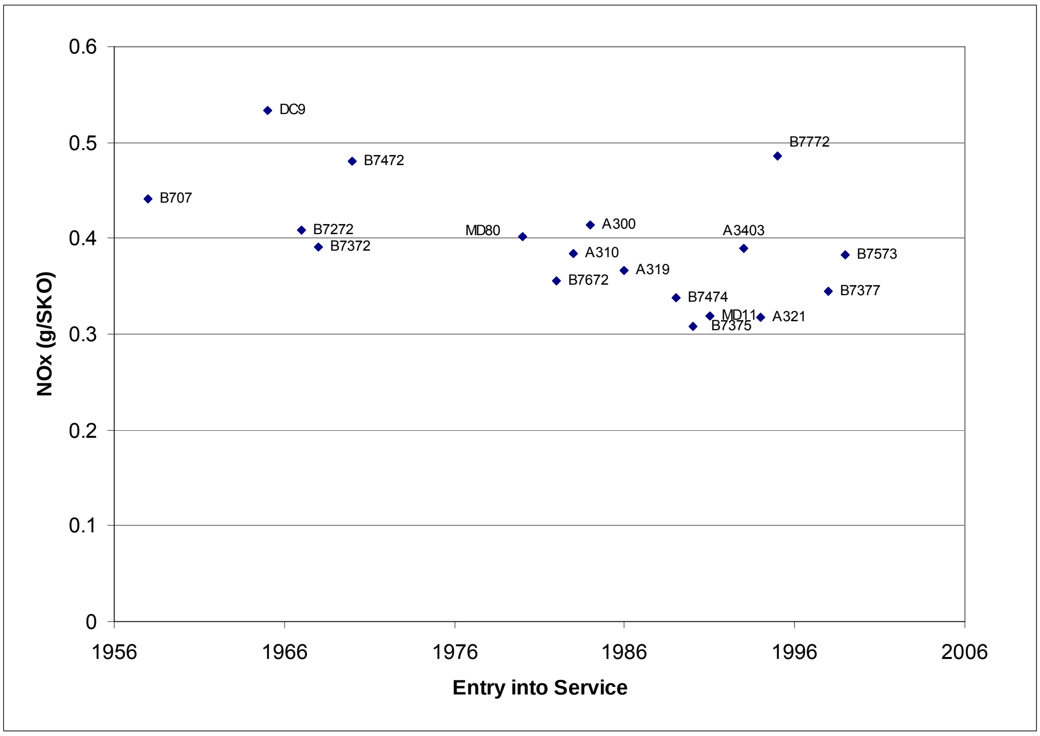


Figure 19 Mass of NO_x emitted resulting from the combination of growth in $EINO_x$ and decline in fuel burn - FAST 2000 model



5.7.6 NO_x : Noise Trade-off

From stakeholder discussions there does not appear to be a proven significant NO_x : Noise trade in the sense that reducing NO_x has not caused an increase in noise.

Any operational procedures requiring high thrust take-offs will have a relationship to increased NO_x, though in the more usual circumstances of reduced thrust take-offs both noise and NO_x will be reduced. In each of these cases, however, the effects will be felt at the local level. The ICAO LTTG 2007 NO_x Report made mention of a single example having been presented where minimising noise had apparently resulted in a 1.5% NO_x penalty, however, its overall conclusion similarly was that there appeared to be a relatively weak relationship though further study was recommended.

There are examples of indirect secondary trades between the mass of NO_x emitted and noise that may be significant in the context of the overall refinement of the aircraft/engine combination and possibly more relevant to altitude effects. For example, if greater noise stringency requires longer ducts or heavier acoustic absorbers, or if there is a thrust loss resulting from Chevron-type noise reduction (changing the shape of the rear of the engine then the increase in weight and/or loss of effective thrust would result in an increase in fuel burn which would in turn result in an increase in mass of NO_x emitted for a fixed $EINO_x$. Another future example would be if active boundary layer control came in to use with consequent thrust loss together with a mass increase. In such cases, for any given technology standard, the additional thrust required must be expected to increase, somewhat, the mass of NO_x produced. Nonetheless, the overall conclusion remains that in respect of NO_x there appears to be a relatively weak direct trade with noise.

5.8 LTO NO_x versus Cruise NO_x

For the purposes of controlling aircraft NO_x at cruise altitudes the ideal would be to have available a way of measuring real time NO_x produced during each flight. Unfortunately, we are far from this ideal. Not only is there no routine way of measuring real time Cruise NO_x but neither is there an agreed database of calculated Cruise NO_x production for each aircraft & engine combination let alone with the added complication of individual flight routings, distances and payloads.

Given this situation, this study has been faced with a choice of either recommending the creation of such a reference database using aircraft performance models to establish fuel flow and from which to calculate NO_x, or alternatively trying to work with an existing database which is available even if it does not contain exactly the cruise information needed. With this difficulty in mind considerable thought has been given to the suitability, or otherwise, of using the current ICAO LTO NO_x certification database which covers essentially all certificated turbo-jet and turbo-fan engines above 26.7 kN (6,000 lb) thrust. Given the certification nature of this database it has the distinct advantage that it is widely accepted and individual engine relative positions are not open to argument.

The major issue with using this internationally recognised dataset is that it is based on an idealized LTO cycle operating at altitudes only up to 3,000 feet (915 metres) and therefore it does not contain Cruise NO_x information. It should also be noted that turbo-prop aircraft are not covered by the ICAO LTO certification scheme (and neither are turbo-fans below 26.7kN (6,000 lbs)) so if they are to be included in any EU scheme additional data sources, will need to be found. Separately, there is a climate science question as to whether the impact of turbo-props is significant given their short range operations and lower cruise altitudes. Some more limited databanks do exist for turboprop LTO NO_x, for example, manufacturers have reported the corresponding data to Swedish Aeronautical Institute (FOI). FOI has published an interim database that, with the manufacturers consent, could be distributed to authorized parties. This database is currently used for inventory purposes and charging schemes at various airports.

The crucial question therefore is to what extent can this idealized but accepted LTO based database be used to address altitude/Cruise NO_x? Considerable effort has been undertaken within this study to address this question.

This same question has been the subject of extensive debate within ICAO CAEP for several years and despite attempts to devise recognised Cruise NO_x metrics and aircraft/engine EIs (emission indexes) none of these have as yet found general favour to the point of being adopted. Several of the stakeholders involved with this debate within CAEP have been interviewed, including the Rapporteur of the lead Working Group. Our clear understanding of the present position in CAEP is that the LTO NO_x procedure and databank is thought to provide a reasonable guide also to altitude NO_x.

This study is aware that there is some disquiet with using LTO based data to address altitude emissions. The key arguments can be summarised as follows:

- The LTO cycle is an idealized procedure carried out at static sea level conditions.
- The LTO cycle does not extend beyond 3,000 feet (915 m) altitude.
- The LTO to cruise relationship appears to work less well for families of engines where, what is termed, throttle push is taking place to certificate engines at greater thrusts - though it appears in these cases that it may be LTO NO_x that increases rapidly rather than altitude NO_x.
- The current possibly workable relationship between LTO and Cruise NO_x may not hold true in the future for all new combustor designs (e.g. lean burn engines), changed engine architectures (e.g. open rotor or propfan engines), and radical airframe designs (e.g. blended wing bodies).
- Airframe characteristics are not involved in the ICAO LTO engine certification and therefore differences between efficient and less efficient airframes will not register.

5.8.1 LTO NO_x : Cruise NO_x - Study Conclusions:

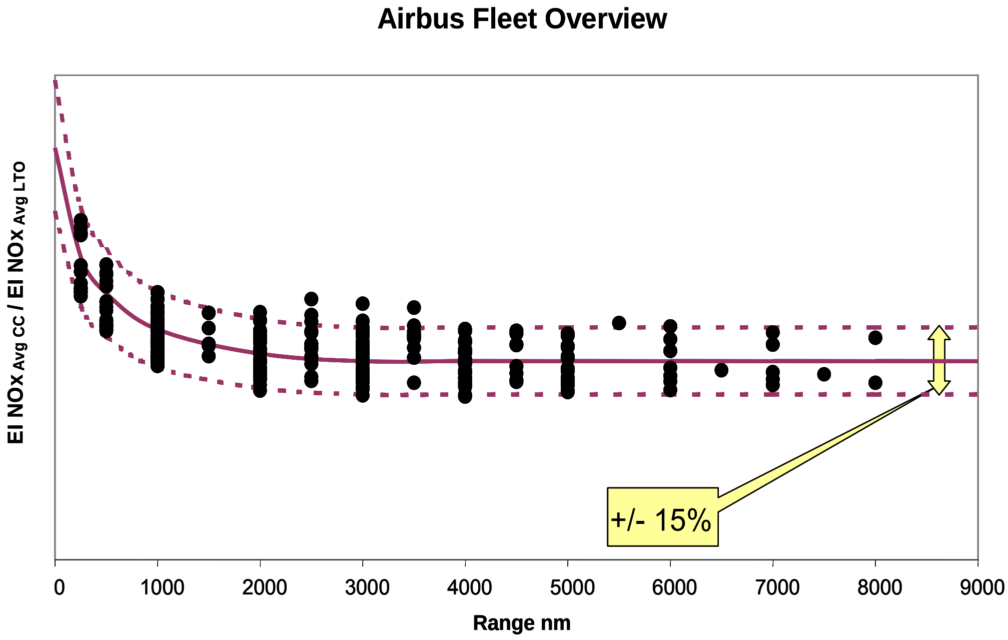
Current technologies:

In principle a database of all engine/aircraft combinations could be created from calculations of altitude NO_x. To do this most accurately would require engine temperature and pressure information – referred to as P3T3 methods – however, such information is commercially sensitive and therefore not freely available. Additionally, for greatest accuracy, information would be required on the payload, fuel load, wind and met conditions for every flight. Clearly such an approach would be hugely burdensome and therefore currently impractical.

An alternative would be to estimate for each aircraft/engine combination the fuel burn for given mission distances using commercially available software tools such as PIANO and using these results to estimate NO_x production using recognised and what are termed ‘fuel flow methods’, for example, Boeing or DLR. This would necessitate creating an accepted database of such estimations again for all aircraft/engine combinations and mission distances but would be subject to estimation errors and liable to dispute.

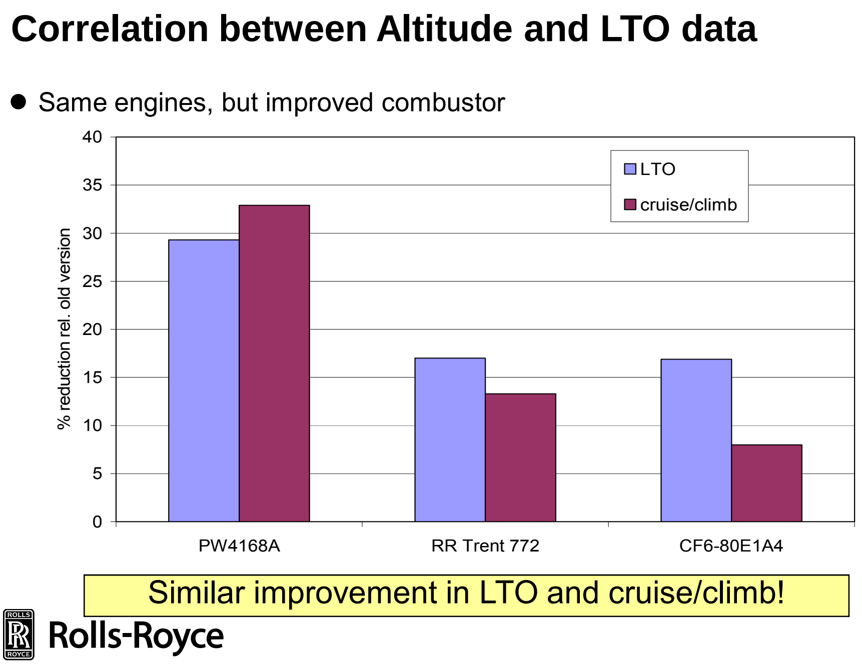
The study team found widespread industry support for using the existing ICAO certification LTO databank rather than creating something new and therefore careful consideration was given as to its suitability for addressing altitude NO_x. Several pieces of work relevant to this issue have been received within CAEP and Figure 20 is but one example presented by Airbus. This shows that industry believes that for all but the shortest ranges there is a good relationship to within +/- 15%.

Figure 20 Industry view of level of agreement between altitude NO_x and LTO NO_x



Within the CAEP community the measure of agreement between LTO Certification NO_x and altitude NO_x has been expressed in terms that if LTO NO_x increases then it is expected that Cruise NO_x would move similarly. It is not claimed that the relative altitude NO_x characteristics of all engines would be accurately reflected but that as a general rule it is acceptable. Figure 21 provided by ICCAIA illustrates some of this variability.

Figure 21 Industry chart showing similarity between improvements in LTO NO_x : Altitude NO_x



Work was undertaken within this study to further examine the strength of this correlation using the Piano aircraft performance tool and the DLR fuel flow method. This appeared to indicate a potentially greater spread than that in Figure 20. Further analysis suggested this effect was related more to families of engines where throttle push was being used and where in such cases LTO NO_x rose to a much greater extent than did altitude NO_x, However, data limitations on engine fuel flow and mission aircraft weights precluded further analysis and may have themselves caused some of the apparent spread.

A considerable body of analysis was completed for this study to further investigate the strength of the correlation between LTO and altitude NO_x. In summary it was concluded that there is a reasonably good correlation between the mass of NO_x calculated from the LTO cycle (including the effect of multiple engines) and when multiplied by mission distance as compared with the mass of altitude NO_x estimated from aircraft performance models and NO_x estimation (fuel flow) models. Details of these calculations together with the detailed statistical analysis can be found at Appendix H.

Future Technologies – will the LTO : Cruise relationship hold?

The short answer is possibly not. Various technologies have been discussed in the preceding pages and many of them hold the possibility of changing not only the NO_x : CO_2 trade-off as already discussed but also of changing the relationship between LTO NO_x and altitude NO_x. This finding should not be a surprise as it repeats the broad conclusions of CAEP’s LTTG review.

The technologies that may potentially be responsible for changing the current relationship are by no means limited to the combustor though here also there are question marks over the not too distant future. Lean Burn staged combustors currently in development cannot automatically be assumed to maintain today's relationship. These combustors appear to offer the possibility of optimizing the cruise condition in its own right and hold the prospect at least of possibly improving cruise NO_x performance though this begs the crucial question of where the pressure for this optimisation will come from in a solely LTO certification world.

Furthemore, radical engine architectural changes, for example the open rotor with a huge increase in BPR, again hold the prospect of significant change. In this case the changes are likely to be complex with the potential at least for significant reductions in LTO NO_x but coupled with a possible increase in cruise $EINO_x$ though given the expected fuel burn improvement overall cruise mass NO_x may still show a reduction.

Even possible airframe changes may require study in respect of LTO to Cruise NO_x. More radical potential changes such as (forced) laminar flow or the development of a blended wing bodied aircraft seem likely to require study though in respect of future 'conventional' airframes there seems no reason to expect significant divergence caused by the airframe itself - though as described above a combustor change or change in engine architecture even on a conventional airframe are likely to change the relationship.

The conclusion of this study is that while today there is a reasonable correlation between LTO NO_x : Altitude NO_x future (even relatively near term) technologies do hold the potential for significant change to this relationship. These future technologies will need to be monitored to ensure the relationship holds or is, if necessary, adjusted. ICAO CAEP's LTTG process offers the prospect of regular review though a specific monitoring process has yet to be developed.

6 Policy options

The policy options studied in this report have been selected in a two stage process. First, a long list of conceivable policy options has been drafted. After a broad evaluation and consultation with stakeholders, five options have been selected for further design and evaluation.

This chapter presents the long list of options in Section 6.1. The selection of the five options is described in Section 6.2. Sections 6.3 through 6.8 describe the design of the selected options.

6.1 Comprehensive list of policy options

A comprehensive list of policy measures was drafted, categorising them in four groups:

1 Standards of emissions at source.
2 Operational procedures to reduce NO_x emissions.
3 Economic and financial incentives.
4 Miscellaneous.

Specifically, the long list included the following policy measures.

1 Standards of emissions at source

- a **EU push for increased stringency of existing ICAO standards for LTO NO_x emissions of new engines**; the EU intensifies its efforts to argue for increased stringency of ICAO standards.
- b **EU action for the introduction of ICAO standards for cruise emissions for new aircraft or engines**; the EU starts to press for the introduction of ICAO standards for cruise emissions, either NO_x or NO_x and CO_2 combined.
- c **EU LTO NO_x emission standards for engines or aircraft newly registered in EU Member States or operated on flights to and from EU airports**; the EU agrees on standards for engine or aircraft LTO NO_x emissions that are more stringent than current ICAO standards.
- d **EU cruise NO_x emission standards for engines or aircraft newly registered in EU Member States or operated on flights to and from EU airports**; the EU agrees on standards for engine or aircraft cruise NO_x emissions.
- e **A phase-out of the worst performing engines on EU registered aircraft or on aircraft operated on flights to and from EU airports, followed by a ban**; the EU agrees to ban aircraft with engines surpassing certain emission standards from registering in EU member states or from landing at EU airports after a phase-out period.

2 **Operational procedures to reduce NO_x emissions**

a **Strengthen implementation of the Single European Sky**; the EU implements measures ensuring efficiency improvements in the European air traffic management system, thereby reducing detours on flights in EU airspace. This would reduce all emissions, including NO_x. This is already part of the comprehensive approach to addressing aviation emissions set out in the Commission's Communication in 2005 (COM (2005)459 final).

b **Climate-optimised air traffic management - flying at altitudes or routes that minimise NO_x emissions, contrail formation and CO_2 emissions)**; the EU implements air traffic management procedures for the entire flight aimed at reducing the climate impact of flights, e.g. by changing altitudes and flying around supersaturated areas in which contrails form, or increased use of continuous descent approach.

3 **Economic and financial incentives**

a **EU-wide differentiation of existing charges according to LTO NO_x emissions or EU LTO NO_x charge**; the EU implements a scheme for the differentiation of charges related to aviation (be it ATM charges, airport charges or government charges) based on NO_x emissions, either LTO NO_x emissions or cruise NO_x emissions. Or the EU implements a LTO NO_x charge, the revenue of which could be used for offsetting or for R&D.

b **EU NO_x en route charges or performance incentive**; the EU implements en route charges for cruise NO_x emissions, be it for flights to and/or from or between EU airports, flights in EU airspace or any other flights within the jurisdiction of EU Member States. The revenue could be used in a number of ways. A performance incentive would not have revenue, since it is a revenue-neutral charge-subsidy system, which may be based upon absolute emission levels or relative criteria such as emissions per RTK, or load factor related.

c **Inclusion of aviation NO_x emissions in the EU ETS**; the EU creates allowances for aviation NO_x emissions that can be traded against CO_2 emission allowances; aircraft operators would need to surrender NO_x allowances in addition to CO_2 allowances for flights to and from EU airports.

d **Introduction of a multiplier for aviation in the EU ETS**; aircraft operators surrendering EU emission allowances (EUAs) to cover their emissions under the EU ETS would be required to surrender more than one EUA for each tonne of CO_2 emitted in order to reflect aviation's non-CO_2 climate impact; the multiplier could be general or aircraft specific.

e **Introduction of a NO_x emission trading system**; aircraft NO_x emissions would be included in an emission trading system for NO_x, which could extend to other sectors.

f **NO_x emissions are included as criterion in airport slot allocation rules;** this way the use of low-NO_x aircraft could be rewarded through preferential access to or advantages in obtaining slots at congested airports.

4 Miscellaneous

a **Voluntary agreements with aircraft engine manufacturers and/or airframe manufacturers and/or aircraft operators on NO$_x$ emissions from engines**; the EU enters into an agreement with aircraft engine manufacturers and/or airframe manufacturers and/or aircraft operators to reduce the NO$_x$ emissions from engines or the emissions per LTO or per passenger or per revenue tonne kilometre according to a specified time path, such as for example set in ACARE's technology goals.

b **Further funding of research into:**

- **Reduction of NO$_x$ emissions from engines**; the EU increases its funding of aircraft engine research and emphasises the reduction of NO$_x$ emissions.
- **Reduction of NO$_x$ emissions or climate impact by changing operational procedures**; the EU increases its funding of air traffic management research and emphasises the reduction of NO$_x$ emissions or climate impact.
- **Best practices to reduce NO$_x$ emissions during flights**; the EU funds a study into the best practices of reducing NO$_x$ emissions during flights and facilitates the dissemination of the findings to the relevant stakeholders.

Giving higher priority to aeronautics research is already part of the comprehensive approach to addressing aviation emissions set out in the Commission's Communication in 2005 (COM (2005)459 final.

6.2 Selection of options

A broad evaluation and a stakeholder consultation led to the selection of two groups of policies and the decision not to study a third group.

The first group of policy measures was found to hold potential for limiting or reducing NO$_x$ emissions, but the policies, however desirable, do not qualify in the context of this study as primarily addressing NO$_x$ or they do not qualify as additional legislation. They include:

- Implementing the Single European Sky.
- Funding of research.

These policies have not been selected for further design and evaluation for a number of reasons:

- To propose a design for these policies within the scope of this project would be inappropriate, as for example the design of policies to implement the Single European Sky is the purpose of SESAR.
- Both SES and funding of research are existing policies. As such, they can hardly qualify as the 'proposal to address the nitrogen oxide emissions from aviation' that the Commission promised to issue in 2008.
- SES does not target aviation NO$_x$ emissions. Rather, it aims at eliminating inefficiencies in the air traffic management system. As a result, fuel burn will be reduced and NO$_x$ emissions will be reduced proportionally. The trade-off between NO$_x$ and CO$_2$ in engine design will not be affected, however.

Furthermore, aviation being a competitive industry, the cost reductions induced by SES will be passed through to the customers, triggering a rise in demand and partially offsetting some of the environmental gains.

The second group was found to be effective in limiting or reducing aviation NO_x emissions, legally feasible, would not encounter severe data problems, would be feasible to implement, and could be designed in such a way as not to distort competition. These are:

1 An LTO NO_x charge.
2 An LTO NO_x charge with a distance factor.
3 A NO_x en route charge.
4 Including aviation NOx allowances in the EU ETS.
5 LTO NO_x emission standards, either issued by the EU or by ICAO following concerted EU action.

To these options a politically relevant sixth has been added, viz. the multiplier as proposed by the European Parliament (P6_TA(2007)0505)[17].

6 A precautionary emissions multiplier.

Other options included in the long list were discarded for the following reasons:

- Options involving cruise NO_x stringency were discarded because there is currently no agreed metric for cruise NO_x emissions nor an agreed method for measuring these. However, it is conceivable that the current relation between LTO NO_x emissions and cruise NO_x emissions may break down (see Chapter 5). Therefore, it is recommended to monitor the relation between cruise NO_x and LTO NO_x.
- A phase-out of dirty engines could be prohibitively costly, as the trend in cruise NO_x emissions per seat kilometre is almost flat. This means that such a policy might imply scrapping new engines with a high residual value, if the criterion would be emissions per SKO, or, if the basis would be CAEP standards, would have very little environmental impact.
- Operational measures such as climate-optimised air traffic management are not feasible at the moment because scientific knowledge in this area is immature.
- Inclusion of a NO_x criterion in slot allocation rules would introduce inefficiencies in the use of slot co-ordinated airports and have welfare costs. Furthermore, it could encounter legal obstacles.

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[17] As long as there are no Community measures which incentivise the reduction of releases of nitrogen oxides from aircraft (…) and which ensure the same ambitious level regarding the protection of the environment as this Directive, (…) the amount of carbon dioxide which an allowance, other than an aviation emissions allowance, or a CER or ERU permits an aircraft operator to emit shall be divided by an impact factor of 2.

6.3 Design of the LTO NO_x charge

An LTO NO_x charge as currently implemented at several European airports primarily targets local air quality. Thus its impact on cruise emissions would normally be considered a co-benefit, but since LTO NO_x emissions and cruise NO_x emissions seem to be aligned in most current technology cases[18], policies that would reduce LTO NO_x would also reduce cruise NO_x. An LTO NO_x charge can thus in this context be seen as a surrogate climate change charge.

The basis of the charge would be the mass of LTO NO_x emissions calculated according to ECAC/ERLIG method[19]. For the calculation of the charge, the ICAO engine emission databank would be used for the large jet engines (>26.7 kN rated output) which power most commercial airliners and regional jets; and the ICCAIA/FOI database for turboprops. Depending on the MTOW threshold for charging, there may be need for an additional database for small jets, although FAA data referenced by ICAO includes some common business jet engines.

The level of the charge per kg of NO_x would be set at the local air quality (LAQ) damage costs of NO_x, in line with established EU policy to internalise external costs, and would thus vary in different Member States. The charge would be levied on aircraft operators by all EU airports, in order to align the geographical scope with the scope of the EU ETS.

Revenue neutrality, if desired, could be achieved either by a simultaneous introduction of the charge and a reduction of landing fees, or by a separate account to which higher-than-average-emitters pay a charge and from which lower-than-average-emitters receive a bonus. The advantage of the former would be that the charge could be made revenue neutral for each aircraft size category since airport fees usually have a weight dependent element and a reduction across the board with a fixed percentage would mean a larger absolute reduction for large aircraft, which also would have to pay the highest NO_x charges. In this way, the most polluting aircraft in each size category would be worse off while the least polluting would be better off. In contrast, the latter (average-based) method for ensuring revenue-neutrality would mean a transfer of funds from large to small aircraft. Both methods would require regular review of the bonus/malus break point at each airport, to maintain such neutrality.

Anecdotal experience, and limited CAEP investigation, would suggest that the effectiveness of an LTO NO_x charge at the LAQ damage cost internalisation level proposed would be marginal, in terms of influencing manufacturer or airline action to reduce emissions. However, these conclusions are based on a situation where a limited number of airports have introduced charges. The higher the

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[18] Future engine design developments could result in the breakdown of this relationship, which should therefore be kept under review.

[19] This broadly correlates with the ICAO Simple Approach, using standard times in mode (TIM) and thrust settings. In the longer term, given international agreement, ICAO Advanced and Sophisticated Approaches respectively using, for example, airport-specific TIM and thrust settings, could provide more accurate measurements, also incentivising operational measures to reduce emissions.

number of airports with charges, the larger the incentive for engine manufacturers to design low NO_x engines.

6.4 Design of the LTO NO_x charge with distance factor

For current engine technology, there appears to be a robust relationship between emissions of NO_x that occur during the standard landing-takeoff cycle (LTO) and those that occur during the cruise phase.
As cruise NO_x emissions are difficult to calculate accurately without access to proprietary P3T3 models and even more difficult to establish empirically, they could be approximated by LTO NO_x emissions. The way this could be done is to assume that there is a correlation between $EINO_x$ in the LTO phase and $EINO_x$ in the cruise phase. If one furthermore assumes that fuel burn in LTO is correlated to fuel burn in cruise, and that fuel burn correlates with distance flown, one could approximate NO_x emissions aircraft i on mission j during a flight by:

$$TOTNOx_{i,j} = \beta \times LTONOx_i \times D_j$$

Where

- $TOTNOx_{i,j}$ is the total NO_x emissions for aircraft *i* on mission *j* in mass units.
- β is the co-efficient of correlation between LTO NO_x emissions times a distance factor and cruise NO_x emissions (per unit of distance).
- LTO NO_{xi} is the mass of the LTO NO_x emissions of aircraft *i* (in mass units).
- D_j is the distance of mission *j* (in distance units).

A charge could then be implemented on the total NO_x emissions. The basic formula for this charge for aircraft i on mission j would be:

$$C_{i,j} = \alpha_{C\lim NOx} \times \beta \times LTONOx_i \times D_j$$

Where

- $C_{i,j}$ is the charge for aircraft *i* on mission *j* in Euro.
- $\alpha_{ClimNOx}$ is the charge level in Euro per unit of mass, set at the monetary value of the climate impact of NO_x (in Euro).
- β is the co-efficient of correlation between LTO NO_x emissions times a distance factor and cruise NO_x emissions (per unit of distance).
- LTO NO_{xi} is the mass of the LTO NO_x emissions of aircraft *i* (in mass units).
- D_j is the distance of mission *j* (in distance units).

Each of the parameters will be discussed below.

The level of the charge would be related to the climate damage costs of NO_x, being the global warming potential (GWP) of NO_x times the damage cost of CO_2. Section 4.4 discusses the NO_x GWP estimates and concludes that a concerted effort of the scientific community is needed to establish one. At this point in time, all that can be said is that a value will probably be in the range between 1 and 130. As for the damage costs of CO_2, this study has chosen to approximate these by the price of emission allowances in the EU ETS. Although this is clearly not a valid assumption from a methodological point of view (the price of allowances reflect the marginal prevention cost rather than the marginal social cost), this approximation is justified by looking at the aim of this policy instrument, i.e. to avoid the exploitation of the NO_x : CO_2 trade-off in engine design to the point that increased NO_x emissions would offset reductions in CO_2. Including aviation in the EU ETS means that CO_2 is valued at the EU ETS allowance price. By valuing NO_x at this price times the GWP, the relative costs of NO_x and CO_2 have the right value, even though the absolute costs may not internalise all externalities.

The co-efficient of correlation can be determined empirically with sufficient accuracy to serve as a basis for a charge (see Appendix H). It can either be aircraft specific or fleet average. In the former case, calculating the co-efficient of correlation would imply performing the calculations outlined in Appendix H for every aircraft type in Europe. This is beyond the scope of this project, but not immensely complicated or time consuming. In the latter case, the co-efficient of correlation would depend on the fleet within the geographical scope and the route network. This would mean that the co-efficient can be determined by analysing a weighted sample of data on LTO NO_x and cruise NO_x for the most widely applied aircraft-engine combinations.

The mass of LTO NO_x emissions would be calculated according to ECAC/ERLIG method (see Section 6.3). The best way to account or distance would be a continuous distance metric based on great circle distance (GCD) between airport pairs.

The basic administrative arrangements comprise three steps:

1 Monitoring the basis for the charge, i.e. LTO NO_x × GCD for every flight.
2 Levying the charge.
3 Recycling the revenue (if desired).

If revenues needed to be recycled, it could be done in a number of ways. A direct reimbursement to aircraft operators would be a clear possibility, as would funding of R&D and climate-related spending by states. At the higher end of the estimates, the sums involved would be high enough to warrant the recycling of revenue in more than one way.

The administrative burden would be lowest if as many steps of the administrative arrangements are dealt with in the same organisation. Every exchange of information or funds between organisations adds administrative complexity to the issue. On the basis of this consideration, we think that it would be best to assign the task of levying the charge to EUROCONTROL. This organisation has all the necessary data for calculating the charge in the major part of the EU Airspace. Moreover, it has well-established financial agreements with most aircraft operators active in this airspace. For a revenue raising charge, EUROCONTROL could reimburse the revenues to the Member States, for example proportional to the number of MTOW km by flights to and from airports in these states. For a revenue neutral charge, EUROCONTROL could recycle the revenue to aircraft operators on the same basis or proportional to the share of RTKs of these operators.

6.5 Design of the cruise NO_x charge

Of all the policy instruments selected, a cruise NO_x charge would be aimed at cruise NO_x emissions and thus the climate impact of aviation NO_x most directly provided that cruise NO_x emissions could be monitored accurately. However, they cannot. And although in principle they could be calculated reasonably well per flight using P3T3 methods, these calculations would require both confidential information from aircraft operators on fuel flow and proprietary information from engine manufacturers on combustor temperatures.

Alternatively, the Boeing 'Fuel Flow Method 2' (BFFM2) can be used to calculate emissions (DuBois and Paynter, 2006)[20]. The BFFM2 requires mainly information which is publicly available, and does not rely on proprietary information. Although not as rigorous as the P3T3 method, it gives a reasonable approximation, especially for NO_x emissions (in the order of +/-10 to15% of the P3T3 method). The only data lacking for calculating NO_x would be the fuel flow. This could be calculated with reasonable accuracy using aircraft performance models such as PIANO though these are more capable for established aircraft types than for new aircraft/engine combinations.

With these calculations, a database could be established with cruise NO_x emissions per aircraft type over a range of distances. Each flight under the system could be assigned a value of NO_x emissions from the database. A charge could be levied based on the emissions and their climate damage costs, calculated in the same way as in the LTO charge with a distance factor (see Section 6.4 and Appendix C.2.1).

The administration of the cruise NO_x charge could be organised in the same way as the LTO NO_x charge with a distance factor (see Section 6.4). Charges could be collected by EUROCONTROL, provided that the EU enters in to an agreement with EUROCONTROL to do so. EUROCONTROL could either reimburse the charges to Member States or recycle it to aircraft operators.

6.6 Design of the inclusion of aviation NO_x emissions in the EU ETS

Inclusion of aviation NO_x emissions in the EU ETS would allow the internalisation of the full climate impact of aviation engine emissions and incentivise aircraft operators and engine manufacturers to reduce it and to design engines to have the minimal combined impact.

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[20] DuBois and Paynter (2006), 'Fuel Flow Method2' for Estimating Aircraft Emissions, SAE Technical Paper Series, no 2006-01-1987, ISSN 0148-7191, Warrendale, US, 2006.

It requires extending the scope of the EU ETS to include emissions of gases with indirect climate impacts, specifically aviation NO_x. Based on the GWP of aviation NO_x, the amount of NO_x that may be emitted per allowance can be established by the formula:

$$Mass - of - NO_x = \frac{1000}{GWP_{NO_x}} (kg)$$

The amount of NO_x for which allowances have to be surrendered can be calculated in the same way as the basis of the LTO NO_x charge with a distance factor:

$$TOTNOx_{i,j} = \beta \times LTONOx_i \times D_j$$

Where
- $TOTNOx_{i,j}$ is the total NO_x emissions for aircraft *i* on mission *j* in mass units.
- β is the co-efficient of correlation between LTO NO_x emissions times a distance factor and cruise NO_x emissions (per unit of distance).
- LTO NO_{xi} is the mass of the LTO NO_x emissions of aircraft *i* (in mass units).
- D_j is the distance of mission *j* (in distance units).

A historical baseline can be calculated for total aviation NO_x emissions in the geographical scope of the EU ETS for each year or set of years for which data are available on aircraft/engine combinations and great circle distances of flights in the system. EUROCONTROL currently has these data for all recent years.

The administration of the inclusion of aviation NO_x emissions in the EU ETS can be organised in the same way as the inclusion of aviation's CO_2 emissions. Moreover, all other design elements would be the same.

6.7 Design of standards

The relevant parameters in the design of options are as follows:
- Level of stringency.
- Slope of the line.
- Implementation date.
- Applicability to large and small engines.
- Geographical scope.
- Inclusion of production cut-off.

The review of stringency standards by CAEP and their progressive tightening on a regular basis (roughly every 6 years) is against the backdrop of continuing technical progress into the future, illustrated by the CAEP NO_x goals assessment. However it is generally recognised that ICAO NO_x standards have not been technology forcing, with their main role being to prevent regression of combustor technology. This is illustrated by the fact that, despite the problems mentioned above with some large engines in production meeting tighter stringency standards, the most recent engines have been certificated with a margin of 5 to 20% below the CAEP/6 standard. Since ICAO standards require international agreement, it may only be possible to set more aggressive standards at the EU level.

This study considers ICAO standards with a stringency increase up to 20%. Consideration was given as to whether standards should be accompanied by a production cut-off, but this was rejected on the ground that there is evidence to indicate that the assumption used for analysis of stringency standards in ICAO, that market forces will result in non-compliant engines being produced after the date of implementation.

The level of the stringency could be based on cost-effectiveness considerations. These are analysed in Section 7.6. Although these figures are provisional and subject to review as CAEP/8 is currently conducting a more thorough analysis, it seems that the cost-effectiveness of CAEP/6 -10% is the best, although the cost effectiveness of CAEP/6 -20% is less than twice as expensive per kg of NO_x, which could be within the confidence range of these preliminary calculations.

6.7.1 EU LTO emissions standards?

LTO NO_x emissions standards introduced by the EU could in theory lead to larger and quicker environmental benefits than ICAO standards, and may provide a de facto global standard if they influence the behaviour of non-EU manufacturers. If the costs of meeting EU standards would exceed ICAO standards by a modest margin, it seems likely that engine manufacturers would react by designing many of their engines to meet these tighter standards, as the cost of maintaining two sets of engines compliant with different standards would be too high.

EU standards could lead to distortions of competition to the disadvantage of European manufacturers, though this would be limited in the absence of a production cut-off and insofar as non-EU manufacturers designed engines in compliance with these tighter standards. In addition with EU standards likely to apply to aircraft registered in the EU, there is the risk of distortion of airline competition, particularly on those routes where EU and non-EU carriers are competing head-to-head. Airlines may also suffer indirect effects through loss of second values of their existing fleets. Global environmental benefits of NO_x standards set by the EU are likely to be relatively small and could be further eroded if these measures had the effect of displacing the problem to other parts of the world. However they will be larger if an EU standard becomes a de facto global standard.
EASA could be the agency responsible for implementing, monitoring and enforcing standards, as it approves engines types that are introduced to the market. All aircraft registered in EU states need to have EASA type approval for the engines fitted on the aircraft. The current environmental essential requirements, as stated in the EASA Basic Regulation (2002/1592), directly references the ICAO Annex 16 requirements and thus it is not possible to implement stricter standards. However EASA has published an Notice of Proposed Amendment (NPA) on Friday 30th May which includes proposals to revise the essential requirements and provide flexibility to deviate from these if

the EU wished to do so. In designing an EU standard that exceeded those set by ICAO, consideration would need to be given on the competitive reaction to regional standards and the legal compatibility with the Chicago Convention. Our view is that engine manufacturers worldwide might be expected to respond to design engines to meet tighter EU standards, provided that the cost of doing so would be less than the cost of exiting the market or manufacturing two sets of engines compliant with different standards.

An analysis of preliminary CAEP/8 data on engines shows that the number of engine families affected by tighter standards and the estimated costs of the technological modifications would not increase much between a stringency increase of -5% and -10% (or even -15% but then only with a slope of 2.2). However, above these values the number of engines families needing modifications and also needing major modifications would rise sharply. As a result, the costs for engine manufacturers of meeting these higher standards would rise significantly. The non-recurring costs would rise from € 320 mln - € 682 mln to up to € 2,358 mln if stringency were increased from -10 to -15% (see Appendix E.2). This would increase the incentive for engine manufacturers to exit the EU market or to manufacture two sets of engines compliant with different standards. Therefore, we consider it unlikely that the EU can set standards that would become de facto world standards, although it has to be stressed that this analysis is based on preliminary data.

6.8 Design of the precautionary emissions multiplier

Most design choices for the precautionary emissions multiplier would be identical to the design of the Commission's proposal to include aviation CO_2 in the EU ETS (COM(2006)818). The only difference would be the precautionary emissions multiplier. A factor can be established as a precautionary emissions multiplier, even though there would currently be no scientific basis for its value. In that case, aircraft operators would have to surrender either one aviation allowance or more than one other emission allowances (be they EU ETS allowances, ERUs or CERs) for each tonne of carbon they emit. This is in line with the P6_TA(2007)0505 proposal of the European Parliament noted in Section 6.2 of this study.

6.9 Conclusion

At present, only the LTO charge and the standards can be fully designed. For the other policy instruments, data and analysis are lacking:

- Both the LTO NO_x charge with a distance factor and the cruise NO_x charge suffer from the fact that there is no consensus value of NO_x GWP. Achieving such consensus would require the mobilisation of the scientific community. It could take around three years to arrive at a value if the different models yield similar results. If not, it could take longer.
- The charge on LTO NO_x with a distance factor currently lacks a correlation factor. The methodology used in this report was based on available data. A full analysis would need to select the most accurate method to calculate

cruise NO_x emissions. It would also need to include more aircraft and engine types and apply the values to the relevant fleet. To undertake this work, a technical committee could be set up along the lines of the committee that advised ECAC on the LTO NO_x charges. Such a committee should be able to agree on a correlation factor in a few years.

- The cruise NO_x charge requires the choice of models to calculate cruise emissions and the actual calculations. The model choice used in this report was based on availability rather than on a thorough analysis of the strengths of available models. We would recommend setting up a technical committee for model choice and model input. Again, such a committee should be able to reach conclusions in a few years.
- The value of the multiplier cannot be determined on scientific grounds. Therefore, this report cannot recommend a value. Any decision on such a value would be a political one.

7 Evaluation of policy options

This chapter evaluates the policy options designed in Chapter 6. After some general considerations applicable to all options in Section 7.1, Sections 7.2 through 7.7 evaluate the options on environmental impacts, the feasibility of implementation, legal issues, costs and cost-effectiveness, environmental trade-offs and impacts on markets or market segements. This chapter is a summary of more elaborate assessments in the Appendices D (on the impacts of market based instruments), E (on the impacts of standards) and F (on legal considerations).

7.1 Some general considerations

7.1.1 Revenue neutrality of environmental charges - the pros and cons

Internalising external costs by means of an environmental charge generates revenue. This revenue may not be the primary purpose of the charge, but since it inherently accrues, the question of the usage of the revenue arises. One aspect of the usage of the revenue is whether the charge is designed as being revenue neutral or non-revenue neutral. In a broad definition, a charge is revenue neutral if there is no net revenue because revenue generated from some actors is ringfenced to other actors in the scheme. In the following we will first go into the different kinds of revenue neutral and non-revenue neutral environmental charges, before turning to the advantages and disadvantages of these.

Revenue neutral and non-revenue neutral charges

Revenue neutral environmental charges

Environmental charges that are designed as being revenue neutral, might take different forms.

1. The revenue is recycled directly to the ones paying the charge, lump sum or via an allocation key. Example: The aircraft landing charges per MTOW are reduced when an LTO NO_x charge is being introduced.
2. The ones whose activity level is above-average have to pay a charge to those whose activity is below average and thus more environmentally friendly. This option corresponds to the definition of revenue neutrality in the narrow sense. Example: The average LTO NO_x emissions of aircraft at a certain airport are determined. The airlines pay a charge for every kg LTO NO_x that an aircraft emits more than the average and get a rebate for every kg LTO NO_x that an aircraft emits less than the average.

Non-revenue neutral environmental charges

Non-revenue neutral charges differ as to the entity that can decide on the use of the charge:

3 The revenue might be used for a purpose that is not directly connected with the activity upon which the charge is based. Example: A government reduces income taxes by means of the revenue of a LTO NO_x charge.

4 The revenue might be recycled indirectly to the ones paying the charge. Example: The revenue of a cruise NO_x charge is used to finance a research project to develop cleaner aircraft engines.

5 Revenue from a charge is part of a global budget of a government

6 Revenue from a charge is part of the budget of the collecting, non-political entity

Advantages and disadvantages of revenue neutral and non-revenue neutral charges

The advantages and disadvantages of the revenue neutral and non-revenue neutral environmental charges are discussed below. We look at the environmental effect of the charge, whether the charge implements the Polluter Pays Principle, the usage of the revenue and, closely related with this, the acceptability of the charge. Note that we assume that the supply side of the market is charged for the polluting activity.

Environmental effect

The environmental effect of a charge depends on changes of demand and supply in the market, on the abatement measures taken by the supplier (other than adapting supply), and on the effects that these changes have on pollution. Note that the scope of the demand and supply effects to be analysed depends on the pollutant under consideration. For a global pollutant the effects on global demand and supply have to be taken into account. For a local pollutant the effects on the demand and supply in the respective geographical entity have to be analysed.

The different design options do not always differ with respect to the effect that they have onto the supply on a market. They will however have different effects on the demand side of the market and probably also on the adaptation behaviour of the supplier with respect to the abatement measures.

If the charge raises revenue and is, at least partially, passed onto the consumers, it will have an effect on the demand side, at least, if demand is not completely inelastic. In contrast, revenue neutral charges will not impact on total demand, assuming that the suppliers that do not pay the charge are able to satisfy the demand of the consumers that no longer make use of the service of the suppliers paying the charge.

The timescale of adoption of abatement measures might be different for the different design options. This depends on the use of the revenue and on the total effect an option has on the budget of the supplier. If the revenue of a charge flows, for example, into an R&D project, a new abatement measure might become available sooner, than if the revenue had been used for reducing income taxes.

Polluter Pays Principle

The Polluter Pays Principle is a principle that postulates that the actor responsible for the pollution has to pay for it when it comes to the internalisation of the external costs of the pollution. Revenue neutral charges are not in line with the polluter pays principle. When revenue is ringfenced to a sector, it is a matter of debate whether it is compliant with the polluter pays principle. In fact, only options that raise revenue (options 3 through 6) are fully in line with the polluter pays principle (CE et al., 2002)[21].

Use of Revenue

Only under option 2 is the usage of the revenue automatically determined. For all other options the question of the use of the revenue arises. From an economic point of view, revenue should be used efficiently, in the sense that it should be so used that the welfare gain is maximised. Lowering distorting taxes by use of such revenue is an often quoted example in this context. Recycling revenue in R&D may provide a larger supply side response (Fullerton and Wolverton, 2005)[22], assuming that the inputs for R&D are unlimited (otherwise subsidies may end up as scarcity rents).

Not earmarking the revenue leads to the risk of government failure (government intervention resulting in less efficient allocation of resources, Buchanan 1962)[23], but earmarking also has its disadvantages. First, it might be difficult to agree on a compensation mode, especially if there are polluters from a variety of States. Earmarking further leads to less flexibility in the use of the revenue. Thirdly, if certain projects are being financed by the revenue, these might last inefficiently long. (CE et al., 2002)[24]. And fourthly, since distribution of the revenue has to be organised, the administrative costs of option 1, 2 and 4 are probably higher than those of the other options.

Acceptability to industry stakeholders

The acceptability to industry stakeholders of an environmental charge is in general higher if it is revenue neutral instead of being non-revenue neutral, in particular if the revenue of the charge is not being used by a political entity (option 6). Looking at the revenue-neutral options, the acceptability will largely depend on the compensation mode chosen.

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[21] CE Delft, ITA, IIASL, Peeters Advies, D. Greenwood and R. Doganis (2002), Economic incentives to mitigate greenhouse gas emissions from air transport in Europe.

[22] Fullerton, Don, and Ann Wolverton, 2005, 'The two-part instrument in a second-best world', Journal of Public Economics 89 (2005) 1961-1975.

[23] Buchanan, James M., ‘Politics, Policy, and the Pigovian Margins’, Economica 29 (February 1962): 17-28.

[24] CE Delft, ITA, IIASL, Peeters Advies, D. Greenwood and R. Doganis (2002), Economic incentives to mitigate greenhouse gas emissions from air transport in Europe.

7.1.2 Financial impacts of revenue raising charges

It has sometimes been argued that revenue raising charges would deprive actors of funds to invest in innovative technologies, and would thus reduce the environmental impact of a charge. Section 7.1.1 demonstrates that revenue raising charges induce a demand side effect in addition to a supply side effect, whereas a revenue neutral charge effectively only incentivises supply side responses. Since demand side effects may also have environmental impacts, the environmental impact of revenue neutral and revenue raising charges could differ. In addition to this argument, this section discusses the merits of the claim that supply side responses could be restricted by revenue raising charges.

In the debate about the inclusion of aviation in the EU ETS, a number of studies have looked into the issue of how ETS would affect aircraft operator's profits, profit margins, and the related question of how much of the costs incurred by aircraft operators could be passed on to customers (CE et al., 2005; PWC, 2005; Ernst & Young et al., 2007; CE, 2007)[25]. On the issue of cost pass through, these studies conclude almost without exception that expenditures will be passed on in ticket prices. PWC (2005) supports their theoretical argument with an econometric analysis of the passing on of changes in kerosene prices, which they find as total, albeit with a two year time lag. Ernst and Young (2007) concludes that costs will be passed on unless airlines operate in a monopoly or oligopoly market. In this case operators will not be able to pass on all the costs as some of the costs will be absorbed in their oligopoly rents.

If aircraft operators are able to pass on cost increases to their customers (unless they currently extract monopoly or oligopoly rents and thus make higher than normal profits anyway), their profit margin would not be affected by the introduction of financial instruments. Of course, there may be a transitional period during which operators would adjust to new circumstances, and in this period there may be a decrease in profit margins. PWC (2005) shows that this period is about two years for variations in fuel prices, which are unexpected, so the period is likely to be shorter for financial instruments that are announced well in advance. It may therefore be argued that profit margins per passenger or tonne of cargo will hardly be affected by the introduction of financial instruments, although there may be circumstances when charges can not be passed on immediately, even if announced in advance. For example if they were introduced during an industry downturn, there could be a short term impact on profits and funds available for investment.

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[25] CE, 2005, Giving wings to emission trading; CE, 2007. Allocation of allowances for aviation in the EU ETS; The impact on the profitability of the aviation sector under high levels of auctioning; CE Delft & MVA Consultancy, 2007, Implications of EU Emission Trading Scheme for Competition Between EU and Non-EU Airlines, Joint Report by CE Delft and MVA Consultancy, Draft Final Report for Directorate General for Trans-port and Civil Aviation, In Association with SEO Amsterdam; E&Y, 2007, Ernst & Young and York Aviation, 'Analysis of the EC proposal to include aviation activities in the Emission Trading Scheme', Brussels; PWC (Price Waterhouse Coopers), 2005, Aviation Emissions and Policy Instruments.

Even if profit margins per passenger or tonne of freight are unaffected, total profits will be affected by reduced demand. Could this dent the ability to invest? This is a difficult question to answer. On the one hand, the funds available from retained profits would be reduced, thus reducing the ability to invest. On the other hand, the business case for investment in clean technology would be strengthened by the financial instrument, thus improving access to the capital market. In summary, there is no evidence to support the argument that the environmental impact of revenue raising charges would be smaller than that of revenue neutral charges due to lower investment in clean technology, and this should not be used as an argument for or against revenue neutrality.

7.1.3 Environmental impact of revenue neutral charges

It has not been possible to model the environmental impact of revenue neutral charges with an acceptable degree of accuracy at the LAQ level, which is where it might most readily be observed. The AERO model is unable to capture all the possible supply-side responses to NO_x charges. In AERO the aircraft fleet is represented by 10 generic aircraft size classes and two technology classes (old and current). In total AERO thus distinguishes 20 generic aircraft types. The NO_x charges are differentiated between these aircraft types based on the average NO_x characteristics of the 20 aircraft types. The difference of the average NO_x emission characteristics between the two technology classes for any of the aircraft size classes, is not very large. This is because historically there has not been a very strong trend towards more NO_x efficient aircraft, and also for the future it is not assumed that the NO_x emissions per SKO of new aircraft will significantly improve.

Because AERO uses 20 generic aircraft types, it cannot capture the results of a possible re-engining of existing aircraft or a substitution of high NO_x aircraft within a generic aircraft type with a low NO_x one. As a result, the supply side effects of the NO_x charges, as computed by AERO, are probably slightly underestimated. However, it is expected that, even if the supply side effects of NO_x charges were to be modelled more accurately, the demand side responses would still be dominant in the reduction of total EU NO_x emissions resulting from NO_x charges. One reason is that most supply side responses would be very costly, such as re-engining aircraft or accelerated fleet renewal.

7.2 LTO NO_x charge

An LTO NO_x charge according to the design summarised in Section 6.3 has proven to be feasible to implement as it is currently levied at various airports in the EU. The enforcement can be organised in a way that is legal and feasible, as payment of the charge could be enforced in the same way as payment of airport charges.

The environmental impact of an LTO NO_x charge as designed in Section 6.3 has been calculated for a charge with a uniform level of € 12 per kg of LTO NO_x and € 4.40 per kg of LTO NO_x. These levels reflect the arithmetic mean damage costs of NO_x emitted at ground level in EU Member States according to CAFE/WHO (BeTa Methodex (version 2, 2007) tables). Impacts of the corresponding ExternE value of € 1.30 have not been calculated as the effects would be minimal. A revenue neutral option has not been calculated due to constraints of AERO (see Section 7.1.3). Table 2 shows the reduction in emissions for the highest charge. Full results of the AERO-MS calculations can be found in Appendix D.

Table 2 Environmental impacts of LTO NO_x charges € 12 per kg of NO_x emitted in LTO

	BaU emissions		% reduction in 2020	
	NO_x (kt)	CO_2 (Mt)	NO_x	CO_2
EU domestic	116.1	25.8	-1.6%	-1.4%
Intra EU international	290.1	70.1	-0.8%	-0.7%
EU ↔ non EU	1,348.7	282.8	-0.4%	-0.4%
Total	1,754.9	378.7	-0.5%	-0.5%

Bron: AERO MS; note that the BaU scenario takes into account ETS and SES.

Table 2 shows that the environmental impacts of the LTO NO_x charge are modest, even at the highest estimate of external costs and in a revenue raising variant. Furthermore, CO_2 emissions and transport demand (shown in Appendix D) are decreased by approximately the same proportion as NO_x emissions. This indicates that the environmental impact is mainly due to an impact on demand (although this may be partly due to limitations of the AERO-MS, in which supply side responses to NO_x charges are limited).

Table 2 also clearly indicates that short haul flights are impacted more severely than long haul flights. The reason is that these flights emit relatively a large amount of LTO NO_x per RTK. As a result, fares have to be increased more than fares of international flights. The climate impacts of NO_x emissions from long haul flights are higher than for short haul flights by an order of magnitude, however. Thus it can be concluded that an LTO charge would be a poorly targeted climate policy instrument. In contrast, short haul flights contribute most to LTO emissions. From a local air quality perspective, an LTO NO_x charge provides the right incentive.

An LTO NO_x charge would provide an incentive to reduce LTO NO_x emissions, especially for the smaller engines which are on short haul aircraft. For the current engines, there is a relation between LTO NO_x emissions and cruise NO_x emissions. However, the introduction of new engine or combustor technologies may lead to the breakdown of this relation. If that were the case, the climate benefits of the charge could be reduced.

