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External costs of aviation

Report

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Foreword

Besides numerous benefits to citizens and companies, air transport also has undesired side-effects such as emissions and noise nuisance. Most of these negative ‘external’ effects, as they are called, are not currently priced or to a limited degree only. The marketplace consequently creates insufficient incentives for the aviation industry and its clients to reduce these external effects.

The present study on ‘External costs of aviation’, commissioned by the German Umweltbundesamt, aims to contribute to the ongoing international process of creating market-based incentives for the aviation industry to reduce the environmental impact of its activities. It does so by estimating, within as narrow margins as possible, the external costs of aviation.

The report at hand is the main report of the ‘External costs of aviation’ study. Besides this main report, a background report is also available with five technical annexes.

We gratefully acknowledge the support of the German Umweltbundesamt, and in particular Mr Friedrich, Mr Huckestein, Mr Heinen and Mrs Mäder for their always constructive comments and flexible and respectful attitude. Needless to say, responsibility for the content of this report rests fully with the authors.

Contents

Executive summary

Brief overview

- This report aims at quantifying, within ranges as small as possible, external costs from environmental impacts of aviation. Benefits of aviation are important too, but they are generally, in contrast to the negative impacts, well captured by the market.
- For the valuation of climatic impacts from aviation, both the damage cost and prevention cost approach is used, leading to a middle estimate of 30 per tonne of CO_2 equivalent, with sensitivities of 10 and en 50 per tonne. As contrails have a relatively large climatic impact and their formation can quite accurately be predicted, the climatic impact is differentiated for situations with and without contrail formation. For this analysis the most important assumption is hat contrails are formed during 10% of flight kilometres.
- For the valuation of regional and local impacts, the damage cost approach has been followed. Avoidance or adaptation costs (e.g. costs of zoning around airports) have been included in the damage cost assessment.
- For aircraft flying at distances up to a few hundred kilometres, external costs related to LTO emissions are dominant, especially noise costs. For flights over about 1,000 km, external costs of climatic impacts exceed those of LTO impacts, also in case no contrails are formed. New technology has more impact on LTO related costs than on costs related to climatic impact.
- Contrail formation has a large influence on the climatic impact of aircraft, and thus on external costs related to this climatic impact. Based on a number of assumptions, a middle estimate is that the climatic impact of a contrail-causing aircraft km is, on average, about eight times as high as an aircraft km that does not lead to persistent contrails.
- Expressed as a share of ticket prices, external costs (without contrail impacts) vary from roughly 5% of ticket prices (long-haul flights, new technology, no contrail formation) to roughly a quarter of ticket prices for 200 km flights with average technology. These figures rise sharply when contrails are formed during part of the trip.

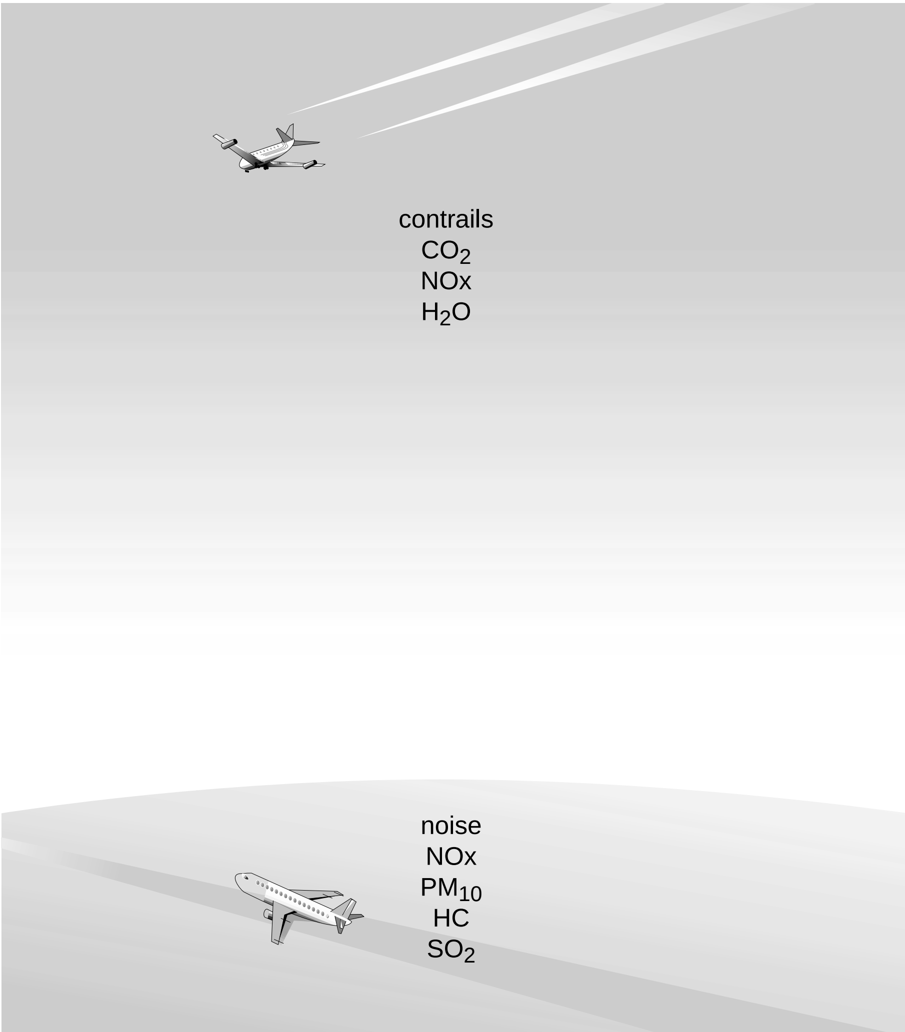
Air transport: benefits and undesired side-effects

Besides numerous and sizeable benefits to citizens and companies, air transport also brings undesired and damaging side-effects to people living near airports and to the local and global environment. The marketplace is generally well-equipped to charge users appropriately for the benefits of transport, in this case aviation. However, this does not hold for its undesired, i.e. negative impacts, such as noise and climate change. These effects are generally external to the market. *External effects are economically relevant impacts that agent A imposes on agent B without recognising or accounting for them.* External effects cause economic inefficiencies because efficient economic decisions are only taken if ALL social costs and benefits are taken into due account in decision-making.

For all modes of transport, therefore, policies are currently being considered to bring costs that are currently ’external’ to the market, such as the costs of noise and climate change, into the transport market. The aim of such actions is not to reduce the negative impacts to zero, nor is it to reduce the volume of transport. The aim is provide market-based incentives for the transport market to reduce its negative impacts to a socially optimal level. Air transport is no exception here: at both ICAO and EU level, options are being sought to achieve this goal. In developing such policies, knowledge about the magnitude and structure of these costs is obviously of crucial importance.

The aim of the present study is consequently to quantify – within ranges as narrow as possible – the external costs of air transport, and in particular the costs of climate change, air pollution and noise, and to provide insight into the principal factors determining these external costs. The report is written from a global perspective as far as the climatic impact of aviation is concerned, and from a European perspective for local and regional environmental effects ('LTO cycle effects'). The study does not provide a description or assessment of policy options. Neither are safety risks assessed or valued. The impacts assessed are shown in Figure 1.

Figure 1 Environmental impacts of aviation considered in this report



Financial valuation of environmental impacts
The extent to which a financial value can be assigned to environmental impacts has been debated extensively. At the outset it is important to note that environmental impacts can lead to *real* economic costs, although these will not generally show up clearly in statistical or financial overviews. Examples include higher hospital bills, decreased productivity (of people and land),

costs of mitigation measures (insulation, cleaning, etc.), costs of zoning, etcetera. For an aggregate assessment of environmental costs, all these costs should obviously be added. In an average cost approach they should be divided by the magnitude of the relevant environmental impact.

However, the aim of this report is not to establish quantitative figures for the total cost of the environmental impact of aviation. The aim, rather, is to support the development of policies to reduce that impact to socially optimal levels. Hence, in this report we are looking for the *marginal* costs of one extra kg of emission or one extra dB(A) of noise.

There are two fundamentally different approaches to estimating marginal costs or, in other words, assigning a *shadow price* to a certain amount of environmental impact. The first is to assess the costs of **damage / nuisance** plus **avoidance / adaptation** resulting from one extra unit of impact. Direct damage costs can be estimated via direct dose-response relationships, questionnaires (revealed preference) or changes in market prices (stated preference). Avoidance or adaptation costs are the costs of avoiding exposure to environmental impacts without reducing the actual impacts themselves, for example the costs of establishing *'cordons sanitaires'* around airports. For overall marginal cost assessment, the avoidance costs should be added to the direct damage costs: increased exposure will lead both to greater direct damage and to more avoidance behaviour.

A second - fundamentally different - approach, is the so-called **prevention** or **abatement** cost approach, use of which may be considered when across-the-board emission reduction targets are in place that have been politically agreed and are duly respected. In this case, one extra unit of emission does not lead to extra damage or avoidance costs, but rather to additional abatement measures - somewhere in the economy - to reduce emissions to the agreed target level. In such cases, the costs of emissions can therefore be represented by the marginal costs of reducing emissions to the agreed target.

Given their different nature, the damage and prevention cost approaches do not necessarily lead to the same shadow prices. Only if the politically agreed target is at a theoretical optimum will shadow prices based on the two approaches be the same. Each approach has its own specific pros and cons, which are considered in greater detail in the main text. An appropriate valuation methodology should be used for each environmental aspect studied.