An LTO NO_x charge would affect the operating costs of airlines marginally. Their total operating costs would increase by 0.1%, their operating costs per RTK by 0.6% (see Appendix D). Since most of these costs can be passed on, operating margines will not be affected.

Since the charge could be implemented regardless of the nationality of the aircraft or the aircraft operator or the destination of the flight, the competitive markets would not be distorted. However, as indicated in Table 2, it is clear that operators with relatively many short haul flights will be more impacted than operators with relatively many long haul flights.

From a legal perspective, as this charge very much touches upon local conditions, it would be less vulnerable to challenges coming from international aviation law. International aviation law is designed to regulate the establishment of aviation charges at various levels, including the Chicago Convention, ICAO rules and principles and recommendations, and bilateral provisions. However, ICAO itself acknowledges the reach of international environmental law mandating this measure, and the responsibility of states for the imposition of local measures designed to mitigate NO_x emissions.

Regard may be had to principles of Community law, geared to maintain a level playing field and strike a balance between internal market objectives, including the freedom to provides services, and environmental goals. Environmental rules must be aligned with air transport rules, as evidenced by the future Directive on airport charges.

7.3 LTO NO_x charge with a distance factor

A LTO NO_x charge with a distance factor would be feasible to implement. If EUROCONTROL were to be assigned with the task of collecting the charge, it would have the infrastructure and the expertise in place for collecting such charges. Enforcement would be possible in the same way that collection of air navigation charges is currently enforced by EUROCONTROL, but this would need a separate legal basis.

The environmental impacts of an LTO NO_x charge with a distance factor have been calculated for a number of values of GWP of aviation NO_x. Since the current scientific knowledge does not permit postulation of a singlevalue for GWP, the environmental impacts are presented as a range here for GWP ranging from 1 to 130. Table 3 shows the reduction in emissions for the corresponding range of charges. Full results of the AERO-MS calculations can be found in Appendix D.

Table 3 Environmental impacts of LTO NO_x charge with a distance factor: $1 \leq \text{GWP } NO_x \leq 130$

	BaU emissions		% reduction in 2020	
	NO_x (kt)	CO_2 (Mt)	NO_x	CO_2
EU domestic	116.1	25.8	0 - -0.9%	0 - -0.7%
Intra EU international	290.1	70.1	0 - -1.7%	0 - -1.4%
EU ↔ non EU	1,348.7	282.8	0 - -3.6%	0 - -3.5%
Total	1,754.9	378.7	0 - -3.1%	0 - -2.9%

Bron: AERO MS.

Table 3 shows that the impacts of the LTO NO_x charge with a distance factor on NO_x emissions of flights to and from the EU vary from zero to a reduction of 3.1%, depending on the value of the NO_x GWP. The impacts are roughly proportional to the GWP value chosen in the model calculations.
In contrast to the LTO NO_x charge without a distance factor, the charge with a distance factor reduces NO_x on long haul flights more than NO_x on short and medium haul flights, though less so than the precautionary emissions multiplier (see Sections 7.2 and 7.7). The reasons are that large aircraft, which are operated on long haul routes, emit more LTO NO_x per seat than small aircraft. As a result, the cost increase per seatkilometre is larger on long haul flights than on short haul. Furthermore, elasticities on route groups vary, resulting in different demand responses.

An LTO NO_x charge with a distance factor would provide an incentive to reduce LTO NO_x emissions for all engines. For the current engines, there is a relation between LTO NO_x emissions and cruise NO_x emissions. However, the introduction of new engine or combustor technologies may lead to the breakdown of this relation. If that would be the case, the climate benefits of the charge could be reduced. If the charge would be introduced simultaneously with the inclusion of aviation in the EU ETS, it would not result in a negative NO_x : CO_2 trade-off, as both external effects would be internalised. In contrast, the charge would ensure that the ETS would result in an exploitation of this trade-off that would have suboptimal climate impacts.

An LTO NO_x charge with a distance factor would affect the operating costs of airlines more that the simple LTO charge. Their total operating costs would increase by up to 0.4%, their operating costs per RTK by 2.9% (see Appendix D). Since most of these costs can be passed on, operating margines will not be affected.

From a legal perspective, the distinction between the LTO NO_x charge and LTO NO_x charge with a distance factor is related to the introduction of the distance factor into the previous option. The distance factor implies that all flights from and into EU airports, whether those flights are operated inside or to/from points outside the EU, are deemed to fall under this option. It would seem that this option is a combination between the previous and the next option, that is, the LTO NO_x charge and the en route charge respectively.

A number of international law considerations may have to be addressed before implementing this option. Amongst others, as foreign operators, flying in foreign, that is, ‘their own’ airspace may be affected by this measure, agreement among EU States, and between EU and third State(s) would be likely to enhance its legal feasibility. Also, as EUROCONTROL would be assigned with collecting the charge, EU states who are a member of that organisation may wish to reach consensus on this charge within the EUROCONTROL framework.

Since the charge could be implemented regardless of the nationality of the aircraft or the aircraft operator or the destination of the flight, the competitive markets would not be distorted.

7.4 Cruise NO_x charge

A cruise NO_x charge as described in Section 6.5 would require building and maintaining a database of cruise NO_x emissions for all aircraft/engine combinations on a large number of distances. While this would require manpower to be assigned to this task, it is our opinion that the amount of work would not be prohibitive.

The monitoring of the relevant parameters for charging (aircraft registration to derive aircraft/engine combination and route to calculate great circle distance) could be done by the organisation collecting the charge. If Member States were to collect the charge, they could instruct their airports to monitor the relevant parameters for them and report them, or they could make aircraft operators responsible for monitoring and reporting. In that case, an external verifier could ascertain that the reported data are correct. If EUROCONTROL collected the charge, relevant parameters such as disnatce, aircraft type and engine configuration would already be registered in its information systems.

The environmental impacts of a cruise NO_x charge have been calculated for a number of values of GWP of aviation NO_x. Since the current scientific knowledge does not allow postulation of a single value for GWP, the environmental impacts are presented here as a range for GWP ranging from 1 to 130. Table 4 shows the reduction in emissions for the range of charges. Full results of the AERO-MS calculations can be found in Appendix F.

Table 4 Environmental impacts of a cruise NO_x charge : $1 \leq \text{GWP } NO_x \leq 130$

	BaU emissions		% reduction in 2020	
	NO_x (kt)	CO_2 (Mt)	NO_x	CO_2
EU domestic	116.1	25.8	0 - -0.9%	0 - -0.9%
Intra EU international	290.1	70.1	0 - -1.6%	0 - -1.4%
EU ↔ non EU	1,348.7	282.8	0 - -3.2%	0 - -3.1%
Total	1,754.9	378.7	0 - -2.8%	0 - -2.6%

Bron: AERO MS.

Table 4 shows that the impacts of the cruise NO_x charge on NO_x emissions of flights to and from the EU vary from zero to a reduction of 2.8%, depending on the value of the NO_x GWP. The impacts are roughly proportional to the GWP value chosen in the model calculations.

Like the LTO NO_x charge with a distance factor, the cruise NO_x charge reduces NO_x on long haul flights more than NO_x on short and medium haul flights, though less so than the precautionary emissions multiplier (see Section 7.7). The reasons are that large aircraft, which are operated on long haul routes, emit more

NO_x per seatkilometre than small aircraft. As a result, cost increases and thus demand impacts are larger for long haul flights than for short haul flights, although different price elasticities also affect the results.

Provided that cruise NO_x emissions can be calculated accurately and that the external costs of CO_2 are internalised, the cruise NO_x charge would not have negative environmental side-effects.

A cruise NO_x charge would affect the operating costs of airlines. Their total operating costs would increase by up to 0.3%, their operating costs per RTK by up to 3.0% (see Appendix D). Since most of these costs can be passed on, operating margines will not be affected.

From a legal perspective, This option affects a number of international and European aviation law regimes. Those regimes regulate the establishment of user charges, including route charges, and define their parameters internationally. Those rules may either have to be fine tuned or even adapted, in order to make the implementation of this charge possible.

If the charge is implemented regardless of the nationality of the airport operator, it would not distort market. Furthermore, its impact on various market segments (long haul, short haul) are proportionate to the climate impact of emissions in these segments.

7.5 Inclusion of aviation NO_x emissions in the EU ETS

It would be feasible to include aviation NO_x in the EU ETS. The administrative procedures, including the monitoring, reporting and verification requirements would be the same or very similar to the inclusion of aviation's CO_2 emissions.

The environmental impacts of the inclusion of aviation NO_x emissions in the EU ETS are the same as the impacts of the LTO NO_x charge with a distance factor. The reason is that the inclusion in the ETS is based on the same formula, so at a given GWP and ETS price, both the charge and the costs of the allowances to be surrendered would be equal. Again, since the current scientific knowledge does not permit postulation of a single value for GWP, the environmental impacts are presented as a range here for GWP ranging from 1 to 130. Table 3 shows the reduction in emissions for the corresponding range of charges. Full results of the AERO-MS calculations can be found in Appendix D.

Table 5 Environmental impacts of the inclusion of aviation NO_x emissions in the EU ETS : $1 \leq \text{GWP } NO_x \leq 130$

	BaU emissions		% reduction in 2020	
	NO_x (kt)	CO_2 (Mt)	NO_x	CO_2
EU domestic	116.1	25.8	0 - -0.9%	0 - -0.7%
Intra EU international	290.1	70.1	0 - -1.7%	0 - -1.4%
EU ↔ non EU	1,348.7	282.8	0 - -3.6%	0 - -3.5%
Total	1,754.9	378.7	0 - -3.1%	0 - -2.9%

Bron: AERO MS.

Table 3 shows that the impacts of the inclusion of aviation NO_x emissions in the EU ETS on NO_x emissions of flights to and from the EU vary from zero to a reduction of 3.1%, depending on the value of the NO_x GWP. The impacts are roughly proportional to the GWP value chosen in the model calculations.

The inclusion of aviation NO_x emissions in the EU ETS would provide an incentive to reduce LTO NO_x emissions for all engines. For the current engines, there is a relation between LTO NO_x emissions and cruise NO_x emissions. However, the introduction of new engine or combustor technologies may lead to the breakdown of this relation. If that would be the case, the climate benefits of the charge could be reduced.

The inclusion of aviation NO_x emissions in the EU ETS would affect the operating costs of airlines more that the simple LTO charge. Their total operating costs would increase by up to 0.4%, their operating costs per RTK by 2.9% (see Appendix D). Since most of these costs can be passed on, operating margins will not be affected.

From a legal perspective, while the inclusion of aviation NO_x emissions in the EU ETS would require changing the ETS directive. Care should be taken that the ETS would still qualify as a compliance mechanism for the Kyoto Protocol, despite the fact that NO_x is not a greenhouse gas. One way to do this is to ensure that aviation as a whole cannot become a net seller to the rest of system. With respect to international law, the inclusion of aviation NO_x emissions would not be fundamentally different that the inclusion of aviation CO_2 emissions.

Since the charge could be implemented regardless of the nationality of the aircraft or the aircraft operator or the destination of the flight, the competitive markets would not be distorted.

7.6 ICAO LTO NO_x Standards

An ICAO LTO NO_x standard would need to be set by CAEP. The EU, or rather, its Member States, may influence the outcome of the CAEP process, but only to a degree as the standards are usually set by consensus. Therefore, and because Section 6.7 concluded that the EU cannot set tighter standards that would become the de-facto world standards, it is questionable whether this policy option is an option that the EU can shape. Still, it is included here in order to allow the comparison with other options that the EU can implement unilaterally.

From a legal point of view, this option can without much ado be applied to operators of aircraft registered in EC states. International arrangements, whether the Chicago Convention, Standards of ICAO or bilateral regimes, create room for more stringent measures applying to operators falling under the jurisdiction introducing such more stringent measures.

Special procedures may apply in case of aircraft used, whether leased or otherwise, by operators of non-EC registered aircraft. Procedures coming under the recently adopted EASA regulation (216/2008) lay down such procedures.

Cost effectiveness

LTO standards for NO_x are currently set by CAEP. Their periodic review and expectations of increased future stringency have an impact in driving research and technology towards lowering engine emissions, and options for increased stringency are currently being assessed in CAEP for decision in 2010. Engine manufacturers consider that ICAO standards are the most appropriate instrument to tackle NO_x emissions as they apply to all aircraft and operators worldwide in a harmonised fashion. They have argued that they aim to introduce new engines that not only comply with current standards, but exceed them by a considerable margin.

On the other hand, an EU push for increased stringency of ICAO standards represents a continuation of current policies through periodic tightening of LTO NO_x emissions standards by ICAO. As such it can be regarded as a default option. These ICAO standards do not have a significant impact in driving engine technology, though they do prevent regression by subsequent later engine types.

An economic assessment of the cost effectiveness of more stringent NO_x emissions standards was conducted for CAEP/6 in 2001. Costs per tonne of NO_x reduced over the LTO cycle were calculated for a range of options compared against a base case of no policy action for two alternative implementation dates, using a range of discount rates. The costs included additional recurring and non-recurring costs borne by manufacturers and airlines, while the benefits were measured by reductions in tonnes of NO_x. The number of non-compliant engines under each of the options was identified, the technology levels required for each engine family to meet each of the options and the estimated development costs associated with these. For major technological changes requiring the development of lean staged combustors, development costs of \$ 500m - \$ 1,000m per engine family were used, together with a 2% fuel burn penalty.

The cost effectiveness results, carried out for CAEP/6, showed that the minus 10% stringency option was the most cost effective, with the lowest cost per tonne of NO_x reduced, followed by the minus 5, 15, 20, 25 and 30% options, with the ranking of options robust to all the sensitivity tests applied to key input assumptions.

Economic analysis of options for CAEP/8 is currently at a very early stage, with no results expected until early 2009. Consequently any cost effectiveness analysis for this study will not be able to anticipate this analysis and will need to draw on the earlier CAEP/6 analysis, with some rough adjustments made as necessary to reflect subsequent changes in the design of options and key economic and technical assumptions. Using the CAEP/6 results as a measure of the cost effectiveness of future ICAO standards is clearly imperfect for a number of reasons. For example the number of non-compliant engine families affected by stringency options relative to CAEP/6 and the costs associated with them will be different, traffic forecasts have been updated and there has been a substantial hike in fuel prices since 2001. The costs of technology response being used for the CAEP/8 stringency assume development costs of \$100-\$500m , with a fuel penalty of 0 - 0.5%. The CAEP/6 estimates have been adjusted to reflect the revised non-recurring manufacturing costs and fuel penalty assumptions being used for CAEP/8 and current fuel prices. Making these adjustments has an impact in reducing the compliance costs of the higher stringency options, particularly 20% and beyond, but is insufficient to change the ranking of options. It is not possible to prejudge of the economic analysis currently being performed for CAEP/8, but it seems likely that the results will display a similar pattern.

For the purposes of this study which is focussing on the climate change impacts of NO_x emissions from aviation, it will be necessary to estimate reductions in cruise NO_x associated with each of these stringency options, and use these as the basis of the cost effectiveness results.

A preliminary estimate of the cost effectiveness of stringency options has been conducted. It shows that a stringency of -10% relative to CAEP/6 would be most cost-effective in terms of cruise NO_x emission reduction at € 10 per kg of NO_x reduced. A stringency increase of -20% would double the costs per kg of NO_x, while a lower increase (-5%) would have significantly higher costs because of its small impact on emissions.

More stringent LTO NO_x standards would affect the purchase price of engines and the maintenance costs and would thus affect operating costs of airlines. Their total operating costs would increase, but the size of the increase could not be calculated. Since most of the cost increases can be passed on, operating margines will not be affected.

7.7 Precautionary emissions multiplier

The precautionary emissions multiplier would be as feasible to implement and enforce as the EU ETS. The only difference in the implementation of the precautionary emissions multiplier is that the administering Member States should ensure that aircraft operators surrender more than one allowance for each tonne of carbon they emit.

The main obstacle in having a precautionary emissions multiplier would be the basis of its value. The RFI value cannot be used as a basis for a precautionary emissions multiplier on CO_2 emissions. This is because:

- It accounts for all non-CO_2 impacts, not just NO_x. If the non NO_x-related terms are removed, this would imply a value of 1.45 (using RF values for 2000 from Sausen et al., 2005) cf 1.9 for the total effect.
- Scientific evaluations have clearly stated that the use of any combination of RF data (calculated from history) is the wrong metric, so no resultant numerical value is sound for this purpose.

Furthermore, the multiplier would give the wrong incentive to engine and aircraft development. It would not incentivise the reduction of cruise NO_x but would only reward a reduction in CO_2 emissions and fuel burn. As there could be a trade-off between CO_2 and NO_x emissions in future engines, a multiplier could result in higher NO_x emissions in the future rather than lower emissions.

The environmental impacts of a precautionary emissions multiplier have been calculated for a number of values. Since there is no scientific basis for any value, the environmental impacts are presented as a range here for a precautionary emissions multiplier ranging from 1.1 to 2.0. Table 6 shows the reduction in emissions for the range of charges. Full results of the AERO-MS calculations can be found in Appendix D.

Table 6 Environmental impacts of a precautionary emissions multiplier with a value 1.1-2.0

	BaU emissions		% reduction in 2020	
	NO_x (kt)	CO_2 (Mt)	NO_x	CO_2
EU domestic	116.1	25.8	0.1% - -2.5%	0.1% - -2.5%
Intra EU international	290.1	70.1	0.1% - -2.8%	0.1% - -2.8%
EU ↔ non EU	1,348.7	282.8	0.3% - -5.3%	0.3% - -5.3%
Total	1,754.9	378.7	0.3% - -4.7%	0.2% - -4.7%

Bron: AERO MS.

A precautionary emissions multiplier would affect the operating costs of airlines. Their total operating costs would increase by up to 0.6%, their operating costs per RTK by up to 4.5% (see Appendix D). Since most of these costs can be passed on, operating margines will not be affected.

From a legal perspective, under this option, the contribution of NO_x to global warming is deemed to be large, in accordance with models and calculations. The precise value of the contribution made by NO_x has yet to be determined. The Precautionary principle is designed to manage the future risk of the contribution made by NO_x emissions to global warning. It is firmly enshrined in international environmental law, international trade law and has been adopted in Community law - for instance, as made by the European Court of Justice - and policy.

International aviation law does not know this principle, whereas the implementation of an ETS allowing for the multiplier effect caused by NO_x emissions has yet to be regulated at an international - aviation law - level. Hence, ad hoc, bilateral or broader, that is, multilateral arrangements may heave to be made in order to create a legal basis for this option, if the scope of the proposed ETS is followed (again, including non-EC operators, and applying to non-EU airspace).

In the short term, with the current fleet, the impact of a multiplier would be the same as the impact of a higher price in the EU ETS: there would be a stronger demand effect and emissions would thus be reduced. In the medium to long term, because of the trade-off between NO_x and CO_2 in engine design, the impacts on NO_x could become perverse.

8 Comparing the options

8.1 Introduction

As stated in the conclusions of Chapter 6, at present, only the LTO charge and the standards can be fully designed. For the other policy instruments, data and analysis are lacking. This means that other policy instruments can only be introduced once these barriers will have overcome. This report estimates that such a process could take a few years.

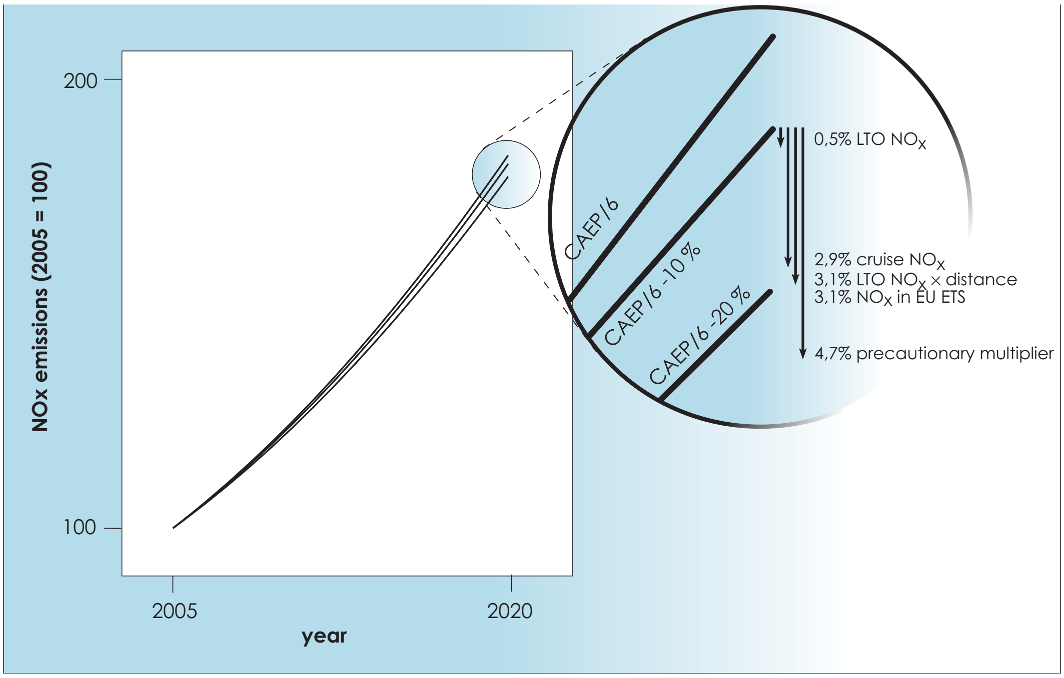
As a result of the provisional design of most policy instruments, the impact analyses are necessarily provisional. For the economic instruments, the environmental impacts depend mainly on demand effects, which in term are determined by the level of the charge, and ultimately on the value of NO_x GWP or the local damage costs of NO_x or the value of the multiplier. Likewise, the costs of the economic instruments depend on change in demand.

8.2 Impacts on the climate impact of aviation NO_x emissions

The climate impacts of aviation NO_x emissions are roughly proportional to the quantity of NO_x emissions (although emissions at cruise altitude have a larger climate impact than emissions at ground level). All instruments reduce the emissions of aviation NO_x emissions, albeit only against a fast growing baseline.

The emission reductions brought about by economic instruments depend on the level of these instruments. This report was only able to specify the level for LTO NO_x charges. For all other charges, either scientific consensus is lacking (LTO NO_x charges with a distance factor, cruise NO_x charges and the inclusion of aviation NO_x in the EU ETS), or there is no scientific argument and the level needs to be determined by a political decision (the precautionary emissions multiplier). This section presents impacts of one possible level of economic instruments, without claiming that this level is likely to be justified on scientific grounds. With that caveat, Figure 22 presents the emission reductions of the selected instruments in 2020.

Figure 22 Emission reductions by selected instruments



Note: The impacts of the economic instruments on NO_x emissions depend on the level of these instruments. The instruments have the same relative impact on every background scenario.

All the estimates of reduced emissions are based on the assumption that the current relation between LTO NO_x emissions and cruise NO_x emissions hold also for future engine types. If this relation would break down, which is considered probable by this report, only cruise NO_x charges would reduce emissions. In that case, the impact of both standards and LTO NO_x charges would become uncertain. LTO NO_x charges with a distance factor, the inclusion of aviation NO_x in the EU ETS, and the multiplier could still reduce emissions, as they mainly reduce emissions by lowering demand.

8.3 Costs and cost-effectiveness

From a policy perspective, the relevant costs of economic instruments are the welfare costs (loss of consumer and producer surpluses), the technical costs and the administrative costs. The impacts of the economic instruments considered here are caused predominantly by changes in demand; supply side responses are limited. Therefore, we assume that the costs of the economic instruments are mainly welfare costs and administrative costs. We assume the administrative costs of all instruments to be € 5 mln per annum. Table 7 summarises the costs.

Table 7 Welfare costs of economic instruments

Instrument	Welfare costs (€$_{2008}$ mln)
LTO NO_x charge (€ 12 /kg NO_x)	10
LTO NO_x charge with distance factor (GWP = 130)	92
Cruise NO_x charge (GWP = 130)	73
Inclusion of aviation NO_x in the EU ETS (GWP = 130)	92
Precautionary emissions multiplier (value = 2)	207

Source: Appendix D, Section D.3.

In terms of cost-effectiveness, the economic instruments have very similar values, as is shown in Table 8.

Table 8 Cost-effectiveness of economic instruments

Instrument	Cost-effectiveness (€$_{2008}$/kg NO_x)
LTO NO_x charge (€ 12 /kg NO_x)	1.1
LTO NO_x charge with distance factor (GWP = 130)	1.7
Cruise NO_x charge (GWP = 130)	1.5
Inclusion of aviation NO_x in the EU ETS (GWP = 130)	1.7
Precautionary emissions multiplier (value = 2)	2.5

Source: Appendix D, Section D.3.

From a business perspective, the change in profits and profit margins may be more relevant. These are presented in Table 9.

Table 9 Impact of financial instruments on airline operating costs

Instrument	Total operating costs	Total operating costs per RTK
LTO NO_x charge (€ 12 /kg NO_x)	+ 0.1%	+ 0.6%
LTO NO_x charge with distance factor (GWP = 130)	+ 0.4%	+ 2.9%
Cruise NO_x charge (GWP = 130)	+ 0.3%	+ 3.0%
Inclusion of aviation NO_x in the EU ETS (GWP = 130)	+ 0.4%	+ 2.9%
Precautionary emissions multiplier (value = 2)	+ 0.6%	+ 4.5%

Source: Appendix D, Section D.3.

The costs of a technical instrument such as standards are of a different nature than the welfare costs presented above. Therefore, both costs should not be compared directly. The costs of the various stringency options are presented in Table 10.

Table 10 Estimated costs of stringencies (recurring and non-recurring costs, 0% discount, no fuel penalty)

Stringency level	Costs (€$_{2008}$ mln)
CAEP/6 -5%	5,000
CAEP/6 -10%	7,000
CAEP/6 -15%	12,000
CAEP/6 -20%	15,000

Source: Appendix E, Section E.2.

The cost-effectiveness of the stringency options is summarised in Table 11. Please note that these figures diverge from the cost-effectiveness figures as presented in CAEP, as the latter typically show the costs per unit of LTO NO_x reduced, whereas the figures in Table 11 show the costs per unit of total aviation NO_x reduced.

Table 11 Cost-effectiveness of stringency options (recurring and non-recurring costs, 0% discount, no fuel penalty)

Stringency level	Cost-effectiveness (€$_{2008}$ / kg NO_x)
CAEP/6 -5%	90
CAEP/6 -10%	19
CAEP/6 -15%	23
CAEP/6 -20%	17

Source: Appendix E, Section E.2.

Note: These figures are provisional; in CAEP/8 better cost estimates will become available.

8.4 Feasibility of implementation

LTO NO_x charges, global LTO NO_x standards and a precautionary emissions multiplier are feasible to implement. For the charge, data are available from public or semi public sources. Its collection could be included in the current collection of airport charges so the administrative burden would be limited. Revenue neutrality could be ensured, if desired, by simultaneously lowering other airport charges.

The global standard would require business as usual in CAEP.

The precautionary emissions multiplier would use the same administrative arrangements as the inclusion of aviation in the EU ETS. Its additional administrative burden would be zero. It would require a political decision on the value of the multiplier.

The LTO NO_x charge with a distance factor, the cruise NO_x charge and the inclusion of aviation NO_x in the EU ETS could not be implemented immediately, as they would require outstanding issues to be resolved first. These instruments would require reaching consensus in the scientific community on a value for the GWP of NO_x, a process that could take three years or more. In addition, the LTO NO_x charge with a distance factor and the inclusion of aviation NO_x in the EU ETS would require establishing the co-efficient of correlation, while the cruise NO_x charge would require choosing models to calculate cruise NO_x, choosing assumptions and building the database. These processes could be undertaken simultaneously and would also take around three years to complete.

Both the LTO NO_x charge and the cruise NO_x charge could be levied and possibly reimbursed by EUROCONTROL. This would significantly reduce the administrative burden as EUROCONTROL already collects most of the data needed for calculating the charges and has the financial arrangements in place for collecting the charges.

The inclusion of aviation NO_x in the EU ETS could have the same administrative procedures as the inclusion of aviation CO_2 in the EU ETS. Thus the additional administrative burden would be low.

8.5 Legal feasibility

All policy instruments are subject to international law considerations, including international environmental law, public international law and especially international aviation law, as flights are operated by airlines flying under internationally agreed rules and principles. Obviously, the above options are also subject to Community law.
When checking the legal feasibility of the policy instruments against the mentioned international law regimes, it is concluded that the establishment of a EU LTO NO_x standard for EU registered aircraft poses relatively few legal obstacles. Also the LTO NO_x charge would not encounter many obstacles. The legal feasibility of the inclusion of aviation NO_x in the EU ETS would be similar to the feasibility of the inclusion of aviation CO_2 in the EU ETS.

The LTO NO_x charge with a distance factor and the cruise NO_x charge differ from the LTO NO_x charge in the fact that foreign aircraft flying part of their routes in foreign airspace would also be affected. Therefore a number of international law considerations may have to be addressed before implementing this option. Amongst others, as foreign operators, flying in foreign, that is, ‘their own’ airspace may be affected by this measure, agreement among the concerned states, that is, the EC states, the EC and the third state(s) is likely to enhance its legal feasibility. Also, the cost base for the charge, i.e. the GWP of NO_x, needs to be clearly established.

The precautionary emissions multiplier is designed to manage the future risk of the contribution made by NO_x emissions to global warning. It is based on the precautionary principle which is firmly enshrined in international environmental law, international trade law and has been adopted in Community law – for instance, as made by the European Court of Justice – and policy. However, international aviation law does not know this principle, whereas the implementation of an ETS allowing for the multiplier effect caused by NO_x emissions has yet to be regulated at an international – aviation law - level. Hence, *ad hoc*, bilateral or broader, that is, multilateral arrangements may have to be made in order to create a solid legal basis for this option.

8.6 Feasibility and legality of enforcement

The enforcement of LTO NO_x charges could be organised in the same way as the enforcement of payment of airport charges is currently organised. At most or all airports where charges are currently levied, they are an integral part of airport charges and are subject to the same legal regime.

Both LTO NO_x charges with a distance factor and cruise NO_x charges would require a separate legal basis for enforcement. If the charges were levied by EUROCONTROL, the enforcement could be ensured by assigning EUROCONTROL with the same legal basis for enforcement as it currently has to recover route charges.

LTO NO_x standards that go beyond ICAO standards could only be enforced for aircraft registered in the EU. In addition, the registrating authority would need to have the legal means to be able to apply other standards than the ICAO standards.

The enforcement of the precautionary emissions multiplier and the inclusion of aviation NO_x in the EU ETS could be ensured in the same way as enforcement of requirements under the EU ETS. Under the current ETS directive (2003/87/EC), Member States are to penalise operators that do not surrender a sufficient amount of allowances and publicise their names.

8.7 Environmental co-benefits and negative trade-offs

The LTO NO_x charge and the LTO NO_x standards, being local air quality policy instruments, would have co-benefits on total NO_x emissions and thus on the climate impact of aviation NO_x. Equally, economic instruments aimed to reduce the climate impact of NO_x would result in lower LTO NO_x emissions. Both these co-benefits will only be realised as long as the current relation between LTO NO_x and cruise NO_x emissions holds. If this relation breaks down, new engine types may no longer have the same environmental co-benefits.

All instruments applying to the current fleet, i.e. the static incentive of all economic instruments, would not have negative trade-offs between NO_x and CO_2. The reason being that to date, improvements in CO_2 emissions (or fuel efficiency) have been constrained more by materials' temperature limits and consequent cooling issues than by the mechanisms employed to reduce NO_x. Thus far there has been little inhibition in CO_2 performance caused by the need to control NO_x.

However, instruments applying to the future fleet, i.e. standards and the dynamic incentive of the economic instruments (the incentive on engine and aircraft R&D), could give rise to a negative trade-off between CO_2 and NO_x at the engine level. This may result in lower than possible increases in fuel efficiency if the value of NO_x would become high. Equally, it would mean that the precautionary emissions multiplier could result in higher than possible NO_x emissions, as it would

encourage engine and aircraft manufacturers to reduce CO_2 emissions of new types even more.
An economic instrument that would internalise the damages of both CO_2 and NO_x would ensure that the dynamic incentive is right. It would ensure that the trade-off between NO_x and CO_2 at the aircraft level is in the optimal point, minimising the climate impact of both substances combined.

At least for the current fleet, there do not seem to be co-benefits or negative impacts on noise. This would be valid for all policy instruments.

8.8 Impacts on specific market segments of aviation

In aviation, a market is generally considered to be a city pair. The EU LTO NO_x standards would have the potential to distort the market in the occasion that EU carriers compete with non-EU carriers. In that case, EU carriers could be disadvantaged as they would face higher capital and operational costs to operate their low NO_x aircraft.

The cruise NO_x charge, the LTO NO_x charge and the inclusion of aviation NO_x in the EU ETS could also distort some markets because of the hub effect (CE and MVA, 2007). On many long haul markets, passengers have the option to either fly direct or transfer. If there would be competition between a direct flight from an EU airport and a flight with a transfer outside the EU, the former would incur the cost increase of the charge for the entire flight, whereas the latter would only incur the cost increase for the first leg of the flight. The second leg, departing from one non-EU airport and arriving at another, would obviously not be charged. As a result, the costs for the direct flight would increase more than the costs for the indirect flights. This could distort the market in favour of indirect flights. Since transfer airports (hubs) outside the EU are generally serviced by non-EU carriers, non-EU carriers could see their competitiveness increase relative to EU carriers.

9 Conclusions

This report sets out to design and evaluate policy instruments that address the climate impact of aviation NO_x emissions. It is well established scientifically that these emissions cause a significant part of the total climate impact of aviation. Currently, these emissions are not controlled directly and they grow roughly at the same pace as air traffic.

After a thorough review of the scientific literature, a comprehensive overview of NO_x formation and control technologies and the environmental trade-offs, and an elaborate policy analysis, this report concludes that it will take around three to five years to design policy instruments that are both well founded in scientific evidence and provide the right incentives to reduce emissions both in the short term and in the long term. The two main issues that will have to be resolved before such an instrument can be developed are:

- Establish a value for a policy-relevant metric for aviation NO_x climate impact, such as a GWP for NO_x.
- Either establish a way to model cruise NO_x emissions or establish the correlation coefficient between LTO and cruise emissions.

Both issues should be capable of being resolved in three to five years. In the meantime, the policy instruments that could be introduced would either have very limited environmental impacts but a solid scientific foundation, or a questionable scientific basis but a significant impact.

An **LTO NO_x charge**, introduced at European airports would primarily be a local air quality instrument, reducing NO_x emissions in the vicinity of airports. It would have a very small co-benefit on NO_x emissions at altitude. However, it may be perceived as an unequitable climate policy instrument, as the short haul flights that have a low contribution to the climate impact will pay most of the charge. It would be feasible to implement technically and legally.

An **LTO NO_x charge with a distance factor** would need a good policy instrument to reduce the climate impact of NO_x. before it can be implemented, however, there needs to be a thorough assessment on the relationship between LTO and cruise emissions. A methodology already exists for the determination of this relationship but is is only applicable to current technology engines since it is empirical, and a more physically-based relationship would be required for this policy application so that future technologies could be robustly modelled. Moreover, it needs a well founded basis for the level of the charge, i.e. a value of the GWP of aviation NO_x. The legal basis for the instrument could be strengthened if international agreement could be reached on this value. New engine technology may lead to the breakdown of the existing relationship between LTO and cruise emissions. If this would occur, the environmental impacts of the charge could be reduced.

A **cruise NO_x charge** would be the best instrument to address cruise NO_x emissions, but it cannot be currently implemented since cruise NO_x emissions can neither be monitored nor modelled by a widely accepted method using publicly available data though manufacturers do possess the necessary information. Moreover, it needs a value for the GWP of NO_x, which is likely to take around three years to develop.

Inclusion of **aviation NO_x emissions in the EU ETS** would need the determination of a method to calculate NOx emissions. One obvious candidate for such a method would be based on the product of LTO NO_x emissions and distance. Moreover, the GWP of aviation NO_x would need to be established. The main advantage of this policy instrument would be that it would give the right incentive to minimise the combined climate impacts of CO_2 and NO_x emissions in engine design.

An **increased stringency of LTO NO_x standards** would reduce cruise NO_x emissions for future technology engines as long as the current relationship between LTO and cruise emissions holds. However, this is by no means a certainty. Standards have a solid legal basis. However, as they would need to be established internationally it is questionable whether the standards would meet EU expectations.

A **precautionary emissions multiplier** in the EU ETS could be readily implemented. Its legal basis would not differ much from the legal basis for the inclusion of aviation in the EU ETS. However, there is no scientific basis for a value of the multiplier at all. Furthermore, as the multiplier would increase the incentive to reduce CO_2 emissions, and since there is a trade-off between CO_2 and NO_x in engine design, it may lead to NO_x emissions that are higher than they would have been without the multiplier.

The **environmental impacts** of most economic instruments are comparable, i.e. in the range of reducing NO_x emissions by 3 to 5% relative to the baseline in 2020 if the levels of the charges reflect damage costs. The only exception is the LTO NO_x charge, which would have very small environmental impacts. Of course, the impacts of standards would depend on the stringency increase and the impacts of economic instruments would depend on the level of the charges imposed. Since most impacts of economic instruments on emissions arise from reduced demand rather than by technological changes, revenue neutral charges would have significantly lower impacts.

The **cost effectiveness** of all financial instruments seems to be in the same range from € 1 to € 2 per kg of NO_x reduced. The main cost item here is welfare costs. In contrast, the main cost item of standards is resource costs. Therefore, the cost-effectiveness should not be directly compared. The cost-effectiveness of a 10% stringency increase seems to be optimal at € 10 to € 25 per kg of NO_x reduced, depending on the fuel penalty of meeting the standard.

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Lower NO_x at Higher Altitudes

Policies to Reduce the Climate Impact of Aviation NO_x Emission

Annexes

Report

Delft, October 2008

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A Current and future NO_x emissions

A.1 Introduction

This section provides European forecasts of aviation NO_x and CO_2 emissions to 2020, and an outlook to 2050, using a global aviation emissions model, FAST (Lee *et al*., 2005).

The FAST model works by combining a global aircraft movements database with data on fuel flow provided by a separate commercial model PIANO (Simos, 2004), which is an aircraft performance model. These data with knowledge on aircraft and engine types, allow calculation of NO_x emissions via a recognized and validated algorithm (Deidiwig *et al*., 1996) that corrects certification (ICAO databank) data for altitude (Gardner *et al*., 1997). Baseline calculations have used the year 2000 and these calculations have been undertaken using the OAG (Official Airline Guide) global aircraft movement database, supplemented by non-scheduled traffic data from the AERO2K air traffic movements database.

A business as usual (BAU) baseline of aviation NO_x emissions has been developed in order to assess the likely future level of aviation NO_x emissions and to provide a reference case for assessing the impacts of increased stringency. The BAU baseline is designed to be ‘policy free’ and includes only the introduction of CAEP6 NO_x stringency for aircraft which will be introduced for all engines certified in and after 2008.

Two significant European policies are to be introduced in the near term namely, Emissions Trading for Aviation and the Single European Skies (SES) policy. The impact of both these policies are addressed in Appendix D using the AERO-MS model. The differentials calculated for Emissions Trading can be applied directly to the FAST model outputs. The impacts of the SES can not be considered in the context of the FAST results as it is important to note that, the FAST model, in common with many other detailed bottom-up inventory tools (e.g. the ANCAT and NASA inventories) assumes that flights operate using the great circle distance i.e. perfect routing and it also assumes no holding or delays – effectively such inventory tools therefore already assume the benefits of a SES. The most recent report by the EUROCONTROL Performance Review Commission ‘An Assessment of Air Traffic Management in Europe during the Calendar Year 2007’ (EUROCONTROL, May 2008), the actual distance flown was found to be 5.8% more than the great circle distance. The great circle assumption and the absence of holding and ground delays, cruise at non-optimum altitudes, etc. are estimated in the IPCC Special Report (1999) to lead to an underestimate of global fuel burn of between 10 and 20%. This effect that can be directly applied to fuel and to emissions in the FAST model for the year 2000. When comparing outputs from the AERO-MS model the FAST fuel and emissions outputs should be factored up to account for this underestimate.

A.2 Review of literature

A.2.1 Prediction methods for whole flight NO_x

The theory of NO_x formation and its reaction rate is complex and requires pre-knowledge of the design aspects of the combustor. Thus methods to correlate NO_x emission indices and engine/combustor operating conditions are normally concentrated on the effect of the combustor inlet pressure and temperature as the dominant parameters. For NO_x correlation and prediction of $EINO_x$ at altitude (the NO_x emission index in g per kg fuel burnt), a number of modelling methods exist based on chemical reaction theory in combination with practical experience.

The method considered most accurate is the P3T3 method (Madden and Park, 2003) which relies on proprietary details of the combustor. There are also 2 simplified methods which are commonly-used, known as the DLR and Boeing 2 fuel flow methods.

A.2.2 The P3T3 Method

The P3T3 method (Madden and Park, 2003) provides a correction of ground level measurements for conditions at altitude, based on the knowledge of the combustor operating environment at both altitude and ground level. $EINO_x$ measurements at ground level are plotted against combustor inlet temperature. The altitude in question determines the combustor inlet conditions. The corresponding ground level $EINO_x$ at the altitude temperature is obtained from the ICAO engine emissions databank for jet engines and the ICCAIA/FOI databank for turboprops. This $EINO_x$ is then corrected for the difference in combustor inlet pressure (p) and fuel-to-air ratio (FAR) between ground level and altitude. The values for the pressure and FAR exponents resolve the severity of the $EINO_x$ correction. A humidity (*h*) correction is also applied.

$$\frac{EINOx_{ALT}}{EINOx_{GL}} = \left(\frac{p_{ALT}}{p_{GL}}\right)^n \times \left(\frac{FAR_{ALT}}{FAR_{GL}}\right)^m \times \exp\left(19\left(h_{GL} - h_{ALT}\right)\right)$$

Where:
- ALT = at altitude.
- GL = ground level (i.e. SLA conditions).

The P3T3 method values agreed through CAEP for n and m are 0.4 and 0 respectively for cruise NO_x emissions (Paul Madden, personal communication June 2008).

A.2.3 Simplified Fuel Flow Methods

For a particular engine, an EINO$_x$ is supplied for a specific fuel flow for each of the 4 ICAO certification points (ICAO, 2007). The ICAO certification measurements for an engine represent thrust settings at sea level static (SLS) and international standard atmospheric (ISA) conditions. During the cruise phase of an aircraft flight, the engine will be running at altitude where the conditions will be other than ISA SLS conditions.

The fuel flow at altitude can be corrected to ISA SLA conditions using a generic formula shown below. A correction is also made for relative humidity conditions (*h*):

$$\frac{EINOx}{EINOx,ref} = Function\left(\frac{p}{pref}.\frac{T}{Tref}.\frac{w}{wref}\right).F(H)$$

Where EINO$_x$ is the NO$_x$ emission index in g per kg fuel burnt, p and T are relevant pressures and temperatures, w is the mass fuel flow and F(*h*) is a humidity correction factor for the decreasing absolute humidity with increasing altitude in the atmosphere (the air above approximately 20,000 feet is almost dry).

Two simplified methods, known as the fuel flow methods, have been developed to predict NO$_x$ emissions from aircraft engines during operational conditions at altitude. One is the Boeing 2 Fuel Flow Method, BFFM 2 (Martin R.L. et al., 1994; Baughum et al., 1996) and another is the DLR Fuel Flow Method (Lecht M., Deidewig F., 1994; Deidewig et al., 1996).

Fuel flow methods use the fact that the production of NO$_x$ emissions in a conventional engine combustor is in line with the engine performance i.e. with higher pressure and temperature inside the engine and hence higher fuel flow the EINO$_x$ increases. In contrast with the more sophisticated methods using sensitive internal engine data, fuel flow methods only need external and easily acquired data in combination with measured reference data as for instance from the ICAO engine emission certification of the landing and take-off (LTO) cycle.

The two methods are similar but they differ in the way corrections are made to the original operating values like fuel flow and EINO$_x$ with respect to their reference values.

The BFFM 2 method corrects for conditions at altitude as follows:

$$\frac{EINOx}{EINOx\,,ref} = \exp(-19 * SH\ - 0.0063) * sqrt\,(\delta_{amb}{}^{1.02} \,/\, \theta_{amb}{}^{3.3})$$

Where:

- SH = specific humidity in pounds of water per pound of air at altitude.
- δ_{amb} =T_{amb} / 518.67 R.
- θ_{amb} =P_{amb} / 14.696 psia.
- T_{amb} = ambient temperature in degrees Rankine (R).
- P_{amb} = ambient pressure in pounds per square inch absolute.

The DLR method (Deidewig, 1996) is used in the FAST model where T_3 and p_3 are determined from the Mach number as follows:

$$\theta = \frac{T3}{288.15K}$$

$$T3 = T\left(1 + 0.2(MachNo)^2\right)$$

$$\delta = \frac{p3}{101.3kPa}$$

$$p3 = p(1 + 0.2(MachNo)^2)$$

$$CorrectedFuelFlow = \frac{Fuelflow}{\delta.\sqrt{\theta}}$$

$$\frac{EINOx}{EINOxref} = \delta^a.\theta^b$$

In the FAST model, where a number of representative aircraft types (GenAir) are used to represent a group of aircraft, the application of the fuel flow method has to take into account the different engine types fitted to the aircraft represented by the GenAir aircraft which may have significantly different NO_x emission indices. For each representative aircraft type the different types of aircraft and engines are considered and the relative proportions of engines in the population are calculated and the fuel flow and $EINO_x$ values are weighted accordingly to produce a relationship of fuel flow and $EINO_x$ representative of the group of engines in the group. This approach has been used in other inventories (e.g. Gardner *et al.*, 1996).

A.2.4 Review of Baseline Inventories

A number of global aviation inventory results exist in the literature, including most recently the NASA aviation inventories, the EC AERO2K project, the US FAA inventory model SAGE and the UK FAST inventory model. The AEM model has also been developed by EUROCONTROL to calculate global aviation emissions but no global totals are currently reported in the literature. Data from these sources supplement and update inventories collated in the IPCC Special Report on Aviation published in 1999 (the NASA, ANCAT/EC2 and DLR inventories). All the inventories discussed in this review use a 'bottom-up' approach in which an aircraft movement database was compiled, aircraft/engine combinations in operation were identified and calculations of fuel burned and emissions for flight routes were made (to differing levels of detail). The baseline year for the inventory data in the IPCC (1999) report was 1992, the more recent inventories use baseline years between 1999 and 2002. The IPCC inventories are described in some detail in Section 9.3.1 of the IPCC report. The main points and assumptions of the more recent inventories are described here. The TRADEOFF inventory was a fuel-scaled version of an earlier inventory produced using 1992 movements data. Changes in fleet between 1992 and 2000 were thus not included and consequently $EINO_x$ were not taken into consideration. The data from the inventories are summarised in Table 12.

In addition to the data from aviation emission inventories, statistics on global aviation fuel use compiled by the International Energy Agency (IEA) are reviewed. It is immediately obvious from Table 12 that the IEA fuel sales data indicate larger CO_2 emissions than implied by 'bottom-up' inventories. There are a number of reasons for this: the inventories shown only indicate civil emissions. Military emissions are much more difficult to estimate but Eyers *et al*. (2005) calculated this to be approximately 11% of the total in 2002, *cf* 18% as calculated by Boeing for 1992 (Henderson *et al*., 1999). The IAE data include aviation gasoline, as used by small piston-engined aircraft but this comprised only less than 2% in 2000. The FAST and NASA 'bottom up' inventories are idealized in terms of missions, in that great circle distances are assumed and therefore perfect route management. This leads to an approximate underestimate of 10 to 15% in fuel usage for the current situation and this is a relevant point discussed further in the FAST modelling section. The AERO2K and SAGE inventories use real flight trajectory data and do not suffer this source of underestimation. However, most inventories also assume no holding patterns or delays. These various factors conspire to systematically underestimate aviation CO_2 emissions, an effect which has been known for some time (e.g. Schumann, 1994) but still remains difficult to reconcile, which is why in RF calculations, it is important to use the total fuel sales data.

Firstly, comparing the inventories presented in the IPCC report, they show very consistent data for fuel and therefore CO_2. Emissions of NO_x are also similar although variations in NO_x are more significant than fuel with the highest $EINO_x$ value being a factor of 1.12 higher than the lowest $EINO_x$. The ANCAT/EC2 and DLR inventories calculated NO_x emissions from the fuel using the DLR fuel flow method producing very similar fleet average $EINO_x$ in each case and the NASA inventory used the Boeing Fuel Flow Method 2 (BFFM2) procedure (see Section 3 for details of NO_x estimation procedures) producing a lower fleet average $EINO_x$.

Comparing the more recent inventory data in the literature, there two main methods for calculating NO_x emissions are again utilised: FAST and AERO2K use the DLR fuel flow method and the NASA and SAGE inventories use the BFFM2 procedure. The $EINO_x$ as a fleet average are remarkably similar with the FAST, AERO2K and NASA data within 1% of each other. The SAGE fleet average $EINO_x$ is 5% higher than the lowest (NASA) value.

Table 12 Summary of Inventory Data (for civil aviation only)

Inventory	Year	Fuel (Tg/yr)	CO_2 (Tg/yr)	NO_x (Tg/yr)	$EINO_x$ (g/kg)	Distance 10^9km	Reference
NASA	1999	134	423	1.77	13.21	27.1	Sutkus et al. (2003)
TRADE OFF	2000	152	476	1.95	12.83	25.1	Gauss et al. (2005)
FAST	2000	152	480	2.03	13.36	30.5	Owen and Lee (2007)
AERO2K	2002	156	492	2.06	13.21	33.2	Eyers et al. (2005)
SAGE	2000	181	572	2.51	13.87	33	Kim et al. (2007)
AERO-MS	2000	181	572	2.37	13.07	32.1	Van Velzen (2008)
NASA/IPCC	*1992*	*114*	*359*	*1.67*	*12.60*	*-*	*IPCC (1999)*
ANCATEC2/ IPCC	*1992*	*114*	*360*	*1.81*	*14.00*	*-*	*IPCC (1999)*
DLR/IPCC	*1992*	*112*	*354*	*1.80*	*14.20*	*-*	*IPCC (1999)*
IEA Fuel Statistics (civil and military aviation)	1992 2000	169 214	532 767	-	-	-	IEA (2008)

Figure 23 Fleet Average $EINO_x$ from Aviation Inventories

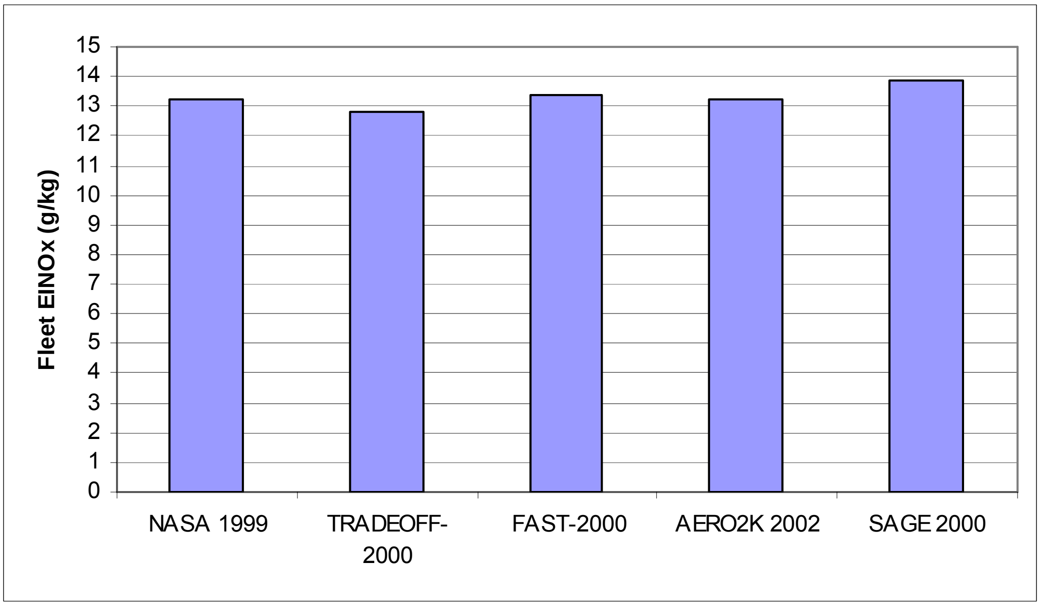
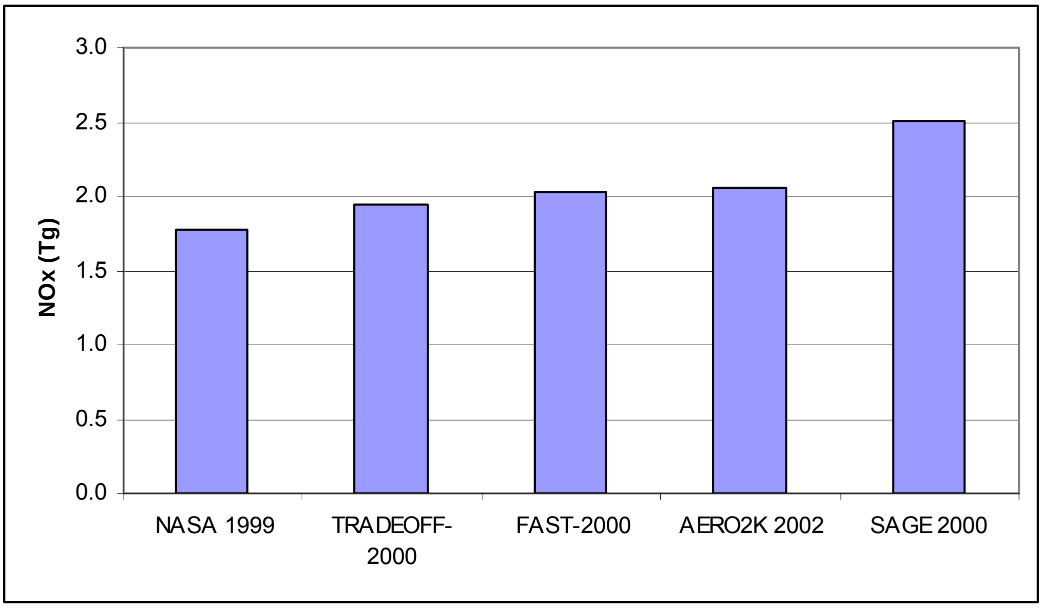


Figure 24 NO_x Emissions (Tg) for Aviation Inventories



A.2.5 Review of NO_x Future Projections

The data shown in Table 13 and Table 16 and Figure 25 and Figure 26 are inventory projections from the literature. The projections cover the period up to 2000 to 2025 with some projections showing an increase in $EINO_x$ and others a decrease due to the different assumptions made. All projections use similar NO_x fuel flow methods for calculating whole flight NO_x emissions. The AERO2K 2025 inventory assumes fairly aggressive improvements in $EINO_x$ over time to meet tightening stringency (it is assumed that by 2020 new aircraft will have to comply with a CAEP4 minus 64% stringency level). Whereas, for the IPCC work, the

NASA trend in $EINO_x$ to 2015 was used as the reference case i.e. an upward trend in $EINO_x$ was assumed. Two scenario cases to 2050 were then developed with the input of industry under the auspices of the ICCAIA (International Coordinating Council of Aerospace Industries Associations). These were labelled technology scenarios 1 and 2: Scenario 1 assumes improved fuel efficiency with some NO_x improvements (LTO NO_x Fleet average will be 10-30% below CAEP/2 limit by 2050; and the fleet average $EINO_x$ will be 15.5g/kg in 2050) and Scenario 2 assumes more aggressive NO_x technology (50-70% below CAEP/2 limit by 2050; fleet average will be 11.4g/kg in 2050).