Estimating the costs of the climatic impacts of aviation

Estimating a shadow price for CO_2 emissions
As a first step towards economic valuation of the climatic impact of aviation, a cost estimate of one tonne of CO_2 emission was established by preparing a compilation of both damage and prevention cost assessments.

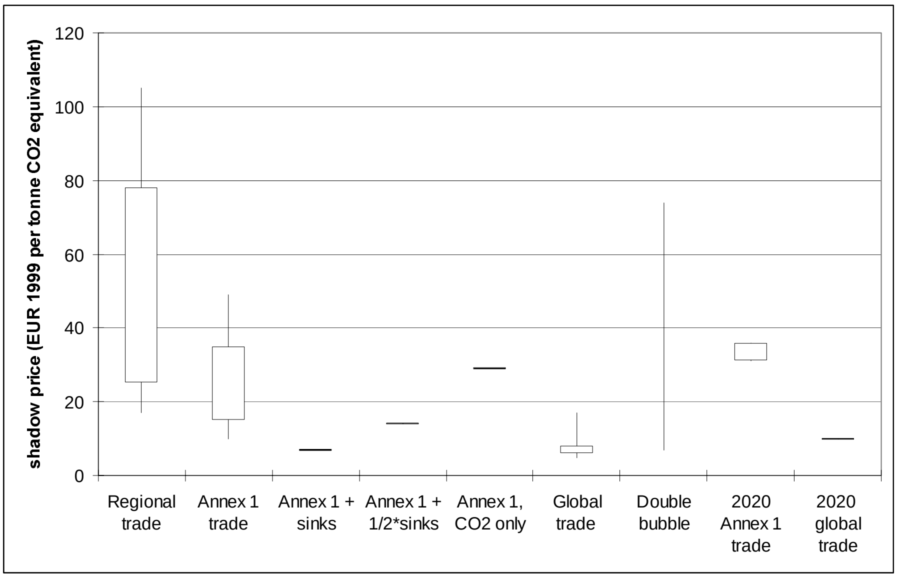
With respect to the damage cost approach, it was found that the social discount rate employed is one of the most important factors governing the calculated CO_2 shadow price (Table 1).

Table 1 Middle estimates of marginal cost of CO_2 emissions in often cited international literature as a function of social discount rate (extreme values omitted); values in € 1999 per tonne CO_2 emitted between 2000 and 2010

Discount rate:	0%	1-2%	3%	5-6%
CO_2 shadow price	47-104	17-56	7-20	2-8

With respect to the prevention cost approach, the only international reduction target on which political agreement has been reached is the Kyoto Protocol. Although separate emission ceilings for the aviation sector have also been considered, these have not (yet) been agreed upon; prevention cost estimates following from such ceilings are substantially higher than those following from the Kyoto Protocol and are given in the main text of the report. Figure 2 reviews the results of prevention cost studies completed prior to the COP meetings in Bonn and Marrakech.

Figure 2 Overview of marginal prevention costs of one tonne of CO_2-equivalent under the Kyoto Protocol, under several assumptions with respect to scale of trade, mechanisms and timeframe



Ranges indicated by *lines* represent the extremes found in the literature, ranges in *boxes* the range disregarding the most extreme values found.

- regional trade: only trade *within* EU, US, and Japan is permitted;
- annex 1 trade: JI (Joint Implementation) permitted (trade between all Annex I countries);
- global trade: JI + CDM (Clean Development Mechanism) permitted, to be considered a variant with maximum use of Clean Development Mechanism;
- (1/2*)sinks: (half of) sinks may be used in addition to JI;
- CO_2 only: infinite prevention costs of non-CO_2 greenhouse gases;
- 'double bubble': trade permitted in two bubbles: one US/Japan/Australia, the other all other Annex 1 countries. Lower value represents costs for first bubble, higher for the second;
- 2020: Kyoto targets apply to 2020 as well.

As can be seen, the shadow price estimates yielded by the damage and prevention cost approaches are of a similar order of magnitude, ranging from around € 5 to over € 100 per tonne of CO_2. The Bonn and Marrakech agreements on sinks will certainly push down the shadow prices from the prevention cost approach to the lower end of the range. On the other hand, it is clear that 'Kyoto' is only an interim target. Figure 2 shows that a mere stabilisation in 2020 will drive shadow prices up.

In this broad range of estimates, we have chosen to work with a middle estimate of € 30 per tonne of CO_2 equivalent and to perform sensitivity analyses using figures of € 10 and € 50 per tonne.

Contrails and other non-CO_2 climate impacts
According to an IPCC middle estimate, in 1992 the full climatic impact of aviation emissions was 2.7 times greater than that of CO_2 alone. Contrail formation and NO_X emissions are the most important environmental impacts besides CO_2 emissions.

Specific attention has been given to contrail formation in this study. This is for two reasons: its substantial contribution to the overall radiative forcing due to aviation, and the specific and fairly well predictable operational circumstances under which contrails arise. It has been assumed in this study that contrails are, on average, formed during 10% of flight kilometres. It is furthermore assumed that contrail formation is not correlated with any other environmental impact of aviation. Finally, the possible additional impact of cirrus cloud formation from persistent contrails has not been addressed.

Under these assumptions, we have differentiated between the climatic impact of average flights that do, and do not, cause contrails (Table 2).

Table 2 Global average perturbation of radiative balance, in W/m^2, differentiated for situation with and without contrails, under assumptions stated below the table, based on 1992 data and 1999 IPCC report

perturbation due to	average situation (with assumed 10 % probability of contrails for each km flown)	situations **without** contrails (about 90% of flight time)	situations **with** contrails (about 10% of flight time)
CO_2	+0.018	+0.0162	+0.0018
contrails	+0.02	0	+0.02
other (NO_X, H_2O, sulphur, soot)	+0.011	+0.0099	+0.0011
total	+0.049	+0.026	+0.023
per flight km (picoW/m^2)	+2.4	+1.4	+11

As the table shows, under the stated assumptions the total average climatic impact of a contrail-inducing flight kilometre is about eight (8) times the *total* average impact of a flight kilometre without contrails (11 vs. 1.4)[1]. For an average contrail-inducing flight kilometre, the climatic impact of the contrail *alone* is about eleven (11) times that of CO_2 *alone* (0.02 vs. 0.0018).

An advantage of the differentiation made is that the 'average' climatic impact of flights, as presented in the first column of Table 2, is in practice never achieved and therefore always 'wrong'. The differentiated figures in the second and third columns provide insight into the additional impact of contrails, and probably come closer to real-world situations.

The climatic impact of NO_X emissions arises from two entirely different processes: net production of tropospheric ozone and net loss of methane. Each

[1] As already mentioned, this factor 8 applies to 1992 and does not include the highly uncertain impacts of additional cirrus cloud formation.

mechanism has a different chemical background and occurs under different circumstances. Although, strictly speaking, the two mechanisms should be valued separately, for reasons of simplicity we have opted here to work with a global average net result. Subsequently, non-LTO NO_X emissions have been valued at € 1.2, 3.6 and 6.0 per kg, as low, middle and high variants. With these values one W/m^2 of radiative forcing due to NO_X emissions is valued identically to one W/m^2 forcing due to CO_2 emissions.

The climatic impacts of sulphur and soot aerosol emissions have not been financially valued because at a global level the two effects cancel.

Estimating the costs of noise and LTO emissions

With respect to the non-climate impacts of aviation, this report assesses the costs of LTO-related emissions of noise, NO_X, PM_{10}, HC and SO_2. The marginal costs of these emissions have been established using a combination of the damage cost and the avoidance cost approach. An extensive literature analysis showed that, once corrected for population density, most of the shadow prices per unit impact were remarkably consistent. We chose to work with typical population densities around large European airports. With respect to noise, the most important cost items are decreased property prices and the costs associated with noise contours around airports. With respect to emissions, the most important cost item is damage to human health.

Results

Below, the results following from the methodological principles and choices explained above are presented. External costs have been calculated for two levels of aircraft technology: fleet-average and state-of-the-art. Other variants calculated but not shown here in this summary include variants with lower and higher valuations per tonne CO_2-equivalent (€ 10 and € 50 respectively)[2].

Results for the ‘fleet average’ and 'state-of-the-art' variants are presented in Figure 3 and Figure 4.

[2] The variants with these lower and higher values for climatic impact lead, respectively, to a two-thirds lower and 60% higher estimate of the external costs of climatic impacts.

Figure 3 External costs in €ct per passenger-kilometre: fleet-average aircraft technology, CO_2 emissions valued at € 30/tonne