Other longer term scenarios in the literature include the CONSAVE scenarios developed for the EU project 'Constrained Aviation Scenarios'. All the CONSAVE scenarios assume a decline in EINOx over between 2000 and 2050. All the scenarios share similar assumptions to the AERO2K work which assumes aggressive NO_x reductions for new aircraft up to 2020 (equivalent to CAEP4 minus 64% stringency). Post-2020 less radical changes are assumed for new aircraft.

Table 13 Summary of Future Fleet $EINO_x$ (g/kg) Data and Projections (civil aviation only)

Inventory	*1992*	*2000*	*2005*	*2010*	*2015*	*2025*	Reference
AERO2K	-	13.2	-	-	-	10.1	Eyers et al. (2005)
NASA, 2003	-	13.2	-	-	14.1	-	Sutkus et al. (2003)
NASA, 1998	-	9.8	11.0	12.0	14.1	-	Baughcum et al. (1998)
NASA/IPCC	12.6	-	-	-	13.7	-	IPCC, 1999
ANCATEC2/ IPCC	14.0	-	-	-	12.4	-	IPCC, 1999
DLR/IPCC	14.2	-	-	-	12.6	-	IPCC, 1999

Table 14 Summary of Future Fleet NO_x (Tg) Projections (civil aviation only)

Inventory	2000	2005	2015	2020	2025	Reference
AERO2K	2.06	-	-	-	3.31	Eyers et al. (2005)
NASA	1.69	-	-	-	-	Sutkus et al. (2003)
NASA/IPCC	-	-	3.95	-	-	Baughcum et al. (1998)
ANCATEC2/ IPCC	-	-	3.37	-	-	IPCC, 1999
DLR/IPCC	-	-	3.41	-	-	IPCC, 1999

Table 15 Summary of FESG IS92 Scenarios for IPCC, 1999

IPCC, 1999	Description	Metric	2050	Reference
Fa1	Medium growth and high NO_x	$EINO_x$ (g/kg) NO_x (Tg)	15.4 7.0	IPCC, 1999
Fa2	Medium growth and high NO_x	$EINO_x$ (g/kg) NO_x (Tg)	11.5 11.3	IPCC, 1999
Fe1	High growth and high NO_x	$EINO_x$ (g/kg) NO_x (Tg)	15.4 11.3	IPCC, 1999
Fe2	High growth and low NO_x	$EINO_x$ (g/kg) NO_x (Tg)	11.5 8.7	IPCC, 1999

Table 16 Summary of CONSAVE Aviation Scenarios for Berghof et al., 2005

Scenario	Metric	2000	2020	2050
CONSAVE ULS, 2003	$EINO_x$ (g/kg)	13.3	12.2	9.5
	NO_x (Tg)	2.2	7.1	7.3
CONSAVE FW, 2003	$EINO_x$ (g/kg)	13.3	12.0	11.4
	NO_x (Tg)	2.2	2.4	3.4
CONSAVE DtE, 2003	$EINO_x$ (g/kg)	13.3	9.6	4.9
	NO_x (Tg)	2.2	1.9	1.1

Figure 25 $EINO_x$ trends from Inventory Projections

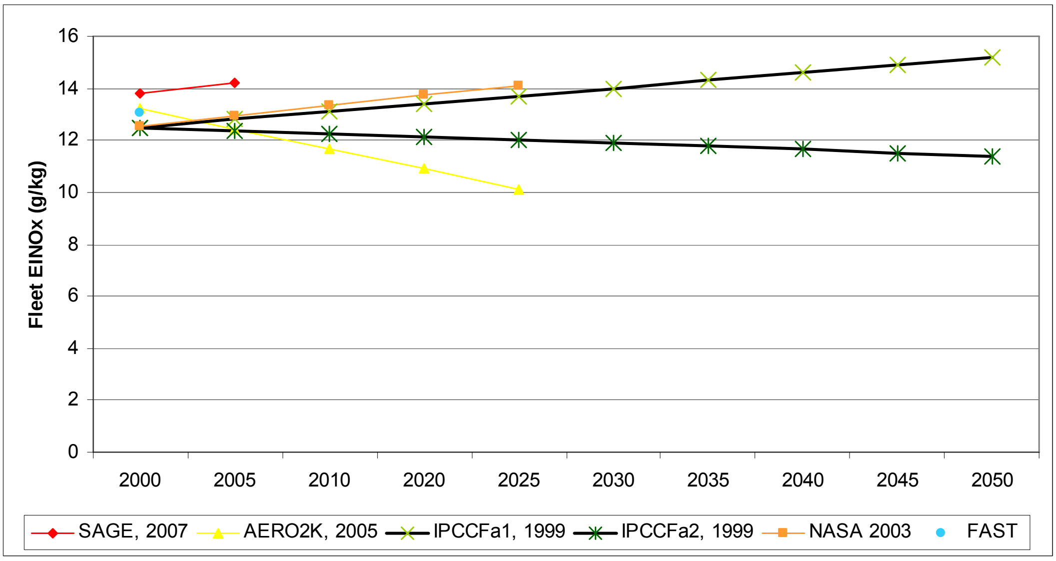
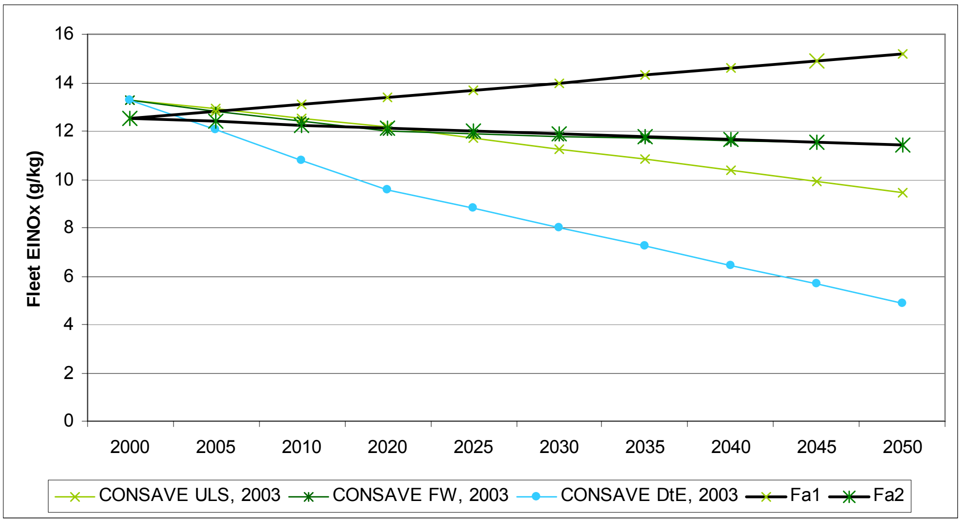


Figure 26 EINO$_x$ Trends from Longer term Aviation Scenario Calculations



A.2.6 Trends in NO$_x$ emissions and EINO$_x$

The SAGE inventory has been produced for each year from 2000 to 2005 using real flight and aircraft fleet data. The SAGE NO$_x$ data show a general upward trend between in EINO$_x$ between 2000 and 2005 - 13.87 gNO$_x$/kg fuel in 2000 to 14.29 gNO$_x$/kgfuel in 2005 (see Table 17). The SAGE results are based on real traffic data for the period 2000 and 2005 and the data show a general upward trend between 2000 and 2005 which agrees with the general received wisdom that newer aircraft tend to have higher pressure ratio engines which tend to have higher EINO$_x$.

The ICAO certification database (v15) certainly shows that the characteristic LTO NO$_x$ emission (as Dp/foo) increases clearly with increase in the overall pressure ratio (OPR) of the engine (see Figure 27). It is also true to say that the OPR of engines has tended to increase over time although this increase over more recent timescales is less clear from the data (see Figure 28). The ICAO certification data provides useful data on trends in NO$_x$ emissions however the database relies on LTO NO$_x$ data and data for engines rather than aircraft. Furthermore, it does not reflect the proportion of engines populating the fleet. As a result, it is helpful to investigate the data within the inventory datasets in addition to the ICAO engine database.

Table 17 Data from SAGE Inventory

Year	Flights (millions)	Fuel Tg	NO$_x$ Tg	EINO$_x$ (g/kg)
2000	29.7	181	2.51	13.87
2001	27.7	170	2.35	13.82
2002	28.5	171	2.41	14.09
2003	28.8	176	2.49	14.15
2004	30.4	188	2.69	14.31
2005	32.4	203	2.90	14.29

Bron: Kim et al. 2007.

Figure 27 ICAO Certification Characteristic NO_x (DP/foo) versus OPR (in-production engines)

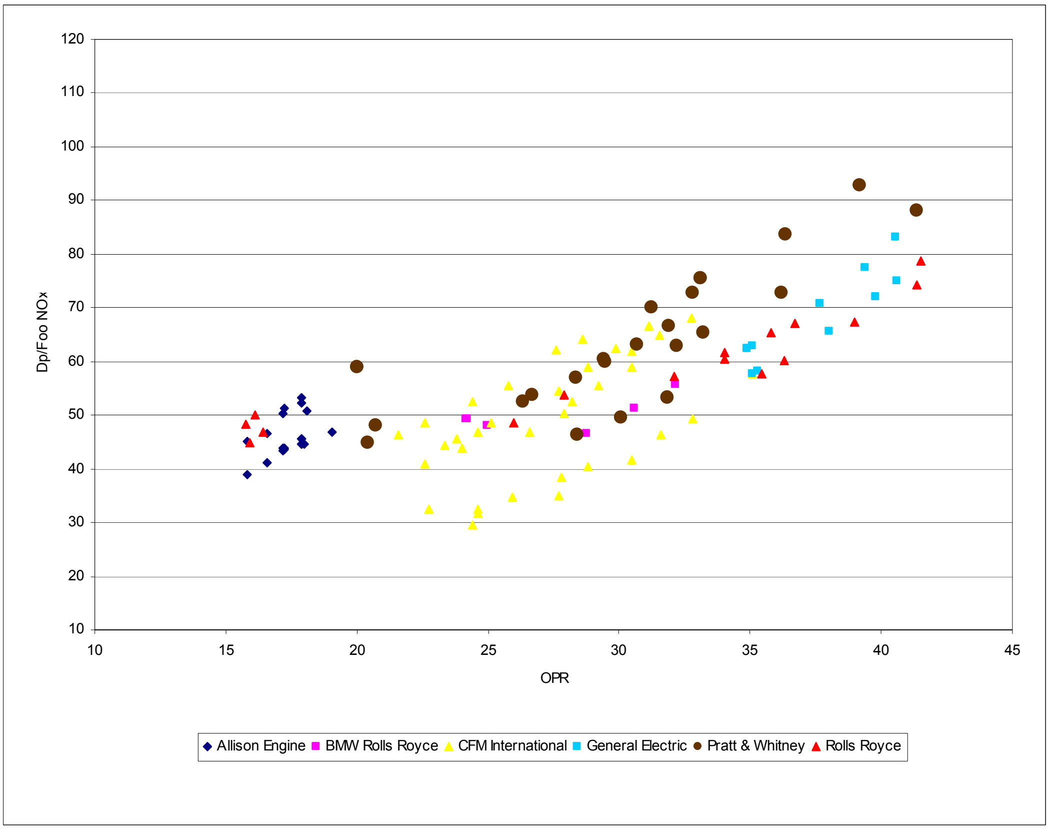
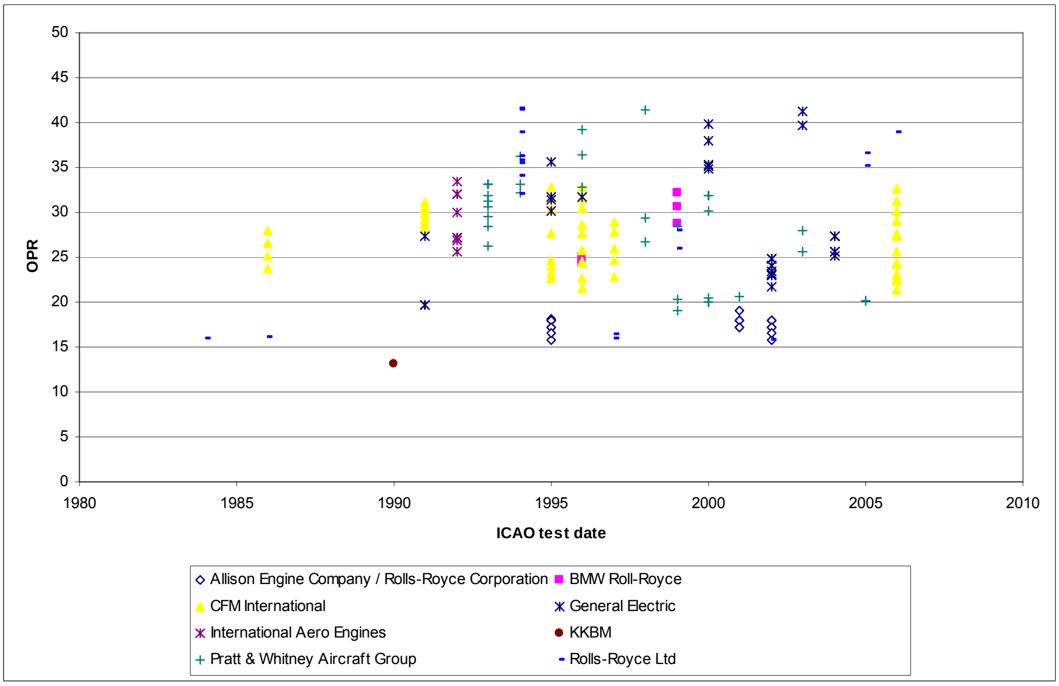


Figure 28 OPR versus ICAO certification test date (in-production engines)



Analysis of NO_x emissions by Entry into Service (EIS) and by seat kilometre

The FAST inventory results for 2000 (FAST 2000) can be disaggregated by aircraft type and by alternative metrics such as NO_x per distance and NO_x per passenger kilometre. The FAST model calculates NO_x emissions using the DLR fuel flow method and the range of engines fitted to the aircraft are proportioned according to the 2000 fleet. The weighted fuel flow method is then used. Each aircraft represented in the inventory therefore takes into consideration the types and proportions of engines fitted). Figure 29 shows the average $EINO_x$ (full flight) for operation during 2000 for a variety of aircraft types plotted against the entry into service (EIS) date for that aircraft. An upward trend is certainly apparent. However, the fuel efficiency of the aircraft (calculated over all full-flight operations during 2000 for the aircraft type) versus the EIS date shows a clear downward trend (Figure 30). If NO_x per SKO is then plotted a flat (or slightly downward) trend is observed (Figure 31).

Figure 29 $EINO_x$ versus EIS date - output from FAST 2000 model

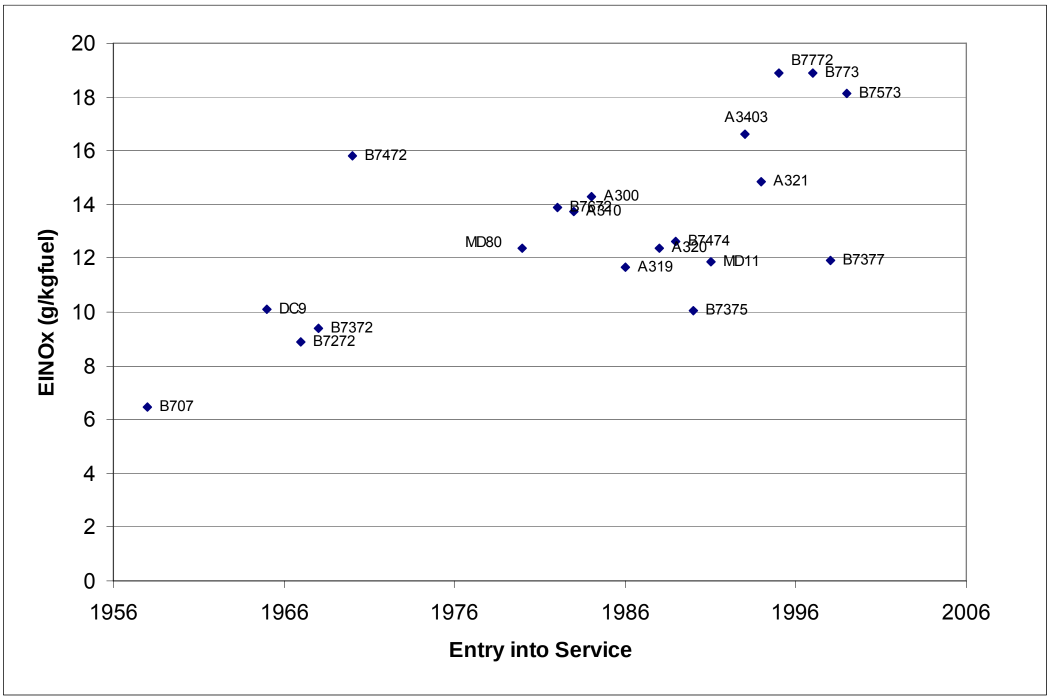


Figure 30 Fuel efficiency as kg per SKO versus EIS date - output from FAST 2000 model

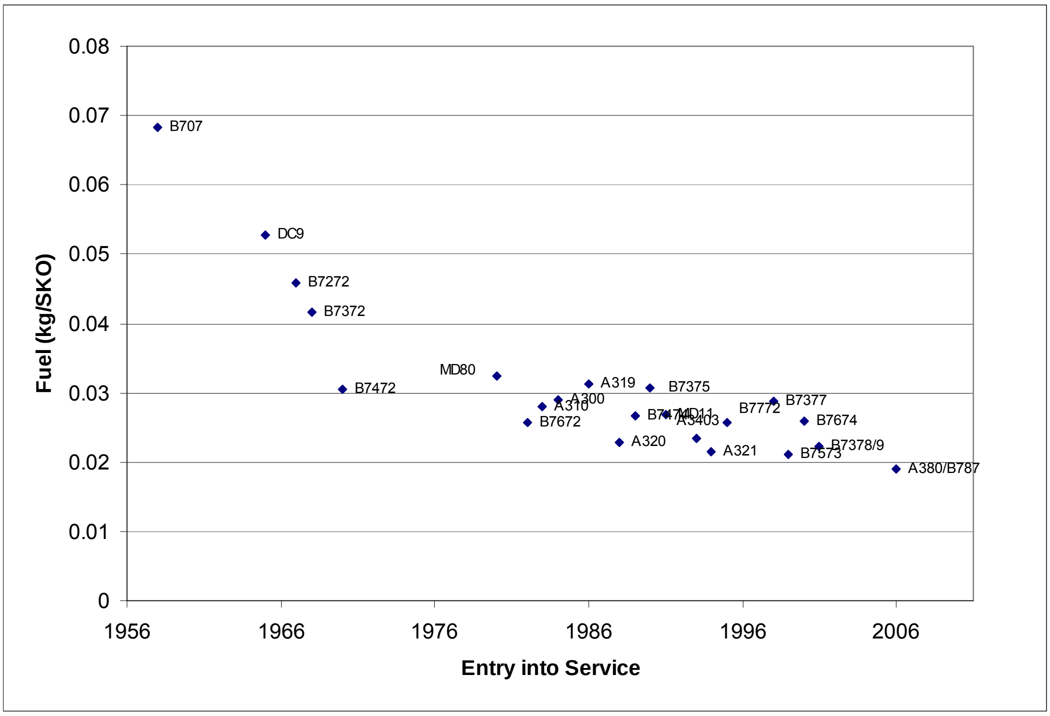
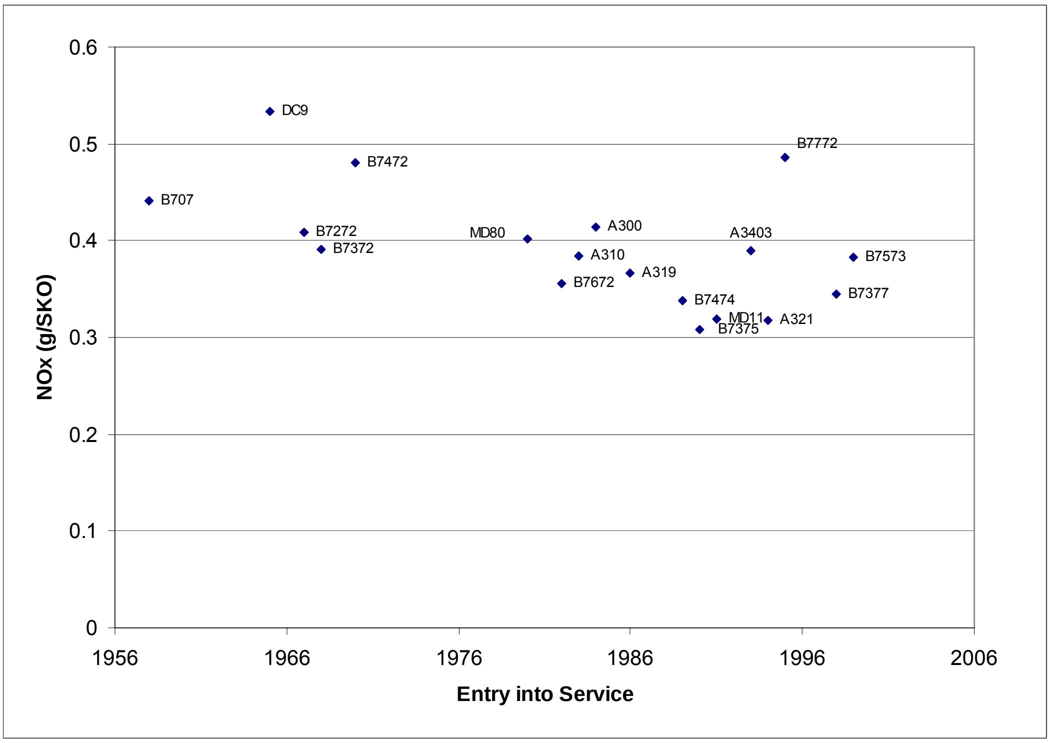
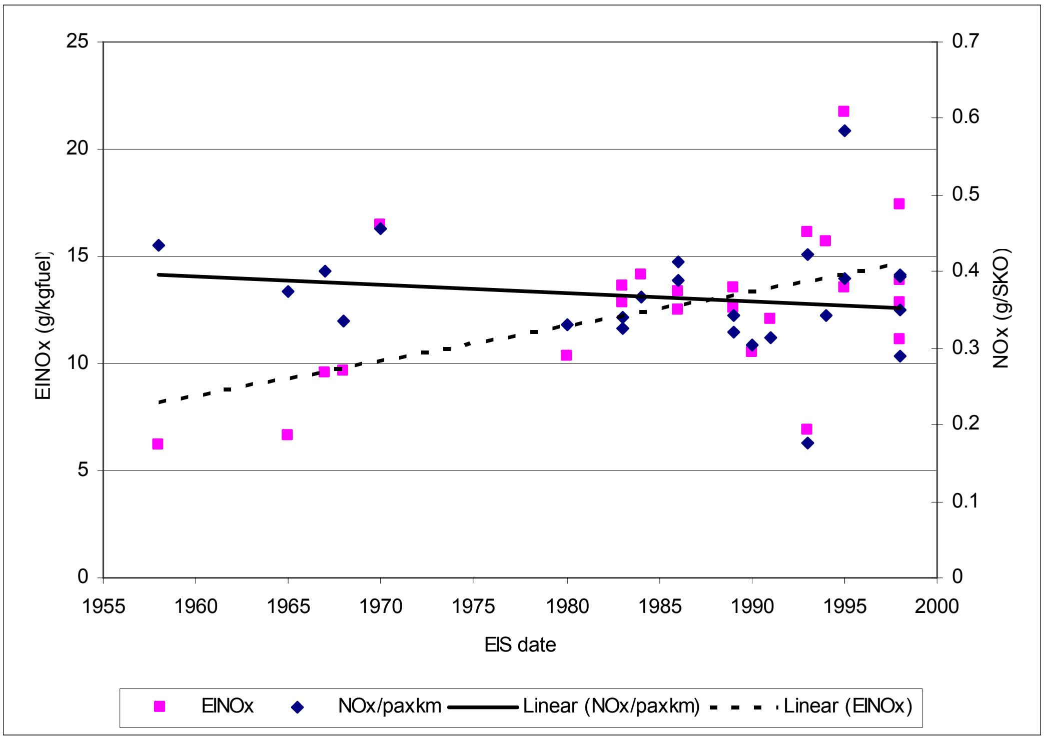


Figure 31 NO_x per SKO versus EIS - output from FAST 2000 model



For the AERO2K 2002 inventory (Eyers *et al.*, 2005), data are provided by aircraft type allowing some comparable analyses (Figure 32).

Figure 32 NO$_x$ per SKO and EINO$_x$ versus EIS (data from AERO2K 2002 inventory)



A.3 Assumptions of the baselines for this report

This report's BAU baseline case makes the following principal assumptions:

Traffic Demand

Traffic demand to 2020 is consistent with the FESG CAEP/6 forecast (ICAO, 2003). The FESG forecast is provided as growth on route groups, allowing growth to be distinguishing between intra-European flights, domestic European flights and EU to non-EU flights. The FESG forecast data are also disaggregated by aircraft size in terms of seat bands. The FESG-derived growth rates are thus applied to the base air traffic movements data by aircraft size and route.

For the 2050 air traffic demand outlook, a simple econometric model, as used by the FESG in the IPCC Special Report on Aviation (1999), has been applied. Regional disaggregation has been undertaken using the regional differences in GDP growth rates and the broad differences in market maturity between the world regions. A global GDP growth rate of approximately 3% per annum for the period 2020 to 2050 has been assumed based on the values provided by Global Insight used by the FESG in their current forecast (www.globalinsights.com). This is consistent with the IS92e scenario (IPCC, 1999) and mid-way between the higher A1 (approximately 4%) and lower range B2 (approximately 2.3%) of the SRES GDP forecasts (IPCC, 2000). The resultant annual average traffic growth rates for 2020 to 2050 show a continued growth in flights between EU and non-EU countries whereas growth on domestic European flights and intra-European flights show slowing growth rates due to market saturation effects. The passenger RPK figures for the route groups and the respective annual growth rates are provided in Table 18.

Table 18 Passenger Demand Forecast to 2020 and 2050 (RPK) for BAU base line

	2000	2020	% annual growth 2000-2020[26]	2050	% annual growth 2020-2050	% annual growth rate for FESG /CAEP8 2026-36 extension[27]
EU_NONEU	1,042	2,401	4.26	8,536	4.32	4.0-5.2
EUDOM	71	161	4.18	350	2.13	1.75-3.52
EU_EUINT	236	536	4.18	1,302	2.50	2.32-3.68

Fleet rollover

The rate of fleet rollover is based on the FESG/CAEP6 data, which provides an estimate of the number of aircraft, classified by seat bandings, required for future years and an estimate of the number of new aircraft required to both replace retiring aircraft and to increase the fleet. These data were provided by FESG CAEP/6 up to 2020 (ICAO, 2003). Extrapolation of the size of the future fleet and the rollover of the fleet was made to 2050. Aircraft replacements (from existing aircraft types) were also made based on retirement dates.

Fuel Efficiency Assumptions

The base year (2000) inventory results produce a fuel efficiency based on the fuel burn calculated by PIANO for the actual aircraft and the operations performed by those aircraft during this period. The future demand is provided in terms of RPK or SKOs by route and aircraft size as described above, however, knowledge of the fuel efficiency of the future fleet is limited particularly as the future fleet will include some aircraft which are not yet currently in existence.

There has been a clear trend of improving fuel efficiency in the aircraft fleet for many years. Gains in fuel efficiency can be split into air traffic management/operational efficiency and to actual aircraft efficiency. Trends in efficiency generally do not distinguish between these two sources and represent total efficiency gains. The fuel efficiency assumptions made in this study will impact on the whole fleet and are consistent with the assumptions made in the IPCC Special Report on Aviation (1999). The figures in the IPCC report are draw on the research of Greene (1992) which looked at fuel efficiency to 2000 (as seat kilometers offered per kg of fuel) and extrapolated forward to forecast the annual fuel efficiency improvements over time shown in Table 19. A review of the evidence of fuel efficiency improvements included in the UK DfT's Aviation Carbon Dioxide Forecast (DFT, November 2007) concluded that there was a consensus that fuel efficiency has improved over recent years and that fuel efficiency would continue to improve but at a slower rate of annual improvement than seen in the past. The review undertaken by Lee et al. (2001) looked at the

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[26] Based on the CAEP6/FESG route group forecast to 2020.

[27] Draft CAEP8/FESG route group forecast to 2026 and extension to 2036.

efficiency changes in the US only also suggests that annual improvements in energy intensity (fuel use per SKO) were relatively strong in the past but are set to slow (present to 2025 0.7 to 1.3% per annum improvements). In this study, the IPCC consistent fuel efficiency improvements have been used to 2020, Post-2020 a value of 0.75% per annum improvement has been applied this is mid-way between the IPCC pre- and post-2020 value.

Table 19 Percentage per annum improvements in fuel efficiency (SKO/kgfuel)

Period	IPCC/Greene	This study
1990-2010	1.30	n/a
2000-2010	1.03	1.03
2011-2020	1.00	1.00
2020-20250	0.50	0.75
Aggregate 2000-2050 (SKO/kg fuel)	50%	55%

Assessment of CAEP6 and increased stringency on NO_x emissions

The impact of CAEP6 stringency on actual fleet NO_x emissions is not straightforward. The CAEP standards allow for higher NO_x emissions for higher pressure ratio engines. The metric used in stringency is not $EINO_x$ but the NO_x D_p/foo, which is g NO_x/kN thrust at static sea-level test conditions versus overall pressure ratio of the engine (OPR). A discussed in Section A.2 there has been a tendency to produce higher OPR turbo-fan engines in recent years as these are more fuel efficient and quieter but as a consequence, the higher pressures and temperatures the result at the combustor inlet make NO_x control a greater challenge. The current standard in place for all engines certified from January 2008 is the CAEP6 stringency, this supersedes the CAEP4 stringency.

As part of the CAEP Long Term Technology Goals (LTTG) impacts study (Owen and Lee, 2007 and Horton, 2006), it was assumed that changes in NO_x D_p/foo are directly proportional to changes in the $EINO_x$. This assumption ignores any change in NO_x emission characteristics that future technologies might produce. However, in the absence of any other information this was considered to be a reasonable assumption (P. Madden, Rolls Royce, pers. comm. September 2006). Furthermore it is assumed that changes in certification $EINO_x$ relate also to $EINO_x$ during the whole flight.

To capture potential trade-off effects between improved fuel efficiency and consequent increase in OPR and increased NO_x emissions, it has been assumed that the OPR for all larger thrust engines (>89.9kN) increases by 0.5 each year up to a maximum of 50. This assumption was similar to that used in the CAEP8 LTTG analysis work (Owen and Lee, 2007 and Horton, 2006).

For each of the certificated engines, the corresponding pressure ratio and the characteristic NO_x (Dp/foo) value from the ICAO emissions databank were identified to determine the engine's location relative to the CAEP6 stringency line. A ratio of the CAEP6 stringency value NO_x (Dp/foo) to the engine's characteristic

NO_x (Dp/foo) was then calculated and used to factor the $EINO_x$ at the four ICAO certification points. It was further assumed that the factors apply during the cruise phase of the flight as is consistent with the fuel flow methods.

In the BAU case it was assumed that all newly delivered (i.e. post 2008) aircraft in the fleet complied with CAEP6 stringency and fuel efficiency improvement was assumed, in line with the IPCC (1999) assumptions and an average increase in OPR of 0.5 per year to a maximum value of 50.

To assess the impacts of increased stringency (CAEP6- minus 10, 15, 20, 25 and 30%) the same methodology as outlined above has been used. For all cases an increase of 0.5 per year in OPR (to a maximum of 50) is assumed to provide the necessary improvements in fuel efficiency. The increased stringency options are assumed to apply to all engines certified from 2012.

A.4 Results

Table 20 Results of CAEP stringency analysis

	$EINO_x$ g/kg			FUEL (Tg)[28]			NO_x (kg)[29]		
	2000	2020	2050	2000	2020	2050	2000	2020	2050
CAEP6									
EU to Non-EU	13.99	14.71	16.22	47	88	253	658	1,290	4,100
EU Domestic	12.17	12.65	14.52	5	9	13	56	109	190
Intra EU	12.05	12.76	14.95	11	21	36	136	268	534
All arriving and departing	13.51	14.21	15.99	63	117	302	850	1,666	4,824
CAEP6-5%									
EU to Non-EU	13.99	14.58	15.85	47	88	253	658	1,278	4,008
EU Domestic	12.17	12.57	14.11	5	9	13	56	108	185
Intra EU	12.05	12.65	14.46	11	21	36	136	265	516
All arriving and departing	13.51	14.09	15.61	63	117	302	850	1,652	4,709
CAEP6-10%									
EU to Non-EU	13.99	14.40	15.43	47	88	253	658	1,262	3,901
EU Domestic	12.17	12.31	13.46	5	9	13	56	106	176
Intra EU	12.05	12.39	13.81	11	21	36	136	260	493
All arriving and departing	13.51	13.89	15.15	63	117	302	850	1,628	4,570
CAEP6-15%									
EU to Non-EU	13.99	14.21	14.94	47	88	253	658	1,245	3,777
EU Domestic	12.17	12.22	13.00	5	9	13	56	105	170
Intra EU	12.05	12.27	13.28	11	21	36	136	257	474
All arriving and departing	13.51	13.71	14.66	63	117	302	850	1,608	4,421
CAEP6-20%									
EU to Non-EU	13.99	13.99	14.41	47	88	253	658	1,226	3,643
EU Domestic	12.17	11.91	12.19	5	9	13	56	103	159
Intra EU	12.05	11.96	12.45	11	21	36	136	251	444
All arriving and	13.51	13.47	14.08	63	117	302	850	1,580	4,247

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[28] The fuel use is based on Great Circle flight distaces (approximately 10% less than actual flight distances).

[29] The NO_x emissions are also based on Great Circle flight distances (approximately 10% less than actual flight distances).

departing									
CAEP6-25%									
EU to Non-EU	13.99	13.73	13.72	47	88	253	658	1,204	3,468
EU Domestic	12.17	11.70	11.53	5	9	13	56	101	151
Intra EU	12.05	11.73	11.74	11	21	36	136	246	419
All arriving and departing	13.51	13.22	13.39	63	117	302	850	1,550	4,038
CAEP6-30%									
EU to Non-EU	13.99	13.44	12.84	47	88	253	658	1,178	3,247
EU Domestic	12.17	11.61	11.12	5	9	13	56	100	146
Intra EU	12.05	11.62	11.25	11	21	36	136	244	402
All arriving and departing	13.51	12.98	12.58	63	117	302	850	1,522	3,794

Table 21 Percentage difference in $EINO_x$ from Base case (CAEP6) for all EU to/from Non-EU flights

	2020	2050
CAEP6-5%	99%	98%
CAEP6-10%	98%	95%
CAEP6-15%	96%	92%
CAEP6-20%	95%	88%
CAEP6-25%	93%	84%
CAEP6-30%	91%	79%

Figure 33 $EINO_x$ (g/kg-fuel) trends for EU-NonEU flights

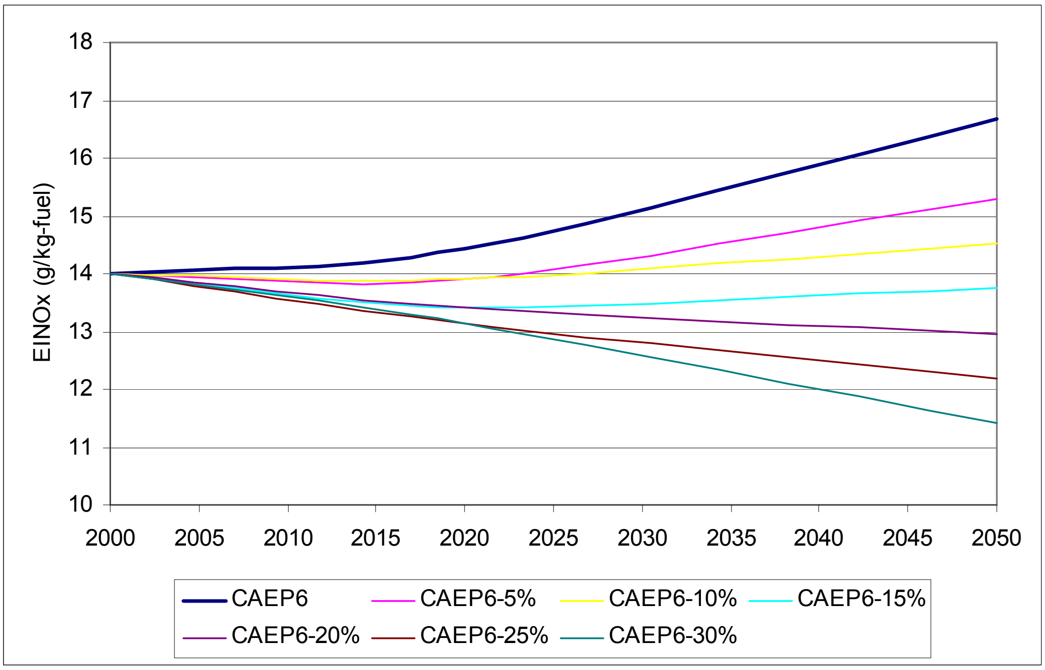


Figure 34 EINO$_x$ (g/kg-fuel) trends for EU Domestic flights

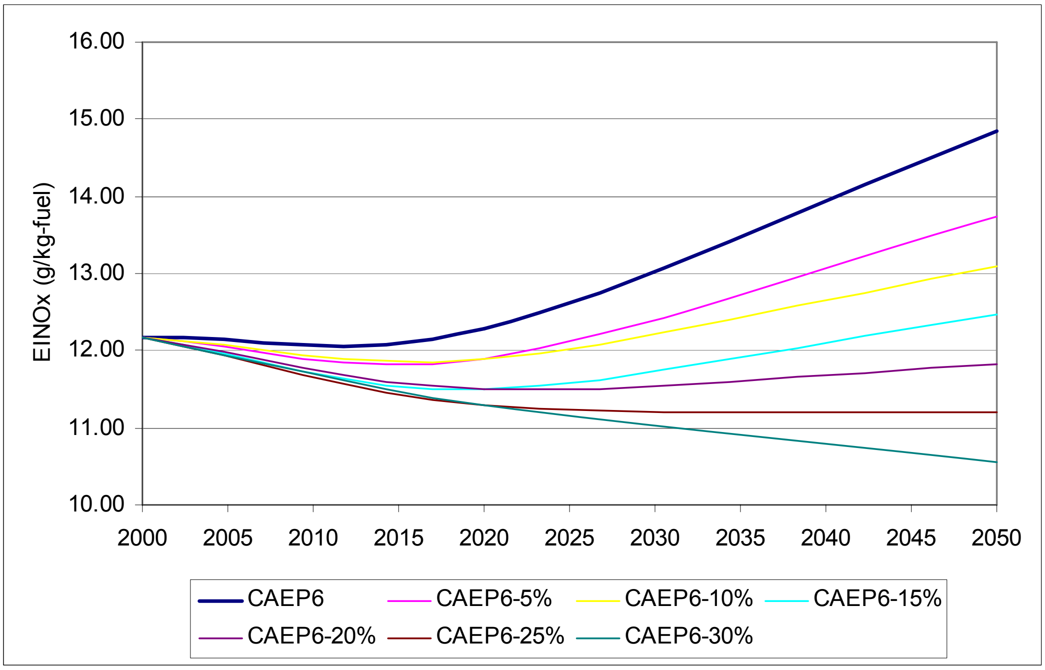


Figure 35 NO$_x$ emissions (kg/year) for all flight (origin and/or destination EU)

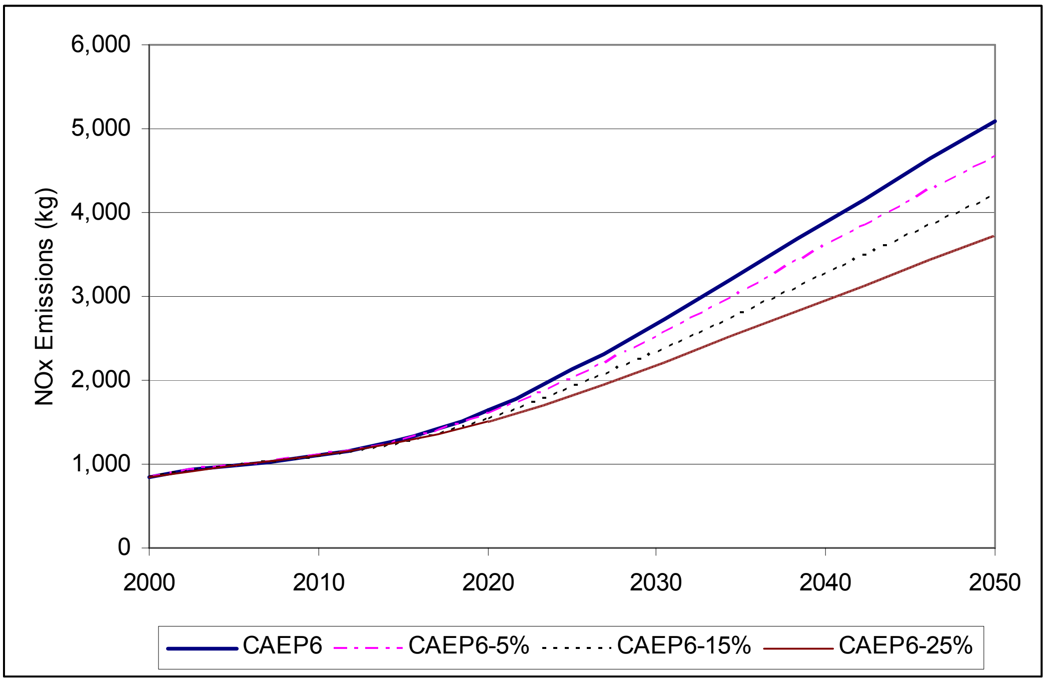
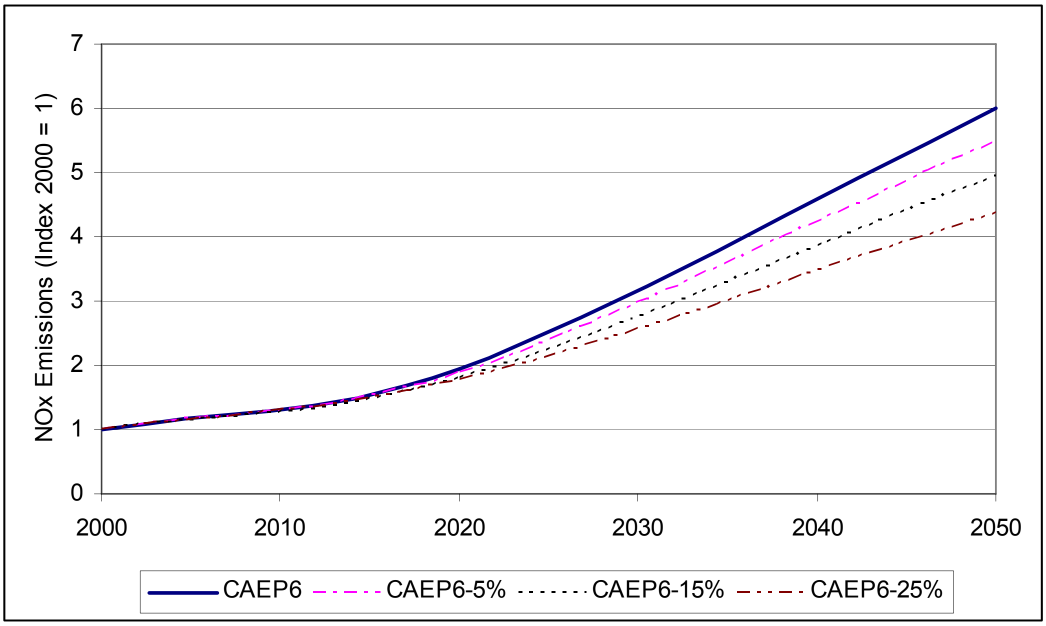


Figure 36 NO$_x$ emissions (kg per year) - Year 2000 emissions = 1 (origin and/or destination EU)



Assessment of CAEP Long Term Technology Goals (LTTG)

The impacts of the CAEP Long Term Technology Goals (LTTG) on NO$_x$ emissions for flights to and/or from the EU have also been assessed, using a similar method as described above. It is assumed in this assessment that the OPR generally increases by 0.5 per year to a maximum of 60. This is the same assumption made in the LTTG assessment work carried out previously (Horton, 2006 and Owen and Lee, 2007).

Figure 37 NO$_x$ emissions (Gg/year) for all flights (origin and/or destination EU)

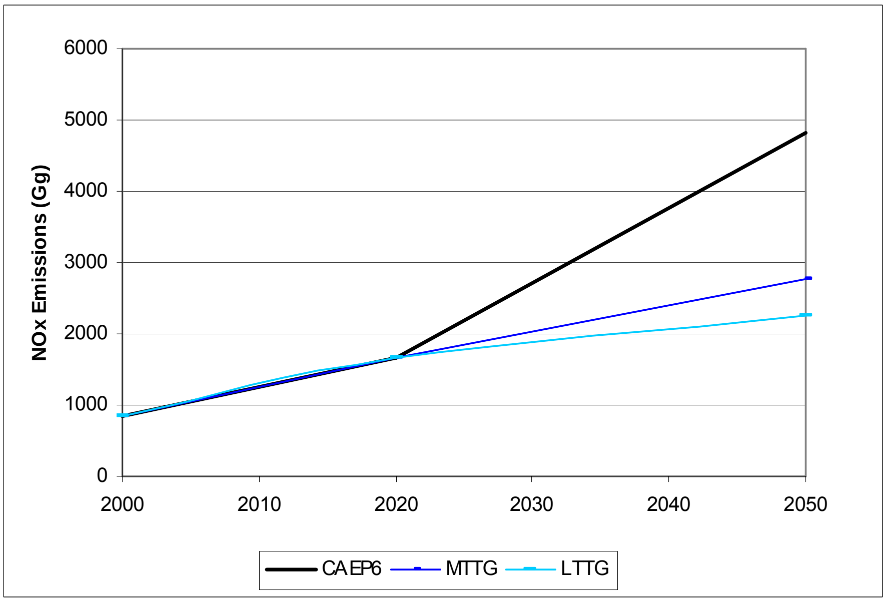


Table 22 Impacts of ICAO Long Term Techonology Goals

	EINO$_x$ g/kg			FUEL (Tg)			NO$_x$ (Gg)		
CAEP6	2000	2020	2050	2000	2020	2050	2000	2020	2050
EU_NONEU	13.99	14.71	16.22	47	88	253	658	1,290	4,100
EUDOM	12.17	12.65	14.52	5	9	13	56	109	190
EU_EUINT	12.05	12.76	14.95	11	21	36	136	268	534
All flights with EU arr/dep	13.51	14.21	15.99	63	117	302	850	1,666	4,824
MTTG									
EU_NONEU	13.99	14.72	9.40	47	88	253	658	1,290	2,376
EUDOM	12.17	12.65	8.28	5	9	13	56	109	108
EU_EUINT	12.05	12.80	8.17	11	21	36	136	269	292
All flights with EU arr/dep	13.51	14.23	9.20	63	117	302	850	1,668	2,776
LTTG									
EU_NONEU	13.99	14.72	7.60	47	88	253	658	1,290	1,921
EUDOM	12.17	12.65	6.89	5	9	13	56	109	90
EU_EUINT	12.05	12.80	6.67	11	21	36	136	269	238
All flights with EU arr/dep	13.51	14.23	7.46	63	117	302	850	1,668	2,250

Table 23 Percentage difference in EINO$_x$ from Base case (CAEP6) for all EU to/from Non-EU flights

	2020	**2050**
MTTG	100%	58%
LTTG	100%	47%

The ACARE Targets and a more aggressive technology scenario

The development of new aircraft types tends to follow a product cycle over many years and it is probable that a new set of aircraft types will enter production and the fleet during the period leading to 2050. These aircraft are likely to be influenced by the Advisory Council for Aeronautics Research in Europe (ACARE) targets for fuel efficiency and for NO$_x$. The industry target is for aircraft manufacturers to deliver a 50% cut in new aircraft fuel consumption between 2000 and 2020 and an 80% reduction in NO$_x$ emissions over the same period. The terms of the commitment are set out in Sustainable Aviation's report 'A Strategy Towards Development of UK Aviation' (2005): 'For CO$_2$, the target is a 50% cut in CO$_2$ emissions per seat kilometre, which means a 50% cut in fuel consumption in the new aircraft of 2020 relative to new aircraft in 2000'. For NO$_x$, an 80% reduction in NO$_x$ emissions is consistent with a 60% reduction in EINO$_x$ taken together with the 50% reduction in fuel consumption. While the ACARE target sets an overall target for new aircraft, there are a range of possible outcomes in terms of uptake and entry into service, so it remains necessary to project the number of aircraft types in service at any future year that will meet the ACARE target. The central case and higher case assumptions used in the UK Air Passenger Demand and CO$_2$ forecast (UK DfT, 2007) for the share of new aircraft entering service drawn from ACARE-consistent aircraft types are applied here (shown in Table 24).

Table 24 Proportion of aircraft entering service that is ACARE Compliant (from UK DfT, 2007)

	2020	2030	2040*
Central	5%	25%	45%
Higher	5%	50%	100%

* Extrapolated value.
Source: UK DfT, 2007.

A simple top-down approach has been developed to assess the likely impact of ACARE targets on both CO_2 and NO_x emissions to 2050 using these assumptions. Under this ACARE target more aggressive fuel efficiency improvements (1.5% per annum) in the period up to 2020 are also implied as industry responds and builds towards the ACARE targets. In view of this assumption, the fleet average $EINO_x$ is assumed to remain at the 2000 level showing no disimprovement with fuel efficiency improvements.

The outcomes of the more aggressive technology scenario approach are shown in Table 25. Under the high ACARE uptake scenario, emissions of NO_x are approximately 2.5Tg (approximately 3 times the 2000 level of NO_x emissions, contrasting with demand over the same period which is estimated at approximately 7 times 2000 levels). The NO_x emissions under this more aggressive technology scenario.

Table 25 ACARE Technology Scenario

YEAR	Fuel (Tg)			NO_x (Gg)		
	Without ACARE assumptions	High ACARE uptake	Central ACARE uptake	Without ACARE assumptions	High ACARE uptake	Central ACARE uptake
2000	63	63	63	850	850	850
2020	117	108	108	1,666	1,459	1,459
2050	302	234	270	4,824	2,558	3,736

Figure 38 Fuel Usage (Tg/year) for all flights (origin and/or destination EU)

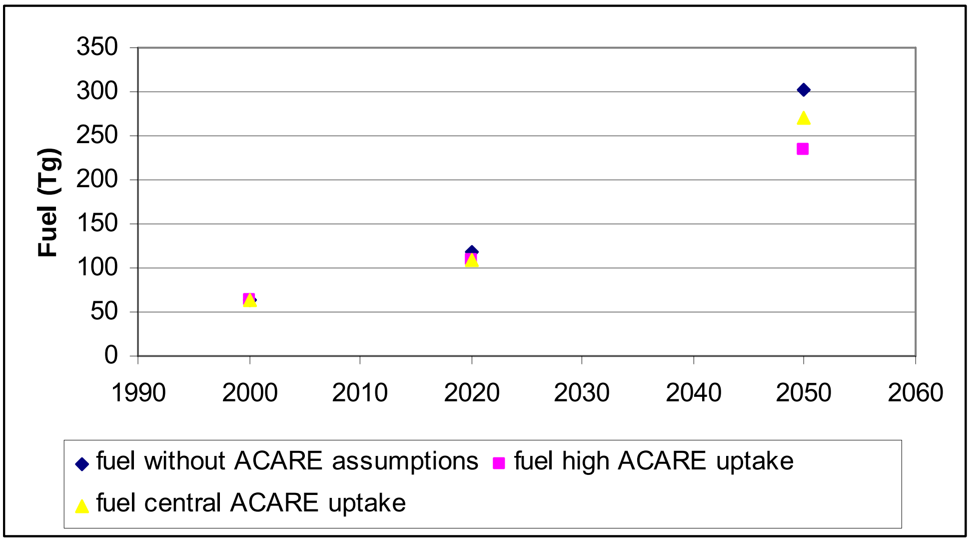
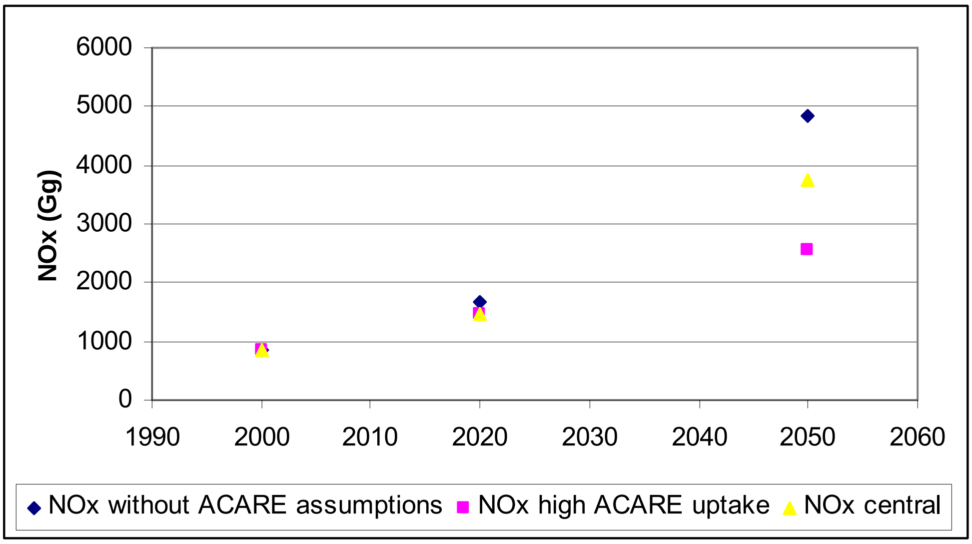


Figure 39 NO_x emissions (Gg/year) for all flights (origin and/or destination EU)



B Selection of policy options

An initial list of options was drafted by the consortium in consultation with Commission Services, and sent to stakeholders for comments. Stakeholders were asked to comment on the list and to identify any additional options. A number of stakeholders replied in writing. In addition, consortium members held meetings with several stakeholders, including engine manufacturers, airlines, airports, and environmental NGOs and consulted experts from Member State governments and relevant organisations. In addition, a formal stakeholder meeting was held on 25 February 2008. Minutes of this meeting can be found in Appendix B.1.

Some stakeholders proposed options that were not on the original list. Most stakeholders commented on the listed options. As can be seen from Section B.1, their comments have been taken into account in the evaluation of the options.

B.1 Comprehensive list op options

The policy measures are categorised in four groups:
1 Standards of emissions at source.
2 Operational procedures to reduce NO_x emissions.
3 Economic and financial incentives.
4 Miscellaneous.

Specifically, the long list included the following policy measures.

1 Standards of emissions at source

- **EU push for increased stringency of existing ICAO standards for LTO NO_x emissions of new engines**; the EU intensifies its efforts to argue for increased stringency of ICAO standards.
- **EU action for the introduction of ICAO standards for cruise emissions for new aircraft or engines**; the EU starts to press for the introduction of ICAO standards for cruise emissions, either NO_x or NO_x and CO_2 combined.
- **EU LTO NO_x emission standards for engines or aircraft newly registered in EU Member States or operated on flights to and from EU airports**; the EU agrees on standards for engine or aircraft LTO NO_x emissions that are more stringent than current ICAO standards.
- **EU Cruise NO_x emission standards for engines or aircraft newly registered in EU Member States or operated on flights to and from EU airports**; the EU agrees on standards for engine or aircraft Cruise NO_x emissions.
- **A phase-out of the worst performing engines on EU registered aircraft or on aircraft operated on flights to and from EU airports, followed by a ban**; the EU agrees to ban aircraft with engines surpassing

certain emission standards from registering in EU member states or from landing at EU airports after a phase-out period.

In addition to the policy options relating to standards of emissions at source, some stakeholders suggested including the NO_x emissions of Auxiliary Power Units (APU) in the LTO standards. While this seems to be a good suggestion for local air quality policy, it has several drawbacks for climate policy. Since APU's are normally not used in flight but only at airports to generate electricity and start the engines, including APU emissions in the LTO emission cycle would increase the recorded volume of LTO emissions without affecting cruise emissions. This could result in a deterioration of the correlation between LTO and cruise emissions. Therefore, in the current context, we decided against inclusion of this policy in the long list of options.

Also, in addition to the policy options above, one stakeholder suggested limiting the cruise speed of existing aircraft or the design speed of new aircraft. As for the former, we have come to the conclusion that any deviation from the optimal cruise speed of existing aircraft comes at a fuel penalty and likely also at a NO_x emission penalty. Therefore, this policy option has not been included in the long list. A limit to the design speed of new aircraft could indeed reduce fuel use and emissions per flight kilometre. However, it cannot be seen as a policy specifically aimed at reducing Cruise NO_x emissions, even though it could have an impact on Cruise NO_x emissions. And apart from the feasibility of implementation, introducing speed limits would only indirectly target emissions and come at a welfare cost, since it would limit the abibility of actors to trade speed for fuel consumption. Therefore, this option has not been included in the long list of options. However it could be a medium term option for industry, for example if a propfan aircraft is developed with lower cruise speed and fuel burn.

Several stakeholders suggested that production or registration cut-offs should be considered. Currently, CAEP standards only apply to new engine types. Existing engine types (i.e. types that have already been certificated) that do not meet current standards may continue to be produced and sold. A policy could be conceived that would forbid the sale of non compliant engines (a production cut-off) or that would not register new aircraft with non-compliant engines on them (a registration cut-off). Even though currently sales of engines not compliant with new standards is very limited, production cut-offs could be introduced as a way to prevent an increase of the sales of old engine types in the future. It has been decided to treat production cut-offs as a special case of ICAO or EU LTO emission standards.

A final suggestion for an addition to the above options has been to include joint EU/US standards for LTO NO_x emissions. This can be seen as an intermediate policy between EU standards and ICAO standards. Legally, the policy would be very similar to EU standards. Therefore, we decided to assess them as a special case of 1c, EU LTO NO_x emission standards.

2 **Operational procedures to reduce NO_x emissions**

- **Strengthen implementation of the Single European Sky**; the EU implements measures ensuring efficiency improvements in the European air traffic management system, thereby reducing detours on flights in EU airspace. This would reduce all emissions, including NO_x. This is already part of the comprehensive approach to addressing aviation emissions set out in the Commission's Communication in 2005 (COM (2005)459 final).
- **Climate-optimised air traffic management - flying at altitudes or routes that minimise NO_x emissions, contrail formation and CO_2 emissions)**; the EU implements air traffic management procedures for the entire flight aimed at reducing the climate impact of flights, e.g. by changing altitudes and flying around supersaturated areas in which contrails form, or increased use of continuous descent approach.

One group of stakeholders suggested the inclusion of an additional policy option in the list, namely improved efficiency of airport operations. However, we are of the opinion that the Single European Sky ATM Research (SESAR) already addresses airport efficiency issues and the EU regulation for the Single European Sky also specifically mentions airports and airport operators[30]. Therefore, we do not see the need to include this option as a separate item in the long list.

3 **Economic and financial incentives**

- **EU-wide differentiation of existing charges according to LTO NO_x emissions or EU LTO NO_x charge**; the EU implements a scheme for the differentiation of charges related to aviation (be it ATM charges, airport charges or government charges) based on NO_x emissions, either LTO NO_x emissions or Cruise NO_x emissions. Or the EU implements a LTO NO_x charge, the revenue of which could be used for offsetting or for R&D.
- **EU NO_x en route charges or performance incentive**; the EU implements en route charges for Cruise NO_x emissions, be it for flights to and/or from or between EU airports, flights in EU airspace or any other flights within the jurisdiction of EU Member States. The revenue could be used in a number of ways. A performance incentive would not have revenue, since it is a revenue-neutral charge-subsidy system, which may be based upon absolute emission levels or relative criteria such as emissions per RTK, or load factor related.
- **Inclusion of aviation NO_x emissions in the EU ETS**; the EU creates allowances for aviation NO_x emissions that can be traded against CO_2 emission allowances; aircraft operators would need to surrender NO_x allowances in addition to CO_2 allowances for flights to and from EU airports.
- **Introduction of a multiplier for aviation in the EU ETS**; aircraft operators surrendering EU emission allowances (EUAs), to cover their emissions under the EU ETS, would be required to surrender more than

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[30] Regulation 594/2004 (REGULATION (EC) No 549/2004 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 10 March 2004 laying down the framework for the creation of the Single European Sky).

  one EUA for each tonne of CO_2 emitted in order to reflect aviation's non-CO_2 climate impact; the multiplier could be general or aircraft specific.
  - **Introduction of a NO_x emission trading system**; aircraft NO_x emissions would be included in an emission trading system for NO_x, which could extend to other sectors.
  - **NO_x emissions are included as criterion in airport slot allocation rules;** this way the use of low-NO_x aircraft could be rewarded through preferential access to or advantages in obtaining slots at congested airports.

In addition to the list above, one consulted expert suggested introducing NO_x quotas for airports and a NO_x quota count system for aircraft. The idea would be to limit the total NO_x emissions at an airport to a quota. Each aircraft would get a quota count, i.e. a number reflecting the NO_x emissions. The sum of all the quota counts would not be allowed to exceed the airport quota.

Such a policy would be primarily aimed at LTO NO_x emissions in the vicinity of the airport. However, since LTO NO_x and Cruise NO_x seem to be correlated, there would be an effect on Cruise NO_x emissions too. The policy would potentially allow more freedom to operators than emission standards. If it could guide research towards meeting a certain quota count, as the Heathrow noise quota count system seems to have done, it could have lower LTO NO_x emissions and even lower Cruise NO_x emissions as a result.

An airport NO_x quota is primarily a policy instrument to reduce NO_x emissions at the airport. It is thus a local air quality policy rather than a climate policy. Even though it could have co-benefits for climate, its primary benefits would be on air quality. Therefore, we have decided not to include this policy in the long list.

4 Miscellaneous

- **Voluntary agreements with aircraft engine manufacturers and/or airframe manufacturers and/or aircraft operators on NO_x emissions from engines**; the EU enters into an agreement with aircraft engine manufacturers and/or airframe manufacturers and/or aircraft operators to reduce the NO_x emissions from engines or the emissions per LTO or per passenger or per revenue tonne kilometre according to a specified time path, such as for example set in ACARE's technology goals.
- **Further funding of research into:**
  - **Reduction of NO_x emissions from engines**; the EU increases its funding of aircraft engine research and emphasises the reduction of NO_x emissions.
  - **Reduction of NO_x emissions or climate impact by changing operational procedures**; the EU increases its funding of air traffic management research and emphasises the reduction of NO_x emissions or climate impact.
  - **Best practices to reduce NO_x emissions during flights**; the EU funds a study into the best practices of reducing NO_x emissions during flights and facilitates the dissemination of the findings to the relevant stakeholders.

Giving higher priority to aeronautics research is already part of the comprehensive approach to addressing aviation emissions set out in the Commission's Communication in 2005 (COM(2005)459 final).

B.2 Broad evaluation of the options

This section evaluated the options identified in Section B.1, taking stakeholder comments into account.

B.2.1 Standards of emissions at source

Five policy options were identified relating to standards of emissions at source:
1a EU push for increased stringency of existing ICAO LTO standards.
1b EU action for the introduction of ICAO standards for cruise emissions.
1c EU LTO emissions standards.
1d EU Cruise NO_x emissions standard.
1e An EU phase-out of the worst performing engines followed by a ban (i.e. a non-addition rule followed by a non-operation rule, similar to the process followed with the phase-out of and final ban on Chapter 2 noise-certificated aircraft in the years leading up to April 2002).

General
Because of the NO_x versus CO_2 trade-off, all policies in this category may lead to an increase in CO_2 emissions. This may either show as an increase in specific fuel consumption (SFC), or a lesser decrease in SFC than could have been realised without reduced NO_x emissions. The existence and scale of this will depend on whether the technology response required to meet tighter standards results in a fuel burn penalty.

LTO standards versus cruise standards
Since the objective of a policy would be to reduce the climate impact of aviation NO_x, and since this impact results from emissions during cruise, a policy needs to reduce cruise emissions. Therefore, a standard relating to cruise emissions would suit the policy objective better than a standard relating to LTO emissions.

However, Cruise NO_x standards do not currently exist. There is currently no certification of NO_x emissions characteristics of engines during cruise. Designing cruise standards would not be straightforward. For a start, one would need to define cruise conditions (temperature, pressure, humidity, etc.) and secondly, engine emissions would need to be measured under these conditions. This would require investments in pressure chambers, et cetera.

The policy options which are related to LTO NO_x standards or a phase-out (policy options 1a, 1c and 1e) are expected to reduce total NO_x emissions in the LTO cycle. A phase-out provides the potential for a larger environmental effect, especially in the short term, because with NO_x standards for newly certificated engine it takes a while before the measure has significantly penetrated the fleet.

The extent to which policies targeted at LTO NO_x can reduce Cruise NO_x at altitude depends on the correlation between the two. If the correlation is only weakly positive, the impact in reducing cruise emissions will be small. Following our analysis in Chapter 5, we conclude that currently, more stringent LTO NO_x standards would indeed have some effect in reducing Cruise NO_x emissions. This means that currently, the need for Cruise NO_x standards is not considered to be large enough to overcome their disadvantages.

However, new developments in engine technology, notably the introduction of lean burn engines with staged combustors, may result in the breakdown of the current correlation in the future. So while current policies could aim for more stringent LTO NO_x standards or be based on LTO NO_x emissions, the correlation between LTO NO_x emissions and Cruise NO_x emissions should be monitored closely in order to prevent perverse effects from materialising.

There are no major problems with data availability and ease of implementation with any of the policies based on LTO NO_x (1a, 1c, 1e), as LTO NO_x emission values are available in the type approval certificates, and are publicly available in the ICAO engine emissions databank[31].

As noted by many stakeholders, LTO NO_x standards are currently set by CAEP. Their periodic review and expectations of increased future stringency drive research towards lowering engine emissions. Engine manufacturers have argued that they aim to introduce new engines that not only comply with current standards, but exceed them by a considerable margin.

ICAO standards versus EU standards

Whereas ICAO standards would require international agreement, EU standards would require agreement amongst a smaller number of countries. Therefore, the EU may be able to agree on standards that are more stringent then ICAO standards.

EASA would be the agency to implement the standards, as it approves engine types that are introduced to the market. All aircraft registered in EU countries need to have EASA type approval for engines on the aircraft. Currently, implementing EU standards that are stricter than current ICAO standards is not possible as the EASA Basic Regulation (2002/1592) directly references the ICAO Annex 16 requirements. However, EASA is working on a revision to the EASA environmental protection essential requirements which will provide flexibility to deviate if the EU so wished.

EU standards would probably encounter no legal obstacles if they apply to aircraft registered in the EU only.

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[31] ICAO Engine Emissions Databank, hosted and maintained bu the UK CAA, http://www.caa.co.uk/default.aspx?catid=702.

Any standards applying only to EU carriers carry the risk of a distortion of competition between carriers from EU and non-EU states, particularly when EU and non-EU are competing head-to-head on individual routes.

Many industry stakeholders expressed concern over the use of regional standards in a global business and argued that such measures would displace the problem to other parts of the world, with limited environmental benefits, and distort competition. We discussed in detail with a number of stakeholders the likely reaction to regional standards. The conclusion we draw from these discussions is that if the EU standards were to exceed the global standards by a margin that is not too large, engine manufacturers would probably react by designing new engines to meet the EU standards. The cost of maintaining two sets of engines, each compliant with another set of standards, would be too high. However, airlines may react by registering aircraft in non-EU states, thereby circumventing the tighter standards.

In sum, the effect of EU standards would depend to a large degree on responses of stakeholders to the EU standards and whether or not they will try to evade them.

Production or registration cut-off[32]

Engine manufacturers informed us that currently most engines meet CAEP/6 standards which came into effect in January 2008. Some engines do not yet comply with the CAEP/6 standard. While some engines are in the process of being made compliant, there are other engines coming towards the end of their production where it does not make commercial sense to modify them. Engine manufacturers aim to design engines that are compliant by a considerable margin and claim that demand for engines complying with old emission standards diminishes sharply as new standards enter into force. This would mean that neither a production nor registration cut-off would have significant environmental benefits if current market conditions prevail nor cost much. However, if market conditions changed to the extent that production phase-outs would no longer be market driven, a production or registration cut-off could act as a backstop against a decreasing impact of new standards.

Phase-out

Again, a phase-out is legally feasible as an internal EU measure operated by EASA for aircraft registered in EU states.

Phasing out of aircraft registered in non-EU states is more complicated if phasing out is based upon certification standards which go beyond the ICAO standards on this subject, unless agreement has been reached in a bilateral or multilateral context with a foreign state on phasing out of worst performing aircraft. If there is no such agreement, and if the measure results into a partial or even total ban on

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[32] A production or registration cut-off could take many forms. We have not yet started to design such an instrument. At present it seems conceivable that the production cut-off could take the form of a ban on producing non-compliant engines (perhaps after a transitional period) or a ban on registering aircraft that have such engines.

operations into and from airports in the EU, disputes and even retaliation may follow.

Moreover, Appendix A indicates that the trend in Cruise NO_x emissions per passenger kilometre have remained more or less constant over time. As a result, the worst performing engines could be either new engines or old engines. Scrapping new engines with long remaining service lives would have a very poor cost-effectiveness, with high costs and limited environmental benefits.

Airline stakeholders were critical of phase-out options on the grounds that they were costly with only limited environmental benefits.

Conclusion
Although an EU push for increased stringency of existing ICAO LTO standards is no more than a continuation of current policies through ongoing tightening of technical standards for LTO NO_x emissions by ICAO, it is recommended that it is taken forward into the shortlist as a default option. It is not recommended to consider a production cut-off of engine types compliant with old standards, as the evidence suggests that this would produce little or no environmental benefit. Problems of data availability are judged to be sufficient to rule out cruise emissions standards at present (options 1b and 1d), but these should be kept under review for future consideration as information becomes available. It is recommended that option 1c (EU LTO emissions standards) should be taken forward into the shortlist, though it is recognised that it will give rise to competition distortions if limited to EU carriers, and could be open to challenge if extended to carriers from non-EU states. A production cut-off would be included in this option, if feasible. In the light of evidence indicating that the trend in NO_x emissions per passenger km has been flat over time, a phase-out would affect a number of relatively new engines and is unlikely to be cost effective with high compliance costs and limited environmental benefits.

B.2.2 Operational procedures to reduce NO_x emissions

Two policy options were identified relating to operational procedures:
2a Strengthen implementation of Single European Sky.
2b Climate optimised air traffic management.

The implementation of Single European Sky air traffic management system offers the prospect of reducing detours and delays of flights in EU airspace, thereby reducing both NO_x emissions during cruise and CO_2. However there is some evidence to suggest that ATM improvements achieved to date have allowed more traffic through releasing capacity constraints, which while leading to improvements in CO_2 and NO_x per passenger km, have not reduced overall CO_2 and NO_x emissions in EU airspace. This option is current policy and its cost effectiveness has already been assessed.

The impact of a climate optimised ATM system in reducing NO_x emissions and the resulting effects of climate change are subject to considerable scientific uncertainty, particularly with regard to the climate effects of contrail formation. In addition the availability of data to assess what the climate-optimised flying attitudes, latitudes or routes (which will vary by time of year) is poor, and such a policy would not be easy to implement. The scientific uncertainties would make any assessment of cost effectiveness difficult. The costs to airlines of deviating from economically optimal routeings would be high, while the impacts on emissions and climate change would be uncertain.

Industry stakeholders were strongly supportive of option 2a, arguing that making airspace more efficient would be a win-win solution, reducing airline fuel costs as well as both CO_2 and NO_x emissions. There was no support from stakeholders for option 2b. Concerns were expressed that it was extremely complex and unrealistic, and would require reliable information on the relative impacts of NO_x, CO_2 and contrails.

Conclusion

It is clear that implementing the Single European Sky may reduce CO_2 emissions and NO_x emissions on most trips in EU airspace. Consequently, measures to accelerate its implementation would clearly be beneficial for the environment, even though some of the gains may be offset by higher demand. However, such a policy would not specifically address NO_x, nor would it prevent the exploitation of the NO_x : CO_2 trade-off to the extent that it would be detrimental to climate. Furthermore, it is an existing policy whose cost effectiveness has already been assessed. As a result, it is not recommended that SES be taken forward into the shortlist of options. There are too many scientific uncertainties with the climate effects of a climate optimised ATM system to recommend taking this option forward.

B.2.3 Economic and Financial Incentives

Six policy options were identified using economic or financial incentives to address NO_x emissions:

3a EU wide LTO NO_x charge (with distance factor).
3b EU NO_x en route charge.
3c Inclusion of aviation NO_x emissions in the EU ETS.
3d Multiplier for aviation NO_x emissions in the EU ETS.
3e NO_x emission trading system.
3f NO_x emissions as a criterion in slot allocation rules.

NO_x emission charges

Like standards, Cruise NO_x charges would target the climate impact of NO_x more directly than LTO NO_x emissions. As argued above, Cruise NO_x emissions of aircraft engines are currently not certificated and if data exists at all, it is not publicly available. It might be possible to model Cruise NO_x emissions using fuel flow models such as PIANO and multiply the cruise fuel flow by the emission index of NO_x ($EINO_x$). However, to the extent that such a model provides accurate data, basing a charge on such data would require modelling a very large number of missions for a very large number of aircraft-engine combinations.

In contrast, LTO NO_x data are available from public databases. A number of EU airports have already introduced LTO NO_x charges to meet local air quality objectives, and there are no major data availability and implementation problems with option 3a. However consideration would need to be given to how the charge would be structured according to distance (e.g. banded or continuous according to mileage).

In theory an EU LTO NO_x charge will reduce LTO NO_x emissions by at least marginally encouraging airlines to change their fleet planning behaviour, but its effectiveness in reducing Cruise NO_x emissions will depend on the strength of the correlation between LTO and Cruise NO_x emissions. However if option 3a is designed to include a distance factor, its effectiveness in reducing Cruise NO_x emissions would be improved. Conversely, an EU NO_x en route charge will reduce Cruise NO_x emissions, but its effect in reducing LTO NO_x emissions is uncertain for the same reasons. With both types of charge, there could be increases in CO_2 emissions where they lead to the purchase of less fuel-efficient aircraft.

Airport and other stakeholders, as well as existing CAEP studies, have indicated that Franco-Swiss, Swedish and London LTO NO_x charges have had no measurable causal effect[33] on airline behaviour, as they are often low in absolute terms[34]. However, we question whether these findings would be applicable to an EU-wide introduction of charges. In that case, there would be a stronger economic incentive for airlines to acquire low NO_x engines on their new aircraft, as charges would apply to every landing or take-off at EU airports and the benefit to be had from low NO_x engines would be much larger. Furthermore, EU-wide implementation would provide a stronger incentive for engine manufacturers to design low NO_x aircraft than implementation at only a small number of airports. Harmonisation would also avoid any distortion of competition between airports. Airport stakeholders are also understandably concerned that any LTO-related charge on cruise emissions should not be incompatible with their existing schemes, often integral to action packages aimed at meeting LAQ requirements under Directive 1999/30/EC.

Some stakeholders have argued that 'ICAO policy requires that local emissions charges, such as NO_x charges, be applied to aircraft in international flight only at airports that have identified local emissions problems. The basis for this flows from Article 15 of the Chicago Convention, which requires linking of charges to airport-specific facilities and services and a cost-basis for such charges.' They

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[33] Clearly no effects can yet be measured from charges currently being introduced in Germany. At other airports, it appears not proven that any LTO emission improvements have been the result of the revenue-neutral charges imposed.

[34] For instance, an A320-200 with twin CFM56-5-A1engines would pay just under € 50 per turn round at Stockholm-Arlanda. However, perceived cumulative effects may be significant. Elsewhere, one airline is expected to save € 0.5 million p/a in landing fees as a result of an overall revenue-neutral LTO NO_x charge at its home airport.

claim that a Europe-wide blanket NO_x charge would violate the Chicago Convention and ICAO policy, without evidence of local emissions problems at each airport. However, we are of the opinion that this legal argument is not clear when the aim of the policy is not local air quality but climate change. Since climate change, through LTO emissions, affects the use of airports and airspace, the argument could be made that airport and air navigation charges may reflect that impact on such airports and airspace.

Charges (options 3a and 3b) would need to be compliant with Article 15 of the Chicago Convention and bilateral air service agreements, and in particular it will be necessary to ensure that any NO_x emissions charge is not so closely related to fuel that it becomes effectively a fuel levy[35]. Subject to these considerations, there appear to be no insurmountable legal obstacles.

Options 3a and 3b could be designed as revenue neutral charges so that no net proceeds are collected. If charges are revenue-raising, consideration will need to be given to the use of the proceeds. One option could include rechannelling them into funding research into engine technology or other climate change abatement measures inside or outside the aviation industry. ICAO guidance states that funds from charges should not go to national exchequers and should be used to mitigate the relevant environmental impacts (possibly including some form of offsetting scheme).

Some stakeholders have argued that charges would have no effect as they would lower profit margins and thus reduce the ability of airlines to renew their fleet. We believe that prior research has demonstrated convincingly that airlines are able to pass on cost increases to their customers to the extent that charges need not impact negatively on profit margins (CE et al., 2005; CE, 2007)[36].

NO_x allowances in the EU ETS and the multiplier

The inclusion of aviation NO_x emissions in the EU ETS should reduce NO_x emissions (either cruise or LTO depending how the mechanism is designed), because of the price attached to these NO_x allowances. Again the success of the measure in reducing both LTO and Cruise NO_x emissions will depend on the strength of the correlation between the two. With NO_x emissions allowances tradeable against CO_2 emissions allowances, there could be adverse effects on CO_2, but this is unlikely as long as aviation continues to be a purchaser of allowances, rather than taking abatement action to reduce emissions.

The major problem with this measure, in common with a number of others, is that it would require data, currently not available, on NO_x emissions of engines during cruise. There are also likely to be implementation issues with designing a measure to enable NO_x emissions allowances for aviation to be traded with CO_2

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[35] Some years ago a fuel levy on domestic flights in Sweden, later ruled incompatible with Community law, was claimed to be responsible for the introduction of a combustor modification on an operator's F28 fleet.

[36] Only in markets where airlines are able to extract monopoly or oligopoly rents, costs will not be passed through in full (Ernst and Young et al., 2007).

allowances for aviation and other economic sectors. This measure might be difficult to introduce in the short term.

A fixed multiplier in the EU ETS to allow for non-CO_2 emissions from aviation would strengthen the incentive to reduce CO_2 emissions, but is likely to lead to an increase in NO_x emissions because of the trade-off between CO_2 and NO_x emissions. Whether the overall climate change effect is positive or negative will depend on the climate impacts of CO_2 compared to NO_x. There remains significant scientific disagreement over the effect of non-CO_2 emissions from aviation with criticism of the use of a fixed multiplier, which implies a stable relationship. Furthermore, the metric used for the current multiplier – RFI – has already been shown to be an unsuitable metric as an emissions equivalent (CE Delft et al., 2005; Forster et al., 2006; IPCC AR4 WG1, 2007).

Despite the scientific uncertainties, a multiplier does not present any serious problems of data availability, ease and speed or implementation or competition.

There was opposition from airlines to including aviation NO_x in the ETS, as the process of including aviation CO_2 into the ETS is not yet finished and because it would be difficult to establish conversion factors between NO_x and CO_2 which have different life spans. There was more general opposition to the use of a multiplier to allow for NO_x emissions, given the scientific difficulties and the likelihood that it could give rise to perverse effects in increasing NO_x emissions.

A NO_x emission trading system

A separate NO_x emissions trading system for aviation (option 3e) would create incentives to reduce NO_x emissions, depending on the tightness of the emissions cap. To the extent that NO_x abatement measures are stimulated by this measure, some adverse effects on CO_2 would result, with uncertain net effects on climate (as with option 3d). With no data available on cruise emissions, there would be design and implementation difficulties with this measure.

However, some industry stakeholders considered that a NO_x trading system offered potential and deserved further examination.

NO_x only has a climate impact at cruise altitudes. Ground level NO_x emissions (which have a well researched regional and local air quality impact) can also have a climate impact, but this depends on the extent to which they are convected upwards to cruise altitude. This means that a NO_x emission trading system that would intend to reduce the climate impacts of NO_x, would either have to be a closed system for aviation or have a complicated design in which NO_x emissions of ground level sectors have a 'convection multiplier'. A closed system is undesirable as a lack of liquidity in the market could make the market less efficient. An open system could take years to implement as complex monitoring and verification rules would have to be set for many sectors and probably additional scientific research would be needed to establish the 'convection multiplier'.

NO_x emissions as a criterion in slot allocation rules

NO_x emissions could be included as a criterion in slot allocation rules through earmarking a category of 'green slots'. This would have an impact in reducing LTO NO_x (and possibly cruise emissions), possibly resulting in some CO_2 increases. There should be no significant data availability problems, if based on LTO NO_x emissions, but implementation would be complex and controversial. Only busy congested airports in the EU are slot co-ordinated and their objective is to encourage efficient use of scarce airport capacity. Introducing an environmental criterion would not only add to the complexity of the system, but create conflicting objectives between economic efficiency and the environment, for example if some small regional aircraft qualify for 'green slots'.

There was strong opposition from airline and airport stakeholders against using the slot allocation rules for environmental purposes as it would add to its complexity and undermine its chief objective of encouraging the efficient use of scarce airport resources.

Conclusion

An en-route emissions charge would be environmentally effective as it would be directly related to cruise emissions. In principle emissions could be priced according to their environmental damage costs. However there is no agreed way of measuring Cruise NO_x emissions and it would be necessary to ensure that charges are not closely related to fuel burn. In these circumstances, although less environmentally effective, it is recommended that an LTO NO_x charge with a distance factor is taken forward into the shortlist. This option would overcome the data collection problem with en-route charges and by making it a distance-based charge, it will create a greater environmental benefit than a simple LTO charge, because it would have a link with actual emissions levels resulting in longer flights paying more. One risk with this measure is if there is a poor direct relationship between LTO and en-route NO_x emissions, or if it breaks down in the future.

A multiplier could have the perverse effect of increasing NO_x emissions and has been challenged on scientific grounds. However it is recommended taking it forward to the shortlist as a benchmark against which to compare other options, particularly as this is an approach which has been supported by the European Parliament in the context of the negotiations on the proposal to include CO_2 emissions from aviation in the EU ETS. We will revisit multipler-based metrics, noting that RFI has already been shown to be an unsuitable metric as an emissions equivalent (CE Delft et al., 2005; Forster et al., 2006; IPCC AR4 WG1, 2007).

Including aviation NO_x into the EU ETS would make the system complex, but would give the right incentive provided that NO_x emissions can be unambiguously calculated and that a NO_x GWP can be established. it is recommended including aviation NO_x in the EU ETS is taken forward into the shortlist

Including NO_x emissions in the slot allocation is not recommended as this could undermine an already complex system, whose objective is to promote the efficient use of airport capacity.

B.2.4 Miscellaneous policy instruments

Two policy options could not be classified in any of the other categories and were labelled ‘miscellaneous’:

4a Voluntary agreements to limit aviation NO_x emissions.
4b Further funding of research into:
  Reduction of NO_x emissions from engines.
  Operational procedures to reduce NO_x emissions.
  Best practices to reduce NO_x emissions during flights.

Voluntary agreements

A number of stakeholders argued that the ACARE goals and the CAEP Long Term Technology Goals acted as de facto voluntary agreements. Engine manufacturers claim they steer their research towards meeting these goals. Their main incentive for doing so seems to be the expectation that ICAO-LTO emission standards may be tightened in current and future CAEP rounds because of local air quality concerns. This implies that there is limited scope to go beyond the current goals in a voluntary agreement.

ACARE goals may act as de facto voluntary agreements for airframe manufacturers as well.

Research funding

No stakeholders opposed additional Community funding of further research into the reduction of NO_x emissions at source, their abatement by operational procedures, and/or the identification of best practice. Some stakeholders identified hypothecated revenues from charging systems (including LTO-based airport charges) as a potential source of such funding; but others felt that such hypothecation should be linked to other goals such as meeting the costs of LAQ improvement or regional external costs (health, etc.).

Considerable funding is already available for environmental research, including eg the Clean Sky JTI. It would be necessary to ensure that additional funding stimulated further technology improvements or brought it forward in time.

Overall, however, while research is a generic element which must be carried forward in this study (given the fields of scientific and technological uncertainty which have already been identified), we regard it as necessarily complementary, and not alternative, to the policy options discussed in the previous sections.

Conclusions

There could be a limited role for voluntary agreements but it would be necessary to ensure that they deliver emissions reductions beyond the base case and that they could be adequately monitored.

We take it as given that academic and industrial research will continue into the climate effects of NO_x and its reduction both at source and in abatement terms. We shall also give further consideration to the potential hypothecation of revenue to such research to assist in the funding of such research. However, earmarking this revenue to the aviation industry is not the only, or necessarily the best option. It may be more cost effective to use revenues to fund climate change abatement through NO_x reduction elsewhere.

B.3 Selection of policies for further design and analysis

In the selection of policy options, several results from the scientific review (Chapter 4) and from the technological review (Chapter 5) need to be taken into account.

Although the scientific evidence shows convincingly that aviation NO_x is contributing to global warming, it cannot at present relate the impact of an additional amount of aviation NO_x to an additional amount of greenhouse gases such as CO_2 in a meaningful way. At the same time, it is clear that the climate impact of aviation's CO_2 emissions is larger than the impact of its NO_x emissions in most of the metrics commonly used to quantify climate impact.

The technological review suggests that there is a NO_x : CO_2 trade-off at the engine level. In other words, a reduction of NO_x will come at the expense of higher CO_2 emissions than would otherwise be possible. This result, combined with the scientific evidence, suggests that any policy with relation to the climate impact of aviation NO_x should be pursued with caution, as too strong a reduction in NO_x would potentially deteriorate aviation's climate impact. In other words, the policy-driven NO_x reduction should be balanced with a policy-driven CO_2 reduction in order to optimally reduce the total climate impact of aviation engine emissions.

In the presence of trade-offs, market based instruments would be the preferred choice for a policy maker, since they leave the trade-off to be made at the optimal point under any market conditions. A charge or tax on Cruise NO_x emissions would be the preferred option in this case. Although a large number of issues need to be solved before this option can be properly designed, this option has been selected for further design and assessment. Amongst the issues to be solved are the way to establish cruise emissions and the size of the climate impact of an additional amount of NO_x emitted at altitude relative to the climate impact of CO_2.

Hedging against the possibility that the issues relating to a cruise NO_x charge may not be solvable, it is recommended that an LTO NO_x charge is taken forward into the shortlist, although this option would be less environmentally effective than a cruise NO_x charge. This option would overcome the data collection problem with en-route charges and by making it a distance-based charge, it will create a greater environmental benefit than a simple LTO charge, because it would have a link with actual emissions levels resulting in longer flights paying more. One risk with this measure is if there is a poor direct relationship between LTO and en-route NO_x emissions, or if it breaks down in the future.

A multiplier could have the perverse effect of increasing NO_x emissions and has been challenged on scientific grounds. However it is recommended to take it forward to the shortlist as a benchmark against which to compare other options.

With regard to standards, although an EU push for increased stringency of existing ICAO LTO standards is no more than a continuation of current policies through ongoing tightening of technical standards for LTO NO_x emissions by ICAO , it is recommended that it is taken forward into the shortlist as a default option. It is not recommended to consider a production cut-off of engine types compliant with old standards, as the evidence suggests that this would produce little or no environmental benefit. Problems of data availability are judged to be sufficient to rule out cruise emissions standards at present (options 1b and 1d), but these should be kept under review for future consideration as information becomes available. It is recommended that option 1c (EU LTO emissions standards) should be taken forward into the shortlist, though it is recognised that it will give rise to competition distortions if limited to EU carriers, and could be open to challenge if extended to carriers from non-EU states. A production cut-off would be included in this option, if feasible. In the light of evidence indicating that the trend in NO_x emissions per passenger km has been flat over time, a phase-out would affect a number of relatively new engines and is unlikely to be cost effective with high compliance costs and limited environmental benefits.

It is clear that implementing the Single European Sky may reduce CO_2 emissions and NO_x emissions on most trips in EU airspace. Consequently, measures to accelerate its implementation would clearly be beneficial for the environment, even though some of the gains may be offset by higher demand. However, such a policy would not specifically address NO_x, nor would it prevent the exploitation of the NO_x : CO_2 trade-off to the extent that it would be detrimental to climate. Furthermore, it is an existing policy whose cost effectiveness has already been assessed. As a result, it is not recommended that SES be taken forward into the shortlist of options in the context of this study. There are too many scientific uncertainties with the climate effects of a climate optimised ATM system to recommend taking this option forward.

There could be a limited role for voluntary agreements but it would be necessary to ensure that they deliver emissions reductions beyond the base case and that they could be adequately monitored.

We take it as given that academic and industrial research will continue into the climate effects of NO_x and its reduction both at source and in abatement terms. We shall also give further consideration to the potential hypothecation of revenue to such research to assist in the funding of such research. However, earmarking this revenue to the aviation industry is not the only, or necessarily the best option. It may be more cost effective to use revenues to fund climate change abatement through NO_x reduction elsewhere.

In sum, we recommend that the following policies be included in the shortlist of options to be studied further:

1. An LTO NO_x charge, either coupled with a distance factor or not.
2. A NO_x en route charge.
3. Inclusion of aviation NO_x emissions in the EU ETS.
4. LTO NO_x emission standards, either issued by the EU or by ICAO following concerted EU action.
5. A multiplier on aviation CO_2 emissions in the EU ETS as a reference option.

C Design of selected policy options

C.1 LTO NO_x charge

C.1.1 Primary Objective

An LTO NO_x charge, as currently implemented at several European airports, primarily targets local air quality (LAQ). Its impact on cruise emissions would thus normally be considered a co-benefit, but since LTO and cruise NO_x emissions seem to have a reasonably constant relationship for current in-production engines, it could additionally be seen as a surrogate climate change charge.

However, it is possible that future developments in engine design could lead to a breakdown of this relationship between LTO and cruise emissions of NO_x. It should therefore be kept under review.

C.1.2 Basis of the Charge

The charge would be levied on the mass of NO_x emitted during the LTO cycle. Ideally an LTO NO_x charge should be based on the actual LTO NO_x emissions of every aircraft movement, but actual emissions vary with operating conditions and meteorological conditions. It is impracticable to measure actual emissions in such circumstances, but they can potentially be modeled, to three levels of accuracy in approach identified by ICAO's Airport air quality guidance manual (ICAO Doc 9889). These are broadly characterised by:

- Simple, using a standardised LTO cycle for identified aircraft types and their UNFCC emission factors.
- Advanced, where engine/aircraft combinations are matched and local differences in time in each mode of the LTO cycle are taken into account.
- Sophisticated, adding the refinement of variations in thrust settings and performance details not generally in the public domain.

Added precision of calculation, taking operational factors into account, could also potentially incentivise operational measures to reduce emissions. There may be long term potential for the use of more accurate model inputs, but given the current state of international consensus the relative simplicity of the ECAC-ERLIG methodology is, we believe, the most appropriate for calculating the mass of NO_x emitted, as a basis for charging, as described in ECAC recommendation 27-4 (see textbox).

Textbox: ECAC recommendation for calculation method of LTO NO_x

In summary, ECAC recommends implementing a continuous scale of charges, i.e. not classifying aircraft into groups, but charging every kilogram of NO_x. It recommends using the same method for calculating emissions of non-regulated engines as for regulated engines. The recommended formula for the calculation of LTO NO_x is:

$$\mathrm{LTONOx}_i = \mathrm{engines} \times \sum_{\mathrm{LTO-modes}} (60 \times \mathrm{time} \times \mathrm{fuelflow} \times \mathrm{NO_x - index} \times 1000)$$

Where:

- LTO NO_x: is the amount of NO_x per LTO in kg of aircraft i.
- Engines: number of engines fitted to the aircraft.
- Time: (standardized representative) time in mode (in minutes).
- Fuelflow: fuel flow per mode (in kg/sec).
- NO_x index: NO_x emission index per mode (in g/kg fuel), as published either in the ICAO engine emission databank or similar generally accepted databases.

Using LTO NO_x emissions derived from a standardized LTO cycle as a basis for charging would reduce the administrative complexity significantly (although it would not incentivise operational measures to reduce emissions). For the larger (>26.7 kN rated output) regulated jet engines, which power most commercial airliners and regional jets, this data is provided by ICAO. The ICAO database also includes or quotes FAA material for some of the most widely used small jet engines which power some business jets, but an MTOW threshold (of, say, 5,700 kg MTOW[37], in line with the proposed EU-ETS threshold) for applicability of a NO_x charge, could largely eliminate the need for these data.

For turboprops, manufacturers have reported corresponding data to the Swedish Aeronautical Institute (FOI). 'The Institute has been charged with producing an interim database that, with the manufacturers' consent, could be distributed to authorized parties. A proposal for an internationally recognized permanent emissions database for such engines has been put to ICAO' (ECAC). Thus for both jet engines and turboprops generally accepted databases are available to calculate standardized LTO NO_x emissions.

C.1.3 Geographical Scope and Administrative Responsibility

The charge would be levied on aircraft operators by all EU airports, and would thus be aligned with the geographical scope of the EU ETS. Airlines already report (e.g.) noise-certificated aircraft movements to airports and other authorities, and airports already have experience in collecting differentiated charges accordingly.

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[37] ECAC recommends an MTOW threshold of 8,618 kg for use of the ERLIG formula.

C.1.4 Level of the Charge

Mathematically, the charge would be:

$$C_i = \alpha_{LAQNOx} \times LTONOx_i$$

Where:

- C_i is the charge for aircraft *i* in Euros.
- α_{LAQNOx} is the charge level in Euros per unit of mass; which we would assume to be set at the monetary value of the damage cost of NO_x emitted at ground level.
- LTO NO_{xi} is the mass of the LTO NO_x emissions of aircraft *i.*

As noted above, the impact on cruise emissions of a LTO NO_x charge implemented primarily for local air quality purposes; would normally be considered a co-benefit. The level of the charge should therefore reflect the marginal social costs of NO_x at ground level, at which it is directed.

Impacts of NO_x are both local and regional (formation of secondary chemical compounds). This means that the damages depend on the population density and background concentration of other compounds. As a result, marginal social costs of NO_x vary between (and within) countries, whereas an EU-wide LTO charging scheme would need an authoritative data-base covering the whole Community, albeit at a less than ideal level of detail.

In the BeTa Method*Ex* (version 2, 2007), tables developed under an EC FWP/6 research programme (www.methodex.org) give values for health damages of NO_x for most EU member states (no data are available for Malta, Cyprus, Romania and Bulgaria). For each country, three values are calculated using three different methodologies. While the range of variation across methodologies is large, we interpret this as representing low, medium and upper estimates of the social costs.

The Method*Ex* values are averages for individual countries. Given that airports are typically close to larger cities, these values may underestimate the social costs of NO_x at airports. Furthermore, impacts on ecosystems are not accounted for, leading to a second possible underestimation. Table 26 presents median and arithmetic mean values of social costs of NO_x for the EU Member States for which values are available.

Table 26 Damage costs in Euro/kg NO_x

	ExternE (2005)	CAFÉ/WHO (low)	CAFÉ/WHO (high
Median EU23	1,300	4,400	12,000
Mean EU23	1,439	4,543	12,352

Source: Method*Ex.*

Table 26 shows that median and mean values from the literature, irrespective of their absolute level, are very similar. For assessment purposes, we therefore propose to model a charge set at the median level and calculate the impacts for the three values reported here. The actual charges could vary by country (or even by airport, given the level of detailed scientific assessment required); as is to be expected from a system primarily targeting local air quality issues. Such variations are already experienced among the countries and airports currently applying such charges, as described below.

The European median level of € 4.4 per kg of NO_x per LTO cycle typically translates to a charge of the order of € 40 for a 66-tonne 179-seat A320, or some € 189 for a 395-tonne 470-seat B747-400. An average 4 to 6 landings per day in Europe for the A320; or a daily European turnround for the long-haul B747, would give either aircraft an annual NO_x bill of around € 75,000 at those prices.

C.1.5 Revenue Neutrality

Charges can either be revenue neutral or revenue raising. If they are revenue neutral, as they are designed to be at all EU airports currently applying them, neutrality can most readily be achieved at the airport level, although neutrality at the Member State or even the EU level is possible, while requiring revenue transfers between airports and/or between Member States, respectively.

Revenue neutrality at the airport level can be achieved in two ways, as exemplified by Swedish and UK charges:

- In Sweden, the introduction of LTO NO_x charges was coupled with a reduction in landing charges. The basic idea is that the reduction on revenue from landing charges is offset by the revenue from LTO NO_x charges.
- In contrast, at the UK airports with NO_x charges, the airports charge those aircraft that emit more than the average LTO NO_x emission at the airport (for every kg above the average) and uses this revenue to rebate the landing fees of those aircraft emitting less than this average.

Both systems are feasible to implement at all European airports. The UK system has the advantage that its revenue neutrality is transparent. Its main disadvantage is that when based on absolute emission volumes, larger-engined aircraft always pay, and the smallest are always rewarded. However, a relative measure (emissions per tonne of MTOW for instance) should not be impossible to devise, but while perhaps appearing to be more equitable this would run counter to the objective of reducing absolute emission levels.

Revenue neutrality at the airport level requires the bonus/malus ‘break point’ to be set at different levels at every airport, and to be regular reviewed to maintain the balance of neutrality with changes in fleet mix. Otherwise, the more successful an airport’s charging system is in reducing NO_x emissions, the less revenue it receives.

C.1.6 Experiences with LTO NO_x charges

On 01 September 1997 Zurich (ZRH) was the first airport in ECAC Europe to introduce NO_x emission charges. This example was followed in Switzerland by Geneva (GVA) and Bern (BRN); Lugano (LUG) is preparing for implementation. The charge applies to all aircraft, and was designed in response to Swiss LAQ legislation. It is based on emission bands, corresponding with charges expressed as percentages of landing fees, between 0% and a maximum of 40%.

Sweden followed with a charge in 1998; earlier NO_x and CO_2 (fuel) taxes on domestic flights having proved incompatible with Community legislation, despite claims of resulting in combustor changes on a domestic operator’s F28 fleet. Charges apply, in the form current since 01 March 2004 (using the 2003 version of the ERLIG model), at all 16 LFV airports including Stockholm-Arlanda (ARN). Aircraft of 5,700 kg MTOW and above are charged.

The Franco-Swiss EuroAirport BSL/MLH/EAP introduced a system very similar to that at ZRH on 01 January 2003, but with a rather lower range of landing fee percentages.

BAA introduced emission charges at London-Heathrow (LHR) in 2004, and London-Gatwick (LGW) in 2005, for aircraft over 8,618 kg MTOW. These are the only UK airports currently making such charges, although one more (non-BAA) is believed to be considering their introduction, and Government has suggested mandatory inclusion of emission charges in landing fees.

Most recently, emission charges came into force at Frankfurt/Main (FRA) on 01 January 2008, as they did at Munich (MUC), for a three year trial period. They apply at Köln-Bonn (CGN) from 01 April 2008, and Stuttgart (STR) is expected to join the scheme from 01 September 2008. All aircraft are charged.

Current LTO NO_x charging systems either:
- Divide aircraft into engine emission classes and charge per class (Switzerland and France (BSL/MLH)). Or,
- Work on the basis of a continuous scale (Sweden, UK, Germany).

ECAC recommends a continuous scale and Switzerland is considering switching to this system. The advantage of a continuous scale system is that the incentives to reduce emissions are optimized when the regulation is more closely oriented to the actual certificated emissions of individual airframe/engine combinations.

Among existing charges at EU airports, only Sweden overtly determines its level of charge on the basis of damage costs, following a regional study[38], although the charge doubled the study's estimated damage cost levels, which were based on ExternE/UNITE and BeTa values, on the precautionary principle. Other airport charge levels are more pragmatically derived.

Like the Method*Ex* damage costs described at C.1.4 above, these charging levels cover a very wide range, encompassing the rates per kg of NO_x equivalent charged at Gatwick (*c.*€ 1.25), Heathrow (*c.*€ 1.38), Frankfurt (€ 3.00), and Stockholm-Arlanda (*c.*€ 5.35). The Zurich and Basel charges can be higher, as they are expressed as a percentage of landing fee (up to 40%). The common factor is that the actual cost to the operator per aircraft movement is only a fraction of the landing fee, and thus (in contrast to fuel costs) only a marginal element of total direct operating costs.

C.1.7 Effectiveness of LTO NO_x Charges

It is thus not surprising that the airports applying LTO NO_x charges at these sort of levels expect them to have only a potentially marginal effect upon airline decision making in terms of engine modifications or re-equipment, or upon NO_x emission volumes. The objective is generally to encourage, rather than force, technological and behavioural changes.

ICAO's Committee on Aviation Environmental Protection (CAEP/7) reported in 2007 (Information Paper IP/4) that the impact of charges at two airports studied (ZRH and ARN) was at best limited, definitive inferences on their cost effectiveness being impossible within the limitations of the analysis. Again the level of charge, rather than the principle, was the feature effectively emasculating its impact.

What cost internalisation-based charges per kg of NO_x mean in terms of cost per landing could mean for actual aircraft operating costs has been exemplified in C.1.4 and C.1.6 above. Except around the 'breakpoint' between cost and rebate, or for particularly 'dirty' engines in a landing fee 'banded' system, the additional or saved cost related to a significant 10 or 20% increase or decrease in emissions per LTO cycle is a relatively insignificant cost item for the operator.

The limited, or potentially marginal, effectiveness of an LTO-based, LAQ-targeted charge, seems therefore to be rather related to the logical damage cost level of the charge, than to the principle of LTO emissions' relationships with cruise emissions, and the relative ease of determination and administration of such charges.

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[38] Pilot study by Elektrowatt-Ekono for the Swedish Civil Aviation Administration and the Swedish Institute for Transport & Communications Analysis, on Estimation of environmental costs of aircraft LTO emissions, 2003. A case study was also undertaken in the Netherlands (Morell and Lu, Social costs of aircraft noise and engine emissions at Amsterdam Airport Schiphol - Transportation Research Board Record n0. 1703, pp 31-38) but Schiphol currently has no NO_x LAQ charging scheme.

In conclusion it may be noted that as an LAQ related instrument, an LTO based charge has a further potential advantage in that it could also be extended to other pollutants such as unburnt hydrocarbons and carbon monoxide, which are listed in the ICAO emissions database.

C.2 LTO NO$_x$ charge with distance factor

In the deliberations of the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection's (CAEP) Working Group 3 (WG3) on emissions, the potential certification of cruise emissions of nitrogen oxides (NO$_x$) has been studied over almost 10 years. In the conclusions of WG3 presented to the Seventh Meeting of CAEP (CAEP/7) in Montreal February, 2007, it was been claimed that there is a robust relationship between emissions of NO$_x$ that occur during the standard landing-takeoff cycle (LTO) and those that occur during the cruise phase, based on a comparison of the emission index of NO$_x$ (EINO$_x$, i.e. g NO$_x$/kg fuel) during both phases of flight.

Information that we have received from engine manufacturers in this project supports this conclusion for current engine technology. Future engine or combustor designs, such as open rotor engines, geared turbofans of staged combustors may not exhibit the same relation between LTO NO$_x$ emissions and cruise NO$_x$ emissions.

As cruise NO$_x$ emissions are difficult to calculate accurately without access to proprietary P3T3 models and even more difficult to establish empirically, they could be approximated by LTO NO$_x$ emissions. The way this could be done is to assume that there is a correlation between EINO$_x$ in the LTO phase and EINO$_x$ in the cruise phase. If one furthermore assumes that fuel burn in LTO is correlated to fuel burn in cruise, and that fuel burn correlates with distance flown, one could approximate NO$_x$ emissions aircraft i on mission j during a flight by:

$$TOTNOx_{i,j} = \beta \times LTONOx_i \times D_j$$

Where:

- TOT NO$_{xi,j}$ is the total NO$_x$ emissions for aircraft *i* on mission *j* in mass units.
- β is the co-efficient of correlation between LTO NO$_x$ emissions times a distance factor and cruise NO$_x$ emissions (per unit of distance).
- LTO NO$_x$*i* is the mass of the LTO NO$_x$ emissions of aircraft *i* (in mass units).
- D$_j$ is the distance of mission *j* (in distance units).

A charge could then be implemented on the total NO$_x$ emissions. The basic formula for this charge for aircraft i on mission j would be:

$$C_{i,j} = \alpha_{C\lim NOx} \times \beta \times LTONOx_i \times D_j$$

Where:

- C$_{i,j}$ is the charge for aircraft *i* on mission *j* in Euro.

- $\alpha_{ClimNOx}$ is the charge level in Euro per unit of mass, set at the monetary value of the climate impact of NO_x (in Euro).
- β is the co-efficient of correlation between LTO NO_x emissions times a distance factor and cruise NO_x emissions (per unit of distance).
- LTO NO_xi is the mass of the LTO NO_x emissions of aircraft *i* (in mass units).
- D_j is the distance of mission *j* (in distance units).

Each of the parameters will be discussed below.

C.2.1 Charge level

To approximate the climate damage costs of aviation NO_x emissions, the charge should be set at the global warming potential of aviation NO_x times the climate damage cost of carbon dioxide.