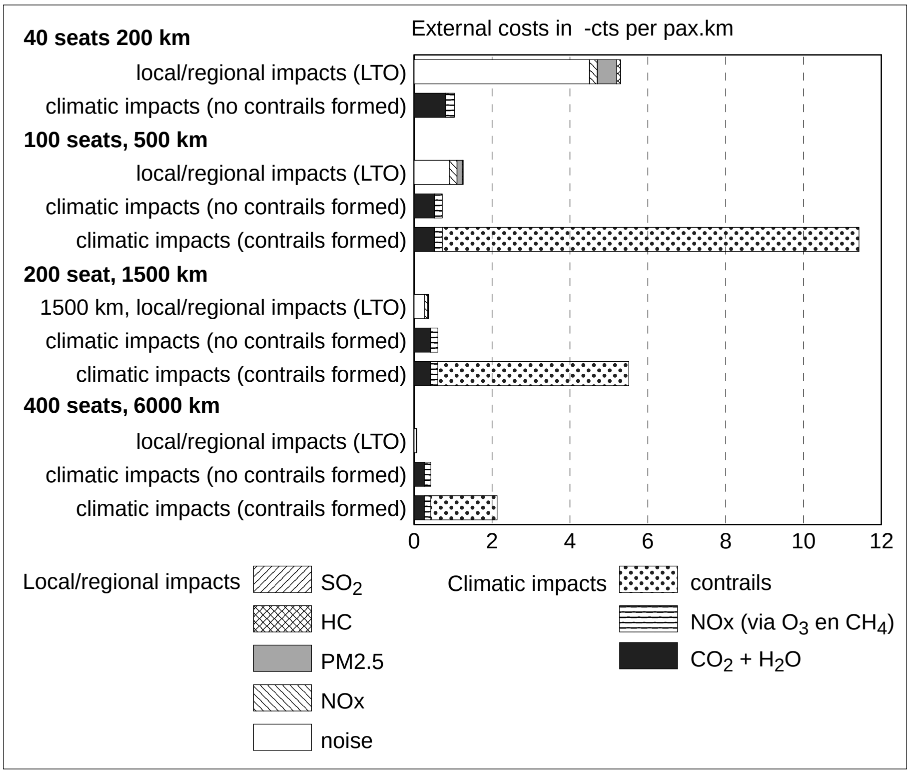
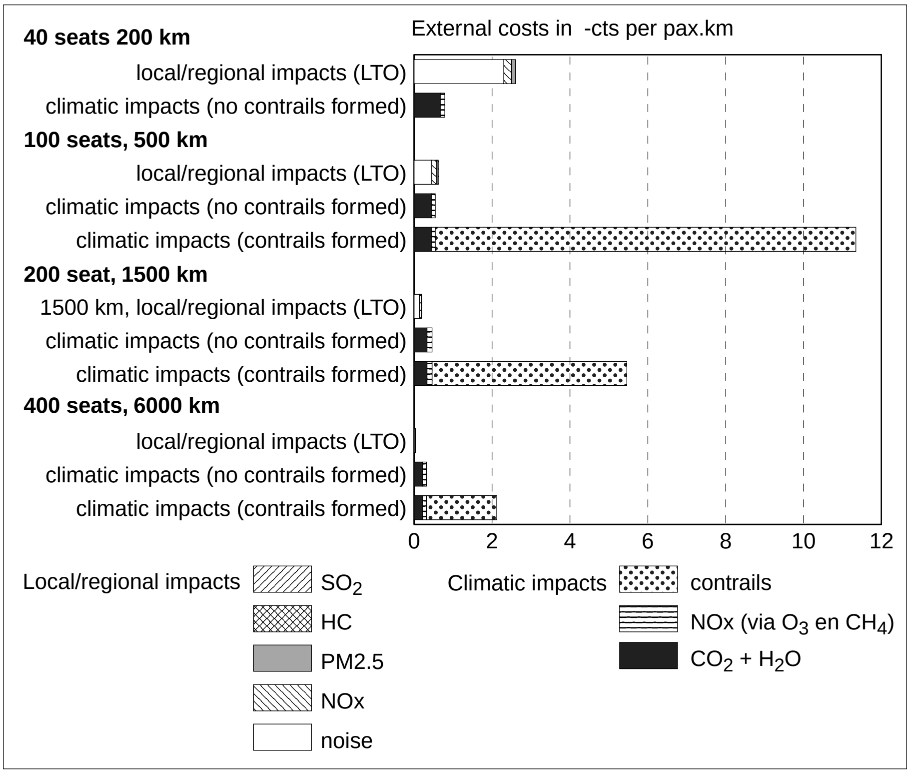


Figure 4 External costs in €ct per passenger-kilometre: state-of-the-art aircraft technology, CO_2 emissions valued at € 30/tonne



From these graphs and from the figures presented earlier the following conclusions can be drawn:

- on flights of up to a few hundred kilometres the external costs of LTO emissions predominate, in particular noise costs. There are several reasons:
    - the LTO phase represents a substantial part of such flights;
    - the generally smaller aircraft have relatively high noise emissions and relatively low NO_X emissions;
    - on such flights aircraft do not reach cruise altitudes, where contrails are formed.