The global warming potential (GWP) is the metric used in the Kyoto Protocol and compliant policy instruments and inventories to express the climate damage of a substance relative to the climate damage of a reference gas, typically CO_2. It is defined as the ratio of the time-integrated radiative forcing arising from the instantaneous release of 1 kg of a trace substance, relative to that of 1 kg of a reference gas (IPCC, 1990), i.e.:

$$GWP_x = \frac{\int_0^{TH} a_x [x(t)] dt}{\int_0^{TH} a_r [r(t)] dt} \quad [2]$$

where TH is the time horizon over which the calculation is made, a_x is the radiative efficiency arising from a unit increase in atmospheric abundance of the substance (*x*) in question (in W m^{-2} kg^{-1}), [*x*(t)] is the time-dependent decay in the abundance of the instantaneous release of the substance, and *r* refers to the reference substance in the denominator (IPCC, 2001). Thus, the GWP represents the integrated forcing of a pulse of a substance relative to the same mass emission pulse of a reference gas over the same time-horizon (typically CO_2).

The assessment of a GWP of NO_x is not straightforward due to the fact that the climate impacts of NO_x are indirect (induced formation of ozone and decay of methane) and some of the species involved are short lived, as opposed to the long-lived Kyoto gases. However, in recent years a small number of publications have shown that it is possible to calculate a GWP of NO_x. Possibly due to the fact that these calculations are few in number and all of recent date, only three GWPs have been published and they show a wide range of values. This study has chosen to assess the impacts of a range of GWPs of NO_x from 1 (a kilogram of NO_x has the same climate impact as a kilogram of CO_2) to 130 (a kilogram of NO_x has the same impact as 130 kilograms of CO_2).

As for the damage costs of CO_2, this study has chosen to approximate these by the price of emission allowances in the EU ETS. Although this is clearly not a valid assumption from a methodological point of view (the price of allowances reflect the marginal prevention cost rather than the marginal social cost), this approximation is justified by looking at the aim of this policy instrument, i.e. to avoid the exploitation of the NO_x : CO_2 trade-off in engine design to the point that increased NO_x emissions would offset reductions in CO_2. Including aviation in the EU ETS means that CO_2 is valued at the EU ETS allowance price. By valuing NO_x at this price times the GWP, the relative costs of NO_x and CO_2 have the right value, even though the absolute costs may not internalise all externalities.

C.2.2 Co-efficient of correlation

The co-efficient of correlation can be determined empirically with sufficient accuracy to serve as a basis for a charge (see Appendix H). It can either be aircraft specific or fleet average. In the former case, calculating the co-efficient of correlation would imply performing the calculations outlined in Appendix H for every aircraft type in Europe. This is beyond the scope of this project, but not immensely complicated or time consuming. In the latter case, the co-efficient of correlation would depend on the fleet within the geographical scope and the route network. This would mean that the co-efficient can be determined by analysing a weighted sample of data on LTO NO_x and cruise NO_x for the most widely applied aircraft-engine combinations.

For the assessment of the impacts in this report, we have used the unweighted sample in our data to arrive at a value of the co-efficient of correlation of 0.0045 per nautical mile.

C.2.3 LTO NO_x

The purpose of the LTO NO_x parameter in this charge is to capture the $EINO_x$ and fuel burn performance of the engine. It is not to accurately estimate actual emissions. Therefore, using the standardized LTO cycle is justified. Most deviations from the standardized LTO cycle would be captured in the correlation factor β.

For regulated jet engines the mass of NO_x emitted during LTO is provided by the ICAO engine emission databank. This databank gives the same values as the ECAC/ERLIG method (see box below). For turboprops manufacturers have reported the corresponding data to Swedish Aeronautical Institute (FOI). FOI has published an interim database which, with the manufacturers' consent, could be distributed to authorized parties. For unregulated jet engines, i.e. engines with a rated thrust less than 26.7 kN, some of these are included in the ICAO databank. Others could be either assigned an estimated value or a measurement program could be set up for these engines.

Textbox: ECAC recommendation for calculation method of LTO NO_x

ECAC has published guidance material for LTO NO_x charges (ECAC recommendation 27-4).

In summary, ECAC recommends implementing continuous charges, i.e. not classifying aircraft but charging every kilogram of NO_x. It recommends using the same method for calculating emissions of non-regulated engines as for regulated engines. And it suggests using the following formula for the calculation of LTO NO_x:

$$LTONOx_i = engines \times \sum_{LTO-\text{mod}\,es} (60 \times time \times fuelflow \times NOx - index \times 1000)$$

Where:

- LTO $NO_{x\,i}$ is the amount of NO_x per LTO in kg of aircraftt.
- Engines: number of engines fitted to the aircraft.
- Time: time in mode according to table 1 (in minutes).
- Fuelflow: fuel flow per mode (in kg/sec).
- NO_x-index: NO_x-emission index per mode (in g/kg fuel), as published either in the ICAO engine emission databank or similar generally accepted databases.

C.2.4 Distance

The distance factor can be either continuous of banded, and either based on actual distances flown or on great circle distance.

A banded distance factor may be easier to implement, but its correlation with NO_x emissions would deteriorate as the number of bands decreases. A continuous distance factor would correlate best with NO_x emissions. Furthermore, air-craft operators in the ETS need to have systems to record the great circle distance of flights in order to be able to calculate their RTK figures.

Actual distance flown correlates better with NO_x emissions than great circle distance. However, great circle distance is easier to verify, as they require information only on the airport of departure and the airport of arrival. Aircraft operators have also argued that using great circle distance is more equitable, as most of their deviations from the great circle are forced upon them by air traffic managers. So they argue that using actual distance would punish them for inefficiencies in the air traffic management system.

In sum, the best way to account or distance would be a continuous distance metric based on great circle distance between airport pairs. This parameter would be feasible to implement, while correlating as well as possible with NO_x emissions.

C.2.5 Revenue

The charge could be implemented in a revenue generating or a revenue neutral way.

The total revenue of a charge would depend on the prevailing EUA price and the GWP of aviation NO_x. Under a business as usual scenario, total aviation NO_x emissions for all flights arriving at or departing from EU airports would amount to over 1,800 million kilogram per annum in 2020. This means that the revenue could range from less than 40 million Euro to over 9 billion Euro annually (see Table 27).

Table 27 Estimate of maximum potential revenue of LTO NO_x charge with a distance factor (€ mln)

		EUA price (€/tCO_2e)	
		20	40
GWP	1	36	72
	130	4,680	9,360

Source: AERO MS.

C.2.6 Administrative arrangements

The basic administrative arrangements comprise three steps

1 Monitoring the basis for the charge, i.e. LTO NO_x × GCD for every flight.
2 Levying the charge.
3 Recycling the revenue (if desired).

Monitoring the basis of the charge can best done either by the aircraft operator, the airport, or by the organisation that levies the charge.

- Airports know or can observe directly the registration number of the aircraft, and using databases can establish the aircraft-engine combination needed to assess the LTO NO_x emissions. Airports know where an aircraft has come from or where it is going to and using databases of airport locations and publicly available algorithms can calculate the great circle distance.
- Aircraft operators know the engine types of their aircraft needed to calculate LTO NO_x emissions. Likewise, they know the airports where their aircraft fly from and to.
- The organisation that levies the charge could monitor the base if it is able to observe registration numbers of the aircraft. One organisation that may be able to do so is EUROCONTROL. The information required to operate a NO_x charging scheme has to be obtained from many sources. EUROCONTROL is already receiving, gathering, and correlating most of this information for other functions managed and operated by EUROCONTROL within its existing remit. This allows EUROCONTROL to identify aircraft registration numbers and thereby specific aircraft motorisation for about 90% of the traffic already operating in the European airspace. Measures could be taken, including statistical assessments, which would allow to identify aircraft registration numbers and motorisation for the remaining traffic.

Levying the charge can either be done by airports, Member States or by EUROCONTROL.

- Airports could incorporate the charge in their landing fees, so making airports responsible for levying the fee would have the advantage that no new financial arrangements would need to be set up. However, since one aircraft operator may use a multitude of airports around Europe, monitoring compliance may be difficult. After all, it would involve ensuring that the total sum of the charges paid by the aircraft operator to a large number of airports equals the total amount due.
- Member States could levy the charge for the airlines they administer under the EU ETS. These are the European airlines that are registered in the state or the non-EU airlines that have the greatest estimated attributed aviation emissions in the base year (COM(2006)818, article 18a1b). In this case new financial arrangements would have to be set up. Furthermore, if Member States were to use their fiscal authorities to collect the charge, there may be opposition against earmarking the revenue in order to ensure revenue neutrality. This would be a disadvantage if the charge would be designed as be to revenue neutral, e.g. in order to ensure compliance with ICAO guidelines, but at odds with EU policy to adhere to the polluter pays principle. If Member States would not assign the collection of the charge to the fiscal authorities, a new organisation may have to be set up to collect the charge.
- EUROCONTROL could operate the scheme, in which case the billing and collection service would be provided on the basis of a new bilateral agreement to be concluded with the relevant competent authority, e.g. the European Commission. This agreement would have to be approved by EUROCONTROL Member States in accordance with the EUROCONTROL regulations. This approval is limited to the conclusion of the agreement for the provision of billing and collection services and does not relate to the features of the scheme. (Please note that the NO_x charge is not an air navigation charge and should thus be calculated separately from air navigation charges).

Recycling of the revenue could be achieved in a number of ways. A recycling of the revenue by lowering airport charges across the EU could be possible as the total airport charges have the same order of magnitude as the possible revenue of the charge[39]. However, while it could be possible to achieve revenue neutrality at the level of all EU airports, it would probably not be possible to achieve

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[39] We estimate the total airport charges, ATC charges and governmental charges to have an upper limit of € 22 to 25 billion. This estimate is based on the average charges for large airports (SEO, 2008) for the summer of 2007 and on Eurostat data for the number of passengers and flights . SEO have calculated the charges for several large airports, based on the type and number of flights that arrived and departed from Schiphol in the summer of 2007. The average total charge for the type and number of flights that arrived and departed from Schiphol in the summer of 2007 is € 710 million.

Assuming that the number of flights per month in summer is equal to the number of flights per month in winter (an overestimate), and that the average charges on all EU airports are equal to the average charges on the large airport listed in the SEO report (again an overestimate) and that the characteristics of flights departing from Schiphol are representative for the whole EU, and extrapolating the charges to all EU airports based on Eurostat data for the number of passengers and the number of flights for Schiphol and the EU-27, we have calculated the total airport charges, ATC charges and governmental charges to be € 22 to 25 billion. Due to some of the assumptions made, this should be regarded as an upper estimate of the charges.

revenue neutrality at every airport. Some airports have mainly short and medium haul traffic, whereas others have a large number of long haul flights. The latter would have to lower their fees by a far larger amount, probably even to the extent that they would have to have negative airport fees. In that case, there would be a need to transfer funds from some airports to others. This could all become quite complicated. Therefore, this route for achieving revenue neutrality is not advocated here.

- Revenues could be recycled in R&D aimed at lowering cruise NO_x emissions. Ignoring opportunity costs, this would be a good way to recycle revenue as long as the funds are spent efficiently, i.e. result in lower emission engines. Although seems that some of the revenues could be spent on R&D efficiently, not everything can. The revenue would simply be too big. For reasons of comparison, FP6 spent a little under € 400 million per year on total aeronautical and space research, FP7 is probably to spend around the same amount[40]. A recycling of all the revenue towards R&D would flood the system with funds that probably couldn't be used efficiently.
- In the EU ETS, the European Commission has proposed to recycle the revenues of the auction of aviation allowances 'to mitigate greenhouse gas emissions, to adapt to the impacts of climate change, to fund research and development for mitigation and adaptation, and to cover the costs of the administering Member State in relation to this Directive'. In this case, the revenues could be recycled in a similar way if Member States would collect the revenue. However, the revenues of this charge could be an order of magnitude higher than the likely revenues of the auctioning of allowances[41]. Therefore, the possibility of spending this money in a welfare increasing way would need to be demonstrated.
- In most airport LTO NO_x charges currently implemented, revenues are recycled by lowering other charges of fees. In this case of a charge on LTO NO_x with a distance factor, a charge that could be lowered in principle could be the route charges as collected by EUROCONTROL. However, route charges are intended to cover the costs of air navigation services. In order not to threaten the financial basis of these services, it would not be advisable to lower these charges. Rather, a separate system could be set up in which the charges are reimbursed to the operators. If EUROCONTROL would collect the charge, administrative burden would be lowest if the charges were reimbursed on the basis of data that EUROCONTROL currently collects. One good measure would be LTO NO_x/MTOW.km. In this case, the charge would act like an incentive to improve the quotient of LTO NO_x/MTOW. As this quotient is not related to aircraft size, the charge would be neutral with regard to route groups and market segments (see Figure 40).
- In the proposal to include aviation in the EU ETS, the free allocation of allowances is proportional to the share of revenue tonne kilometres that an aircraft operators produces. The logic behind this benchmark is that it rewards operators that have taken measures to improve the efficiency of the

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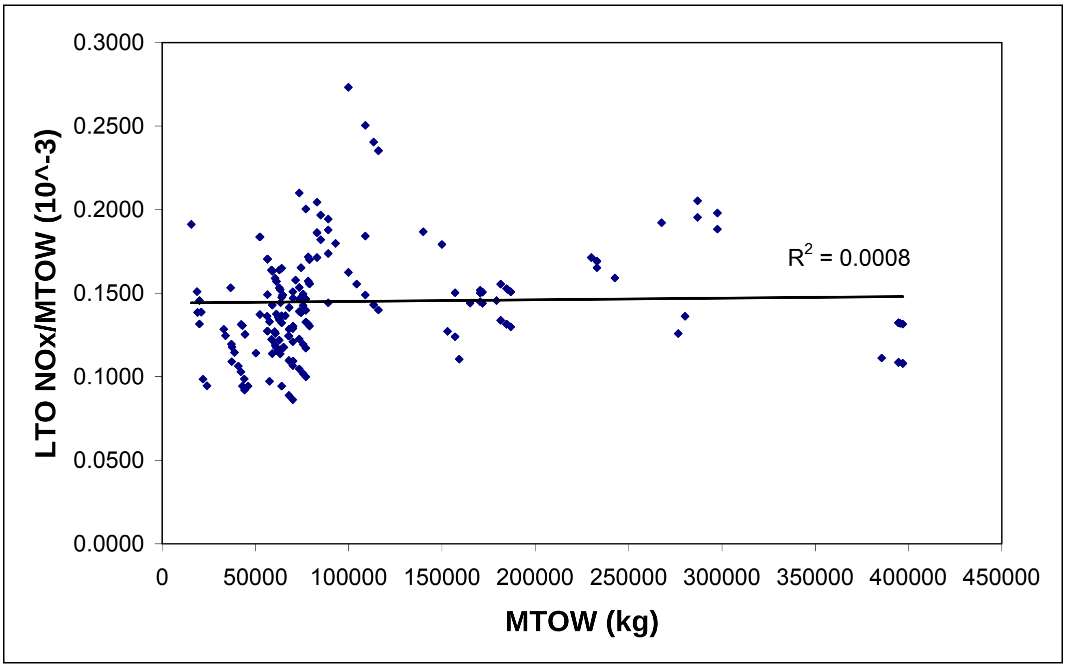
[40] In FP7, transport including aeronautical research is budgeted at about € 1,000 million per year. http://cordis.europa.eu/fp7/budget_en.html, accessed 22 May 2008.

[41] Aviation's emissions in the geographical scope of the EU ETS are estimated at approximately 218 Mt of CO_2 in 2005. If 25% of this amount is auctioned at prices between € 20 and € 40 per allowance, the likely revenue would be between € 1,090 million and € 2,180 million.

service they offer. If this same logic would be applied to LTO NO_x charges with a distance factor, the revenue could be recycled proportionate to the production of RTK. This would involve administrative costs, as currently aircraft operators are not obliged to surrender RTK data to authorities, other than two years prior to the start of a trading period in the EU ETS. However, they could be asked to surrender the same data to EUROCONTROL, which it can then use to recycle the revenue of the charge.

Figure 40 No correlation between LTO NO_x/MTOW and MTOW



Bron: CE, 2008.

In sum, if revenues would need to be recycled, it could be done in a number of ways. A recycling based on MTOW.km or on RTK would be a clear possibility, with the first having lower administrative costs and the second rewarding early action, as would funding of R&D and climate-related spending by states. At the higher end of the estimates, the sums involved would be high enough to warrant the recycling of revenue in more than one way.

The administrative burden would be lowest if as many steps of the administrative arrangements are dealt with in the same organisation. Every exchange of information or funds between organisations adds administrative complexity to the issue. On the basis of this consideration, we think that it would be best to have EUROCONTROL levy the charge on behalf of the EU Member States. It could either reimburse the revenues to the Member States or recycle it to aircraft operators on the basis of MTOW.km or RTK.

C.3 Cruise NO_x charge

C.3.1 Scope of NO_x emissions

In order to design a cruise NO_x charge, the scope of the NO_x emissions under the charge needs to be defined. There are three options for the scope of the NO_x emissions. First of all, one could base the charge on the NO_x emitted during the whole flight, i.e. on the emissions of both the LTO and the cruise phase. The advantage is that this is relatively simple from an administrative point of view, as there is no need to distinguish between the LTO phase and the cruise phase of the flight. However, it means that part of the charge is based on NO_x emissions (i.e. the NO_x emissions at ground level) that contribute little to climate change.

The second option is to base the charge on cruise NO_x emissions, defined as all NO_x emissions that are not part of the LTO cycle. This has the advantage that it leaves out NO_x emitted at or near ground level (namely NO_x emitted below 915 metres (3,000 feet) altitude). Thus, it might provide a more accurate estimation. For more details about the calculations, please refer to Section C.3.4.

All in all, a choice needs to be made between basing the charge on the total NO_x emitted during flight and basing the charge on the NO_x emission during the cruise phase of the flight. Since NO_x emitted during the LTO phase would be subject to air quality instruments at several airports in the EU, this report chooses to have only NO_x emitted above 915 metres in the basis of the charge.

C.3.2 Geographical scope

One of the requirements of the Commission is that any charge to reduce climate impacts from aviation NO_x emissions has to be in line with the EU ETS for aviation. Therefore, the charge needs to apply to all arriving and departing flights. Any other options for the geographical scope (such as intra-EU only or all flights passing through EU airspace) are not in line with the ETS, and are therefore not considered.

C.3.3 Charge level & revenue

As discussed in Appendix C.2.1, to approximate the climate damage costs of aviation NO_x emissions, the charge level should be set at the global warming potential of aviation NO_x times the climate damage cost of carbon dioxide.

For a more in-depth discussion of the assessment of the GWP(100) of NO_x and of the damage costs of CO_2, please refer to Chapter 4.

Just like with an LTO NO_x charge with a distance factor, the charge could be implemented in a revenue generating or a revenue neutral way (see Sections C.2.5 and C.2.6).

C.3.4 Calculation of NO_x emissions

NO_x emissions can be assessed in several ways. Best in terms of having the polluter pay but not feasible would be to measure NO_x emissions in-flight. Although this could theoretically be more precise than the alternatives, it is technically not feasible, and the fact that it would imply fitting measurement equipment to every aircraft used on EU airports, makes it extremely expensive and extremely impractical. Therefore, the preferred way to assess NO_x emissions would be to use a model to calculate them.

The preferred method to calculate NO_x, HC and CO emissions of aircraft engines is the P3T3 method (DuBois and Paynter, 2006)[42]. Unfortunately, this method requires proprietary information on engine performance models and on engine emissions characterization, which is not publicly available. Alternatively, the Boeing 'Fuel Flow Method 2' (BFFM2) can be used to calculate emissions. The BFFM2 requires mainly information which is publicly available, and does not rely on proprietary information. Although not as rigorous as the P3T3 method, it gives a reasonable approximation, especially for NO_x emissions (in the order of +/-10 to15% of the P3T3 method).

Boeing Fuel Flow Method

Eventually, the aim is to calculate the $EINO_x$ emissions during flight, i.e. $EINO_x$ emissions at altitude. However, the only data publicly available are the relationships between fuel flow at sea level and $EINO_x$ at sea level found in e.g. the ICAO engine emissions databank[43] (please refer to Section C.3.7 for more details). This means that two conversion factors need to be determined:

a factor which describes the relationship between fuel flow at sea level and fuel flow at altitude. This relationship is needed because in reality $EINO_x$ depends on combustor temperature (which in turn depends on fuel flow). It is thus necessary to find a relationship between fuel flow at sea level and fuel flow at altitude, such that both fuel flow produce the same combustor temperature. Once this factor is known, the fuel flow at altitude can be converted to a fuel flow at sea level, and the corresponding $EINO_x$ emissions at sea level can be looked up.

a factor which describes the relationship between $EINO_x$ at sea level and $EINO_x$ at altitude. Once the $EINO_x$ emissions at sea level are known (from the first step), a conversion factor is needed to convert $EINO_x$ at sea level to $EINO_x$ at altitude.

DuBois and Paynter (2006) have deducted these conversion factors, using thermodynamic relationships and energy balances. They conclude that the relationship between fuel flow at altitude and flue flow at sea level is as follows:

$$W_{f\,SL} = W_{f\,alt} \frac{\theta_{amb}^{4.5}}{\delta_{amb}} e^{0.2M^2}$$

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[42] DuBois and Paynter (2006), 'Fuel Flow Method2' for Estimating Aircraft Emissions, SAE Technical Paper Series, no 2006-01-1987, ISSN 0148-7191, Warrendale, US, 2006.

[43] The ICAO engine emissions databank is maintained by the UK CAA. See http://www.caa.co.uk/default.aspx?catid=702.

Where $W_{f\,SL}$ is the fuel flow at sea level, $W_{f\,alt}$ is the fuel flow at altitude, θ_{amb} is a measure of the ambient temperature at altitude, δ_{amb} is a measure for the ambient pressure at altitude and M is the Mach number.

The relationship between $EINO_x$ at altitude and $EINO_x$ at sea level is as follows:

$$EINOx_{alt} = EINOx_{SL}\left(\frac{\delta_{amb}^{1.02}}{\theta_{amb}^{3.3}}\right)^{y} e^{H}$$

Where $EINOx_{alt}$ is the $EINO_x$ emission at altitude, $EINOx_{SL}$ is the $EINO_x$ emission at sea level, δ_{amb} is a measure for the ambient pressure at altitude, θ_{amb} is a measure of the ambient temperature at altitude, y is an exponent which depends on the engine/combustor[44] and H is a measure of humidity.

Required input data

Summarising the above, the following data would be needed to calculate cruise $EINO_x$ using the Boeing Fuel Flow Method 2:

- Ambient temperature, pressure and humidity at altitude.
- Fuel flow at altitude.
- Cruise speed.
- An engine specific factor y (either a theoretical value, a typical value, or a value given by the manufacturer).

Ambient temperature, pressure and humidity at altitude could theoretically be measured. However, this would mean collecting data far each flight, and storing the data somewhere to use in calculations. Technically, this is probably not a problem, but it is unfeasible from a practical point of view. Instead, standard values for the ambient temperature, pressure and humidity at altitude could be used. Although this would introduce some inaccuracies due to variations in temperature, pressure and humidity at altitude, over time these inaccuracies would largely cancel each other, as long as the standard value is equal to the mean value.

Fuel flow and cruise speed are confidential data, known only by the operators themselves. However, an aircraft performance model such as PIANO[45] can be used to calculate typical fuel flow and cruise speed values[46] as a function of aircraft type and mission distance. This might introduce some inaccuracies if operators decide to operate their aircraft above or below the typical speed, but

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[44] Theory would suggest a value of 0.5, but published empirical data suggest that 0.4 would be a typical value. According to DuBois and Paynter (2006), the value for y has been in the range of 0.2 to 0.5 in rig and engine tests.

[45] http://www.lissys.demon.co.uk/index.html#find.

[46] PIANO works with fixed aircraft-engine combinations, which means that it automatically assumes a certain engine type once the aircraft type is given. The calculation also requires an assumption about load factor.

these inaccuracies would largely cancel each other[47]. In general, airlines tend to fly close to the Long-Range Cruise speed, which represents an optimum of fuel costs and other costs, although the high fuel prices are incentivising operators to fly closer to the Maximum Range Cruise speed, which is the most fuel-efficient speed. These speeds are close enough to each other not to lead to large differences in the $EINO_x$ calculations.

Finally, the engine/combustor specific factor y is needed for the calculation. The value of y is generally empirically derived by manufacturers (DuBois and Paynter, 2006). If manufacturers are willing to disclose the information, it could be used for the calculations. Otherwise, a theory-based value of 0.5 could be used, or a value of 0.4, which seems to be a typical value, as seen from published empirical data.

Simplified alternative

As a simpler alternative for the calculations above, one might consider if it would be possible to determine a typical $EINO_x$ value depending only on the aircraft type. This would require making assumptions about typical the typical power settings in cruise (and hence typical speed and fuel flow at altitude). These assumptions could e.g. be based on calculations by an aircraft performance model such as PIANO. The typical $EINO_x$ could then be multiplied with fuel use to result in the total cruise NO_x emissions. However, given the explicit dependence on fuel flow, this option might lead to legal issues.

C.3.5 Database requirement

As discussed above, an aircraft performance model such as PIANO can be used to calculate typical fuel flow and cruise speed data as a function of aircraft type and mission distance. Using these data to calculate cruise NO_x emissions would require either the calculations are done for each individual flight, or that the data are stored in a database. As it is not feasible to run the calculations for each individual flight, this paragraph will assess which characteristics a database would need to have, and how feasible such a database would be.

First of all, the database would need to store the typical fuel flow and cruise speed at altitude as calculated by the aircraft performance model for all existing aircraft at several mission distances (e.g. every 100 or 250 km for short-haul flights and every 500 or 1,000 km for long-haul flights). Data between these mission distances could be interpolated if necessary. There is a large number of different aircraft. PIANO currently lists over 290 aircraft types and variants[48]. While the most common aircraft types are in it, a large number of aircraft types is missing. For these aircraft, either calculations have to be made or their fuel flow has to be based on similar aircraft. Building a fuel flow database for all these aircraft for twenty mission distances on average would require close to 6,000 calculations. This would be feasible.

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[47] Strictly speaking, the differences would not exactly cancel, as fuel flow increases as speed increases, and $EINO_x$ increases as fuel flow increases, leading to a quadratic increase of absolute cruise NO_x emissions with speed. However, the non-cancelling parts are second-order and hence small.

[48] http://www.lissys.demon.co.uk/dbase.html, accessed 28 May 2008.

Secondly, the database would need to store the relationships between the fuel flow at sea level and $EINO_x$ emissions at sea level (as taken from the ICAO engine emissions databank).

Thirdly, it would need a module to do the calculations:

1 Calculate the fuel flow at sea level as a function of the fuel flow at altitude and the cruise speed using:

$$W_{f\,SL} = W_{f\,alt} \frac{\theta_{amb}^{4.5}}{\delta_{amb}} e^{0.2M^2}$$

As discussed in Section C.3.4. It can be seen that this relationship only requires fuel flow at altitude, cruise speed and some constants[49] to calculate the fuel flow at sea level.

2 Use the table with the relationship between fuel flow and $EINO_x$ at sea level to look up/calculate the $EINO_x$ at sea level.

3 Calculate the $EINO_x$ at altitude using:

$$EINOx_{alt} = EINOx_{SL} \left(\frac{\delta_{amb}^{1.02}}{\theta_{amb}^{3.3}} \right)^{y} e^{H}$$

As discussed in Section C.3.4. It can be seen that the calculations requires only $EINO_x$ at sea level and some constants.

4 Calculate cruise NO_x emissions by multiplying the $EINO_x$ at altitude with the fuel flow.

In short, the database would need two main tables (one with fuel flow and cruise speed data as a function of aircraft and mission distance and one with $EINO_x$ data as a function of fuel flow at sea level) and a calculation module which takes the relevant data from the tables and uses it to calculate $EINO_x$ at altitude and total cruise NO_x.

C.3.6 Database ownership and charge collection

Considerations about database ownership and charge collection are partly the same as for the LTO NO_x charge with a distance factor.

Like with the LTO NO_x charge with a distance factor, the cruise NO_x charge could be collected by EUROCONTROL in order to reduce the administrative burden. In that case, the EU would need to enter into an agreement with EUROCONTROL on the legal basis for the charge. For a revenue neutral charge, EUROCONTROL could levy the charge and recycle it on the same basis as the LTO NO_x charge with a distance factor. In that case, EUROCONTROL could also monitor the

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[49] Strictly speaking, these values are not constants, but as discussed in Section E.3.4, it suffices to use mean values for ambient pressure and temperature, which effectively makes them constants for the calculations.

charge basis, although it should be open to appeal if aircraft operators can demonstrate that the base has been mistaken.
Enforcement would be possible in the same way that collection of air navigation charges is currently enforced.

Database ownership should be in the same hands as charge collection, although the initial calculation and maintenance of fuel flow and cruise speed data as a function of aircraft and mission distance and $EINO_x$ data as a function of fuel flow at sea level might be outsourced to a third party. The infrastructure required for the database would be largely the same as the infrastructure for the slightly simpler database needed for the LTO NO_x charge with a distance factor.

C.3.7 Potential problems

There are a few potential problems with regard to the database. First of all, not all aircraft are listed in PIANO[50]. This means that other means than PIANO would be needed to assess the fuel flow and cruise speed at altitude for those aircraft.
Secondly, it would need to be assessed if the BFFM2 is valid for turboprops as well as for jet engines. For example, the engine specific factor y might be fundamentally different for turboprops than for jet engines. This uncertainty would warrant further research if this option is seen as the preferred policy option to address NO_x emissions. Also, the relationship between fuel flow and speed might be different for turboprops than for jet engine.
Thirdly, several data sources would be needed for the relationship between fuel flow and $EINO_x$. The ICAO engine emission databank would be used for the large jet engines (>26.7 kN rated output) which power most commercial airliners and regional jets; and the ICCAIA/FOI database for turboprops. Depending on the MTOW threshold for charging, there may be need for an additional database for small jets, although FAA data referenced by ICAO includes some common business jet engines.

C.4 Inclusion of aviation NO_x emissions in the EU ETS

Aviation's CO_2 emissions will be included in the EU ETS by 2012.[51] In addition to the CO_2 emissions, NO_x emissions could also be included. Most of the design choices for the inclusion of NO_x emissions would be the same as for the inclusion of CO_2 emissions (geographical scope, trading entity, setting the total amount of allowances to be allocated, initial allocation of allowances). Three aspects would be different, however. These are monitoring emissions, establishing the amount of NO_x per allowance and setting a baseline. Each of these design choices will be discussed below in separate subsections.

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[50] Such as the Ilyushin 18, 76 and 86.

[51] European Commissiobn legislative proposal: COM(2006)818; European Parliament position: P6_TC2-COD(2006)0304.

C.4.1 Monitoring NO_x emissions

As discussed above, NO_x emissions cannot be adequately measured in situ. Emissions can be modelled per flight, however. As indicated above, there are several ways to do so. One would be to build a database of emissions for different flight lengths and different aircraft-engine combinations. The other would be to approximate emissions by the product of LTO NO_x emissions and flight distance. The former would probably be more accurate than the latter, but the latter would require less work and be administratively less complex. The latter would also be easier to monitor, report and verify than the latter. Therefore, we propose to calculate NO_x emissions with the formula below:

$$TOTNOx_{i,j} = \beta \times LTONOx_i \times D_j$$

Where:

- TOT $NO_{xi,j}$ is the total NO_x emissions for aircraft *i* on mission *j* in mass units.
- β is the co-efficient of correlation between LTO NO_x emissions times a distance factor and cruise NO_x emissions (per unit of distance).
- LTO NO_{xi} is the mass of the LTO NO_x emissions of aircraft *i* (in mass units).
- D_j is the great circle distance of mission *j* (in distance units).

From the discussion in Section C.2.2 is is clear that the value of β would need to be established. For this purpose, a technical committee could be instituted with this task.

Calculating NO_x emissions with the above formula would approximate actual emissions. If the approximation would be in the same order as the spread in $EINO_x$ at cruise and in LTO, ±15%, then the uncertainty would be much larger than the uncertainty in other ETS emissions. This could have impacts on the ETS itself which are not addressed here.

C.4.2 How much NO_x may be emitted per allowance?

EU ETS directive (2003/87/EC) allows for the inclusion of other gases and in its recent proposal to amend the directive the Commission has not recommended to change this. Specifically, Directive 2003/87/EC creates allowances ‘to emit one tonne of carbon dioxide equivalent’ (article 3.a.), with the latter defined as ‘one metric tonne of carbon dioxide (CO_2) or an amount of any other greenhouse gas […] with an equivalent global-warming potential’. This means that a NO_x allowances would allow the emission of 1,000/$GWPNO_x$ kg of NO_x. The allowance would be fully fungible with other allowances in the system.

When aviation NO_x emissions would be included in the EU ETS, other changes to the directive need to be made:

- The definition of greenhouse gases needs to be changed to allow the inclusion of gases with indirect climate impacts.
- The list of gases in Annex II would need to be extended with NO_x.

C.4.3 Setting a baseline

The inclusion of aviation in the EU ETS uses a historical baseline on the basis of which the total amount of allowances allocated to the sector is calculated. A baseline for NO_x could be set in the same way, provided that a calculation method for NO_x emissions is established and that the necessary data are available. Based on the formula in Section C.4.1, the data necessary to establish a baseline is a comprehensive set of flights and aircraft/engine combinations for a baseline year or set of years. EUROCONTROL has this data and should be able to calculate a baseline either for a year or for a set of years.

C.5 Standards

This section presents recommendations on the design of NO_x stringency options.

C.5.1 Background

ICAO has regulated NO_x stringency standards since 1986 and they were last tightened in 2004 at CAEP/6 when a 12% increase compared with the previous CAEP/4 standard was agreed, with an implementation date of 1st January 2008. The decision was based on a cost effectiveness analysis which considered reductions of 5, 10, 15, 20, 25 and 30% below the CAEP/4 standard at a pressure ratio of 30, with alternative implementation dates of 2008 and 2012. Until CAEP/4 the standard was a simple straight line of permitted NO_x rising with increasing overall pressure ratio (OPR). However from CAEP/4 onwards, an increased slope kink in this line appeared at OPR 30, which permitted higher OPR engines to produce more NO_x than would be the case with a straight line. Also at CAEP/6 the slope of the line was reduced somewhat for engines below OPR 30.

One element of the future work programme for CAEP/8 was ‘to analyse the technological response to a range of NO_x stringency options up to CAEP/6 minus 20% at OPR=30 for application no sooner than 2012’. Following an analysis of emissions certification data for engines that are in production and have been recently certified, a range of potential options was submitted to the CAEP Steering Group in November 2007. The Steering Group agreed that a range of options up to 20% below the CAEP/6 standard should go forward for economic analysis. This analysis is currently at a very early stage and is not due to be completed until summer 2009.

The technical analysis submitted to the Steering Group in November 2007, was split into three parts:

1. Large engines with a thrust rating (Foo) >89 kN and overall pressure ratio (OPR) >30, covering large wide-bodied aircraft.
2. Large engines with Foo >89 kN and OPR <30, covering large narrow- bodied aircraft.
3. Small engines (26.7 kN- 89 kN), covering regional and business jets.

In the light of the technical assessment that more than 50% of the large engines in production with OPR>30 would not meet a 10% stringency increase and that all engines in the largest seat category of 401-500 seats would not be able to meet a 20% increase, it was considered that there was a technical justification for revising the slope upwards for all options in excess of 10%, but reverting to the existing CAEP/6 line when it was crossed at high OPRs.

It was acknowledged that small engines, particularly those close to the lower threshold of 26.7kN, faced design challenges in achieving NO_x emissions reductions. In view of this problem and the relatively small global environmental effects of these engines, it was agreed that these smaller engines should be assessed separately, with the options defined to include some thrust alleviation.

It was recognised that any engine certification project which was in response to a new NO_x standard approved at CAEP/8 in February 2010 would take 2-3 years to complete. Accordingly two alternative dates for potential CAEP/8 options of 31 December 2012 and 31 December 2016 were proposed.

The options identified for economic analysis for large are 5% at a slope of 2, 10 and 15% at slopes of 2 and 2.2, and 20% at a slope of 2.2. The options for smaller engines broadly match this, but include some sensitivity analysis to reflect the design challenges involved.

The European position on the proposed stringency options was presented in a paper prepared by the European Commission and European CAEP members. This noted the increasing concern regarding the contribution of aviation towards climate change and local air quality around airports, with consequent implications for airport capacity if air quality could not be met. The CAEP Steering Group supported this analysis in agreeing to a full analysis of NO_x stringency options.

C.5.2 Design of Options

The relevant parameters in the design of options are as follows:

- Level of stringency.
- Slope of the line.
- Implementation date.
- Applicability to large and small engines.
- Geographical scope.
- Inclusion of production cut-off.

The review of stringency standards by CAEP and their progressive tightening on a regular basis (roughly every 6 years) is against the backdrop of continuing technical progress into the future, illustrated by the CAEP NO_x goals assessment. However it is generally recognised that ICAO NO_x standards have not been technology forcing, with their main role being to prevent regression of combustor technology. This is illustrated by the fact that, despite the problems mentioned above with some large in production engines meeting tighter stringency standards, the most recent engines have been certificated with a margin of 5% to 20% below the CAEP/6 standard. Since ICAO standards require international agreement, it may only be possible to set more aggressive standards at the EU level.

Consideration was given as to whether an EU standard should be accompanied by a production cut-off, but this was rejected on two grounds. First there is evidence to indicate that the assumption used for analysis of stringency standards in ICAO, that market forces will result in non-compliant engines no longer being produced after the date of implementation, is borne out. Secondly there is the risk that a production cut-off in EU states will result in manufacturing moving to other countries. A phase-out of aircraft registered in EU states has not been considered as a shortlisted option.

EASA would be the agency responsible for implementing, monitoring and enforcing standards, as it approves engines types that are introduced to the market. All aircraft registered in EU states need to have EASA type approval for the engines fitted on the aircraft. The current environmental essential requirements, as stated in the EASA Basic Regulation (2002/1592), directly references the ICAO Annex 16 requirements and thus it is not possible to implement stricter standards. However EASA has published an Notice of Proposed Amendment (NPA) on Friday 30th May 2008 which includes proposals to revise the essential requirements and provide flexibility to deviate from these if the EU wished to do so. In designing an EU standard that exceeded those set by ICAO, consideration would need to be given on the competitive reaction to regional standards and the legal compatibility with the Chicago Convention. Our view is that engine manufacturers worldwide might be expected to respond to design engines to meet tighter EU standards, provided that they exceeded ICAO standards by only a small margin. This has been reflected in the specification of an EU standard 5% in excess of ICAO standards.

C.6 Precautionary emissions multiplier

The scientific evidence on climate impacts of aviation shows convincingly that aviation has had additional climate impacts over those from CO_2 emissions, as demonstrated by calculations of current-day radiative forcings (RFs) from aviation. These are caused by NO_x and other emissions and by physical perturbations of the atmosphere causing contrails and cirrus clouds.

The main drawback of the usage of the RFI in this fashion is that it is based on the accumulation of historical emissions of CO_2 in the atmosphere. Thus it captures the contribution of aviation to climate change to date from CO_2. Moreover, there is no unique value of an RFI since it depends entirely on the historical growth rate of emissions and, like RF, it is a partially 'backward-looking' metric (the CO_2 term). Applying this in a policy context would seem like punishing a sector for past behaviour, which cannot be changed, rather than encouraging changes in the future. Also, RFI cannot be related to the common metric used in climate policy i.e. the Global Warming Potential (indexed to a 100 year time horizon). CE et al. (2005) evaluated a number of other potential metrics for a multiplier but concluded that none were suitable. Most potentially suitable forward-looking metrics are still in the research domain and currently being assessed and evaluated, i.e the Global Temperature Potential (GTP) (Shine et al., 2005), a modification to this for aviation, the Global Temperature Index (GTI) (CE Delft et al., 2005) or the Emissions Weighting Factor (EWF[52]) (Forster et al., 2006; Corrigendum 2007). What they all suffer from is the uncertainty in underlying integrated RFs over a fixed time horizon from ozone and methane (Fuglestvedt et al., 2008). This is a function of the complexity of the responses in a physico-chemical system of a pulse or sustained NO_x emissions.

The scientific basis for a 'multiplier' on CO_2 emissions is embedded in the Kyoto Protocol with GWPs. At present, too much uncertainty remains over the value of an aviation NO_x GWP to recommend a value for policy purposes. However, given the clear evidence that aviation has positive RF impacts on climate in addition to those from the impacts of its CO_2 emissions, it could be argued that the precautionary principle should be invoked to justify a multiplier.

The precautionary principle is enshrined in the Treaty on the Functioning of the European Union[53], where article 191 para 2 states: 'Union policy on the environment shall aim at a high level of protection taking into account the diversity of situations in the various regions of the Union. It shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source and that the polluter should pay'.

In a communication on the precautionary principle, the Commission states that 'Recourse to the precautionary principle presupposes:

- Identification of potentially negative effects resulting from a phenomenon, product or process.
- A scientific evaluation of the risk which because of the insufficiency of the data, their inconclusive or imprecise nature, makes it impossible to determine with sufficient certainty the risk in question.' (COM(2000)1).

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[52] Actually, Forster et al.'s 'Emissions Weighting Factor' is simply a GWP.

[53] Consolidated version of the Treaty on the Functioning of the European Union (Tr5eaty of Lisbon), which comes into force, if ratified, on 01 January 2009 (OJ C115/132 of 09 May 2008). This Article replaces Article 174 of the Treaty Establishing the European Community (OJ C325 of 24 December 2002).

Arguably, the absence of a reliable metric for assessing the non CO_2 climate impacts meets these criteria. It can then be argued that the precautionary principle may be applied. Although there would be no scientific basis for any value, a value could be established as a precautionary emissions multiplier.

In that case, aircraft operators would have to surrender either one aviation allowance or more than one other type of emission allowance (be they EU ETS allowances or JI/CDM credits) for each tonne of carbon they emit.

As for the other design options, they would be identical to the Commission's proposal (COM(2006)818).

D Impacts analysis of market based instruments

D.1 Emissions for the Business as Usual (BaU) scenario

The Business as Usual (BaU) CO_2 and NO_x aviation emissions have been assessed with the AERO model for the year 2020. Further projections have not been made as most financial instruments do have impacts at this time interval.

The CO_2 and NO_x emissions for the year 2005, as computed by EUROCONTROL, are used as a basis for this assessment. The expected BaU growth of aviation emissions over the period 2005 to 2020 is based on the FESG2002 scenario. This FESG2002 scenario forecasts passenger km for the global aviation industry (including a forecast for routes to, from and within the EU).

For the AERO computations, the FESG2002 scenario is supplemented with assumptions regarding the BaU developments of costs and aircraft technology. Regarding costs developments, the main assumption relates to the crude oil price in the BaU scenario. It is assumed that the crude oil price will remain at a high level. The fuel costs computed for the BaU scenario 2020 is based on a crude oil price of US$ 100 per barrel.

Regarding aircraft technology developments, in the BaU scenario it is assumed that the fuel efficiency of new aircraft improve by 0.5% per year. Furthermore the NO_x emission indices (in terms of gram NO_x emitted per kg of fuel use) of new aircraft are assumed to deteriorate by 0.5% per year. The NO_x mass per SKO for new aircraft are thus assumed to remain constant over time until 2020, in line with the historical development in the past decades.

In line with the analysis made with the AERO model for the impact assessment of the EU ETS[54], for the period 2013-2019 an ATM efficiency improvement of 1% per year is assumed. This ATM improvement is assumed to be the result of the implementation of the Single European Sky (SES). The 1% efficiency improvement per year over the 7 year period, implies an average reduction of the detour of flight by 7%. The average actual flight distances are thus assumed to be reduced by 7% in 2020 (compared to what is was in 2005). This implies that fuel use and emissions are also roughly 7% lower in 2020, compared to a BaU scenario without the assumed ATM efficiency improvement resulting from the SES.

In this document, where it says EU, this relates to 30 countries:

1. The present 27 EU Member States.
2. Norway, Iceland and Liechtenstein (countries which are outside the EU but a member of the EEA).

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[54] Results of this analysis are included in the report: Technical Assistance for the IA of inclusion of aviation in the EU ETS. CE, January 2007.

We have computed CO_2 and NO_x emissions for all flights departing or arriving from any of the 30 countries. The CO_2 emissions on these flights are planned to be subject to emission trading when the EU ETS is implemented in 2012. Table 28 provides an overview of the BaU CO_2 and NO_x aviation emissions for 2020 (relative to the emissions of 2005). Hereby a distinction is made between the following route groups:

1. Emissions related to the domestic flights within any of the 30 countries considered (referred to as 'Intra EU - domestic').
2. Emissions related to the flights between the 30 countries considered (referred to as 'Intra EU - international').
3. Emissions related to flights between any of the 30 countries considered and other (non-EU) countries (referred to as 'EU to non-EU / non-EU to EU').

The numbers for 2005, as computed by EUROCONTROL, exclude the CO_2 and NO_x aviation emissions related to aircraft with an MTOW <20 ton[55]. Also in the emission quantities computed for the future years, the emissions of these small aircraft are not included.

Table 28 CO_2 and NO_x emissions in the years 2005 and 2020 according to BaU scenario

BaU scenario CO_2 and NO_x emissions in the years 2005 and 2020 (in Kton)				
Route group/geographical scope of EU ETS	CO_2 emissions		NO_x emissions	
	2005	2020	2005	2020
Route groups				
a Intra EU – domestic	14,591	26,555	59	119
b Intra EU – international	40,035	72,255	152	299
c EU to non-EU/Non-EU to EU	163,065	299,492	745	1,428
Total				
EU – All arriving and departing (a+b+c)	217,691	398,302	955	1,846
BaU scenario CO_2 and NO_x emissions (indexed to year 2005 = 100)				
Route group/geographical scope of EU ETS	CO_2 emissions		NO_x emissions	
	2005	2020	2005	2020
Route groups				
a Intra EU – domestic	100	182	100	201
b Intra EU – international	100	180	100	197
c EU to non-EU/Non-EU to EU	100	184	100	192
Total				
EU – All arriving and departing (a+b+c)	100	183	100	193
BaU scenario CO_2 and NO_x emissions (growth per year in period 2005-2020)				
Route group/geographical scope of EU ETS	CO_2 emissions		NO_x emissions	
	2005-2020		2005-2020	
Route groups				
a Intra EU – domestic	4.1%		4.8%	
b Intra EU – international	4.0%		4.6%	
c EU to non-EU/Non-EU to EU	4.1%		4.4%	
Total				
EU – All arriving and departing (a+b+c)	4.1%		4.8%	

Source: EUROCONTROL (data for year 2005) and AERO modelling system (data for year 2020).

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[55] Note that the proposal for the inclusion of aviation in the EU ETS has a different threshold, viz. 5,7 tonnes. So more emissions will be included in the EU ETS. Most likely, the difference will be a few percent.

Table 28 shows that the expected BaU growth in aviation CO_2 emissions over the period 2005-2020 is 80 to 85% (some variation across route groups). This is an average yearly growth in CO_2 emissions of about 4%. The expected BaU growth in aviation NO_x emissions over the period 2005-2020 is somewhat higher. The stronger growth of NO_x emissions follows from the assumed deterioration of the NO_x emission indices for new aircraft over time.

It has to be emphasized that the growth of both CO_2 en NO_x emissions, as presented in Table 28, is mitigated because of the assumed implementation of the Single European Sky (i.e. without the SES the growth in emission would be higher). A question is whether the reduction in operation costs, following from the SES, will imply additional demand effects. As the aviation industry is highly competitive, it is conceivable that the cost reductions are passed on to consumers, implying an extra demand effect on top of the demand growth following from the FESG2002 scenario. This would mean that part of the fuel use reductions would be offset by the additional flights required to meet the extra demand. In the default BaU scenario we have stuck to the demand forecast of the FESG2002 scenario. The possible extra demand, following from the SES related reduction in operation costs, is thus not taken into account in the default BaU scenario. From a sensitivity analysis with AERO however, it follows that the reduction in operation costs, following from the SES, could lead to an additional demand of 3 to 4%, and to additional fuel use and emissions of 2 to 3%. About 30 to 40% of the environmental benefits following from the SES, could thus be offset by the additional demand.

D.2 Effects of financial incentives

D.2.1 Specification of financial incentives

Chapter 6 specifies the policy options for the reduction of NO_x emission considered in the present study. Hereby a distinction is made between financial incentives and the introduction of standards. The effects of financial incentives are assessed by the AERO model. As specified in Chapter 6, within the category of financial incentives, the following policies are considered:

1. Precautionary emissions multiplier:
2. LTO NO_x charge.
3. Cruise NO_x charge.
4. LTO NO_x charge with distance factor.
5. Inclusion of aviation NO_x emissions in the EU ETS.

Furthermore we have presented the effects of the introduction of the EU ETS only. These effects are presented relative to the BaU scenario for 2020 as presented in Section D.1. The effects of the financial incentives for the reduction of NO_x emission are presented relative to the BaU scenario in 2020 including the effects of the EU ETS (without a multiplier). This in order to isolate the effects of the (additional) alternative NO_x policies.

The charging levels for the various policies follow from the specifications made in Chapter 6. Hereby the following levels are assumed:

- Precautionary emissions multiplier. In order to conduct some exploratory costings/impacts a CO_2 emissions multiplier of 2 was used. Usage of such a value does not imply either its recommendation or endorsement but is simply illustrative only, since the European Parliament proposed a value of 2. Furthermore the impacts are assessed for a multiplier of 1.1.
- LTO NO_x charge: Charging levels of respectively € 12.00 and € 4.40 per kg NO_x in the LTO.
- Cruise NO_x charge: Charging level based on GWP NO_x values of respectively 130 and 25.
- LTO NO_x charge with distance factor: Charging level based on GWP NO_x values of respectively 130 and 25.

Furthermore, for the cruise NO_x charges a distinction can be made between two variants: i) the charge applies to cruise NO_x emissions only (i.e. the NO_x emissions except the NO_x emissions during the LTO); and ii) the charge applies to all NO_x emissions (cruise and LTO emissions).

The above leads to the following overview of policies within the category of financial incentives for which the effects are computed by the AERO model.

For all policies it is assumed that the NO_x charges (or multiplier) will apply to all flights departing from and arriving at EU airports, which is in line with the proposed geographical scope of the EU ETS.

Aviation in EU Emission Trading Scheme (EU ETS)

1 EU ETS only (no NO_x policy) - assumed allowance price of € 20 per ton CO_2.
2 EU ETS only (no NO_x policy) - assumed allowance price of € 40 per ton CO_2.

Precautionary emissions multiplier

3 EU ETS with precautionary emissions multiplier of 2 - assumed allowance price of € 20 per ton CO_2.
4 EU ETS with precautionary emissions multiplier of 2 - assumed allowance price of € 40 per ton CO_2.
5 EU ETS with precautionary emissions multiplier of 1.1 - assumed allowance price of € 20 per ton CO_2.
6 EU ETS with precautionary emissions multiplier of 1.1 - assumed allowance price of € 40 per ton CO_2.

LTO NO_x charge

7 LTO NO_x charge - charging level of € 12 per kg NO_x in the LTO.
8 LTO NO_x charge - charging level of € 4,40 per kg NO_x in the LTO.

Cruise NO_x charge

9 NO_x charge for cruise emissions - charging level based on GWP NO_x value of 130.

10 NO_x charge for cruise emissions - charging level based on GWP NO_x value of 25.
11 NO_x charge for cruise and LTO emissions - charging level based on GWP NO_x value of 130.
12 NO_x charge for cruise and LTO emissions - charging level based on GWP NO_x value of 25.

LTO NO_x charge with distance factor and the inclusion of aviation NO_x emissions in the EU ETS.
13 LTO NO_x charge with distance factor - charging level based on GWP NO_x value of 130.
14 LTO NO_x charge with distance factor - charging level based on GWP NO_x value of 25.

The effects of the EU ETS are computed for an allowance price of € 20 and € 40 per ton CO_2. The effects of the precautionary emissions multiplier options are computed and presented for both allowance prices (policies 3 through 6). The effects of policies 7-14 are computed and presented relative to the BaU scenario including EU ETS whereby a price of € *40* per ton CO_2 is assumed.

D.2.2 Presentation of effects and main observations and conclusions

The effects of the 14 policies presented above are presented in Table 29 through Table 42. Hereby effects are split out by 3 route groups: 1) Intra EU - domestic; 2) Intra EU - international; and 3) EU to non-EU / non-EU to EU. A distinction is made between effects on:

- Air transport and aircraft operations (passenger and cargo demand; flights; aircraft km).
- Aviation fuel consumption and emissions (fuel use; CO_2 and NO_x emissions).
- Fuel efficiency (fuel per RTK; fuel per aircraft km).
- NO_x efficiency (NO_x per RTK; NO_x per aircraft km; NO_x emission index).

All tables both present the absolute quantities for the BaU scenario 2020, and the % effects of the alternative policies relative to the BaU scenario.

Furthermore Table 43 presents the financial effects for EU carriers for a selective number of policies.

Effects of EU ETS only (Table 29 and Table 30)
The analysis of the effects of the EU ETS only ware extensively studied as part of previous studies for the Commission, and the results presented here are comparable. The amount of allowances initially allocated to the aviation sector (AAIAA) is assumed to be equal to the CO_2 aviation emissions in 2005 on the routes covered by emission trading (i.e. flights on all routes departing from or arriving at an airport in the EU). It is assumed that the AAIAA are partly auctioned and partly grandfathered in line with the Commission proposal (COM(2006)818). In the computations with AERO it is assumed the opportunity costs of the

grandfathered allowances are entirely passed on by the trading entities (i.e. the airlines) to the consumers of air transport services.

The following main observations can be made in relation to the results presented in Table 29 and Table 30.

- An allowance price of € 40 per ton CO_2 implies an increase of the total operating costs for airlines by a few percent (3 to 4%). As it is assumed that all costs increases are passed on to consumers by increasing fares. The effects on demand result from the fare increase and the assumed price elasticities for demand.
- The reduction of CO_2 emissions within the aviation sector is generally a few percent. This is by far not enough to cover all projected growth of CO_2 emission over the period 2005-2020. The majority of the emission growth will thus be covered by acquiring allowances from other economic sectors included in the EU ETS.
- The reduction of CO_2 emissions within the aviation sector is both related to demand and supply side effects. The demand side effects are caused by the assumption that airlines pass on the policy induced cost increases which results in less operations (and hence less emissions). The supply side effect reflects that the costs for acquiring allowances will provide an incentive to airlines to shift more strongly to newer, more fuel-efficient (and associated lower emissions), technology aircraft than they would have in case of no emission trading. It is noted that AERO does not take into account a so-called manufacturer's response which implies that the fuel efficiency of new aircraft would be improved as a result of the introduction of an emission trading scheme. The supply side effect is illustrated by a slight improvement of the fuel efficiency resulting from the introduction of emission trading (see effects on fuel per RTK and fuel per aircraft km).
- A reduction in the number of operations not only results in a reduction of CO_2 emission but also in a reduction of NO_x emissions. The percentage reduction of NO_x is comparable to the reduction of CO_2 emitted by the aviation sector.

Effects of precautionary emissions multiplier (Table 31 through Table 34)

If a precautionary emissions multiplier would be introduced, for every ton of CO_2 emitted by the aviation industry over the 2005 baseline, two CO_2 emission allowances must be bought by airlines from other economic sectors. Because the total cost increase for airlines of including aviation the EU ETS with a precautionary emissions multiplier for aviation is twice as large (compared with EU ETS without a precautionary emissions multiplier for the aviation industry), the effects for the airline industry are also about twice as large. The effects presented in Table 31 and Table 32 (effects of the EU ETS with a precautionary emissions multiplier relative to the BaU scenario 2020 with EU ETS without a multiplier) are thus very similar to the effects presented in Table 29 and Table 30 (effects of EU ETS without a multiplier relative the BaU scenario 2020 without EU ETS). Clearly if a multiplier of 1.1 would be introduced, the effects for the aviation industry are much more limited (see Table 33 and Table 34).

Effects of LTO NO_x charge (Table 35 and Table 36)

The LTO NO_x charges result in modest emission reductions. The larger part of these emission reductions is related to the policy-induced cost increases and the fall in demand following from that. The cost increases for airlines introduced by the LTO NO_x charges are however limited. The highest charging level considered is € 12.00 per kg NO_x in the LTO. Typically the larger aircraft (+ 300 seat) emit about 50 kg of NO_x during the LTO. The total charge for a large aircraft is thus in the order of € 600 per flight. This roughly equals to a cost increase of about € 2 per passenger. Clearly the demand effects following from a cost increase of this magnitude are very limited.

The effects for the domestic flights within EU countries are relatively large in the case of an LTO NO_x charge, because an LTO NO_x charge is in fact a fixed charge per flight of a certain aircraft type. In comparison with the longer, international flights, for the shorter, domestic flights a fixed charge imply a relative large increase in operating costs, and thus a relatively large effect on demand.

Compared with the demand effects, the supply side effects of the LTO NO_x charges (but also of the other NO_x charges) are relatively modest. Table 35 for example shows a very modest improvement of the NO_x emissions per RTK following from an LTO NO_x charge.

This has partly to do with the way aircraft types are modeled in the AERO model. In AERO the aircraft fleet is represented by 10 generic aircraft size classes and two technology classes (old and current). In total AERO thus distinguishes 20 generic aircraft types. The LTO NO_x charges (and the other NO_x charges) are differentiated between these aircraft types based on the average NO_x characteristics of the 20 aircraft types. The difference of the average NO_x emission characteristics between the two technology classes for any of the aircraft size classes, is not very large. This is because there has not been a very strong trend towards more NO_x efficient aircraft over the past, and also for the future it is not assumed that the NO_x emissions of new aircraft will significantly improve.

Because AERO uses 20 generic aircraft types, whereby the mapping of named aircraft types to the generic aircraft types is not based on NO_x characteristics, the supply side effects of the NO_x charges, as computed by AERO, are probably underestimated. However, it is expected that, even if the supply side effects of NO_x charges would be modeled more accurately, the demand side responses will still be dominant in the reduction of NO_x emissions following from NO_x charges.

Effects of cruise NO_x charge (Table 37 through Table 40)

For the cruise NO_x charges, values of respectively 130 and 25 for the Global Warming Potential (GWP) for aviation NO_x emissions have been considered.

A GWP of 25 for NO_x implies that the climate effect of the emission of a certain amount of NO_x (say a ton) is equal to 25 times the climate effect of the same amount of CO_2 emission. The GWP values are used to derive cruise NO_x charging levels from the assumed permit price of € 40 per ton CO_2. A GWP value for NO_x of 130 thus implies a charging level for NO_x of 130 * € 40 = € 5,200 per ton of NO_x (or € 5.20 per kg of NO_x). Note that the charging levels are related to the assumed permit price of CO_2. In case the permit price would be assumed to be € 20 per ton CO_2 instead of € 40 per ton CO_2, the charging levels for NO_x (assuming a certain GWP for NO_x) would also be reduced by half.

The charges are modeled as a charge per kg of NO_x emitted during the cruise phase. Furthermore a variant is considered whereby the charge per kg of NO_x relates to both cruise and LTO emissions. Note that roughly about 15% of the aviation NO_x emissions are emitted during the LTO.

Table 37 presents the effects for a cruise NO_x charge based on a GWP for NO_x of 130. For the policy presented in Table 39 the same GWP is assumed, but there the charge relates to both cruise and LTO emissions. The effects of the cruise NO_x charge are somewhat lower. For example the reduction in passenger demand on the routes between EU and non-EU countries (following from the policy-induced cost increase) is 4.4% for the NO_x charge for cruise emissions only (see Table 37), and 4.9% if the NO_x charge is applied to both cruise and LTO emissions (see Table 39).

The demand effects of a NO_x charge based on a GWP for NO_x of 130 (presented in Table 37), are smaller than the demand effects of the precautionary emissions multiplier option (presented in Table 31). For the multiplier option the policy-induced cost increase is € 40 per ton CO_2. For the NO_x charge the policy induced-induced cost increase is 130 * € 40 = € 5,200 per ton NO_x. The charge per unit of mass is thus 130 higher in the case of the NO_x charge, but the ratio between the total CO_2 and NO_x emissions is higher. For example for the route group EU to non-EU/non-EU to EU, the amount of CO_2 and NO_x emissions in 2020 for the BaU scenario with emission trading is respectively 282.8 and 1,348 Megaton (i.e. the total mass of CO_2 emitted is 210 times the total mass of NO_x emitted). The policy induced costs increases for the option of a multiplier of 2, and thereby the demand effects, are thus very larger. With respect to the supply side effect, for the NO_x charge there a slight improvement of the NO_x emission index is computed, which is not the case for the multiplier option. As indicated above however, the supply side effects of NO_x charges are probably underestimated by the AERO model.

Furthermore it can be seen that if a GWP for NO_x of 25 is assumed (see Table 38 and Table 40) the effects on emissions are very limited (less then 1% reduction of emissions on all route groups).

Effects of LTO NO_x charge with distance factor (Table 41 and Table 42) and the inclusion of aviation NO_x emissions in the EU ETS.

The effects of the LTO NO_x charges with distance factor are very comparable with the effects of the cruise NO_x charges (where both charges are based on the same GWP value for NO_x). Moreover, since the inclusion of NO_x in the EU ETS would be done by calculating NO_x emissions on the basis of LTO emissions and a distance factor, the impacts would be the same. Only for shorter flights (f.e. the domestic flights within EU countries) the effects of the LTO NO_x charge with distance factor are somewhat less. This is related to the way the charging levels for the LTO NO_x charges with distance factor are assessed. Hereby use is made of a single factor β reflecting the ratio between cruise emissions per km and LTO emissions for the total aircraft fleet. However, in comparison with larger aircraft, the smaller aircraft operating on shorter flights on average have relatively low LTO emissions (compared to cruise emissions per km), and are therefore charged relatively low in the case of this charging regime.

Effects for EU airlines (Table 43)
Table 43 presents the effects for EU based airlines of a selective number of financial instruments. Because it is assumed the financial instruments are applied to all flights departing and arriving at an EU airport, almost all operations of EU airlines will be affected by the policy-induced cost increases. This whereas for airlines which are not based in the EU, only part of their operations will be affected (i.e. only their operation to and from EU countries).

For the multiplier option (multiplier of 2 and assumed allowance price of € 40) for EU airlines the direct operating costs per RTK increase by 6.6% on average. For the other policy options considered the cost increases are more limted. The smallest cost increase is associated with the LTO NO_x charge of € 12 per kg. The policy-induced cost increases are assumed to be passed on to airline consumers of EU carriers, implying an increase in fares and an associated demand effect. For the multiplier option the average increase of fares of EU carriers is 4.5% (see effect on revenues per RTK in Table 43) resulting in a demand effect for EU carriers of -3.8%. Following, the decrease in demand, the supply of airline services will be reduced. The effects on total operating costs and revenues are very comparable for all financial instruments, implying no or a very limited effect on the profit margin of EU airlines. However, it has to be borne in mind that the assumption that all policy-induced cost increases can and will be passed on to consumers is very crucial for this conclusion.

Table 29 Effects of Emission Trading for all flights arriving and departing from the EU in 2020 - allowance price € 20 per ton CO_2

Effect	Unit	BaU scenario 2020			% change relative to BaU scenario		
		Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	165.7	637.4	2,351.5	-1.2%	-1.5%	-2.4%
Cargo demand	Billion ton-km pa	1.5	5.0	169.7	-2.4%	-1.5%	-2.1%
Revenue Ton Km (RTK)	Billion RTK pa	18.1	68.7	404.9	-1.3%	-1.5%	-2.3%
Flights	Million flights pa	7.8	6.5	4.9	-1.5%	-1.3%	-1.9%
Aircraft Km	Billion ac-km pa	2.5	6.6	13.4	-1.5%	-1.5%	-2.5%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.4	22.9	94.9	-1.4%	-1.6%	-2.9%
CO_2 emissions	Billion kg pa	26.6	72.3	299.5	-1.4%	-1.6%	-2.9%
NO_x emissions	Million kg pa	119.3	299.3	1,427.7	-1.4%	-1.6%	-2.8%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.47	0.33	0.23	-0.1%	-0.1%	-0.6%
Fuel/aircraft km	kg/ac-km	3.36	3.48	7.06	0.0%	-0.1%	-0.4%
NO_x efficiency							
NO_x/RTK	gr/ton-km	6.6	4.4	3.5	-0.1%	-0.1%	-0.6%
NO_x/aircraft km	gr/ac-km	47.6	45.5	106.3	0.1%	-0.2%	-0.4%
NO_x emission index	gr/kg fuel	14.2	13.1	15.0	0.1%	0.0%	0.0%

Source: AERO modelling system.

Table 30 Effects of Emission Trading for all flights arriving and departing from the EU in 2020 - allowance price € 40 per ton CO_2

Effect	Unit	BaU scenario 2020			% change relative to BaU scenario		
		Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	165.7	637.4	2,351.5	-2.4%	-2.9%	-4.6%
Cargo demand	Billion ton-km pa	1.5	5.0	169.7	-4.6%	-3.0%	-4.1%
Revenue Ton Km (RTK)	Billion RTK pa	18.1	68.7	404.9	-2.6%	-2.9%	-4.4%
Flights	Million flights pa	7.8	6.5	4.0	-2.9%	-2.4%	-3.6%
Aircraft Km	Billion ac-km pa	2.5	6.6	13.4	-2.9%	-2.8%	-4.8%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.4	22.9	94.9	-2.8%	-3.0%	-5.6%
CO_2 emissions	Billion kg pa	26.6	72.3	299.5	-2.8%	-3.0%	-5.6%
NO_x emissions	Million kg pa	119.3	299.3	1,427.7	-2.7%	-3.1%	-5.5%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.47	0.33	0.23	-0.2%	-0.1%	-1.2%
Fuel/aircraft km	kg/ac-km	3.36	3.48	7.06	0.1%	-0.2%	-0.8%
NO_x efficiency							
NO_x/RTK	gr/ton-km	6.6	4.4	3.5	-0.1%	-0.1%	-1.2%
NO_x/aircraft km	gr/ac-km	47.6	45.5	106.3	0.2%	-0.3%	-0.8%
NO_x emission index	gr/kg fuel	14.2	13.1	15.0	0.1%	-0.1%	0.0%

Source: AERO modelling system.

Table 31 Effects of Emission Trading with precautionary emissions multiplier of 2 for aviation (effects relative to Emission Trading without multiplier - allowance price € 20 per ton CO$_2$)

Effect	Unit	BaU scenario 2020 with Emission Trading without multiplier			% change relative to BaU scenario with Emission Trading without multiplier		
		Intra EU - domestic	Intra EU – international	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – international	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	163.7	627.9	2,295.6	-1.2%	-1.5%	-2.3%
Cargo demand	Billion ton-km pa	1.5	4.9	166.2	-2.3%	-1.5%	-2.0%
Revenue Ton Km (RTK)	Billion RTK pa	17.8	67.7	395.7	-1.3%	-1.5%	-2.2%
Flights	Million flights pa	7.7	6.4	3.9	-1.4%	-1.2%	-1.8%
Aircraft Km	Billion ac-km pa	2.5	6.5	13.1	-1.4%	-1.3%	-2.3%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.3	22.5	92.1	-1.4%	-1.5%	-2.8%
CO$_2$ emissions	Billion kg pa	26.2	71.1	290.9	-1.4%	-1.5%	-2.8%
NO$_x$ emissions	Million kg pa	117.7	294.5	1,387.0	-1.3%	-1.5%	-2.8%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.46	0.33	0.23	-0.1%	0.0%	-0.6%
Fuel/aircraft km	kg/ac-km	3.36	3.48	7.03	0.0%	-0.1%	-0.4%
NO$_x$ efficiency							
NO$_x$/RTK	gr/ton-km	6.6	4.4	3.5	-0.1%	0.0%	-0.6%
NO$_x$/aircraft km	gr/ac-km	47.7	45.5	105.9	0.1%	-0.1%	-0.4%
NO$_x$ emission index	gr/kg fuel	14.2	13.1	15.1	0.0%	0.0%	0.0%

Source: AERO modelling system.

Table 32 Effects of Emission Trading with precautionary emissions multiplier of 2 for aviation (effects relative to Emission Trading without multiplier – allowance price € 40 per ton CO$_2$)

Effect	Unit	BaU scenario 2020 with Emission Trading without multiplier			% change relative to BaU scenario with Emission Trading without multiplier		
		Intra EU - domestic	Intra EU – international	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – international	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	161.7	618.7	2,243.1	-2.3%	-2.8%	-4.3%
Cargo demand	Billion ton-km pa	1.4	4.8	162.8	-4.5%	-2.9%	-3.8%
Revenue Ton Km (RTK)	Billion RTK pa	17.6	66.7	387.1	-2.5%	-2.8%	-4.1%
Flights	Million flights pa	7.6	6.3	3.8	-2.7%	-2.2%	-3.2%
Aircraft Km	Billion ac-km pa	2.4	6.4	12.8	-2.7%	-2.6%	-4.3%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.2	22.2	89.6	-2.6%	-2.8%	-5.3%
CO$_2$ emissions	Billion kg pa	25.8	70.1	282.8	-2.6%	-2.8%	-5.3%
NO$_x$ emissions	Million kg pa	116.1	290.1	1,348.7	-2.5%	-2.8%	-5.3%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.46	0.33	0.23	-0.1%	0.0%	-1.2%
Fuel/aircraft km	kg/ac-km	3.36	3.47	7.00	-0.1%	-0.2%	-1.0%
NO$_x$ efficiency							
NO$_x$/RTK	gr/ton-km	6.6	4.3	3.5	0.0%	0.0%	-1.2%
NO$_x$/aircraft km	gr/ac-km	47.7	45.4	105.4	0.2%	-0.2%	-1.0%
NO$_x$ emission index	gr/kg fuel	14.2	13.1	15.1	0.1%	0.0%	0.0%

Source: AERO modelling system.

Table 33 Effects of Emission Trading with precautionary emissions multiplier of 1.1 for aviation (effects relative to Emission Trading without multiplier - allowance price € 20 per ton CO_2)

Effect	Unit	BaU scenario 2020 with Emission Trading without multiplier			% change relative to BaU scenario with Emission Trading without multiplier		
		Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	163.7	627.9	2,295.6	-0.1%	-0.2%	-0.2%
Cargo demand	Billion ton-km pa	1.5	4.9	166.2	-0.2%	-0.2%	-0.2%
Revenue Ton Km (RTK)	Billion RTK pa	17.8	67.7	395.7	-0.1%	-0.2%	-0.2%
Flights	Million flights pa	7.7	6.4	3.9	-0.1%	-0.1%	-0.2%
Aircraft Km	Billion ac-km pa	2.5	6.5	13.1	-0.1%	-0.1%	-0.2%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.3	22.5	92.1	-0.1%	-0.1%	-0.3%
CO_2 emissions	Billion kg pa	26.2	71.1	290.9	-0.1%	-0.1%	-0.3%
NO_x emissions	Million kg pa	117.7	294.5	1,387.0	-0.1%	-0.1%	-0.3%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.46	0.33	0.23	0.0%	0.0%	-0.1%
Fuel/aircraft km	kg/ac-km	3.36	3.48	7.03	0.0%	0.0%	0.0%
NO_x efficiency							
NO_x/RTK	gr/ton-km	6.6	4.4	3.5	0.0%	0.0%	-0.1%
NO_x/aircraft km	gr/ac-km	47.7	45.5	105.9	0.0%	0.0%	0.0%
NO_x emission index	gr/kg fuel	14.2	13.1	15.1	0.0%	0.0%	0.0%

Source: AERO modelling system.

Table 34 Effects of Emission Trading with precautionary emissions multiplier of 1.1 for aviation (effects relative to Emission Trading without multiplier – allowance price € 40 per ton CO_2)

Effect	Unit	BaU scenario 2020 with Emission Trading without multiplier			% change relative to BaU scenario with Emission Trading without multiplier		
		Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	161.7	618.7	2,243.1	-0.2%	-0.3%	-0.5%
Cargo demand	Billion ton-km pa	1.4	4.8	162.8	-0.5%	-0.3%	-0.4%
Revenue Ton Km (RTK)	Billion RTK pa	17.6	66.7	387.1	-0.3%	-0.3%	-0.4%
Flights	Million flights pa	7.6	6.3	3.8	-0.3%	-0.2%	-0.3%
Aircraft Km	Billion ac-km pa	2.4	6.4	12.8	-0.3%	-0.3%	-0.5%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.2	22.2	89.6	-0.3%	-0.3%	-0.6%
CO_2 emissions	Billion kg pa	25.8	70.1	282.8	-0.3%	-0.3%	-0.6%
NO_x emissions	Million kg pa	116.1	290.1	1,348.7	-0.3%	-0.3%	-0.6%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.46	0.33	0.23	0.0%	0.0%	-0.1%
Fuel/aircraft km	kg/ac-km	3.36	3.47	7.00	0.0%	0.0%	-0.1%
NO_x efficiency							
NO_x/RTK	gr/ton-km	6.6	4.3	3.5	0.0%	0.0%	-0.1%
NO_x/aircraft km	gr/ac-km	47.7	45.4	105.4	0.0%	0.0%	-0.1%
NO_x emission index	gr/kg fuel	14.2	13.1	15.1	0.0%	0.0%	0.0%

Source: AERO modelling system.

Table 35 Effects of LTO NO_x charge - charging level of € 12 per kg NO_x in LTO (effects relative to Emission Trading without multiplier - allowance price € 40 per ton CO_2)

Effect	Unit	BaU scenario 2020 with Emission Trading without multiplier			% change relative to BaU scenario with Emission Trading without multiplier		
		Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	161.7	618.7	2,243.1	-1.2%	-0.7%	-0.4%
Cargo demand	Billion ton-km pa	1.4	4.8	162.8	-2.6%	-1.2%	-0.3%
Revenue Ton Km (RTK)	Billion RTK pa	17.6	66.7	387.1	-1.3%	-0.7%	-0.4%
Flights	Million flights pa	7.6	6.3	3.8	-1.4%	-0.6%	-0.5%
Aircraft Km	Billion ac-km pa	2.4	6.4	12.8	-1.0%	-0.5%	-0.4%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.2	22.2	89.6	-1.4%	-0.7%	-0.4%
CO_2 emissions	Billion kg pa	25.8	70.1	282.8	-1.4%	-0.7%	-0.4%
NO_x emissions	Million kg pa	116.1	290.1	1,348.7	-1.6%	-0.8%	-0.4%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.46	0.33	0.23	0.0%	0.0%	-0.1%
Fuel/aircraft km	kg/ac-km	3.36	3.47	7.00	-0.3%	-0.2%	-0.1%
NO_x efficiency							
NO_x/RTK	gr/ton-km	6.6	4.3	305	-0.2%	-0.1%	-0.1%
NO_x/aircraft km	gr/ac-km	47.7	45.4	105.4	-0.5%	-0.4%	-0.1%
NO_x emission index	gr/kg fuel	14.2	13.1	15.1	-0.2%	-0.1%	0.0%

Source: AERO modelling system.

Table 36 Effects of LTO NO_x charge - charging level of € 4,40 per kg NO_x in LTO (effects relative to Emission Trading without multiplier - allowance price € 40 per ton CO_2)

Effect	Unit	BaU scenario 2020 with Emission Trading without multiplier			% change relative to BaU scenario with Emission Trading without multiplier		
		Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	161.7	618.7	2,243.1	-0.5%	-0.2%	-0.1%
Cargo demand	Billion ton-km pa	1.4	4.8	162.8	-1.0%	-0.4%	-0.1%
Revenue Ton Km (RTK)	Billion RTK pa	17.6	66.7	387.1	-0.5%	-0.3%	-0.1%
Flights	Million flights pa	7.6	6.3	3.8	-0.5%	-0.2%	-0.2%
Aircraft Km	Billion ac-km pa	2.4	6.4	12.8	-0.4%	-0.2%	-0.1%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.2	22.2	89.6	-0.5%	-0.3%	-0.2%
CO_2 emissions	Billion kg pa	25.8	70.1	282.8	-0.5%	-0.3%	-0.2%
NO_x emissions	Million kg pa	116.1	290.1	1,348.7	-0.6%	-0.3%	-0.2%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.46	0.33	0.23	0.0%	0.0%	0.0%
Fuel/aircraft km	kg/ac-km	3.36	3.47	7.00	-0.1%	-0.1%	0.0%
NO_x efficiency							
NO_x/RTK	gr/ton-km	6.6	4.3	3.5	-0.1%	0.0%	0.0%
NO_x/aircraft km	gr/ac-km	47.7	45.4	105.4	-0.2%	-0.1%	0.0%
NO_x emission index	gr/kg fuel	14.2	13.1	15.1	-0.1%	0.0%	0.0%

Source: AERO modelling system.

Table 37 Effects of NO_x charge for cruise emissions - charging level based on GWP NO_x value of 130 (effects relative to Emission Trading without multiplier - allowance price € 40 per ton CO_2)

Effect	Unit	BaU scenario 2020 with Emission Trading without multiplier			% change relative to BaU scenario with Emission Trading without multiplier		
		Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	161.7	618.7	2,243.1	-0.9%	-1.5%	-2.6%
Cargo demand	Billion ton-km pa	1.4	4.8	162.8	-1.7%	-1.3%	-2.4%
Revenue Ton Km (RTK)	Billion RTK pa	17.6	66.7	387.1	-0.9%	-1.5%	-2.5%
Flights	Million flights pa	7.6	6.3	3.8	-0.7%	-0.9%	-1.7%
Aircraft Km	Billion ac-km pa	2.4	6.4	12.8	-0.9%	-1.2%	-2.5%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.2	22.2	89.6	-0.9%	-1.4%	-3.1%
CO_2 emissions	Billion kg pa	25.8	70.1	282.8	-0.9%	-1.4%	-3.1%
NO_x emissions	Million kg pa	116.1	290.1	1,348.7	-0.9%	-1.6%	-3.2%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.46	0.33	0.23	0.1%	0.1%	-.06%
Fuel/aircraft km	kg/ac-km	3.36	3.47	7.00	0.0%	-0.2%	-0.6%
NO_x efficiency							
NO_x/RTK	gr/ton-km	6.6	4.3	3.5	0.0%	-0.1%	-0.7%
NO_x/aircraft km	gr/ac-km	47.7	45.4	105.4	0.0%	-0.4%	-0.7%
NO_x emission index	gr/kg fuel	14.2	13.1	15.1	-0.1%	-0.2%	-0.1%

Source: AERO modelling system.

Table 38 Effects of NO_x charge for cruise emissions - charging level based on GWP NO_x value of 25 (effects relative to Emission Trading without multiplier - allowance price € 40 per ton CO_2)

Effect	Unit	BaU scenario 2020 with Emission Trading without multiplier			% change relative to BaU scenario with Emission Trading without multiplier		
		Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	161.7	618.7	2,243.1	-0.2%	-0.3%	-0.5%
Cargo demand	Billion ton-km pa	1.4	4.8	162.8	-0.3%	-0.3%	-0.5%
Revenue Ton Km (RTK)	Billion RTK pa	17.6	66.7	387.1	-0.2%	-0.3%	-0.5%
Flights	Million flights pa	7.6	6.3	3.8	-0.1%	-0.2%	-0.3%
Aircraft Km	Billion ac-km pa	2.4	6.4	12.8	-0.2%	-0.2%	-0.5%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.2	22.2	89.6	-0.2%	-0.3%	-0.6%
CO_2 emissions	Billion kg pa	25.8	70.1	282.8	-0.2%	-0.3%	-0.6%
NO_x emissions	Million kg pa	116.1	290.1	1,348.7	-0.2%	-0.3%	-0.6%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.46	0.33	0.23	0.0%	0.0%	-0.1%
Fuel/aircraft km	kg/ac-km	3.36	3.47	7.00	0.0%	0.0%	-0.1%
NO_x efficiency-							
NO_x/RTK	gr/ton-km	6.6	4.3	3.5	0.0%	0.0%	-0.1%
NO_x/aircraft km	gr/ac-km	47.7	45.4	105.4	0.0%	-0.1%	-0.1%
NO_x emission index	gr/kg fuel	14.2	13.1	15.1	0.0%	0.0%	0.0%

Source: AERO modelling system.

Table 39 Effects of NO$_x$ charge for cruise and LTO emissions - charging level based on GWP NO$_x$ value of 130 (effects relative to Emission Trading without multiplier - allowance price € 40 per ton CO$_2$)

Effect	Unit	BaU scenario 2020 with Emission Trading without multiplier			% change relative to BaU scenario with Emission Trading without multiplier		
		Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	161.7	618.7	2,243.1	-1.2%	-1.9%	-3.0%
Cargo demand	Billion ton-km pa	1.4	4.8	162.8	-2.2%	-1.7%	-2.7%
Revenue Ton Km (RTK)	Billion RTK pa	17.6	66.7	387.1	-1.2%	-1.8%	-2.9%
Flights	Million flights pa	7.6	6.3	3.8	-1.0%	-1.3%	-2.1%
Aircraft Km	Billion ac-km pa	2.4	6.4	12.8	-1.3%	-1.7%	-3.0%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.2	22.2	89.6	-1.2%	-1.8%	-3.6%
CO$_2$ emissions	Billion kg pa	25.8	70.1	282.8	-1.2%	-1.8%	-3.6%
NO$_x$ emissions	Million kg pa	116.1	290.1	1,348.7	-1.2%	-1.9%	-3.6%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.46	0.33	0.23	0.1%	0.1%	0.7%
Fuel/aircraft km	kg/ac-km	3.36	3.47	7.00	0.1%	-0.1%	-0.6%
NO$_x$ efficiency							
NO$_x$/RTK	gr/ton-km	6.6	4.3	3.5	0.0%	-0.1%	-0.8%
NO$_x$/aircraft km	gr/ac-km	47.7	45.4	105.4	0.1%	-0.3%	-0.7%
NO$_x$ emission index	gr/kg fuel	14.2	13.1	15.1	0.0%	-0.2%	-0.1%

Source: AERO modelling system.

Table 40 Effects of NO$_x$ charge for cruise and LTO emissions - charging level based on GWP NO$_x$ value of 25 (effects relative to Emission Trading without multiplier - allowance price € 40 per ton CO$_2$)

Effect	Unit	BaU scenario 2020 with Emission Trading without multiplier			% change relative to BaU scenario with Emission Trading without multiplier		
		Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	161.7	618.7	2,243.1	-0.2%	-04%	-0.6%
Cargo demand	Billion ton-km pa	1.4	4.8	162.8	-0.4%	-0.3%	-0.5%
Revenue Ton Km (RTK)	Billion RTK pa	17.6	66.7	387.1	-0.2%	-0.4%	-0.6%
Flights	Million flights pa	7.6	6.3	3.8	-0.2%	-0.3%	-0.4%
Aircraft Km	Billion ac-km pa	2.4	6.4	12.8	-0.3%	-0.3%	-0.6%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.2	22.2	89.6	-0.2%	-0.4%	-0.7%
CO$_2$ emissions	Billion kg pa	25.8	70.1	282.8	-0.2%	-0.4%	-0.7%
NO$_x$ emissions	Million kg pa	116.1	290.1	1,348.7	-0.2%	-0.4%	-0.7%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.46	0.33	0.23	0.0%	0.0%	-0.1%
Fuel/aircraft km	kg/ac-km	3.36	3.47	7.00	0.0%	0.0%	-0.1%
NO$_x$ efficiency							
NO$_x$/RTK	gr/ton-km	6.6	4.3	3.5	0.0%	0.0%	-0.2%
NO$_x$/aircraft km	gr/ac-km	47.7	45.4	105.4	0.0%	-0.1%	-0.1%
NO$_x$ emission index	gr/kg fuel	14.2	13.1	15.1	0.0%	0.0%	0.0%

Source: AERO modelling system.

Table 41 Effects of LTO NO_x charge with distance factor and the inclusion of aviation NO_x emissions in the EU ETS - charging level based on GWP NO_x value of 130 (effects relative to Emission Trading without Multiplier - allowance price € 40 per ton CO_2)

Effect	Unit	BaU scenario 2020 with Emission Trading without multiplier			% change relative to BaU scenario with Emission Trading without multiplier		
		Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	161.7	618.7	2,243.1	-0.9%	-1.6%	-3.0%
Cargo demand	Billion ton-km pa	1.4	4.8	162.8	-1.8%	-1.4%	-2.6%
Revenue Ton Km (RTK)	Billion RTK pa	17.6	66.7	387.1	-0.9%	-1.6%	-2.8%
Flights	Million flights pa	7.6	6.3	3.8	-0.4%	-0.6%	-1.6%
Aircraft Km	Billion ac-km pa	2.4	6.4	12.8	-0.5%	-0.9%	-2.7%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.2	22.2	89.6	-0.7%	-1.4%	-3.5%
CO_2 emissions	Billion kg pa	25.8	70.1	282.8	-0.7%	-1.4%	-3.5%
NO_x emissions	Million kg pa	116.1	290.1	1,348.7	-0.9%	-1.7%	-3.6%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.46	0.33	0.23	0.2%	0.2%	-0.7%
Fuel/aircraft km	kg/ac-km	3.36	3.47	7.00	-0.2%	-0.5%	-0.8%
NO_x efficiency							
NO_x/RTK	gr/ton-km	6.6	4.3	3.5	0.1%	-0.1%	-0.8%
NO_x/aircraft km	gr/ac-km	47.7	45.4	105.4	-0.4%	-0.8%	-0.9%
NO_x emission index	gr/kg fuel	14.2	13.1	15.1	-0.1%	-0.3%	-0.1%

Source: AERO modelling system.

Table 42 Effects of LTO NO_x charge with distance factor and the inclusion of aviation NO_x emissions in the EU ETS - charging level based on GWP NO_x value of 25 (effects relative to Emission Trading without multiplier - allowance price € 40 per ton CO_2)

Effect	Unit	BaU scenario 2020 with Emission Trading without multiplier			% change relative to BaU scenario with Emission Trading without multiplier		
		Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU	Intra EU - domestic	Intra EU – inter-national	EU to non-EU/non-EU to EU
Air transport and aircraft operations							
Passenger demand	Billion pax-km pa	161.7	618.7	2,243.1	-0.2%	-0.3%	-0.6%
Cargo demand	Billion ton-km pa	1.4	4.8	162.8	-0.3%	-0.3%	-0.5%
Revenue Ton Km (RTK)	Billion RTK pa	17.6	66.7	387.1	-0.2%	-0.3%	-0.6%
Flights	Million flights pa	7.6	6.3	3.8	-0.1%	-0.1%	-0.3%
Aircraft Km	Billion ac-km pa	2.4	6.4	12.8	-0.1%	-0.2%	-0.5%
Aviation fuel consumption and emissions							
Fuel use	Billion kg pa	8.2	22.2	89.6	-0.1%	-0.3%	0.7%
CO_2 emissions	Billion kg pa	25.8	70.1	282.8	-0.1%	-0.3%	-0.7%
NO_x emissions	Million kg pa	116.1	290.1	1,348.7	-0.2%	-0.3%	-0.7%
Fuel efficiency							
Fuel/RTK	kg/ton-km	0.46	0.33	0.23	0.0%	0.0%	-0.1%
Fuel/aircraft km	kg/ac-km	3.36	3.47	7.00	0.0%	-0.1%	-0.2%
NO_x efficiency							
NO_x/RTK	gr/ton-km	6.6	4.3	3.5	0.0%	0.0%	-0.1%
NO_x/aircraft km	gr/ac-km	47.7	45.4	105.4	-0.1%	-0.2%	-0.2%
NO_x emission index	gr/kg fuel	14.2	13.1	15.1	0.0%	-0.1%	0.0%

Source: AERO modelling system.

Table 43 Effects of various market based instruments for EU based airlines.

Effects	Policy option				
	Multiplier 2 - allowance price € 40	LTO NO_x charge - € 12 per kg NO_x	NO_x charge for cruise - GWP NO_x 130	NO_x charge for cruise and LTO - GWP NO_x 130	LTO NO_x charge distance factor or inclusion of NO_x in the EU ETS - GWP NO_x 130
Air transport and aircraft operations of EU airlines (% change relative to BaU scenario)					
Revenue Ton Km (RTK)	-3.8%	-0.5%	-2.2%	-2.6%	-2.5%
Flights	-3.0%	-1.2%	-1.1%	-1.5%	-0.8%
Aircraft Km	-3.4%	-0.5%	-1.8%	-2.3%	-1.7%
Effects on costs and revenues EU airlines (% change relative to BaU scenario)					
Direct operating costs	2.6%	0.6%	1.4%	1.7%	1.6%
Total operating costs	0.6%	0.1%	0.3%	0.3%	0.4%
Total operating revenues	0.6%	0.1%	0.3%	0.4%	0.4%
Direct operating costs / RTK	6.6%	1.1%	3.8%	4.4%	4.2%
Total operating costs / RTK	4.5%	0.6%	2.6%	3.0%	2.9%
Total operating revenues / RTK	4.5%	0.6%	2.6%	3.0%	2.9%

Source: AERO modelling system.

D.3 Cost-effectiveness of financial instruments

By definition, the costs of financial instruments are the sum of the welfare loss, the costs of measures incentivised by the instruments and the administrative costs. As is apparent from the AERO results, very little measures are incentivised by the economic instruments as evaluated here (see Section D.2). Therefore, we found it reasonable to ignore these costs. The welfare costs C are generally taken to be the loss in consumer surplus, or, when Q_1 and p_1 represent the quantity and price produced before the introduction of the financial instrument and Q_2 and p_2 the quantity and price after the financial instruments have been designed[56]:

$$C = \frac{1}{2} \times (Q_2 - Q_1) \times (p_2 - p_1)$$

Q_1 and Q_2 are the values of RTK in the AERO results. For the prices, it is assumed that p_2-p_1 is equal to the cost price increase. AERO yields the following cost price increases for the different instruments:

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[56] Formally, this is only valid if the price elasticity of supply is zero.

Table 44 Cost price increases for financial instruments

	Route Group	
	Intra EU (domestic + international)	EU – non EU / non EU – EU
LTO NO_x charge; Euro 12 per kg NO_x	1.0%	0.5%
LTO NO_x charge * distance or the inclusion of NO^x in the EU ETS; GWP=130	1.7%	3.6%
NO_x charge for cruise emissions; GWP=130	1.5%	3.2%
NO_x charge for cruise and LTO emissions; GWP=130	1.9%	3.6%
Multiplier of 2	3.2%	5.2%

Bron: AERO MS.

We have applied this cost price increase to the average yield per RTK of AEA airlines in the different route groups over the years 2003-2006, as presented in Table 45.

Table 45 Yield per RPK, AEA airlines average (€)

	2003	2004	2005	2006	Average
Europe	0.139	0.135	0.133	0.132	0.13475
Interconti-nental	0.059	0.06	0.062	0.067	0.062
Total	0.087	0.087	0.089	0.092	

Bron: AEA, 2007: Key Figures.

Assuming the administrative costs to be € 5 mln per year, except for the multiplier where the additional administrative costs are zero, we arrive at the following cost-effectiveness figures:

Table 46 Cost effectiveness of financial instruments (€/kg NO_x)

Instrument	Cost-effectiveness
LTO NO_x charge; Euro 12 per kg NO_x	1.1
LTO NO_x charge * distance or the inclusion of NO_x in the EU ETS; GWP=130	1.7
NO_x charge for cruise emissions; GWP=130	1.5
NO_x charge for cruise and LTO emissions; GWP=130	1.8
Multiplier of 2	2.4

If the administrative costs are assumed to be five times as high, the cost effectiveness decreases to € 1.9 to € 3.2 per kg of NO_x, with the largest increase for the LTO NO_x charge.

E Impact analysis of standard based instruments

E.1 Environmental impacts

The environmental impacts of stringencies in terms of reduced NO_x emissions are reported in Appendix A. Here, the main results are summarised in Table 47.

Table 47 Emission reductions of LTO NO_x Standards on flights to and from EU airports

	2020		2050	
	Gg NO_x	% reduction relative to baseline	Gg NO_x	% reduction relative to baseline
CAEP/6 -5%	6	0.4%	9	0.2%
CAEP/6 -10%	38	2.3%	254	5.3%
CAEP/6 -15%	53	3.2%	321	6.7%
CAEP/6 -20%	86	5.2%	577	12.0%
CAEP/6 -25%	116	7.0%	786	16.3%
CAEP/6 -30%	149	8.9%	1,045	21.7%

Bron: Appendix C.

E.2 Economic impacts

The discussion of economic impacts is limited to an analysis of the cost-effectiveness of the standards.

Tentative calculations on the cost effectiveness of NO_x standards

In the following we include some rough estimates of the global costs incurred if aircraft engines have to comply to a standard that is stricter than the CAEP/6 standard. We subsequently relate the costs to the amount of NO_x emission reduced per stringency option. The stringency options are then being compared as to their costs per unit NO_x reduced. Note that we do not take the reduced environmental damage into account in these cost effectiveness calculations.

When tightening a NO_x standard for aircraft engines two kind of costs do accrue. First there are the so called non-recurring costs for the development of engines to make them compliant with the standard. Secondly there is an increase of the recurring costs with respect to engine production, maintenance of the engines, a higher number of spare engines. If a stringency option leads to an aircraft using more fuel (‘fuel penalty’), these additional fuel costs come along with a higher MTOW[57], leading in turn to higher production costs but also to higher landing fees. Finally, there might be some diminution of the value of the existing fleet. However this is not included here as there has been debate as to whether these losses in fleet value represent a genuine resource cost.

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[57] The increase in MTOW preserves mission capability by allowing the aircraft to carry the additional fuel necessary for the engine complying with the standard.

The costs are derived under the assumption that the stringency year is 2012, i.e. engines have to fulfill the standard that is stricter than the CAEP/6 standard from 2012 on. The non-recurring costs are based on CAEP/8 data. Three possible technological upgrades are being differentiated here. For each of these modification status levels the costs per engine family is given as follows:

Table 48 Costs of modification per engine family (million US$)

Modification Status Level	Cost Estimate (million $)	
	Low Estimate	High Estimate
1	1	15
2	50	100
3	100	500

Making use of the estimation given in CAEP/8 as to how many engine families require which upgrade per stringency level we are able to derive the non-recurring costs. For small engines we thereby take only the stringency options into account where independent of the kN the percentage of reduction is the same. For large engines we differentiate the scenarios ‘Slope 2’ and ‘Slope 2.2’ where the former stands for a stricter standard. We derived the following non-recurring costs:

Table 49 Scenario 1: Slope 2, Non-recurring costs for small and large engines (million 2008 Euro)

	Low Estimate	High Estimate
CAEP/6-5%	213	439
CAEP/6-10%	320	682
CAEP/6-15%	690	2,358

Table 50 Scenario : Slope 2.2, Non-recurring costs for small and large engines (million 2008 Euro)

	Low Estimate	High Estimate
CAEP/6-10%	265	545
CAEP/6-15%	374	804
CAEP/6-20%	1,168	4,928

Note that for the scenario 1 there is no information available as to CAEP/6-20% and for the second scenario not for CAEP/6-5%. And further, since it is not clear to us to which year the costs in U.S. $ per engine family correspond, we assumed in line with the CAEP/6 study that these are 2002 U.S. $.

The recurring costs are taken from the CAEP/6 study. Since the CAEP/6 standard constitutes a CAEP/4 – 12% standard we approximated the costs of a stringency CAEP/6 – x% option by making use of the costs of the CAEP/4 – (x-10)% stringency option. These costs are, without taking a fuel penalty or a loss in fleet value into account, as follows for the period from 2002-2020:

Table 51 Incremental recurring costs with no fuel burn penalty related costs (million 2008 Euro for 2000-2020)

CAEP/6-5%	5,360
CAEP/6-10%	6,990
CAEP/6-15%	12,170
CAEP/6-20%	14,390

Note that in the CAEP/6 study the recurring costs are given for 2030 as well. However, we do only dispose of emission reduction data for 2050. Thus we do only calculate the cost effectively of the stringency option with the time horizon being 2020.

The above specified recurring costs are given for the case that the fuel burn penalty is zero. In the CAEP/6 study the recurring costs are given for the case that the fuel burn penalty is 2% and the fuel price per gallon is $ 0.95. In CAEP/8 the fuel burn penalty is adjusted to be 0-0.5%. We therefore adjusted the fuel burn penalty related costs also allowing for a increased fuel price. The latter is assumed to be $ 3.5 per gallon. The adjustment of the fuel expenditure is straightforward, when assuming that the amount the amount of extra fuel does not change. For the adjustment of the higher production costs due to a rise of the MTOW and the adjustment of higher landing fees we assumed that the ratio between extra fuel costs and the respective cost, which in the CAEP6 study is rather similar per stringency option, is the same than in the CAEP6 study. The resulting incremental recurring costs inclusive the fuel burn penalty related costs are then as follows.

Table 52 Incremental recurring costs with fuel burn penalty related costs (million 2008 Euro for 2000-2020)

CAEP/6-5%	6,800
CAEP/6-10%	9,300
CAEP/6-15%	25,620
CAEP/6-20%	33,890

Note that only if the highest technological modification status level applies a fuel burn penalty is incurred. Therefore the costs for the two most strict stringency levels rise the most.

As to the NO_x emissions of the aircraft per stringency option we dispose of data for the following routes:
- EU to non-EU.
- EU domestic. And,
- Intra EU.

In order to get the emissions for the global fleet we assume for the non-EU to EU route that the emissions are just the same as on the EU to non-EU route. Since we know the total NO_x emissions for the year 2000 we can thus derive the NO_x emissions for the route non-EU to non-EU. For the years 2020 and 2050 we assume that the latter route is responsible for the same share of total emissions than in 2000. Assuming that the share of emissions to and from the EU will remain constant between 2000 and 2020 at 42% of the world total, the resulting non cumulative NO_x emission reduction for 2020 are given in Table 53.

Table 53 Global non cumulative NO_x reduction in 2020 under various stringencuy levels

	Global non cumulative NO_x reduction in 2020 (kt)
CAEP/6-5%	14
CAEP/6-10%	91
CAEP/6-15%	127
CAEP/6-20%	205

So far we did only take the non-cumulative NO_x emission reduction into account. Assuming that stringencies would lead to a linear decrease in emissions from 2000 to 2020, the cumulative emission reductions can be estimated as being ½*20*ΔNO_x, or a factor 10 higher than the Table 53.

The costs per cumulative reduced ton of NO_x are thus:

Table 54 Costs per cumulative reduced tonne of NO_x in 2020

	Costs per ton reduced NO_x, no fuel burn penalty (€$_{2008}$ / kg NO_x)				**Costs per ton reduced NO_x, fuel burn penalty: 0,5% (€$_{2008}$ / kg NO_x)**			
	Slope 2		**Slope 2.2**		**Slope 2**		**Slope 2.2**	
	Low Estimate	**High Estimate**	**Low Estimate**	**High Estimate**	**Low Estimate**	**High Estimate**	**Low Estimate**	**High Estimate**
CAEP/6-5%	38	40			49	50		
CAEP/6-10%	8	8	8	8	11	11	11	11
CAEP/6-15%	10	11	10	10	21	22	21	21
CAEP/6-20%			8	9			17	19

Discount factor 0%. Applying a higher discount factor would change the numbers but probably not the order.

Either with or without a fuel burn penalty, and regardless of the slope, the lowest stringency option of -5% is the least cost-effective, largely because of the limited NO_x reduction. With no fuel burn penalties, increasing stringencies by 10% to 20% would have similar cost-effectiveness. With a fuel penalty, the -15% and -20% options are more expensive than the -10% option. It is important to note that these calculations which include reductions in total NO_x are not comparable with those previously produced for CAEP, which are limited to LTO NO_x.

F Legal analysis

F.1 Full legal analys of short list

Synopsis

This chapter examines the legal feasibility of four short-listed options. Those options concern the establishment of:

1. A local LTO NO_x charge on flights within, from and to the EU, with particular reference to airports with local air quality problems caused by such emissions.
2. An LTO NO_x charge on flights within, from and to the EU with a distance factor.
3. An cruise NO_x charge on flights within, from and to the EU.
4. Inclusion of aviation NO_x emissions in the EU ETS.
5. Imposition of more stringent NO_x certification standards.
6. A NO_x charge proceeding from a multiplier effect regarding CO_2 emissions in accordance with an ETS, with reference to the Precautionary principle.

All options above are subject to international law considerations, including international environmental law, public international law and especially international aviation law, as flights are operated by airlines flying under internationally agreed rules and principles.

Obviously, the above options are also subject to Community law.

When checking the legal feasibility of the above four options against the mentioned international law regimes, it is concluded that the establishment of option 3 poses relatively few legal obstacles, followed by option 1, if adequately implemented (as suggested below). As options (2) and (4) are affected by a number of internationally agreed rules and principles, basically under national aviation law, their establishment must be placed in the context of those rules and principles.

F.2 LTO NO_x charge

EU LTO NO_x charge; the EU implements a scheme for the differentiation of charges related to aviation (be it ATM charges, airport charges or government charges) according to NO_x emissions, either LTO NO_x emissions or cruise NO_x emissions. Or the EU implements a LTO NO_x charge at EU airports.

Short answer:

International environmental law allows this option.
Under international aviation law, a number of provisions and principles must be taken into account when introducing this measure, in particular if the position of airlines of third states may be affected by this measure. However, states members of a regional economic integration organization are permitted to implement an emission-related levy *on operators of those states*[58].

Hence the legality of this option depends on its scope: if it is extended to non-EC operators, even if they are flying within the airspace of EC states, their rights may be affected under international air law as explained below. On the other hand, ICAO appears to allow the establishment of local charges designed to mitigate NO_x levels, and to confirm that 'positive discrimination' is permitted under international air law, as it is under international trade law. In sum, it would seem that this measure has a fair chance.

As this charge principally aims to enhance *local air quality* - henceforth also referred to as *LAQ*, local conditions and local regulations play an important role. Both ICAO Policy and Guidelines, and European Community law and policy refer to the domestic conditions governing regulation and policy of this question. This facet of the LTO NO_x charge becomes even more articulated if airport operators – like other operators of stationary installations – would be designated as the persons liable, who may recover the costs from airlines, as to which see blow.

Explanations:

A International environmental law

A.1 The Rio Declaration on Environment and Development (1992)

Pursuant to Principle 16 of the *Rio Declaration on Environment and Development* (1992), the 'internalisation' of external – that is, environmental – costs may be included with the costs of air navigation:

> 'National authorities should endeavour to promote the *internalization of environmental costs* and the use of economic instruments, taking into account the approach that the polluter should, in principle, bear the cost of pollution, with due regard to the public interest and without distorting international trade and investment.'

The 'Rio' Principle is in line with EC law and policy based rules stating that the polluter must compensate the damages he caused. Reference is made to Title XIX of the EC Treaty, in particular Art. 174(2).

In a number of instances, ICAO refers to the above 'Rio Principle'[59]. It would seem that, by virtue of making such references without arguing that this principle is wrong or should be fine tuned, ICAO accepts it, at least implicitly. Hence, it can be argued that the aviation sector is bound by this Rio Principle, in particular the promotion of the internalisation of environmental costs.

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[58] See Annex I of ICAO Resolution 35-5 (Doc 9848).

[59] See, for instance, in the context of ICAO Resolution A35-5.

A.2 The UNFCC/Kyoto Protocol

The UN Framework Convention on Climate Change (UNFCC) addresses greenhouse gas emissions differently, depending on whether they are generated by domestic or international operations. The UNFCC regime focuses on the reduction of greenhouse gases, to be included with an Emission Trade System. NO_x is treated differently, that is, not directly falling under this regime, as it is not a greenhouse gas.

Under the Kyoto Protocol, Annex I Parties have the obligation to reduce GHG emissions of aviation through ICAO[60]. ICAO is conducting policies on measures designed to reduce not only greenhouse gases but also NO_x, as to which see further below.

B International aviation law

B.1 The Chicago Convention (1944)

If the NO_x charge is to be applied to all carriers landing at an airport in the EU or flying through the airspace of EU states, the non-discrimination principle of Articles 15 and 11 of the Chicago Convention respectively apply. These provisions contain mandatory – 'hard law' – provisions forbidding discrimination and prescribing 'national treatment' of aircraft, irrespective of their nationality. Again, there is no international law problem if only Community air carriers are affected by the measure, as 'Reversed discrimination' is not forbidden by international air or trade law.

Article 15 of the Chicago Convention concludes by stating that:

> 'No fees, dues or other charges shall be imposed by any contracting State in respect *solely* of the right of transit over or entry into or exit from its territory of any aircraft of a contracting State or persons or property thereon.' (italics added)

This provision is designed to prevent contracting states (of the Chicago Convention) from requiring foreign operators to pay for the right of transit. The idea is that national airspace is subject to sovereignty of the underlying state but should be made available for international air navigation without further costs than those which are necessary to recover the costs for using airports and air navigation facilities.

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[60] See Article 2(2) of the Kyoto Protocol: 'The Parties included in Annex I shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively.'

B.2 ICAO measures

B.2.1 ICAO Resolutions on Charges

ICAO has made a number of resolutions on the subject of charges contained in ICAO Doc 9082 entitled ICAO's *Policies on Charges for Airports and Air Navigation Services*, including specific guidance on environmental charges[61]. When implementing an aircraft emissions charging scheme, such as the NO_x charge, states should:

- Take into account the interests of all parties concerned.
- Respect the non-discrimination – national treatment principle (see Article 15 of the Chicago Convention as referred to above).
- Evaluate the potential impact on the developing world.
- Avoid distortion of competition with other modes of transport (as to which see the discussion under the *Precautionary principle*, below).
- Avoid that charges affect the efficient use of existing aircraft capacity.
- Set up a transparent scheme.
- Realise that charges should be 'cost-based'.
- Be encouraged to adopt 'cost effective measures', and to 'minimize competitive distortions' - as to which see further below (under the OAA agreement).
- Avoid fiscal aims when establishing a charge, the revenues of which should be used to mitigate the environmental impact.

While realising that the 'existing … guidance is not sufficient at present to implement greenhouse gas emissions charges internationally', ICAO concedes that states members of a regional economic integration organization may be permitted to implement an emission-related levy *on operators of those states*[62]*.* European states and their organisations realise that this allowance – to impose charges exclusively on their own operators – would amount to discrimination – that is, 'positive discrimination'. Since such a measure would negatively affect their own airlines, the mentioned European parties state 'that this is not a realistic option for any State'[63].

B.2.2 ICAO's policies and guidelines on the establishment of charges addressing local air quality problems

In addition, ICAO has drawn up *Guidance Materials on Local Air Quality* (*LAQ*) *Assessment*[64]*.* Under this policy, states 'should' make an assessment of the existing and forecast future airport local air quality by comparing pollutant concentrations in the air in the vicinity of the airport against the relevant LAQ

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[61] See General Assembly resolution A 35-5, in particular Annex I.

[62] See Annex I of ICAO Resolution 35-5 (Doc 9848), under 2(b)(3).

[63] See, the European Community, its Member States, ECAC and Eurocontrol, *A Comprehensive Approach to Managing Aviation's Environmental Impacts*, Working Paper presented at the 36th Session of the Assembly of the International Civil Aviation Organisation (ICAO), Montreal, 18 to 28 September 2007 (Agenda Item 17, *Environmental Protection*).

[64] See ICAO Doc 9884, in particular Chapters 3 and 4.

standards. Responsibility for defining and achieving acceptable air quality in and around airports rests with states.