  The LTO impacts of state-of-the-art aircraft are, on average, about half those of fleet average aircraft;
- the longer the trip, the more dominant climatic impacts become compared with local and regional (LTO) impacts. For flights over about 1,000 km, the external costs of climatic impacts exceed those of LTO impacts (when no contrails are formed);
- external costs of the climatic impacts associated with NO_X emissions are approximately half those of CO_2 and H_2O emissions; the share of NO_X increases slightly with aircraft size, owing to the higher NO_X/CO_2 emission ratios of the engines in these large aircraft;
- the question of whether or not *contrails* are formed is of major influence on the external costs of the climatic impacts of aviation. This report estimates that, for fleet-average technology, the climatic impact of a contrail-causing aircraft-kilometre is, on average, about eight times as high as an aircraft-km that does not lead to persistent contrails. It should be stressed that:
    1 the factor 8 is based on the assumption that contrails are formed on 10% of global aircraft-kilometres;
    2 the factor 8 results from a middle estimate of the globally averaged climatic impact of contrails;
    3 there is a 67% probability that the true climatic impact of contrails falls within one-third to three times this middle estimate;
    4 the IPCC judges scientific evidence on the climatic impacts of contrails as 'fair'; hence much work still needs to be done on this issue.
- the external costs calculated in this study can also be expressed as a percentage of ticket prices. On flights on which *no* contrails are formed, total external costs are approximately 5% of average ticket prices for a 6,000 km flight, and about 20-30% of average ticket prices for a 200 km flight. This share is naturally lower for high-fare tickets and higher for low-fare tickets. These percentages rise sharply for flights on which contrails *are* formed during a substantial part of the trip. For example, external costs of medium and long-distance flights on which contrails are formed during half the flight are about 20-25% of the ticket prices paid for such flights.

By their very nature, studies that endeavour to assess external costs involve numerous methodological choices. This study is no exception and we have tried to describe and underpin the most important choices made as transparently as possible. It is therefore our sincere hope that this study will serve not only as a quantitative contribution to the debate on external costs, but also as an analytical framework for other assessments of external costs.

1 Introduction

1.1 Why this report?

Air transport brings numerous benefits to both citizens and companies. It allows people to visit new countries, opens up new markets and permits greater contact with existing markets. The air transport industry is still relatively young and is still undergoing rapid development. Against a backdrop of overall economic growth, the volume of air transport is currently growing at about 5% per year.

In addition, though, air transport brings a number of undesired side-effects to people living near airports as well as to the local and global environment. These negative effects are not necessarily more important than the benefits. Undoubtedly, the benefits of most flights far outweigh their negative impacts.

The reason for writing this report, though, is that the benefits and the undesired side-effects of air transport are not well-balanced. While the benefits of air transport are generally adequately captured by the market and thus reflected in the prices paid by customers for air transport services, most of the negative side-effects remain unpriced. This is an inefficient situation, for efficient economic decisions are only taken if *all* relevant benefits and costs are taken into due account.

Aviation is not the only economic activity associated with so-called negative external effects. In fact, practically all economic activities and certainly all forms of transport have such effects. In order to boost economic efficiency, options are being sought in all transport modes to internalise these externalities as far as possible, by means of economic instruments, regulation or voluntary agreements, for example.

In the past few years a number of studies (ECMT 1998, CE 1999, Infras/IWW 2000) have been published in which the external costs of a variety of transport modes are calculated. However, despite the fact that the environmental effects of aviation emissions are substantially different from those of land transport, none of these reports focused specifically on aviation. A more specific approach for aviation was therefore in order.

This main report was written by authors at CE and is based on a background report with annexes written by CE and one subcontractor, Mr W. Fransen, contracted by Integral Knowledge Utilisation B.V

1.2 Aim

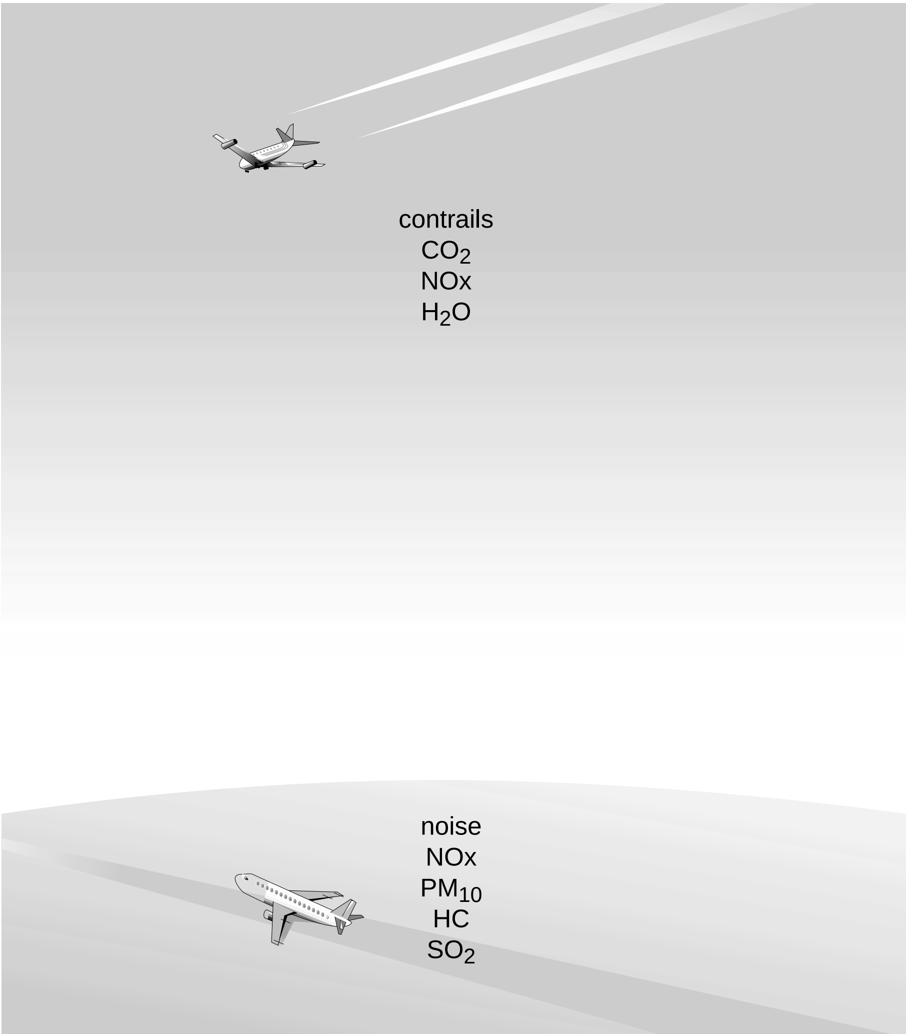
The aim of this report is to quantify – within as narrow ranges as possible – the external costs of air transport, in particular the costs associated with the impacts of climate change, air pollution and noise, and to provide insight into the principal factors determining these external costs. Information on the structure and magnitude of external costs is useful for developing policies to mitigate the environmental impacts of aviation.

1.3 Scope

This report is limited in scope to a quantification of the principal external costs of aviation, in each case taking into account the main determining factors. The report does not contain an assessment of policy options, or even a description of policy options. We emphasise that this report is merely one of the inputs to discussions in these issues. Furthermore, it is written from a global perspective where the climatic impact of aviation is concerned, and from a European perspective where local and regional environmental effects (LTO cycle effects) are concerned.

Figure 5 shows the impacts of aviation covered by this report.

Figure 5 Environmental impacts of aviation considered in this report



1.4 Report structure

Chapter 2 is a broad discussion of the theoretical context of this study, with particular focus on how external costs relate to the economic benefits of air transport.

Chapter 3 treats the contentious ['central and controversial'?] issue of assigning a value to environmental impacts. Available methodologies are described and those used in the present report justified.

Actual valuation of environmental effects takes place in Chapters 4 and 5, with separate calculations provided for climate change, local air pollution and noise nuisance. Chapter 6 presents the conclusions of the study.

As already mentioned, an elaborate background report is also available which describes the exact methodologies followed in assessing external costs. The background report also describes in full detail the extensive literature reviews conducted for this study.

The following annexes are contained in the background report:

- I External costs of greenhouse gas emissions.
- II The contribution of contrail occurrence to climatic change induced by air traffic (W. Fransen).
- III External costs of LTO emissions.
- IV External costs of noise nuisance.
- V Allocating costs to passengers, freight and aircraft types.

2 Economic benefits and external costs

2.1 Introduction

The concepts of external effects and external costs of transport and, more specifically, aviation, give rise to frequent discussions and misunderstandings. This chapter therefore seeks to clarify the most important issues.

The chapter consequently starts with a little economics, which is then brought to bear on the benefits and costs of the aviation sector. Finally, we discuss the important linkages between policies to internalise external costs and policies to reform fiscal treatment of aviation.

2.2 Internal and external effects

To properly grasp the context of the present study it is, in the first place, very important to understand the distinction between internal and external effects. The concept of external effects was first introduced by Marshall (*Principles of Economics*, 1890) and later refined by Pigou (*Economics of Welfare,* 1920)[3]. In an era encompassing two world wars, mass unemployment and hyperinflation the concept was originally deemed primarily a theoretical refinement. However, in the last few decades the practical implications have become much more apparent. This has led to multiple and increasingly refined definitions of external effects, of which the following is perhaps the easiest to understand:

External effects are economically relevant impacts that agent A imposes on agent B without recognising or accounting for them[4]*.* Note that external effects are thus not synonymous with 'damage', but with 'costs unaccounted for'.

Frequent discussions arise from the fact that some studies take the **transport user** as the reference point of distinction between internal and external effects. From the perspective of the transport sector, it is clear that not all benefits accrue to the direct user. Many direct user benefits are processed in a 'second round' by markets by way of changes in relative prices (see following section). These so-called *pecuniary* external transport benefits are external to the user but still no reason for government intervention as they are properly captured by the market.