The ICAO Council has established criteria which emission related aircraft charges to address local air quality problems at or around airports must meet before states can proceed to their establishment[65]. Such charges should:

- Only be imposed at airports with a defined local air quality problem.
- Be based on costs, that is expenses which must be made to mitigate the adverse air quality effects.
- Be established in a transparent fashion – both in terms of procedure and of identification of the cost basis.
- Take into consideration the position of aircraft operators from the developing world.
- Be associated to airport charges or being imposed as a separate fee.

The ICAO Council suggests that the costs related to the compensation of damages caused by NO_x emissions 'may … be attributed to airports and received from the users.' In another document, ICAO examines a number of 'accountable entities' who have to pay charges[66]. Next to aircraft operators mention is made of fuel suppliers, Air navigation Service Providers, Airport operators and aircraft manufacturers [67].

As this charge aims to enhance *local air quality*, local conditions and local regulations play an important role. This facet of the LTO NO_x charge becomes even more articulated if airport operators – like other operators of stationary installations – would be designated as the persons liable, rather than aircraft operators flying under international rules, as to which see the following sections. Airport operators should then somehow recover these expenses from the users, perhaps via airport charges – in which case the above international rules on airport charges become relevant again.

The ICAO Council points at the voluntary, non-mandatory character of the above charges. It uses such terms as: 'States *may opt* to apply emissions charges'; costs coming from local NO_x emissions may, *at the discretion of States*, be attributed to airports, and recovered from users; whereas 'States have *the flexibility* to decide on the method of cost recovery.'

It follows that the establishment of this charge is optional. If EC states proceed to their establishment, they may wish to or should take into account the factors mentioned above. The next sub section explains the legal status of the above ICAO measures.

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[65] See, ICAO's Policies on Charges for Airports and Air Navigation Services, Doc 9082/7, Amendment No. 1 of 24 August 2007.

[66] See Table 2-1 in Doc 9885: *Draft Guidance on the Use of Emissions Trading for Aviation* (Provisional edition, 2007).

[67] See also, under F.2.3, on the Eurocontrol regime, and the suggestion made above to designate airport operators as the accountable entity.

B.2.3 The legal status of Resolutions and Guidelines

The above Resolutions, let alone Guidance Materials, are not laid down in Standards as formulated in Annexes of the Chicago Convention so that there legal status is not as strong as that of provisions of the Chicago Convention and of ICAO Standards. However:

1. ICAO Resolutions of the ICAO General Assembly are made by consensus. That is how this body works. Theoretically, states, for instance, EU states, can make a reservation absent a resolution but this is not an easy step from a political point of view. In doing so, EU states must be quite eager to promote their viewpoints as the making of reservations is not seen as a collaborative act in the consensus based ICAO policy and law making machinery.

2. Some of the ‘principles’ contained in the ICAO Policies and Resolutions are laid down in provisions of bilateral air agreements so as to make them enforceable as between states. In this regard, special reference is made to the EC-US agreement on air transport of 2007 (which entered into fore on 30 March 2008), hereafter also referred to as the Open Aviation Area (*OAA*) agreement as this agreement is so important for the external aviation relations of the EU generally and for the operations of the airlines flying under it in particular.

Finally, ICAO is a central legislator for world wide aviation. As stated above, the legal force of its measures vary. Standards may receive binding force through implementation in national legislation, whereas resolutions have a moral rather legal effect – depending upon the circumstances under which they were adopted. As ICAO bodies have no – or hardly – any enforcement powers, states are responsible for the enforcement of Standards in particular and in some instances other ICAO measures – as to which see the next sub-section.

B.3 Bilateral agreements: the example of the OAA agreement (2007/8)

The OAA agreement states that[68]:

> ‘User Charges … shall be just, reasonable, not unjustly discriminatory, and equitably apportioned among categories of users.’

Whereas:
Such charges ‘may reflect but shall not exceed, … the full cost’ of the provision of ‘airport environmental … facilities and services’ whereas they ‘may include a reasonable return on assets.’

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[68] See Article 12(1) of the OAA agreement.

The same OAA agreement values:

> ‘the importance of protecting the environment when developing and implementing international aviation policy. The parties recognise that the costs and benefits of measures to protect the environment must be carefully weighed in developing international aviation policy’[69].

Moreover:

> ‘When a party is considering proposed environmental measures, it should evaluate possible adverse effects on the exercise of rights contained in this Agreement, and, if such measures are adopted, it should appropriate steps to mitigate any such adverse effects.’

The Parties also agreed that when environmental measures should be introduced, the adverse effects on the exercise of rights contained in the OAA agreement should be evaluated. If such environmental measures are adopted, it must take appropriate steps to mitigate such adverse effects[70].

The question then becomes whether the introduction of an LTO NO_x charge, if considered as an environmental measure as foreseen in the OAA agreement, affects the rights of US airlines under the agreed level playing field designed to ensure fair competition between the airlines exercising the rights under the OAA agreement[71].

This is not a legal but an economic and technical question, which has been studied, more in particular for CO_2 emissions in the context of the introduction of a European ETS system[72]. The same question would have to be investigated for the introduction of a NO_x emission charge.

If the above provision of the Rio Declaration may be combined with Chicago Convention, ICAO and bilateral provisions, external environmental costs may be included with user charges, that is, airport and air navigation charges. The combined effect of said provisions is liable to enhance the legality of the NO_x charge – unless other parties argue that the introduction of a NO_x component amounts to a unilateral environmental measure affecting the agreed level playing field between the parties.

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[69] See Article 15(1) of the OAA agreement.

[70] See Article 15(2) of the OAA agreement.

[71] As to which see also Article 2 of the OAA agreement on ‘Fair and equal opportunity’ reading: ‘Each party shall allow a fair and equal opportunity for the airlines of both parties to compete in providing the international air transportation governed by this agreement.’

[72] See, Janina Scheelhaase, Wolfgang Grimme and Martin Schaefer of the German Aerospace Center (DLR), *How does the latest EU Proposal on Aviation and Climate Change affect competition between European and US-airlines*? Published in: Air Transport Research Society (ATRS) 2007 Berkeley; see: www.atrsworld.org

C ECAC

ECAC is also concerned with the establishment of a NO_x emission classification scheme. ECAC 'recommends' that economic aspects, including the monetary value that may be charged per unit of emissions, are left to the appropriate national or European authority.

However, ECAC suggests that account should be taken of the 'international guidelines on aviation charges' and of the 'polluter pays' principle. ECAC notes that some countries, have already introduced local systems for the establishment of aircraft engine emission charges[73]. These countries include Sweden and Switzerland.

D European Community law

For the sake of completion, a number of rules and principles of European Community law are referred to below, as the proposed NO_x charge:

- Should take into account the internal market legislation as currently laid down in the 'Third aviation Package', in particular Regulation 2408/92 on *market access*; Should be aligned with the provisions of a future Directive on airport charges at Community airports which currently being prepared but the last draft does not specifically address the introduction of an environmental component of the Community law based airport charge[74].
- Must be neutral from a fiscal point of view so that domestic services do not enjoy a preferential treatment as a consequence of the introduction of the NO_x charge.
- More generally, may not infringe the freedom to provide (air) services which is one of the basic freedoms guaranteed under the EC Treaty, and must meet the objective of eliminating intra-EC trade barriers.
- May not amount to state aid (which is not very likely).
- Must conform to the EC based principle of subsidiarity and the EC based policy (as confirmed by the EC Commission) according to which the conduct of an airport policy is a matter coming under national competencies of EC Member States[75].

which above points may have to be taken into account when the establishment of a – Locally designed – NO_x charge is being established.

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[73] See, Recommendation ECAC/27-4, *NO_x Emission Classification Scheme.*

[74] See, Proposal for a directive of the European Parliament and of the Council on *airport charges* COM(2006) 820 final, of 24 January 2007.

[75] See, for instance, Commission Decision 94/290 on *TAT/Orly* and 98/701 on *Milan/Linate*, from which decision the following is quoted: '(54) This Decision in no way calls into question the right of Italy to pursue an active airport policy …'

E World Trade Organization (WTO)

WTO is increasingly concerned in finding an appropriate balance between world trade and the protection of the environment as evidenced by, for instance, the Preamble to the WTO Agreement[76]. However, the operation of air services does not fall under the WTO regime so that it would seem difficult to strike this balance under the WTO regime.

F Conclusion

This charge very much touches upon local conditions, making this measure perhaps less vulnerable for challenges coming from international aviation law. As explained above, international aviation law is designed to regulate the establishment of aviation charges at various levels, including the Chicago Convention, ICAO rules and principles and recommendations, and bilateral provisions. However, ICAO itself acknowledges the reach of international environmental law mandating this measure, and the responsibility of states for the imposition of local measures designed to mitigate NO_x emissions.

Finally, regard may be had to principles of Community law, geared to maintain a level playing field and strike a balance between internal market objectives, including the freedom to provides services, and environmental goals. Environmental rules must be aligned with air transport rules, as evidenced by the future Directive on airport charges.

F.3 LTO NO_x charge with distance factor

Short answer:

The distinction between the previous option (LTO NO_x charge) and this one is related to the introduction of the distance factor into the previous option. The distance factor implies that all flights from and into EU airports, whether those flights are operated inside or to/from points outside the EU, are deemed to fall under this option. It would seem that this option is a combination between the previous and the next option, that is, the LTO NO_x charge and the *en route* charge respectively.

A number of international law considerations may have to be addressed before implementing this option. Amongst others, as foreign operators, flying in foreign, that is, 'their own' airspace may be affected by this measure, agreement among the concerned states, that is, the EC states, the EC and the third state(s) is likely to enhance its legal feasibility. Also, as this option is closely related to a matter regulated under the EUROCONTROL regulatory regime, EC states who are a member of that organisation may wish to reach consensus on this charge within the EUROCONTROL framework.

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[76] 'The Parties to this agreement … recognising that their relations in the field of trade and economic endeavour should be conducted with a view of raising standards of living, ensuring full employment and a large and steadily growing volume of real income and effective demand, and expanding the production of and trade in goods and services, while allowing for the optimal use of the world's resources in accordance with the objective of *sustainable development*, seeking *both to protect and preserve the environment* and to enhance the means for doing to in a manner consistent with their respective needs and concerns at different levels of economic development ….'

The distance factor, as reflected by its application to all flights, within, to and from points in the EU, may affect a number of aviation law based rules.

- If the charge applies to flights partly operated in foreign airspace, that is, airspace of non-EU states, such states could rely on the principle of sovereignty in their airspace, as confirmed by Articles 1 and 2 of the Chicago Convention.
- If the charge applies to flights over the high seas – as defined under Article 2 of the Chicago Convention – non-EU states and ICAO may argue that ICAO is the legislator there, that is, in the airspace above the high seas[77].

Since flights from and into EU airports, irrespective of their origin and destination, and irrespective of their nationality, are involved herewith, aircraft operators are the accountable entities for the charge in question. That conclusion calls the international framework into play, which has been discussed in Section F.2:

- The Chicago Convention addresses not only airport charges but also charges for the use of air navigation facilities (see Article 15 of this convention).
- ICAO policies pertain to user charges, including this charge, and emissions related levies generally.
- Bilateral air agreements use the term ‘user charges’, as to which see the example cited above regarding the EU-US (OAA) Agreement of 2007/8.

Hence, from an international aviation law point of view, the conclusions as to the feasibility of this option are the same as under D.2.1. When establishing this charge, regard must be had to the non-discrimination principle (in terms of nationality of the aircraft emitting the NO_x), the cost base of the charge, the transparency of the charge, the fair treatment of air transport in relation to other modes of transport.

F.4 Cruise NO_x charge

EU NO_x en route charges or performance incentive; the EU implements en route charges for cruise NO_x emissions, be it for flights to and/or from or between EU airports, flights in EU airspace or any other flights within the jurisdiction of EU Member States. A performance incentive is a revenue-neutral charge-subsidy system.

A The EUROCONTROL regime

In the airspace of EC states, *en route* charges are established and collected through EUROCONTROL. Reference is made to the Multilateral Agreement relating to Route Charges (1981, as entered into force in 1986).

EC states – most of whom are EUROCONTROL states[78] – have agreed to adopt a common policy with respect to the establishment and collection of *en route* charges. Such charges must reflect the costs incurred either directly or indirectly

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[77] By virtue of the third sentence of Article 12 of the Chicago Convention stating that: ‘Over the high seas, the rules in force shall be those established under this Convention.’

[78] Exceptions are Latvia and Estonia who are EC but not Eurocontrol states.

in the provision of en route services, including the costs of EUROCONTROL. The *en route* charges are established in accordance with a common formula, based upon, amongst others, the weight of the aircraft and the distance flown. There again, the person liable to pay the charge is the operator, and, if he is now known, the owner of the aircraft.

There is no reference to environmental costs or internalisation of external costs[79]. Thought could be given to the word ‘indirectly’ referred to the in the previous alinea. Moreover, prior to implementation, it would be necessary to analyse the impacts of introducing environmental charges or modulation of existing charges and implementing, as required such arrangements into the route charges system[80].

B The regime of the Single European Sky (SES)

Under the single European sky regime, the charges for the provision of air navigation services are regulated under the regulation for the provision of air navigation services. This regulation is aimed to create more transparency, and holds airspace users – that is, in practice, aircraft operators – as accountable entities. Charges are made on a cost base and must be consistent with the rules laid down in Article 15 of the Chicago Convention.

A Commission Regulation made under the SES regime lays down a charging scheme for air navigation services[81]. This regulation does not refer either to environmental criteria for the establishment of this charge.

Moreover, such charges are without prejudice to the charging system of EUROCONTROL (see above). The SES regime is currently being reviewed.

C The international regime

In addition, the remarks made above on provisions stemming from:
- The Chicago Convention (article 15).
- ICAO policies.
- Bilateral and multilateral provisions on *User Charges.*

Continue to apply to the imposition and establishment of this charge.

D Conclusion

This option affects a number of international and European aviation law regimes. Those regimes regulate the establishment of user charges, including route charges, and define their parameters internationally. Those rules may either have to be fine tuned or even adapted, in order to make the implementation of this charge possible.

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[79] As laid down in Principle 16 of the Rio Declaration, quoted above.

[80] See, Eurocontrol, *Eurocontrol environmental activities*, paper presented at the Fourth meeting of the ALLPIRG/Advisory Group, ALLPIRG/4-WP37 dated 5/2/01.

[81] Commission Regulation 1794/2006 *laying down a common charging scheme for air navigation services.*

F.5 Inclusion of aviation NO_x emissions in the EU ETS

An assessment of the legality of the inclusion of aircraft emissions in the EU ETS has been carried out in section 7 of 'Giving wings to emission trading – Inclusion of aviation under the European emission trading system: design and impacts', CE Delft, July 2005. The main conclusions of this section have been summarised as follows:

1 The EU has a mandate under the UNFCCC and the Kyoto Protocol to implement effective climate policies, including on aviation. The EU also disposes of the necessary legal basis under the EC Treaty to cover aviation under an EU emissions trading scheme.

2 As an expression of the sovereignty of its Member States, the EU is entitled to introduce an emissions trading system with respect to aviation.

3 Emissions trading does not relate to the operation of aircraft. It would establish obligations relating to arrival and/or departure of aircraft within the EU territory. The regulation of these conditions needs to be in compliance with international public law and EU law.

4 The quantity of aircraft emissions, within or outside the EU, only serves as a calculation parameter for determining how many allowances the aircraft operator must surrender with the competent authorities within the EU.

5 Consequently, coverage of international aviation by an EU emissions trading scheme would not interfere with the sovereignty of other states or have any other regulatory impact on other territories outside the EU, including the high seas.

The provisions of the Chicago Convention, notably its Article 11, and similar provisions in bilateral agreements and EU law, require a non-discriminatory application of the scheme with respect to international flights. The possible extension of the EU ETS to international aviation within, to and from the EU is therefore feasible provided that it is applied without distinction as to nationality.

Unlike CO_2 and other Kyoto gases which are or may be included in the EU ETS, NO_x is not a greenhouse gas. However, its impact upon climate results from chemical reactions of this gas with other gases in the atmosphere.
The EU ETS is intended as an instrument to reduce emissions of greenhouse gases. Hence, if NO_x is included, the scope of EU ETS may need to be broadened so as to include climate impacts of non-greenhouse gases.

As the EU ETS has been designed as a compliance mechanism for the Kyoto Protocol, it may cease to be used as such if non-Kyoto, that is, non-greenhouse gases, such as NO_x, are included. Hence, it should be examined whether the submission of NO_x to the EU ETS is legally feasible in the light of the commitments of the EU and its Member States under the Kyoto Protocol, in which case an extension of Directive 2003/87 so as to encompass non-greenhouse gases such as NO_x should and could be considered as NO_x is not included with the scheme for gases listed in Annex II of this Directive. Consequently, that Directive should be amended for the above purpose.

F.6 Imposition of more stringent NO_x certification Standards

Short answer:

This option can without much ado be applied to operators of aircraft registered in EC states. International arrangements, whether the Chicago Convention, Standards of ICAO or bilateral regimes, create room for more stringent measures applying to operators falling under the jurisdiction introducing such more stringent measures.

Special procedures may apply in case of aircraft used, whether leased or otherwise, by operators of non-EC registered aircraft. Procedures coming under the recently adopted EASA regulation (216/2008) lay down such procedures.

A The Chicago Convention

Contracting states of the Chicago Convention must respect Standards drawn up by ICAO unless they notified ICAO that it is impossible to comply with them[82]. Under this convention, EC states are responsible for complying with the above standards in relation to third states.

EC states will probably not notify ICAO that they cannot comply with ICAO's minimum standards in relation to the establishment of certification norms for NO_x emissions. In addition, EC states must admit aircraft which are certified in accordance with such minimum standards made by ICAO[83].

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[82] *Article 38 Departures from international standards and procedures*
'Any State which finds it impracticable to comply in all respects with any such international standard or procedure, or to bring its own regulations or practices into full accord with any international standard or procedure after amendment of the latter, or which deems it necessary to adopt regulations or practices differing in any particular respect from those established by an international standard, shall give immediate notification to the International Civil Aviation Organization of the differences between its own practice and that established by the international standard. In the case of amendments to international standards, any State which does not make the appropriate amendments to its own regulations or practices shall give notice to the Council within sixty days of the adoption of the amendment to the international standard, or indicate the action which it proposes to take. In any such case, the Council shall make immediate notification to all other states of the difference which exists between one or more features of an international standard and the corresponding national practice of that State.'

[83] *Article 33 Recognition of certificates and licenses*
'Certificates of airworthiness and certificates of competency and licenses issued or rendered valid by the contracting State in which the aircraft is registered, shall be recognized as valid by the other contracting States, provided that the requirements under which such certificates or licenses were issued or rendered valid are equal to or above the minimum standards which may be established from time to time pursuant to this Convention.', as confirmed in bilateral air services agreements, for instance – as many bilateral air agreements contain such a clause -, in Article 8(1) of the OAA agreement reading: 'The responsible authorities of the parties shall recognize as valid, for the purposes of operating the air transportation provided for in this Agreement, certificates of airworthiness, certificates of competency, and licenses issued or validated by each other and still in force, provided that the requirements for such certificates or licences (are) *at least equal the minimum standards* that may be established pursuant to the (Chicago) Convention.' (*italics added*)

B Bilateral air services agreements

Again, reference is made to the OAA agreement which entered into force on 30 March 2008. The EC, EC states and the US confirm their adherence to minimum standards drawn up by ICAO[84]. EC states may refuse aircraft registered in non-EC states to operate air services in their airspaces and on their territories in case such aircraft do no comply with the relevant ICAO minimum Standards[85].

The OAA agreement also stipulates that the coming into force of new environmental standards may not affect the level playing field agreed upon in the OAA Agreement[86].

The question the becomes the coming into being of more stringent NO_x standards as imposed upon operators of EU aircraft affects the level playing field between EC and US carriers in a negative sense for US carriers. Again, this would be a case of ‘positive’ or ‘reversed’ discrimination, affecting EC rather than US carriers.

In such cases, the concerned EC state must begin with consultations with the third state[87]. The ultimate remedy – for non-compliance – may be refusal of entry into its airspace, that is, by revoking the operating authorisation.

Under the OAA agreement, EC states reserved the right to apply *higher* certification standards to aircraft registered in one of the EC states and operated in EU airspace[88]. Again, this could be termed as a provision permitting ‘positive discrimination’ as referred to variously above and allowed under international trade law.

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[84] See Article 14(3) of the OAA Agreement: ‘When environmental standards are established, the aviation environmental standards adopted by the International Civil Aviation Organization in Annexes to the [Chicago] Convention shall be followed except where differences have been filed. The Parties shall apply any environmental measures affecting the air services under this Agreement in accordance with Article 2 and 3(4) of this Agreement.’

[85] See again, for instance, Article 5(3) of the OAA, which is formulated as follows:
Revocation of Authorization
‘This Article does not limit the rights of either Party to withhold, revoke, limit or impose conditions on the operating authorization or technical permission of an airline or airlines of the other Party in accordance with the provisions of Article 8 (Safety) or Article 9 (Security).’

[86] See Article 14(2) of the OAA Agreement: ‘When a Party is considering proposed environmental measures, it should evaluate possible adverse effects on the exercise of rights contained in this Agreement, and if such measures are adopted, it should take appropriate steps to mitigate any such adverse effects.’

[87] As to which see applicable provisions of bilateral air services agreements.

[88] As to which see the last sentence of the last mentioned provision (Art. 8(1)) from the OAA agreement, reading: ‘The responsible authorities may, however, refuse to recognize as valid for purposes of flight above their own territory certificates of competency and licenses granted to or validated for their own nationals by such other authorities.’

C ICAO

As stated variously above, Standards laid down in ICAO Annexes are considered as *minimum* standards[89]. Obviously this is also true for Annex 16 Vol. II, including norms for NO_x demission in the process of certification of aircraft (type, model or individual).

The standards for NO_x emissions have been updated[90]. Following the 4th and 6th meetings of the Committee on Aviation Environmental Protection (CAEP) in 1999 and 2004 respectively, ICAO imposed an increased stringency of NO_x emission limits. The new limits are applicable as from 24 November 2005.

The increased stringency limits vary in accordance with the date of manufacture of the engine, beginning with engines which were manufactured before 1 January 1996, and ending with engines which were made after 31 December 2007.

D Community law

As stated above, EC states may apply higher standards to aircraft registered in EC states than those made by ICAO but cannot impose such higher standards to operators of aircraft established outside the EC. A special situation may arise if a Community air carrier operates aircraft registered in a third state, in which case the state in which the Community air carrier has its principal place of business must apply EU standards[91].

EASA assists the National Aviation Authorities of EC states and the Commission through standardisation and inspection. At several instances does the newly adopted ‘EASA Regulation’[92] refer to the need of compliance with obligations stemming from the Chicago Convention and ICAO[93].

A common EC standpoint in relation to safety may lead to the adoption of a new regulation along the lines of Regulation 2111/2005 on the blacklisting of air carriers not meeting specified safety standards. A similar move could be considered in relation to non-compliance with minimum norms for NO_x emissions.

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[89] See Article 33 of the Chicago Convention, quoted above, and Standard 1.2 of Annex 16, Vol. II.

[90] See Standards 2.3.2 of ICAO Annex 16, Vol. II.

[91] See Article 4(1)(c) of EC Regulation 216/2008 cited in the next footnote.

[92] EC Regulation 216/2008 on *common rules in the field of civil aviation and establishing a European Aviation Safety Agency* (repealing Council Directive 91/670, Regulation 1592/2002 and Directive 2004/36).

[93] See, Articles 59d), 8(6), 9(1) and 9(4)(a) of EC Regulation 216/2008.

F.7 Precautionary emissions multiplier principle, with reference to the ETS scheme

Short answer:

Under this option, the contribution of NO_x to global warming is deemed to be as large as that of CO_2, in accordance with models and calculations. The precise value of the first mentioned contribution – hence, made by NO_x – has yet to be determined.

The Precautionary principle is designed to manage the future risk of the contribution made by NO_x emissions to global warning. It is firmly enshrined in international environmental law, international trade law and has been adopted in Community law – for instance, as made by the European Court of Justice – and policy.

International aviation law does not know this principle, whereas the implementation of an ETS allowing for the multiplier effect caused by NO_x emissions has yet to be regulated at an international – aviation law – level. Hence, *ad hoc*, bilateral or broader, that is, multilateral arrangements may have to be made in order to create a legal basis for this option.

A The Precautionary principle

Amongst others, the following criteria must be observed when a measure – such as the establishment of a multiplier based NO_x charge – relies on the Precautionary principle. Such a measure should be:

- In line with the *proportionality* principle (the means, that is, the measure must be proportional to the goals to be pursued, that is mitigating global warming).
- *Non-discriminatory* in their application – meaning that similar situations should be treated in a similar fashion, and that different situations should not be treated in the same way, unless there is an objective justification for doing so, as to which condition see ICAO's standpoint as reflected above, in which ICAO calls for a fair treatment of air transport in relation to other modes of transport.
- *Consistent* with policy and legal measures which have been adopted in comparable situations.
- Based on a *cost and benefit analysis*, whereby costs and benefits include non-economic criteria.
- *Subject to review*, based on scientific findings.

B International aviation law

International air law does not know the precautionary principle. The Chicago Convention prescribes that international air services must be operated 'soundly and economically'[94] whereas ICAO is mandated to 'prevent economic waste caused but unreasonable competition'[95] but this is obviously different from 'environmental waste' - which was not foremost in the minds of the drafters of the Chicago Convention in 1944.

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[94] See the Preamble of the Chicago Convention.

[95] See Article 44(e) of the Chicago Convention.

Besides, ICAO is attempting but not always succeeding in preventing 'environmental waste', amongst others, as it has to take into account the interests of its 190 contracting states with different degrees of development.

Also, bilateral agreements state that the costs related to the use of air navigation facilities may be charged[96]. There is nothing here allowing states to request compensation for the use of the airspace – in which case it might be easier to impose charges for environmental reasons, as such an environmental component of the user charge could be viewed as an 'internationalisation of external costs'[97].

C Conclusion

While referring to non-aviation law related regimes, including international environmental law and Community law and policy, the EU may want to try to impose the ETS scheme unilaterally. Such a move would amount to implementing a policy decision, designed to move the protection of the environment forward.

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[96] Under the China-Germany bilateral air services agreement (1978, as variously amended), it is provided that: 'The designated airline of one Contracting party shall be charged for the *use* of airport(s), equipment, technical services and air navigational facilities of the other Contracting Party at fair and reasonable rates prescribed by the appropriate authorities of the other Contracting party. Such rates shall not be higher than those normally paid by airlines of other States.' (*italics added*)

[97] As to which see above (F.2, under A).

G Route Charge System of EUROCONTROL

G.1 EUROCONTROL Route Charge System

In 1969, the EUROCONTROL Member States adopted the basic principles for a harmonised regional en-route charges system, involving a single charge per flight, which came into operation in 1971. The EUROCONTROL Central Route Charges Office (CRCO) was set up to operate this system on behalf of the States.

Under the EUROCONTROL International Convention relating to Co-operation for the Safety of Air Navigation of 1960, as amended in 1981, and in 1997 (subject to ratification), the Member States consider that the operation of **a common route charges system**, with due regard to the guidelines recommended by the International Civil Aviation Organization (ICAO), in particular concerning equity and transparency, contributes to the funding of the uniform European air traffic management system and facilitates consultation with users. Accordingly, the Member States have agreed to implement a common policy for the establishment and calculation of charges levied on aircraft operators of en-route air navigation facilities and services, hereinafter called '**route charges'**. This common policy builds on the provisions of the Multilateral Agreement relating to Route Charges, which has been in force since 1986. The EUROCONTROL Route Charges System is open to all European States wishing to participate and in particular those States which are members of ECAC[98].

The CRCO offers Member States, additional to route charges, a calculation, billing and collection service for **terminal charges** and the same mechanisms for air navigation charges on a bilateral basis to *non*-Member States.

G.2 Mission and tasks of CRCO

Mission

The mission of the Central Route Charges Office (CRCO) is to provide its stakeholders with an efficient cost-recovery system that funds air navigation facilities and services and supports ATM developments.

The CRCO strategy to fulfil this mission is 'Sustainable Growth' and the primary objectives flowing from it are as follows:

- Reduction of the administrative unit rate through cost control and flexibility in resource allocation.
- Integration of CRCO developments within the Agency strategy to foster secure and equitable funding of the ATM system in Europe.
- Raising the level of quality to improve internal performance and services to the customers.

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[98] ECAC is the European Civil Aviation Conference, an inter-governmental organisation established in 1955 at the initiative of the Council of Europe and with the active support of the International Civil Aviation Organization (ICAO). The ECAC Objective is the promotion of the safe and orderly development of civil aviation on routes within, to and from Europe.

Tasks

The tasks of the CRCO include:

- Establishment and collection of route charges and disbursement to the Member States of charges collected.
- Participation in the development of the Route Charges System.
- Provision of resources or technical assistance in connection with air navigation charges not covered by the Multilateral Agreement for Member or non-Member States.

G.3 Calculation method for current route charges

The EUROCONTROL Route Charges System is a harmonised regional system whereby route charges:

- Are established according to a common formula which takes account of the costs incurred by Member States in respect of air traffic facilities and services. And,
- Are collected by EUROCONTROL as a single charge per flight.

The CRCO operates the EUROCONTROL Route Charges System. It issues one bill per flight or series of flights, irrespective of the number of Member States overflown. The bill is settled by a single payment, in one currency - the Euro, to one body - the EUROCONTROL CRCO.

Calculation method charges

Member States provide air traffic control (ATC) facilities and services to ensure the safe, efficient and expeditious flow of air traffic through their airspace. They recover the costs of providing these facilities and services by means of route charges levied on users of their airspace.

The route charge is levied for each flight performed under Instrument Flight Rules (IFR) in the Flight Information Regions (FIRs) falling within the competence of the Member States.

The *total charge per flight* collected by EUROCONTROL ($\mathbf{R}$) equals the sum of the charges ($\mathbf{r_i}$) generated in the FIRs of the individual States ($\mathbf{i}$) concerned. The individual charge ($\mathbf{r_i}$) is equal to the product of:

- The distance factor ($\mathbf{d_i}$) within the airspace of a Member State.
- The weight factor ($\mathbf{p}$) for the aircraft concerned.
- And the unit charge rate ($\mathbf{t_i}$).

The **distance factor** ($\mathbf{d_i}$) is equal to one hundredth of the great circle distance, expressed in kilometres, between points of entry into and exit from the airspace of State ($\mathbf{i}$) (or the airports of take-off and landing, if applicable) as described in the last filed flight plan. This flight plan incorporates any changes made by the operator to the flight plan initially filed as well as any changes approved by the operator resulting from air traffic flow management measures.
The distance to be taken into account is reduced by a notional twenty kilometres for each take-off and for each landing on the territory of State ($\mathbf{i}$).

The **weight factor** (**p**) is based on the maximum certified take-off weight (MTOW) of the aircraft. The weight factor increases with MTOW, but less than proportionately: weight factor **p** equals the square root of the quotient obtained by dividing MTOW expressed in metric tons by fifty.
Where the maximum take-off weight authorised of the aircraft is not known to the CRCO, the weight factor is calculated by taking the weight of the heaviest aircraft of the same type known to exist.

The **unit rate** (**t_i**) for flights in the FIRs of State (**i**) is established by each State in advance of the year in which it will be applied. Essentially, each State establishes its forecast cost-base, applying the common principles[99] for the year in which the charges are collected. This cost-base comprises operating costs plus depreciation costs and cost of capital, as well as the State's share of EUROCONTROL's costs (excluding CRCO costs).
A unit rate is then established for each State. It is expressed in Euro and consists of two parts:

- The **national unit rate**, obtained by dividing the en-route facility cost-base of the State concerned for the reference year by the number of service units[100] generated in the airspace of that State during the same year.
- The **administrative unit rate**, the purpose of which is to recover the costs of collecting route charges (CRCO costs). It is obtained by dividing these costs by the number of service units generated in the EUROCONTROL charging area as a whole. The component of the unit rate representing the CRCO costs therefore is identical in all States.

These figures are presented by the States' representatives in June (preliminary figures) and November (final figures). The unit rates are then determined by the (enlarged) Commission of Transport Ministers. The unit rates are applicable as from 1 January of each year[101].
As it is the objective to cover the costs of air navigation services, under- or over recovery of costs in the latest year will be considered in the calculation of the following year in order to minimise divergence of charge revenues from costs.

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[99] The common principles adopted by the Member States for the calculation of costs are enshrined in the ‘Principles for Establishing the Cost-Base for Route Facility Charges and the Calculation of the Unit Rates’, which are available from EUROCONTROL on request. The principles are based on those described in the ‘Statements by the Council to Contracting States on Charges for Route Air Navigation Facilities’ as contained in ICAO Document 9082/5 and in the ‘Manual on Air Navigation Services Economics’ as contained in ICAO Document 9161/3, subject to any modification made in order to take account of other methods specific to the EUROCONTROL Route Charges System.

[100] The product of the distance factor **d_i** and the weight factor **p** is defined as the number of service units in State (**i**) for this flight**.**

[101] To reduce the effects of exchange rate fluctuations on the System, the unit rates are adjusted every month in line with the exchange rate of the euro against the national currencies concerned. However, States experiencing high inflation can establish their national costs in Euro without any subsequent monthly adjustment of their unit rate.

G.4 How works the current data collection and billing procedure?

The national Route Charge Offices of the Member States supply the basic data required for calculating the route charges and are responsible for the accuracy of these data.
In order to limit the volume of data, only one message per flight is transmitted to the CRCO irrespective of the number of Member States overflown. Thus, the State responsible for collecting and sending the flight data is the State on whose territory the aerodrome of departure is situated, or via whose airspace the aircraft enters the EUROCONTROL charging area.

The following information is available at the CRCO for all IFR flights performed within the airspace of EUROCONTROL Member States (including overflights):

- Date of flight/actual time of departure or time of entry into EUROCONTROL airspace.
- Last filed flight plan.
- Great circle distance flown in EUROCONTROL airspace.
- Airport of departure/airport of destination.
- Aircraft type (and thus MTOW-average per user and aircraft type).
- Aircraft call sign (aircraft registration, flight number or military call sign).

Flight messages are sent within 10 days after the day of flight and according to a pre-established transmission calendar.

The EUROCONTROL Central Flow Management Unit (CFMU) provides the CRCO with the route description filed by the aircraft operator, based on the last filed flight plan. This is to calculate the distances flown in each State's airspace.

Based on the information received by the CRCO, bills are send to the operators of airlines every month. In addition, users may receive credit notes and bills for interest on late payment, as well as Value Added Tax (VAT) invoices on behalf of those States where route charges are subject to VAT.

G.5 How is the disbursement of revenues of current route charges organised?

Route charges income is disbursed weekly to the States. Interest earned on short term investment of funds, as well as interest on late payment, is also paid to the States. Payment can also be made to third-parties on behalf of States, at their instructions.

H The co-efficient of correlation in the LTO NO_x charge with a distance factor

H.1 Modelling methods, data and tools

The basis of all the calculations of both LTO and non-LTO NO_x is the ICAO Certification database. Version 14 was used.

The aircraft performance model PIANO was used (Simos, 2004) as the basis of calculating fuel flow over non-LTO phases of flight and the NO_x emissions at altitude.

The following eight sample aircraft were modelled over a variety of mission distances ranging between 250 and 7,000 nautical miles: A340-300, A330-200, A319, A321, B747-300/400, B777-200/300, B737-700, and E145. The missions modelled were at 250 nautical mile (nm) increments for the first 2,000 nm and 500 nm increments thereafter for longer-range aircraft, and at 200 nm increments for shorter-range aircraft.

Data on $EINO_x$/fuel flow for the four Certification data points were taken from the ICAO Certification Database that related to engines fitted to various aircraft, both current in-production and historical (according to Jane's). These data were implemented into the PIANO engine description files and used iteratively for the airframe selected and the missions flown. The airframe-engine combinations used are given in Table 55.

The above procedure used 69 aircraft-engine combinations flown over multiple distances, resulting in 992 individual model calculations.

The parameters set within PIANO approximated to those used in the ICCAIA/Airbus studies as follows: maximum payload; drift-up cruise profile (except for missions of 250 nm where a single cruise altitude of 30,000 feet was selected for all aircraft); fuel loading optimized for mission distance.

The NO_x emissions were taken from cruise, climb and descent and were calculated with the BFF2 method, implemented within PIANO, and used the LTO coefficients from the ICAO Certification Database, as above.

Table 55 Parametric study of fuel efficiency and EINO$_x$ changes for notional 10 years development of 'frozen fleet'

Aircraft	Engines
A340-300	CFM56-5C4/P (SAC), CFM56-5C4 CFM56-5C2 CFM56-5C3
A330-200	CF6-80E1A2 CF6-80E1A3 Trent 772 (imp trav) CF6-80E1A4 PW4168A (Floatwall) PW4168A (Talon II) CF6-80E1A4 PW4164 (Floatwall) PW4164 (Talon II) PW4168 (Floatwall) PW4168 (Talon II) Trent 768 Trent 768 (imp trav) Trent 772
A321	V2530-A5 CFM56-5B3/P CFM56-5B1 CFM56-5B1/2P (DAC II) CFM56-5B2 CFM56-5B3/2P (DAC II) V2533-A5
A319	CFM56-5A4 CFM56-5A5 CFM56-5B5/P CFM56-5B6/P CFM56-5B6/P CFM56-5B6/2P (DAC II) V2522-A5 V2524-A5
B747-300/400	CF650E2 CF6-80C2B1 CF6-80C2B1F CF6-80C2B5F JT9D-7R4G2 PW4056 RB211-524C2 RB211-524D4 RB211-524G-T RB211-524G RB211-524H RB211-524H-T
B777-200/300	PW4090 GE90-92B (DAC I) GE90-90B (DAC I) Trent 892 GE90-94B (DAC II) PW4084 PW4077 Trent 884 GE90-85B (DAC I) Trent 875 Trent 895 GE90-90B (DAC I) PW4084D

Aircraft	Engines
	Trent 877 GE90-76B (DAC I) GE90-110B1 (DAC)
B737-700	CFM56-7B20 CFM56-7B22 CFM56-7B26 CFM56-7B24 CFM56-7B27
E145	AE3007A AE3007A1 (type 1) AE3007A1/1 (type 1) AE3007A1E (type 3) AE3007A1P (type 1)

H.2 Regression analysis

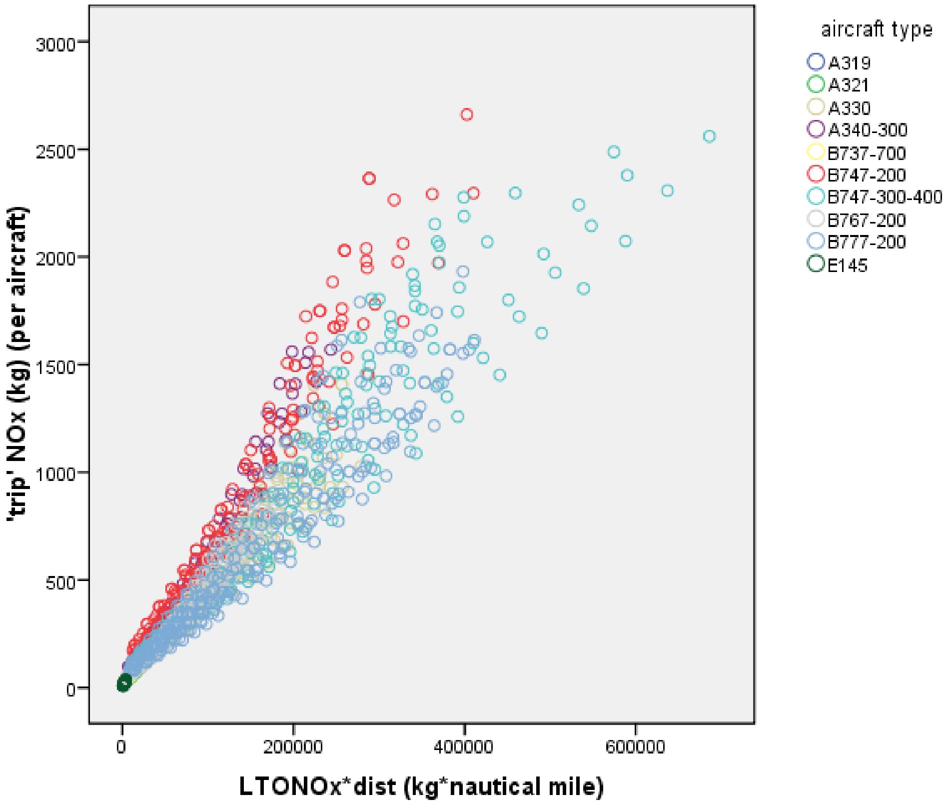
We have used three different variables to account for differences in trip NO_x between aircraft and engine types and mission distance: LTO*dist, mission distance and fuel use. We have done regression analyses on the whole dataset, but have also assessed the results per aircraft type and per mission distance. The results of the analyses with LTO*dist will be described in this chapter, the results of the other analyses are in the Appendix.

The data contain trip NO_x (i.e. all NO_x emissions except LTO NO_x) and total distance. As the total distance includes both the distance flow during LTO and the distance flown during the non-LTO phase of the flight, while trip NO_x includes only the NO_x emissions during the non-LTO phase of the flight, there is a ‘mismatch’ between flight distance and trip NO_x. To compensate for this effect, we allowed for a constant in the regression analyses, leading to an equation of the form $y = a+ bx$ rather than $y = bx$.

H.3 Results

Figure 41 gives a graphical representation of the relationship between trip NO_x (defined by PIANO as block NO_x – total NO_x emissions on a mission – minus LTO NO_x emissions) and LTO NO_x*dist.

Figure 41 Relationship between trip NO_x and distance * LTO NO_x



H.4 Whole data set

Regression analyses were done with trip NO_x as a dependent variable and LTO*dist as a predictor variable. No distinction was made between aircraft types, as the aim was to estimate how much of the variance in trip NO_x can be explained by LTO*dist alone, and to estimate a β for the entire population as present is the dataset, without distinguishing between different aircraft types[102]. A summary of the results can be seen in Table 56. It can be seen that LTO*dist explains approximately 90% of the variance in trip NO_x emissions. Please note that the values of β listed in Table 56 depend on the units used (1/nautical mile, in this case).

Table 56 Summary results regression analysis

			95% confidence interval			95% confidence interval	
Predictor	R2	Constant	Upper	Lower	β	Upper β	Lower β
Dist*LTO	0.89	47.6	34.3	60.9	4.5 E-3	4.4E-3	4.6E-3

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[102] Please not the difference between the confidence interval of β and the spread in the population. The confidence interval of β is a measure of how exactly the average has been calculated. It is NOT a measure of the spread in the population or in the data.

H.5 Per aircraft type

Separate regression analyses were done for each aircraft type. Again, LTO*dist was used to predict trip NO_x emissions and to estimate β. The analyses show that dist*LTO explains between 84 and 98% of the variance in trip NO_x, which is of the same order of magnitude as the explanatory power of dist*LTO for the undifferentiated data. The estimates of β and of the constant are listed in Table 57. β ranges from 4.0E-3 for the B777-200 to 7.6E-3 for the E145. based on this sample, we cannot see a systematic bias towards either large or small aircraft, or towards high or low thrust engines.

Table 57 Summary results regression analysis per aircraft type

Aircraft type	Constant	β
B777-200	38,3	4,02E-03
B747-300-400	67,9	4,16E-03
B737-700	19,8	4,45E-03
A330	30,1	4,46E-03
B767-200	6,7	4,64E-03
A321	9,6	5,17E-03
A319	12,9	5,43E-03
B747-200	34,6	6,31E-03
A340-300	0,15	6,63E-03
E145	4,2	7,63E-03

H.6 Per mission distance

Finally, a regression analysis was done per mission distance[103]. The idea behind this analysis was to assess how well the LTO*dist predictor does when predicting trip NO_x emissions of various aircraft types that all fly the same mission distance. Table 58 shows the results. LTO*dist is a fairly good predictor of NO_x emissions, with explained variance ranging from 58 to 84%.

Table 58 Summary results regression analysis per mission distance

Predictor	R2 min	R2 max	β min	β max
Dist*LTO	0.58	0.84	2.3E-3	8.4E-3

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[103] Only 250, 500, 750, 1,000, etc., have been considered, because the contain most data. 700, 900, 1,100, etc. have been left out, because most aircraft weren't modelled at these distances.

H.7 Conclusions

Dist*LTO is a reasonably good predictor of trip NO_x, which means that a reliable estimate of β can be made. However, β depends on the sample of aircraft, engines and distances. Variations in the sample can lead to variations in β. The dependence of β on the distribution of distances implies that β also depends on the geographical scope of the policy option. In order to calculate β for policy purposes, the geographical scope of the option as well as the distribution of aircraft and engine types over the various distances is needed. Once these are know, β can be calculated for the average fleet in the same way as above.

I Airport experience with LTO NO_x charges

I.1 Summary and Conclusions

I.1.1 Interviews

This paper reviews the telephone interview reactions of selected airport stakeholders to possible EU measures to reduce aviation's NO_x emissions. Formal written responses to the CE scoping paper followed in most cases, and were taken into account in our report. Besides ACI-Europe as a representative body, the interviewed AMS, BAA, ARN, FRA and ZRH airport authorities are characterised by existing or expected charges related to NO_x LTO emissions. Such charges often also apply to other airports in the same country.

I.1.2 LTO

The emphasis thus naturally tended toward LTO emissions, which airports felt were under-emphasised in the scoping paper. Charges are important within their holistic approaches to local air quality issues, and baselines vary widely from € 1.32 to € 5.35 per kg of NO_x, or between minus-6% (saving) and 40% (surcharge) on the landing fee. These levels of charge are universally aimed at 'marginally encouraging' airline decisions, from re-equipment to fleet allocation. They are generally revenue-neutral (on introduction), often determined pragmatically with an element of penalty/reward, in only one case (Sweden) being overtly related to external cost valuation. There are mixed reactions to an EU standard level of charge, but general opposition to a load-efficiency-relative concept of charging.

I.1.3 Cruise

Airport operators were also asked about cruise emissions, reactions ranging from disassociation to active contribution to international fora on the matter. There was a range of views on the design, implementation and effectiveness of economic measures. More or less (not universally) common elements included:

- The need for more research-backed data on the climatic effects of cruise emissions.
- The need for international agreement on economic measures, with doubt about the legality and/or efficacy of EU charging.
- Opposition to inclusion of NO_x in the EU CO_2 ETS by means of a multiplier.
- General, if unquantified, underlying consensus that real reductions in NO_x emissions will have to be achieved at source, by technological means, encouraged economically but ultimately enforced through global stringency.

I.2 Introduction

This Appendix, having briefly reviewed reactions of airports to the new measures proposed for evaluation, in public policy rather than scientific or technical terms (already taken into account in our report, along with those of other stakeholders), is confined to the experience of these airports with LTO charges aimed at LAQ.
Telephone approaches were made to appropriate interviewees at :

- Airports Council International – Europe (ACI-Europe).
- Amsterdam Airport Schiphol (AMS).
- BAA for Heathrow (LHR) and Gatwick (LGW).
- Luftfartsverket (LFV) Sweden for Stockholm Arlanda (ARN), with reference to 18 other LFV airports with emission charges.
- Flughafen Frankfurt/Main AG for Frankfurt (FRA), with reference to three other German airports introducing emission charges.
- Unique Flughafen Zürich AG for Zürich, (with reference to three other Swiss and one Franco-Swiss airport with or planning emission charges), where Mr Emanuel Fleuti responded as an individual expert rather than formally representing ZRH.

These introductory calls were followed up by e-mailing :

- A copy of the study team's letter of credentials from the European Commission. And,
- A copy of the CE Delft scoping paper '7.536.1/Stakeholder consultation ...' setting out options identified, and posing a framework set of seven questions for stakeholders.

It quickly became clear that many airports would need time-consuming internal discussions before being able to respond in detail on such policy issues. Thus relatively informal telephone interviews were conducted, establishing the background to each airport's experience with emission-oriented measures, and seeking initial reactions to the measures under evaluation, preparatory to formal written responses to the scoping paper. The notes of these interviews were all sent to the interviewees for approval or correction.

Airport websites, user charges and conditions of use, environmental reports, conference presentations and learned papers referred to during interviews were also consulted, and a select bibliography is Annexed.

I.3 LTO cycle

I.3.1 Background

Airports' primary emission concerns relate naturally to the LTO cycle (although aircraft emissions in that phase of flight account for only some 10% of those during the rest of the flight), because the operational function of airports is to provide landing and take-off facilities. Furthermore, such emissions can affect local air quality in agglomerations or zones in the vicinity of airports, to which local legislation transposing Directive 1999/30/EC[104] may be relevant. Such regulation can provide an initial impulse or requirement to airport action, as in the case of Swiss Federal and Cantonal legislation. Swiss airports are now legally required to consider emissions when setting charges, which the UK 2003 White Paper on the future of air transport also proposed. Indeed, in the UK the key focus of BAA emission charges is full compliance with the Air Quality (England) Regulations 2000, which transpose Directive 1999/30, setting air quality limit values (near ground level) in airport-adjacent local authority air quality management areas. In Sweden, NO_x is seen as a regional (rather than local) pollutant in impact terms around airports.

While the focus of this study is aircraft emissions, most airports stressed their holistic approach. As recognised in the ICAO Airport Air Quality Guidance Manual[105], the LTO cycle as modelled is only part of the story with its approach, taxi/ground idle, take-off and climb reference segments. For instance, APU use can be a significant contributor to emissions on airport, which airports can and do alleviate by provision of fixed electric ground power (FEGP) on stand, (provided airlines are satisfied with their output for wide-bodies). Airport vehicles, terminal heating, and landside vehicular traffic are all sources of NO_x which airports can control and/or influence through means other than airline charges or regulation. On the other hand, airline/airport co-operation in behaviour on the ground as an influence on actual emissions (as against certificated reference levels), such as use of reverse thrust, engine-out taxying, and efficient surface movement guidance and control from the tower, are all areas of potential operational improvement to reduce actual emissions, which airports feel may be overlooked in concentrating upon operational amelioration of cruise emissions.

I.3.2 Introduction and Application of LTO Charges and NO_x Caps

- On 01 September 1997 Zurich (ZRH) was the first airport in Europe to introduce NO_x emission charges. This example was followed in Switzerland by Geneva (GVA) and Bern (BRN); Lugano (LUG) is preparing for implementation. Refined since that pioneering introduction, the charge applies to all aircraft, a Swiss/Swedish matrix having been developed to cover aircraft not in the ICAO Aircraft Engine Emissions Database for jet engines, supplemented as necessary by the Swedish Defence Research Agency (FOI) Database for propeller engines.

  ZRH also effectively has a Federal DETEC cap of 2,400 tonnes of NO_x emissions p/a – beyond that threshold additional measures would have to be introduced in order to maintain expansion permissions. In 2006, ZRH produced 1,208 tonnes (excl. landside road traffic) 85% of it from aircraft.

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[104] Council Directive 1999/30/EC of 22 April 1999 relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air.

[105] ICAO Doc 9889.

- Sweden followed with a charge in 1998; earlier NO_x and CO_2 (fuel) taxes on domestic flights having proved incompatible with Community legislation, despite resulting in combustor changes on SAS' F28 fleet. Charges apply, in the form current since 01 March 2004 (using the 2003 version of the ERLIG model), at all 16 LFV airports including Stockholm-Arlanda (ARN). Aircraft of 5,700 kg MTOW and above are charged.
- The Franco-Swiss EuroAirport BSL/MLH/EAP introduced a system very similar to that at ZRH on 01 January 2003, but with a rather lower range of landing fee percentages.
- BAA introduced emission charges at London-Heathrow (LHR) in 2004, and London-Gatwick (LGW) in 2005, for aircraft over 8,618 kg MTOW. These are the only UK airports currently making such charges, although one more (non-BAA) is believed to be considering their introduction, and Government has suggested mandatory inclusion of emission charges in landing fees.
- Most recently, emission charges came into force at Frankfurt/Main (FRA) on 01 January 2008, as they did at Munich (MUC), for a three year trial period, They will apply at Köln-Bonn (CGN) from 01 April 2008, and Stuttgart (STR) is expected to join the scheme from 01 September 2008. All aircraft are charged.
- Amsterdam-Schiphol (AMS) has no emission charge, but a national 'eco-tax' of € 24 per passenger is expected to be introduced in July 2008. While oriented toward CO_2, it is understood that 'this tax takes NO_x into consideration'.

  Dutch national legislation also effectively sets a 'relative' cap on emissions in terms of average NO_x/MTOW. If exceeded, this would trigger imposition of an absolute annual cap, limiting movements in the succeeding year (unless average NO_x/movement reduced).
- ACI-Europe advised that they are not aware of any other current or impending LTO emission charge schemes in Europe.

I.3.3 Levels of LTO Charge and their Selection

The levels of charge vary widely from a 6% saving (bonus) on landing fees for the 'cleanest' aircraft at BSL/MLH (and rebates for low emissions at LGW and LHR), to a 40% surcharge on the tiny minority of 'dirtiest' at ZRH. Elsewhere the charges are expressed as a fixed sum per kg of NO_x equivalent, ranging from UK£1.00 (€ 1.32) at LGW, through € 3.00 at FRA, to SEK50 (€ 5.35) at ARN.

Charging on a flat 'per kg' basis gives a continuous linear charge/emission relationship. Current rates per kg NO_x equivalent are (e.g.) :

- LGW UK£1.00 = +/-€1.35 (bonus/malus threshold 16 kg) on landing.
- LHR UK£1.10 = +/-€1.48 (bonus/malus threshold 23 kg) on landing.
- ARN SEK50.00 = +/- €5.35 on take-off.
- FRA €3.00 per turnround[106], invoiced half on landing and half on take-off (whereas MUC invoices same total rate on landing).

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[106] Fraport Flughafenentgelte can appear to specify a charge of € 3 per kg per LTO per landing and per take-off, totalling €6 per turnround; but in fact the charge is invoiced at a rate of € 3 per kg per turnround, half

Landing fee percentage rates are applied in bands according to engine emission class, (e.g.) :

- BSL/MLH 5 engine emission classes, to which are applied landing fee surcharges in steps of -6% (rebate), 5, 10, 20 and 30%.
- ZRH 5 engine emission classes, to which are applied landing fee surcharges in exponential steps of 0% (free), 5, 10, 20, and 40% respectively.

The level is often selected pragmatically with an element of benchmarking ('the going rate') and consultation ('what the market will bear'). In the Swiss case it related to clean air programme costs, although ZRH pointed out the anomaly that air quality regulation is relevant to 300 metres agl, while the LTO cycle extends to 3,000 feet (915m) agl (and another airport noted that what happens up there - during CDA for instance - is not immediately relevant to ground level NO_x concentrations around airports). FRA sees no relation between airport expenditure on air quality and the level of charge, In only one case (Sweden) is there an overt attempt to apply a researched valuation for social costs of emissions at the local and regional level, although it has been considered elsewhere. Thus the selection processes may be summarised as (typically for each country) :

- BAA

  Revenue-neutral compromise rates (in context of capped total charges), selected after consultation, with an element of benchmarking against Swiss/Swedish experience.
- FRA

  Part of the tripartite (Bundesministerium, DLR and airports) German Airports Transport Initiative, revenue-neutral after prior reductions in weight-related landing fees, pragmatically determined and felt to be not incompatible with BAA, Swiss and Swedish levels.
- ZRH

  Levels designed to reflect 5% of airport costs related to compliance with clean air legislation[107], initially achieving revenue neutrality by reducing landing fees for a 5% reduction in revenue, and designing emission charge bands on the basis of then current fleet (aircraft/engine) mix to replace the lost revenue, also incorporating bonus/malus principle.
- ARN

  Level designed to reflect local and regional social costs of NO_x emissions estimated in a 2003 Swedish study[108] using ExternE/UNITE and BeTa prices (of up to € 2.6 per kg in Sweden in 2000 prices), which stressed the primarily regional effects of NO_x. Precautionary upward adjustments were made for inflation, local and unidentified/unquantified effects to give the relatively high SEK50 (€ 5.35) per kg rate charged.

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on landing and half on take-off (in accordance with FRA noise charge practice), while MUC charges at the same rate but invoices wholly on landing.

[107] Switzerland, not an EU or EEA State, has (at 30 µg/m^3) a lower annual NO_2 limit than that prescribed by Directive 1999/30 ().

[108] Pilot study by Elektrowatt-Ekono for the Swedish Civil Aviation Administration and Swedish Institute for Transport and Communications Analysis, on Estimation of environmental costs of aircraft LTO emissions, 2003.

- AMS
  Although AMS has no LTO NO_x charge, Schiphol was the location for a case study[109] on the social costs of engine emissions which noted that the costs derived for specimen aircraft were similar to the charges for those aircraft at ARN. However, this is but another (albeit specific airport-related) of several studies on the marginal external costs of NO_x in recent years.
- ACI-Europe
  Believes that airports should be free to decide individually whether to impose emission charges, and to set their own levels, appropriate to local needs and circumstances. These should not, therefore, be matters for EC legislation. In that context one airport felt, while agreeing with ACI that legislation on LTO charges at the European level is inappropriate, that *if* such an initiative were, nonetheless, taken by the Commission, the system and the level of charge should be harmonized, in order to avoid market distortion. Reasonable consistency between airports' levels of charge was mentioned by others as desirable, for competitive reasons.

The conclusion may be drawn that there is far from universal agreement on a common level of charge or its *raison d'être*; or indeed on the level of external costs to which the 'polluter pays' principle might be expected to relate. Thus many airports called for further research on the effects of emissions and their valuation. It seems that the level of such costs may well vary with location of the region affected, its population, and land use; (as well as more mundane aspects like the extent of the effects considered, such as climate, health and agriculture).

I.3.4 Impact of LTO Charges on Airlines

All airports interviewed recognised that their LTO charges could have only a marginal influence on airline fleet re-equipment and allocation decisions because they are not high enough *per se* to have a critical effect on unit costs and competitiveness (at least for legacy airlines). The objective is generally to encourage, not force, technological and behavioural changes, although such influences might result in 'costless' reallocation of particular aircraft/engine combinations to routes, thus exporting pollution. Some necessarily 'of the order of' examples of emission charges relative to other user fees can perhaps give a more perceptible idea of impact on airline costs :

- ARN
  A321-200 with two CFM56-5-A1 engines (NO_x 4.5 kg each per LTO) : emission charge SEK450 (+/- € 48), of the order of 10% of weight-related take-off fee and noise fee totalling up to € 520 for an 88t MTOW variant, excluding passenger fees and terminal area navigation fees.
- ZRH
  A320 emission charge some CHF30 (+/- € 19), about 5% of weight-related landing fee of the order of € 400.

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[109] Morrell and Lu, Social costs of aircraft noise and engine emissions – a case study of Amsterdam Airport Schiphol – Transportation Research Board Record no.1703, pp 31-38.

- B747-400 emission charge some CHF200 (+/- €124), again about 5% of weight-related landing fee of the order of € 2,500.

- BAA
  Taking a *hypothetical* ‘Chapter 3 high’ noise-class B747-400 with four RB211-2B engines (10 kg NO_x each per LTO) at LHR, emission charge UK £ 40.40 (€ 53), some 5% of the weight-related landing fee of € 1,012 (excluding passenger and navigation service charges); at LGW, emission charge UK £ 40 (€ 52), about 6% of the weight-related landing fee of € 825 at peak times, but nearly 20% of the much lower weight-related off-peak landing fee of € 265 (all excl. passenger and navigation service charges).
- FRA
  Cumulative airline cost impacts can be substantial in absolute terms. Before introduction of the scheme, DLR estimated[110] that Lufthansa with its relatively ‘clean’ fleet would enjoy a net saving of € 0.5 mn p/a at FRA in that airport’s overall revenue-neutral scheme, while others like Condor and United would face net extra costs of € 0.05 mn p/a each, although most of the total burden would fall on unspecified ‘other’ airlines.

Overall, these impacts were expressed (in a presentation at the ICAO May 2007 Colloquium on Aviation Emissions) as typically between 0.5 and 1.5% of aircraft direct operating costs. An intuitive reaction might be that cost penalties/savings of around € 50 per flight are not going to be decisive in airline planning; but equally, a change of around 1% in doc’s could indeed be seen as a significant consideration at the margin for an airline (particularly a budget carrier), despite the airports’ modest ambitions.

I.3.5 Revenues from LTO Charges

ACI-Europe feels that any revenues from emission charges should be recycled to aviation, probably most effectively through being directed to research, although this would probably not be appropriate for individual airport LTO schemes. At AMS, the proceeds of the passenger ‘eco-tax’ will accrue to the Netherlands Government. LTO charge revenues at BAA airports, and at FRA are not hypothecated. At ARN LTO charge revenue is earmarked for that airport’s improvement programme, not the LFV general airport revenue account. LTO charge revenues at ZRH are hypothecated to fund emission reduction measures.
Although LTO charging schemes are generally initially designed to be revenue neutral this does not always remain the case. In most cases revenue neutrality is calculated by reducing weight-related landing fees sufficiently to offset the revenue from emission charges. BAA, with capped total user charges, has the flexibility to adjust its rebate/charge NO_x threshold (currently LHR 23 kg, LGW 16kg) in the ring-fenced scheme selected to demonstrate revenue neutrality. At ZRH, however, initial emission charge revenue of the order of CHF4 mn (€ 2.5 mn) or more p/a, has fallen to CHF3 mn (+/-€ 1.9 mn) or less p/a over the life of the scheme, and the scheme is no longer revenue-neutral, This could be a measure of the long term success of the scheme – traffic mix has changed so

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[110] www.dlr.de/fw/en/Portaldata/42/Resources/dokumente/Landeengelte-english.pdf.

that there are more class 5 (0% surcharge) movements and fewer class 1 (40% surcharge).

I.3.6 Results of LTO Charging (and Operational & Technical Measures)

Like the summary of these charges in Europe, and their impacts in Europe, the results have also been studied in international fora, notably CAEP/FESG. The consensus seems to be that it is very difficult to determine cause and effect in this area. There have been desirable fleet mix changes observed, technological advances in newer engines are coming through into service, but such mix changes are perhaps more likely to be driven by fuel savings, noise restrictions and charges, and other economic and operational factors.

As far as the LTO cycle is concerned as a metric reference, fleet mix influences can be expressed (with at least the virtue of consistency) using certificated emission data for different aircraft/engine combinations. Operational measures in the LTO phase (or at airports if not formally included in the cycle as defined) such as :

- Restricted use of reverse thrust.
- Engine-out taxying.
- Replacement of APU by FEGP on stand. And,
- Potentially, CDA.

can also reduce fuel consumption and/or emissions, and are researched, advocated or required at some airports, but quantified results have not been obtained for such operational measures.

Technical measures generically describe other airport initiatives such as improved terminal heating efficiency and clean fuel vehicle use. These can be measured through estimates of emissions prevented, and actual measures of pollutant concentrations at and around airports. None of these indicate the extent to which LTO charges or other aviation-related measures have contributed or might do so.

While AMS has no emission charges, and FRA's are very new, the following indicators are reported as being considered worthy of note by airports, but not necessarily attributable to particular policies or instruments:

- ARN
  LFV's own activities (not aircraft, although newer types are now serving ARN) show total NO_x varying around 100t p/a, in absolute terms, but relatively reducing from 3.9 to 3.1 grams per passenger.
- BAA
  The airport operator's ambition to increase the proportion of movements by aircraft meeting or exceeding CAEP/4 standards has not yet been met in the short term life of the charging scheme, having fallen slightly between 2004/5 and 2006/7 to just over 1 in 5. This may be due to new operators and new routes, but is expected to reverse in the long term. In terms of technical measures, there has been progress in installing FEGPs. Air quality measurements in surrounding zones mostly show compliance with 2010 EC Directive limits (NO_2) but the adjacent motorways have a high negative influence.

- ZRH

The fall in emission charge revenue, partly due to fleet mix improvements, has been noted above. These changes have also been influenced by Chapter 2 (noise) phase-out as well as natural fleet replacement. In the recent short term, airport technical measures have done more than aviation to stabilize NO_x emissions in absolute and per movement relative terms, but fleet mix (larger aircraft with more efficient emission performance) has helped improve traffic-relative emission performance, as the following recent summary statistics show.

Table 59 Recent ZRH NO_x

	A/c Mvts '000	WLU '000	Aviation NO_x (t)	Airport NO_x (t)	Total NO_x (t)	Aviatn NO_x kg per Mvt	Aviatn NO_x g per WLU
2004	266.6	21.118	1.006	239	1.245	3.8	47.6
2005	267.4	21.824	991	231	1.222	3.7	45.4
2006	260.8	23.099	1.024	220	1.244	3.9	44.3

Source : Consultants' analysis of ZRH 2006 Environmental Report.

Despite highlighting traffic-relative rather than absolute recent NO_x emission results, like most airports interviewed ZRH does not favour a traffic-relative scheme of charges, rewarding (e.g.) the contribution of high load factors to emission efficiency, It is felt that airlines are already rewarded by other reduced unit costs and higher revenue. The most remarkable achievement at ZRH may well be its innovative role and raising of awareness of LTO and airport NO_x.

Overall the consensus conclusion seems to be that the effects of charges *per se* can not be isolated and quantified, but together with operational and technical measures at airports and in the LTO phase of aviation, they have a marginal and potentially cumulative part to play.

I.4 Cruise NO_x

In general, it became clear that airports are naturally mainly concerned in action terms with LTO cycle emissions (since LTO is their business), and with the impact of such emissions on local air quality (since that is an area in which they are regulated). The relationship is not simple or seamless, since:

- As already noted, the ICAO reference LTO cycle as defined has a 3,000 ft (915m) 'ceiling', while local air quality (and to a great extent the height agl to which airport action can affect actual emissions) is only 300 feet.
- LTO inventories inevitably rely upon certificated data, and are necessarily used for consistency, but local air quality is regulated and measured in actual pollutant concentration terms.
- The LTO cycle as defined does not take account of APU use (a significant contributor to ground level pollution), nor of aircraft operational differences which in practice can and do impact upon actual emissions.
- Airports are also regulated (and regulate) in noise terms as well as emissions, and conflicts are potentially possible. Landing is less likely to give problems (e.g. CDA can reduce noise and save fuel, a 'win/win' situation), but locally

appropriate noise-abatement take-off procedures[111] can increase fuel flow and emissions.

Nonetheless, most airports[112] interviewed were ready to discuss the cruise emissions to which the Scoping Paper is generally oriented. They were adamant as an over-arching concern that care must be taken, in considering measures aimed at cruise NO_x emissions, to ensure absence of conflict with their efforts to address LTO emissions.

Detailed responses to the specific questions posed in the CE scoping paper about the policy options considered by this study have been taken into account in our report, along with those from other organisations.

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[111] e.g. As a very broad simplification, Proc A faster climb exposing smaller area to more noise *versus* Proc B slower climb exposing larger area to less noise.

[112] The FRA interview concentrated almost exclusively upon LTO in view of the new charging system in Germany, yielding authoritative and very helpful data and views in this area.

J Stakeholder consultation process

J.1 Introduction

During the course of this project, there have been two official meetings with stakeholders. For each meeting, an input note has been prepared and sent out. Many stakeholder took the opportunity to comment on these input notes, both at the meetings and in writing.

This Appendix presents the first stakeholder consultation document (J.2), the notes of the first meeting (J.3), the second consultation document (J.4) with the notes of the second meeting (J.5) and finally a list of organisations represented (J.6) and a list of organisations that have sent comments in writing (J.7).

J.2 First stakeholder consultation document

J.2.1 Introduction

In 2006, the European Commission published its legislative proposal to extend the EU Emission Trading Scheme (EU ETS) to aviation. That proposal applies only to carbon dioxide (CO_2) emissions from aircraft and is intended, as part of a comprehensive approach to managing emissions, to incentivise the industry to take action to limit or reduce its emissions.

The Commission's proposal to include aviation in the EU ETS recognised that aviation also has an impact on the climate through emissions of nitrogen oxides (NO_x), water vapour and sulphate and soot particles. The inclusion of CO_2 emissions from aviation in the EU ETS will increase the incentive to reduce CO_2 emissions but will not incentivise reductions of NO_x emissions unless specific measures are taken to address such emissions. Therefore, the Commission undertook to propose further measures to address NO_x emissions in 2008.

At the international level, the International Civil Aviation Organization (ICAO) recommends technical design standards for aircraft engine certification to limit such NO_x emissions at source. It has made a series of stringency increases in the last two decades. However, these have been insufficient to avoid aircraft NO_x emissions from growing substantially in absolute terms, and this trend is set to continue in the future. According to work by ICAO’s Committee on Aviation Environmental Protection (CAEP), these emissions are projected to continue growing strongly over the next two decades. Unless action is taken the contribution of aircraft NO_x emissions to air quality problems and climate change is therefore expected to increase significantly for many years to come.

The European Commission therefore wishes to consider what cost-effective options for further European action to limit or reduce aircraft NO_x emissions should form the basis of its proposal on this issue. It appointed a consortium led by CE Delft to consult on policy measures.

A vital and integral aspect of this study comprises stakeholder consultation. The consortium intends to consult stakeholders on potential policies and their advantages and disadvantages. Among the stakeholders to be consulted are engine and aircraft manufacturers, airlines, airports, their professional and trade associations, and NGOs.

To facilitate the discussion with the stakeholders, the consortium has prepared this scoping paper on policy measures to reduce aircraft NO_x emissions. The paper comprises 4 sections. After this introduction, the purpose of the consultation is laid out in Section J.2.2., Section J.2.3 presents an initial 'long list' of policy options. Finally, a short list of questions to the stakeholders is presented in Section J.2.4.

J.2.2 Purpose of the consultation

The stakeholder consultation will enable the consultants to evaluate the initial 'long list' of options for potential policy measures which are presented in this scoping paper, taking into account the opinions received. The European Commission will select from the long list a smaller number of measures to be designed and studied in more detail.

The aim of this consultation is thus twofold.

First, to identify as many ideas for policy measures as practicable in order to reduce the possibility of overlooking any potential options.

Second, and most importantly, to collect opinions of stakeholders on the advantages and disadvantages of various policy measures. These opinions will assist the consultants in their evaluation of the measures, and help the Commission in the selection of the measures to be studied further. The questions presented in Section J.2.4 ask specifically for pros and cons of the policy options.

J.2.3 Non-exhaustive long list of possible policy measures to reduce NO_x emissions

A number of possible EU policies have been identified by the consultants. They are presented here to facilitate brainstorming for policy measures, and to focus the discussion on advantages and disadvantages of different measures. *The list of measures does not reflect the initial opinion of the consultant or the European Commission on the desirability of any measure.*

Policies need not be mutually exclusive. It is conceivable that some policy measures are complementary and strengthen each other. Undoubtedly, the implementation of some seems more likely than that of others, some seem more effective, others less efficient, and some may or may not encounter legal objections.

The policy measures are categorised in four groups:
1 Standards of emissions at source.
2 Operational procedures to reduce NO_x emissions.
3 Economic and financial incentives.
4 Miscellaneous.

Specifically, the long list includes the following policy measures.

1 **Standards of emissions at source**
  - a **EU push for increased stringency of existing ICAO standards for LTO NO_x emissions of new engines**; the EU intensifies its efforts to argue for increased stringency of ICAO standards.
  - b **EU action for the introduction of ICAO standards for cruise emissions for new aircraft or engines**; the EU starts to press for the introduction of ICAO standards for cruise emissions, either NO_x or NO_x and CO_2 combined.
  - c **EU LTO NO_x emission standards for engines or aircraft newly registered in EU Member States or operated on flights to and from EU airports**; the EU agrees on standards for engine or aircraft LTO NO_x emissions that are more stringent than current ICAO standards.
  - d **EU cruise NO_x emission standards for engines or aircraft newly registered in EU Member States or operated on flights to and from EU airports**; the EU agrees on standards for engine or aircraft cruise NO_x emissions.
  - e **A phase-out of the worst performing engines on EU registered aircraft or on aircraft operated on flights to and from EU airports, followed by a ban**; the EU agrees to ban aircraft with engines surpassing certain emission standards from registering in EU member states or from landing at EU airports after a phase-out period.

2 **Operational procedures to reduce NO_x emissions**
  - a **Strengthen implementation of the Single European Sky**; the EU implements measures ensuring efficiency improvements in the European air traffic management system, thereby reducing detours on flights in EU airspace. This would reduce all emissions, including NO_x. This is already part of the comprehensive approach to addressing aviation emissions set out in the Commission's Communication in 2005 (COM (2005)459 final).
  - b **Climate-optimised air traffic management - flying at altitudes or routes that minimise NO_x emissions, contrail formation and CO_2 emissions)**; the EU implements air traffic management procedures for the entire flight aimed at reducing the climate impact of flights, e.g. by

changing altitudes and flying around supersaturated areas in which contrails form, or increased use of continuous descent approach.

3 **Economic and financial incentives**

a **EU-wide differentiation of existing charges according to LTO NO_x emissions or EU LTO NO_x charge**; the EU implements a scheme for the differentiation of charges related to aviation (be it ATM charges, airport charges or government charges) based on NO_x emissions, either LTO NO_x emissions or cruise NO_x emissions. Or the EU implements a LTO NO_x charge, the revenue of which could be used for offsetting or for R&D.

b **EU NO_x en route charges or performance incentive**; the EU implements en route charges for cruise NO_x emissions, be it for flights to and/or from or between EU airports, flights in EU airspace or any other flights within the jurisdiction of EU Member States. The revenue could be used in a number of ways. A performance incentive would not have revenue, since it is a revenue-neutral charge-subsidy system, which may be based upon absolute emission levels or relative criteria such as emissions per RTK, or load factor related.

c **Inclusion of aircraft NO_x emissions in EU ETS**; the EU creates allowances for aviation NO_x emissions that can be traded against CO_2 emission allowances; aircraft operators would need to surrender NO_x allowances in addition to CO_2 allowances for flights to and from EU airports.

d **Introduction of a multiplier for aviation in the EU ETS**; aircraft operators surrendering EU emission allowances (EUAs) to cover their emissions under the EU ETS would be required to surrender more than one EUA for each tonne of CO_2 emitted in order to reflect aviation's non-CO_2 climate impact; the multiplier could be general or aircraft specific.

e **Introduction of a NO_x emission trading system**; aircraft NO_x emissions would be included in an emission trading system for NO_x, which could extend to other sectors.

f **NO_x emissions are included as criterion in airport slot allocation rules;** this way the use of low-NO_x aircraft could be rewarded through preferential access to or advantages in obtaining slots at congested airports.

4 **Miscellaneous**

a **Voluntary agreements with aircraft engine manufacturers and/or airframe manufacturers and/or aircraft operators on NO_x emissions from engines**; the EU enters into an agreement with aircraft engine manufacturers and/or airframe manufacturers and/or aircraft operators to reduce the NO_x emissions from engines or the emissions per LTO or per passenger or per revenue tonne kilometre according to a specified time path, such as for example set in ACARE's technology goals.

b **Further funding of research into:**

- **Reduction of NO_x emissions from engines**; the EU increases its funding of aircraft engine research and emphasises the reduction of NO_x emissions.

- **Reduction of NO_x emissions or climate impact by changing operational procedures**; the EU increases its funding of air traffic management research and emphasises the reduction of NO_x emissions or climate impact.
- **Best practices to reduce NO_x emissions during flights**; the EU funds a study into the best practices of reducing NO_x emissions during flights and facilitates the dissemination of the findings to the relevant stakeholders.

Giving higher priority to aeronautics research is already part of the comprehensive approach to addressing aviation emissions set out in the Commission's Communication in 2005 (COM (2005)459 final).

J.2.4 Questions for stakeholders

The consultant would like to invite all stakeholders to send any comments on the long list of policy options. It would be very helpful if your feedback would at least address the following questions.

1 In your opinion, is the long list of measures comprehensive? If not, please suggest other measures.
2 In your view, what would be the most important ‘pros’ and ‘cons’ of the various measures in this list?
3 Which measures would you consider most effective to reduce aviation cruise NO_x emissions and why?
4 Which measures would you consider to be the most cost-effective and why?
5 Could measures to reduce cruise NO_x emissions have negative trade-offs? Please specify which measures and why.
6 Which negative impacts could measures to reduce NO_x emissions have? Please specify which measures and why.
7 Apart from the climate impact, which other positive effects could measures to reduce NO_x emissions have? Please specify which measures and why.

J.3 Notes of first stakeholder meeting

European measures to reduce emissions of nitrogen oxides from aviation.

Minutes of the first stakeholder meeting held on February 25th 2008 at the Rue Demot 2-4 in Brussels.

These minutes summarise the discussion that took place in the first stakeholder meeting, which is part of a broader study to identify and evaluate European measures to reduce emissions of nitrogen oxides from aviation. The discussion mainly focussed on the pros and cons of a longlist of policy options under consideration.
A list of the stakeholders who attended the meeting can be found in the last section of this Appendix.

Please note that these minutes record the views expressed in the stakeholder meeting. They do not necessarily reflect the views of the Commission.

General discussion

Jasper Faber presented an outline of the project execution and of the consortium. After the presentation, there are several questions.

Several stakeholders expressed their concern about the scientific uncertainties about the climate effects of NO_x emissions. One asks if there will be a science review, while another suggests the timelines of science and policy should be synchronised more: if science is not yet mature enough, maybe it is still too early to have a proposal. One of the airlines asks if there will be a review of the current NO_x emissions.

Jasper Faber answers that professor David Lee and his team will to a review of the scientific literature, as well as of current NO_x emissions. Professor Lee is a renowned expert, he has done many studies and published in many good journals. He has also been involved in CAEP. Jasper Faber assures the stakeholders that if the literature review shows that there is too much uncertainty, the Consortium will advise the Commission not to take any measures yet.

One NGO argued that although there is a lack of certainty about the exact impact of NO_x, it is sure that there is an impact. The NGO urges the Consortium and the Commission to take action, even without 100% scientific certainty about the exact impacts.

One of the engine manufacturers ask if there will be an opportunity to see the outcomes before the end of the process, e.g. an interim report. Jasper Faber replies that there will be an interim report for the Commission, but it will not be public.

An airline organisation asks if the Consortium will assess the effects of the measures on the competitiveness of aviation compared to other modes of transport. The Consortium will not, because Commission has not included that subject in the study. Mr Rohart replies that part of this study should be seen as preparatory work for an impact assessment, which will be done in a later stage of the process. There a cost-benefit analysis of the effects on aviation and on the environment, but the project will not assess the possibilities to shift measures from aviation to other sectors or modes of transport.

An NGO asks what approach the consortium will take with regard to the warming effects of NO_x. The NGO argues that it is known that the effect of NO_x varies with latitude and that the effects of NO_x are higher than average in the EU. Will the Consortium use the global average or the EU average? Jasper Faber answers that the scope of measures should be in line with the scope of the ETS, and therefore the Consortium favours the EU average. However, this has not been completely decided upon yet.

An NGO asks about the exact goal of the proposal. Is it to limit and reduce NO_x emissions, or is it to avoid any relative increase in NO_x due to manufacturers' focus on fuel-efficiency and carbon? Jasper Faber answers that the consortium is discussing this. The TOR are not specific about it. As the consortium understands it, the policy is aimed at preventing that the NO_x/CO trade-off totally or partially offsets of the benefits of including aviation CO_2 in the ETS.

Discussion of the policy options

1 Standards of emission at source

An NGO argues that options 1a and 1b should not really be seen as policy, because they are happening anyway. It would be good to look at EU standards for cruise NO_x (option 1d), because cruise NO_x standards are not addressed through ICAO yet. However, the NGO is not sure if the EASA mandate would cover this.

An engine manufacturer adds that the stringency of the ICAO standards was increased at CAEP 6, and EU members argued in favour of a further increase of the standards at CAEP 8, so the push already exists. Engine manufacturers aim their designs at the next standard, not just the current standard, so the standards push toward cleaner technology.

One of the operators asks why the measures are aimed at operators, rather than at manufacturers. He says that this is different from the automotive industry, where standards are aimed at manufacturers. Jasper Faber replies that it depends on how standards are designed, whether they are aimed at operators or manufacturers. Standards for manufacturers are easier than standards for operators.

An airline organisation argues that EU LTO NO_x standards would have no effect, because aircraft will move to an other part of the world. Jasper Faber answers that the benefits of this option depend on the correlation between cruise and LTO NO_x. If the EU standard would become the de facto standard (the way the Californian standard for cars has de facto become the US standard for car design), then the measure will have an effect.

Many stakeholder believe that a phase-out would have no effect, because aircraft that are phased-out in the EU, will be sold to other parts of the world and fly there. In the noise phase-out of Chapter 2 aircraft, this was no problem, because noise is a local problem. However, climate change is a global problem, so a phase-out in Europe wouldn't be effective if the phase-out aircraft will continue to fly in other parts of the world.

Operational procedures to reduce NO_x emissions

Stakeholder unanimously agree that the Single European Sky should be implemented (option 2a).

An NGO suggests that climate-optimised air traffic management (option 2b), would in practice mean NO_x-optimised ATM, because the effects of NO_x are much stronger than the effects of CO_2. Jasper Faber answers that the focus is on NO_x, but that the study needs to take a broader look. Theoretically, it could be beneficial if CO_2 emissions increase a little if that means that NO_x emissions can decrease.

An airline organisation thinks that CDA is probably a quick win, but that other options mentioned under 2b (e.g. redirecting around supersaturated areas) are longer-term issues. Safety risks and capacity should be taken into account, and some options would increase the complexity and the cost of ATM.

Economic and financial incentives

An airline organisation asks if any revenue from these incentives would be refunded to R&D. I shouldn't happen that revenues might be spent elsewhere, while the study does not assess the options of reducing NO_x in other sectors. Mr Rohart answers that the measure could also be revenue neutral.

An NGO thinks that it should be a charge, not a tax. The revenue is taken for effect on climate change, and it could be spent on climate change, possibly elsewhere.

One stakeholder thinks that this could erode the existing charges on LTO NO_x. another asks how aircraft that cross EU territory, but do not land will be dealt with. An airline organisation says that 3b and 3d are extraterritorial measures, so there will be legal problems, like with the ETS.

An NGO feels that NO_x en route charges (option 3b) are the best option, with LTO NO_x charges (option3a) as flanking measures. Slot allocation (option 3f) is also feasible, according to the NGO.

An airline organisation argues if an operator has e.g. invested in a aircraft 3 years ago, and the lifetime is 12 years, en route charge would not be an incentive to reduce NO_x emissions. Jasper Faber answers that it wouldn't be an incentive for the current aircraft, but it would be an incentive when making decisions about investing in new aircraft. The airline says that there already is a strong incentive, being fuel efficiency, and that there is a natural progression to more efficient aircraft. Jasper Faber agrees that fuel efficiency is an incentive. However, there is a trade-off between CO_2 and NO_x, and the external costs should be internalised.

The engine manufacturers say that they are trying to understand the value of cruise NO_x. If manufacturers don't understand the value, it they might over- or undervalue NO_x relative to CO_2. If science would be clearer, it would be easier to value NO_x relative to CO_2. Manufacturers try to reduce CO_2, NO_x and noise, but it takes time and money.

An airline organisation argues that if the recommendations need to be made in 5 months, this rules out the option of the multiplier, as scientific understanding has not advanced enough since the previous discussion on the multiplier (unless the term is extended). Jasper Faber answers that the project cannot be extended, but the consortium could e.g advise Commission that science on the subject is still immature, or that some aspects would need further study before implementing a certain measure.

An NGO believes it would be easy to append NO_x emissions to the ETS, once you know the GDP 100 of NO_x and make an inventory of NO_x emissions.

An airline organisation feels that it is rather disappointing that the multiplier is reintroduced. The organisation is not in favour of inclusion of aircraft NO_x emissions into the ETS, as it would mean creating NO_x allowances and a parallel system. Jasper Faber answers that the multiplier is a reference option. Any option we propose should be better than the multiplier.

An engine manufacturer warns that the multiplier sends the wrong message: 'never mind NO_x, focus on CO_2'.

Another engine manufacturer thinks that if NO_x emissions are included as a criterion in airport slot allocation, this would mean that small-body aircraft would be favoured over wide-body aircraft. Jasper Faber replies that this would depend on the design of the measure.

An airport organisation says that slot allocation based on NO_x emissions would easily become complicated. It could only apply to new slots, which are scarce, and it would need much study. An airline organisation argues that only a minority of airports is slot-coordinated.

An airline organisation say that of all options, this one is amongst the worst. Slot allocation is commercially extremely sensitive. It gives flexibility to how airlines operate, and this measure would undermine the current slot use system.

An NGO feels that if slots are so scarce, then slot allocation could be an effective measure.

Miscellaneous
An NGO would like to suggest an extra option: speed reduction.

An engine manufacturer remarks that voluntary agreements are already in place, and they are driving research.

An airline organisation supports the option of research, but since climate change is a global problem, he believes that research should be done where it will have the widest return.

An NGO is reluctant about the research option, unless it is combined with charging. The NGO asks if the problem is in funding or in technology. An engine manufacturer replies that more funding will not lead to quicker improvements, but it will lead to more improvements. The only thing that works in the long term, is technology. Research reduces fuel burn, which reduces both NO_x and CO_2. The NGO says that there is already a lot of money for research, e.g. Clean Skies. Is there any need for additional funding? The engine manufacturer says that the manufacturers generate 50% of the research funding, which means that extra money would definitely help.

An airline organisation says that operators use the latest technology and the only fuel that is available for aircraft. They have no alternatives. Several stakeholder issue a clear call for any revenues to go to R&D, or argue that extra charges would only be acceptable if the SES is implemented.

An NGO says that the EU has already tried voluntary agreements (with car manufacturers) and that did not work. An airline organisation answers that ACARE is already in place. The industry wants to reduce fuel burn. Any manufacturer that can reduce fuel burn, has a benefit over the other manufacturers.

An NGO argues that more funding would come from tax paid by tax payers. The NGO would prefer to use market forces, and believes that even a revenue neutral scheme would drive money into research.

J.4 Second stakeholder consultation document

J.4.1 Introduction

The European Commission wishes to consider what cost-effective options for further European action to limit or reduce aircraft NO_x emissions exist (see CE, 2008). It has appointed a consortium led by CE Delft to consult on policy measures.

A vital and integral aspect of this study comprises stakeholder consultation. The consortium intends to consult stakeholders on potential policies and their advantages and disadvantages. Among the stakeholders to be consulted are engine and aircraft manufacturers, airlines, airports, their professional and trade associations, and NGOs.

A first meeting with stakeholders was held on 25 February 2008. At this meeting, the consultant presented a long list of options and received comments from stakeholders on the advantages and disadvantages of the various options.
After this meeting, the Commission and the consultants selected four policy options for further study. The consultant is currently designing the options. It envisages to discuss the design with the stakeholders in order to be able to make well-founded design choices. A second stakeholder meeting has been planned for 16. May.

To facilitate the discussion with the stakeholders, the consortium has prepared this short paper on the design of the selected policy measures to reduce aircraft NO_x emissions.

J.4.2 Selection of options

The consultant's analysis and the stakeholder consultation process identified a number of policies that are currently being implemented and that seem to hold potential for reducing NO_x emissions. These include:

- Implementing the Single European Sky.
- Funding of research.

Operational options such as implementing SES would reduce NO_x emissions per seat kilometre, as well as other emissions. The importance of the SES for the environmental performance of aviation large. However, the costs and benefits of implementing SES have been extensively studied, so assessing them in this report could be superfluous. Furthermore, since the SES would not address NO_x directly, nor affect the CO_2 : NO_x trade-off, it hardly classifies as an instrument to reduce the climate impact of NO_x.

Research funding in aeronautics is already aimed at reducing the environmental impact of aviation. The Clean Sky JTI is a clear example. The expectations are that this research will demonstrate technologies that will enable lower NO_x emissions.
However, since these policies are already being implemented, the Commission and the consultant agreed not to study their cost-effectiveness, legal situation, economic impacts and other relevant aspects in this study.

For this study, the consultant and the Commission have selected three policies that seem to be effective in limiting aviation NO_x emissions, legally feasible, would not encounter severe data problems, would be feasible to implement, and could be designed in such a way as not to distort competition.

These are:

1 An LTO NO_x charge, either coupled with a distance factor or not.
2 A NO_x en route charge.
3 LTO NO_x emission standards, either issued by the EU or by ICAO following concerted EU action.

Options involving Cruise NO_x stringency were discarded because there is currently no agreed metric for Cruise NO_x emissions nor an agreed method for measuring these. However, it is conceivable that the current relation between LTO NO_x emissions and Cruise NO_x emissions may break down. Therefore, it is recommended to monitor the relation between Cruise NO_x and LTO NO_x.

A phase-out of dirty engines would be prohibitively costly, as the trend in Cruise NO_x emissions per seat kilometre is almost flat. This implies that such a policy would need scrapping new engines with a high residual value.

Operational measures such as climate-optimised air traffic management are not feasible at the moment because scientific knowledge in this area is immature.

Inclusion of a NO_x criterion in slot allocation rules would introduce inefficiencies in the use of slot co-ordinated airports and have welfare costs. Furthermore, it could encounter legal obstacles.

In addition to the three policy options identified above, a fourth will be studied as a reference:

4 A multiplier on aviation CO_2 emissions in the EU ETS.

This option has been proposed by the European Parliament and thus has political relevance.

J.4.3 Design of options

LTO NO_x charge

A LTO NO_x charge as currently implemented at several European airports would primarily target local air quality. Its impact on cruise emissions would normally be considered a co-benefit, but since LTO NO_x emissions and cruise NO_x emissions seem to be aligned in most cases, policies that would reduce LTO NO_x would also reduce cruise NO_x and could thus be seen as a surrogate climate change charge.

The basis of the charge would be the mass of LTO NO_x emissions calculated according to ECAC/ERLIG method. For the calculation, the ICAO engine emission databank will be used for large jet engines, the ICCAIA/FOI database for turboprops. Depending on a threshold, there may be need for an additional database for small jets. The level of the charge would be set at the damage costs of NO_x, in line with established EU policy to internalise external costs. The charge would be levied at all EU airports in order to align the geographical scope with the scope of the EU ETS. Aircraft operators would be liable for the charge. Airports would levy the charge. The charge could either be revenue neutral or not. If the charge is revenue neutral, this could be achieved either by a simultaneous introduction of the charge and a reduction of landing fees, or by a separate account to which higher-than-average-emitters pay a charge and from which lower-than-average-emitters receive a bonus.

LTO NO_x charge with distance factor

In contrast to the pure LTO NO_x charge, the LTO NO_x charge with a distance factor would be primarily introduced to address the climate impact of aviation NO_x. The reason for basing the charge on LTO NO_x with a distance factor rather than on cruise NO_x emissions would be that LTO NO_x and distances can be calculated using generally accepted methods. The extent to which LTO NO_x with a distance factor correlates with cruise NO_x emissions is currently being studied by the consortium.

The LTO NO_x charge with a distance factor would share most of the design choices with the LTO NO_x charge, except for the level of the charge and the basis of the charge. The basis for the charge would be LTO NO_x emissions as calculated with the ECAC/ERLIG method times the great circle distance between the airports. The charge would be collected by airports and would have to be paid by all flights arriving at EU airports and all flights departing from EU airports to non-EU airports. In this way, the geographical scope would be the same as the scope of the EU ETS.

The level of the charge would relate to the climate impact of aviation NO_x and the ratio between cruise NO_x emissions and LTO NO_x emissions multiplied with distance.

En route NO_x charge

In theory, an en route NO_x charge would be an economic incentive to reduce NO_x emissions where they do the most climate damage, i.e. at altitude. If en route NO_x can be accurately calculated, the charge would reflect the environmental impact more accurately than the two charges discussed above.

The basis for the charge would be the mass of NO_x emitted during a flight. As this cannot be determined empirically on each flight, cruise NO_x emissions have to be calculated. There are broadly speaking two ways to do this. One would be to build a database with results of model calculations of flights with various engine- and aircraft types. For a specific flight, a charge can be levied on the modelled NO_x emissions as retrieved from the database. Alternatively, models could be used to calculate values of $EINO_x$ (the emission index of NO_x, i.e. the mass of emissions of NO_x per unit of mass of fuel burned) for engine-aircraft combinations. The charge can than be based on actual fuel use on a trip multiplied by the $EINO_x$.

The geographical scope of a cruise NO_x charge could be the same as the scope of the EU ETS: all flights arriving at and departing from EU airports. The level of the charge would be set at the climate damage costs of aviation NO_x emissions. The charged entity would be the aircraft operator. The charging entity could be the Member State.

LTO NO_x emission standards

ICAO has regulated NO_x stringency standards since 1986 and they were last tightened in 2004 at CAEP/6 when a 12% reduction in permitted NO_x output (compared with the previous CAEP/4 standard) was agreed, with an implementation date of 2008.

It may be taken as a given that work will continue at CAEP on this aspect of NO_x emission reduction, with or without EU encouragement. In addition, it may be conceivable that the EU sets slightly more stringent standards that ICAO. In designing an EU standard that exceeded those set by ICAO, consideration will need to be given on the competitive reaction to regional standards. The initial view is that if EU standards exceeded global standards by a relatively small margin, even engine manufacturers outside the EU might well respond by designing engines to meet these tighter EU standards.

This study will consider stringency standards set by ICAO up to 20% for analysis. We further believe that additional options of an EU standard involving up to a 25% increase in stringency (i.e. reduction in permitted NO_x output), accompanied by a production cut-off for those engines that remain non-compliant at the date of implementation, should also be addressed.

EASA would be the agency responsible for implementing, monitoring and enforcing standards, as it approves engines types that are introduced to the market. All aircraft registered in EU states need to have EASA type approval for engines on the aircraft. Currently, implementing standards that are stricter than the current ICAO standards is not possible as the EASA Basic Regulation (2002/1592) directly references the ICAO Annex 16 requirements.

Multiplier

A multiplier has been proposed by the European Parliament. In line with its position, we will evaluate a multiplier of 2. all the other design options of the multiplier will be the same as the options of the EU ETS.

J.4.4 Questions for stakeholders

The consultant would like to invite stakeholders to send comments on the design of the policy options. (Please note that comments on the selection of policy options will not have an impact on the results of the study, as the Commission and the consultant have agreed on the four options outlined above). It would be very helpful if your feedback would at least address the following questions.

1 Which of the selected measures would you consider most effective to reduce aviation cruise NO_x emissions and why?

2 Which measures would you consider to be the most cost-effective and why?
3 What are the most important advantages and disadvantages of the design choices outlined above?

J.5 Notes of second stakeholder meeting

Minutes of the 2nd stakeholder meeting
May 16th, 14.00-17.00

Mr Rohart opens the meeting and stresses that the options that will be presented are under study; they are not formal policy options of the Commission.

David Lee gives a presentation about the effects of aviation NO_x on climate and aviation NO_x emissions equivalency climate metrics.

An airline organisation asks if there is enough evidence to say that policy is needed. David Lee answers that there is enough evidence.

An engine manufacturer asks how much of the effect is caused by NO_x emissions at ground level that diffuse to higher altitude? He would like to have an IPCC report on transport, as science is important for policy. He also remarks that everything shown in the presentation relies on modelling, and asks if a signature of NO_x has been found yet. David Lee answers that the influence of NO_x emissions at ground level has been accounted for. He acknowledges that it is mostly modelling, because these effects are difficult to measure. He says that the scientific community are starting to see NO_x data from satellites: they see trails from shipping, and also from aviation.

An airline organisation asks what the effect of NO_x from aircraft relative to other sectors is. He wonders if policy should be made for aviation before it is clear where the biggest source of the problem is. Another airline organisation also wants to know how aviation compares with everything else. David Lee answers that according to the IPCC, aviation currently causes 3.5% of the total manmade forcing impact and will cause 5% in 2050 (all figures excluding the impacts of cirrus clouds). An airline organisation would also like to know the effect of total transport. An engine manufacturer and David Lee answer that the effect of transport is approximately 10% of the total manmade changes in radiative forcing.

An airline organisation asks if all NO_x emitted at ground level climbs up to higher altitude. David Lee answers that NO_x in the boundary layer (1 km) is removed quite quickly, due to meteorological physics. If there is much convection, the exchange time is small. The airline organisation asks if eventually the NO_x always climbs up to higher altitude. David Lee answers that it doesn't, because there is an equilibrium, so the NO_x goes two ways, and there are decay mechanisms which remove NO_x.

An airline organisation remarks that if the GWP of NO_x is 100, so the effects of NO_x are 100 times as strong as of CO_2, but that's all based on calculations with a time horizon of 100 years. David Lee agrees that the results would be different for a time horizon of 25 or 500 years. The airline organisation asks if the difference in life time been accounted for?
David Lee says that the difference has been accounted for by integrating the effect over time, but if the life time is longer than the time horizon, the effects that occur after that time are 'sliced off' in the integration.

Jasper Faber presents the design of selected policy options. Questions are asked during the presentation.

An airline organisation asks if the review of current and future NO_x emissions will be shared with the stakeholders as information, so they know the projections of future NO_x emissions. There have been misleading statements in the media, and they would like to be sure that the projections are used correctly. David Lee answers that the consortium is not doing unique modelling runs, but that most of the information comes from the literature (CAEP, etc.). The consortium does not use a frozen technology scenario.

Several airline organisations argue that the potential and costs of SES and research should be compared to other options. Otherwise, how could they assess which of the options is best? Jasper Faber answers that the SES and research will go on regardless of what our report says, and they are not NO_x policy. However, in the report the consultant will include a scenario that includes the benefits of SES.

An airline organisation asks if the Commission wouldn't be interested to know the potential and costs of these two options compared to the others. Mr Rohart answers that these options already exist, and they are not under discussion. The subject of this research is 'how can NO_x better be addressed'. There is no reason to do a new cost-benefit analysis of these two options. An airline organisation says that there has never been an assessment of the NO_x effects of the SES. Another airline repeats that it is necessary to know the effect of SES and research, because without knowing the effect of these two options, how can they know the need for additional policy. The airline organisation asks not to exclude these two options from the beginning. The airline organisation would like to know the time scale, the size of the problem, how much the NO_x reduction should be, and when. Jasper Faber answers that the consortium does assess the size of the problem and takes SES and research into account in the final report.

An NGO asks if the policy options will contribute to internalising the external costs. An engine manufacturer asks the consortium to take technology scenarios into account in modelling. The consultant answers that he will compare the effects against a scenario which includes SES.

An airline organisation says they recognise the pressure from the parliament. But assuming the sincerity of the parliament, why disregard the research option? The airline organisation says it is almost like aviation is being penalised, and it feels like we're excluding the biggest potential breakthroughs. Jasper Faber answers that the consortium does recognise the potential of research.

Mr Rohart says that when the European Parliament wanted a multiplier, the European Commission was bombarded with email, because the multiplier does not look at the trade-off between NO_x and CO_2. If one wants to target NO_x and the NO_x-CO_2 trade-off, one needs to use specific NO_x policy. We need to give a signal. The SES is not specific NO_x policy, so it is not a signal.

Another airline organisation says that in order to be able to assess the options, they need to know the objectives: the time scale and the goal. Mr Rohart answers that the main objective is to give the correct signal. If there is no signal, the NO_x : CO_2 trade-off could go in the wrong direction. The signal should be effective.
An airline organisation asks if Mr. Rohart could quantify the signal. Mr Rohart says that this will depend on the study and on the impact assessment.

An airline says that the problem is that it is unclear what question they are being asked. The minutes of the previous meeting are unclear. Is the aim to limit or reduce NO_x emissions, or is it to internalise the external costs? In the short term or in the long term? If the aim is to have an effect on the short term, an aircraft that I buy now might not stay with for its entire lifetime. If the aim is to have an effect on the long term, I will buy a better aircraft, but not yet today. What are you incentivising me to do? Buy new Russian fleet, or buy the aircraft that is best from an environmental perspective (which in freight carriers is 2nd hand aircraft)?
Jasper Faber answers that the aim is to address the climate impact of NO_x. NO_x emissions must be limited or reduced, but the overarching goal is not to make things worse. It is not a project with a quantitative target.
An NGO states that the overall objective is clear: 20% reduction of greenhouse gasses in 2020.

An engine manufacturer ask the consortium to consider using various scenarios in AERO. Baseline = frozen technology, scenario 1= technological improvements, scenario 2 = technology + SES, scenario 3= technology + SES + policy options.

Jasper Faber goes on with the presentation and presents the 4 policy options.

LTO NO_x charge, either coupled with a distance factor or not.
An engine manufacturer says they support the idea of a revenue neutral scheme. However, the way that revenue neutral is currently implemented at Heathrow rewards small aircraft over large aircraft. In other places, the scheme works with percentages. LTO charges are already spreading, and the engine manufacturers asks why the consortium is suggesting to introduce them at all EU airports? Jasper Faber answers that there are two reasons for this. Firstly, the system needs to be in line with ETS (for political reasons). Secondly, there is no threshold in the damage done by NO_x, so introducing a charge on all airports makes sense if you want to internalise the external costs.

An airline association says that LTO NO_x is not a climate issue, it is a local air quality problem. Jasper Faber agrees that it is not primarily a climate issue, but introducing an LTO NO_x charge has co-benefits for the climate.
An NGO says that the damage costs of LAQ are inadequate costing for the damage costs of climate change.

An airline association says that there is ICAO guidance on LAQ. It clearly prescribes performance-based measures, not ICAO standards. Jasper Faber answers that the consortium will look into this guidance.

An airport association says that within its membership, there are mixed view on this option. A blanket could endanger the existing initiatives for LAQ. It could erode the existing schemes.

A government representative says option 1a (a charge on LTO NO_x) is not a climate policy option, but 1b is (a charge on LTO NO_x coupled to a distance factor). Jasper Faber agrees and adds that 1a could be easier to implement than 1b.

An airline organisation says that the GWP of NO_x is still unsure, and it will take 3-5 years to get the data. Jasper Faber agrees and says that the report will mention this.

An NGO urges the consortium to use the precautionary principle. Jasper Faber answers that the consortium is doing cost-effectiveness calculations with several GWP's.

An airline organisation asks if there is a reliable estimate of the damage costs of NO_x. Jasper Faber answers that the damage costs of NO_x emissions at ground level have been estimated fairly reliably. The airline association asks what is recommended by ECAC. Jasper Faber explains that ECAC-ERLIG recommends to base a NO_x charge or a differentiation of charges according to NO_x emissions on mass of NO_x emitted during a standardised LTO cycle.

An engine manufacturer says that the process doesn't allow enough time to design a robust system
An airline association asks if the distance factor is measured only in EU airspace or on the whole flight distance? Jasper Faber answers that the basic idea is to have the same geographical scope as the EU ETS, so the whole flight distance.
An airline association asks who will do the distance calculation, and warns that it is complicated.

NO_x en route charge

An NGO believes that this is the most effective option, although other option might also be adequate. The NGO thinks it would be a lost opportunity if the Commission proposes a revenue neutral scheme. The external costs should be internalised. A revenue neutral scheme go againste established EU policy principles.

An airline organisation says that a better reasoning would be that any revenues should go to research.

An NGO says that we should distinguish between two things: one is what the right price signal is, the other is how any revenues should be spent. Jasper Faber answers that the consortium would welcome a written reaction on this.

An airline organisation says that the longlist had an option of cruise NO_x standards. That option was discarded because of the complexity. How then can the en route charge be calculated? Jasper Faber answers that there are several models available, and the consortium is currently assessing their accuracy.

Somebody calls for a comprehensive cost-benefit analysis. Greater costs could for example result in slower fleet renewal, which could be bad for the environment. Also, higher costs of flying could induce a modal shift of which the impacts should be assessed.

An airport association asks if the consortium will look at the potential trade-off with noise. Jasper Faber answers that the consortium has looked at a possible NO_x-noise trade-off, but has not reached a conclusion yet. Michael Mann says that the LTTG (long term technology goals) had a figure for the NO_x noise trade-off, but the report also said that this figure needed more work.

LTO NO_x emission standards

An airline organisation says that the airlines do not want regional standards, only global standards, and asks if the consortium's calculations take into account that the EU fleet is 5% more efficient than the global fleet? Jasper Faber answers that the standards would only apply to new engines. He says that regional standards could lead to 3 possible responses from manufacturers. First of all, they could decide not to produce for the EU market. Secondly, they could make two sets of engines. Thirdly, they could completely comply with the most stringent standards. However, the consultant has considered regional standards and concluded that they would be hard to implement effectively.

An engine manufacturer urges the consortium to be careful of a production cut-off, because it could apply to very new aircraft, and hence be very expensive. Jasper Faber says that the consortium will be careful.

Multiplier

An engine manufacturer says that he is a bit disappointed that the multiplier is still there. He says it feels wrong to use it as a reference option. Jasper Faber answers that it is still in because it seems to be the preferred option for the European Parliament. The advantage of this option is that it reduces CO_2 and NO_x together, the disadvantage is that it could induce the NO_x : CO_2 trade-off in engine design to go the wrong way.

An airline organisation asks what the scientific underpinning for the multiplier is. David Lee answers that the multiplier is not recommended from a scientific point of view, see e.g. the report ‘Giving Wings to Emission Trading’.

An airline organisation asks which type of multiplier the consortium will analyse? The multiplier suggested by the European Parliament is rather complicated. Jasper Faber answers that the consortium will evaluate a simple multiplier.

The airline organisation says that they are definitely interested in seeing how the consortium calculates it and what the results are, because they don’t manage to calculate it themselves.

An NGO asks if David Lee is against all types of multiplier? David Lee answers that he is not against all types of multipliers. The RFI is not robust, so he is against using it as a multiplier, but he is not against multipliers per se. The GWP is also a multiplier, but it’s robust.

An NGO says that there is no perfect option. The NGO has advocated the multiplier as an interim solution, because of its simplicity. It can be implemented quickly. The NGO would prefer an en-route charge if it is possible, but the multiplier has administrative strengths because it is simple.

David Lee answers that precaution is fine. However, using the RFI as a multiplier is not fine, because the RFI for shipping is negative, which means that we would pay shipping to pollute.

Mr Rohart thanks all the representatives for attending the meeting, and asks if there are any other questions.

An airline organisation asks who will do the impact assessment. Mr Rohart answers that he will write it, and the steering committee will review it). The airline organisation asks if there is enough time to produce a good regulation. Mr Rohart says that there is, but that it also depends on the instrument that is chosen. The airline organisation asks why there is such a rush. Mr Rohart answers that that the proposal to include aviation in the EU ETS promises a proposal on NO_x by the end of 2008.

An airline organisation asks when the report will be available. The airline organisation has two remarks and wants them to be put in the minutes. Firstly, they do not believe that we are on a good track if 2 options are excluded. The second remark is about the timing: next year, the EP will not have enough time for this issue due to the elections.

Mr Rohart answers that the consultants will finish the report by the end of May. Once it has been accepted by the Commission, it will be published on DG TREN’s website.

An engine manufacturer ask if the Commission support the idea of an IPCC assessment of the transport sector? Mr Rohart says that he can't answer that question. An airline organisation says that they do support that idea.

J.6 List of organisations present at stakeholder meetings

ACI Europe
AEA
AEF
Air France
Airbus
ASD
Boeing
Continental Airlines
EASA
EBAA
EEA
ELFAA
ERA
EUROCONTROL
FAA
FEDEX
GE Aviation
IACA
IATA
Pratt & Whitney
Rolls Royce
SAFRAN Group
SAS
T&E

J.7 List of organisations that sent comments in writing

AEA
AEF
ASD
BDF
ELFAA
IATA
T&E