However, external effects as we define them here *are* ground for government intervention as they do **distort** markets and thus cause economic **inefficiencies**. These *technological* external effects occur when economic actors use assets without paying for them. The opposite is also possible: external benefits occur when economic actors provide assets without being paid for them. It is clear, however, that while economic actors will generally

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3 Pigou describes the example of the 'uncompensated disservices', as he calls them, of a smoke-producing factory, '… for this smoke in large towns inflicts a heavy uncharged loss on the community, an injury to buildings and vegetables, expenses for washing clothes and cleaning rooms, expenses for the provision of artificial light, and in many other ways'.

4 Based on the literature survey conducted in (Delucchi 1998).

themselves try to internalise all external *benefits* as far as possible, third parties such as governments are generally necessary to make them pay their external *costs*. This is why debates on government intervention in the aviation sector usually focus on external costs, with less attention given to external benefits.

Examples of technological external costs include the costs of air pollution, noise and accidents involving people off the actual aircraft. In these cases the transport users use the 'assets' clean air, peace and quiet and public safety without paying for that use. At root, the problem is that there are no property rights for these goods: no one 'owns' the markets in question.

A clear example of a technological external *benefit* of air transport is plane-spotting. Plane-spotters enjoy the pleasure of watching the aircraft, but do not generally pay the airlines for it (except in the case of air shows, or levying of a fee for a particularly good spot).

2.3 Benefits of air transport

The benefits of air transport are obviously large. To a major extent these benefits are reflected in the willingness of citizens and companies to pay airlines for their services. However, the revenues from tickets and cargo do not tell the full story. As holds true for every economic good, in the case of air transport, too, aggregated benefits to consumers are (far) greater than aggregated expenditure on tickets. This is because citizens and companies only buy tickets if this improves their welfare. In economics this difference between society's willingness to pay and actual payment is referred to as the *consumer surplus*. Airlines continuously strive to reap as much of the consumer surplus from their clients as possible by offering them a broad range of services and ticket price options. The consumer surplus minus ticket and cargo fares paid probably forms a good proxy for the net user benefits of air transport (Button, 1999)[5].

Spill-over effects
In the context of transportation, an often-discussed category of benefits is the so-called 'spill-over' effect: the fact that not all transport benefits accrue to the user (as described in the previous paragraph). Many non-aviation business activities are able to operate more efficiently thanks to the existence of the (air) transport industry. In the case of business transport, the passenger's consumer surplus is transferred to his employer, who might in turn transfer these benefits to his customers by supplying better services or cheaper products. Another example of benefits that do not accrue to transport users is the relocation of businesses following airport expansion to benefit from the improved accessibility. Businesses can balance these new transport benefits against the costs of relocation. Because these spill-over effects are indirectly part of market decisions and private calculation, they are not considered external effects according to the definition adopted here and would, as such, not form grounds for government intervention.

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5 Another often used criterion, the value added by the aviation industry, is interesting because it provides insight into the *sectoral* economic interest. However, it is not a good measure for *societal* economic benefits. Consider cost reduction in the aviation industry: this could decrease added value within the sector, at the same time increasing overall societal benefits.

Imperfect markets
It should be noted, however, that this reasoning is based on neo-classical economic theory, under the assumption that markets work perfectly. In reality, though, this is not always the case. Distortions arise because of cross-border competition, for example, which restricts the scope for domestic decision-making. Non-economic factors such as consumer perception and 'brand image' also play a major role in business decisions and may lead to clustering effects, for example.

Virtually all studies agree that (air) transport does not *in itself* give rise to external benefits, apart from the aforementioned case of plane-spotting. It is the airlines' business to internalise as many of the benefits of air transport as possible, so there is no specific role for governments here.

Most studies also agree that, under very specific circumstances, (air) transport *infrastructure* might lead to additional benefits (or additional costs)[6]. In other words: all relevant benefits of air *transport* can generally be considered as internal to the market. In the case of airport infrastructure investments, all benefits and costs should be carefully analysed to establish whether any additional benefits or costs arise.

Finally, it is worth noting that even if air transport does give rise to external benefits in certain situations, it is still always economically efficient to internalise any external costs. This is because costs and benefits have an entirely different background and should therefore be treated separately. It is always economically efficient to reduce unwanted noise and emissions due to aviation to optimum levels, irrespective of the benefits that the same aviation brings to society. See section 2.6.

2.4 Costs of air transport

Before mapping out the external costs of air transport, it is useful to provide the context of a full cost review. Aviation costs can be divided into costs borne by the user, external costs and costs incurred by the state.

User costs (internal costs)
These encompass all *private expenditure on transport*. In aviation this is generally the price paid for tickets. These costs are not the subject of this study. It is assumed that the market mechanism brings about proper prices for these types of costs, and that this is not therefore an issue for the state.

Government expenditure (direct and indirect financial support)
Government expenditures on (air) transport are unpaid costs, to the extent that the user does not take them into consideration in his mobility decisions. Expenditures can be classified as either:
- direct financial support, i.e. direct money transfers, or
- indirect financial support, such as tax exemptions or lower tax rates.

In this study we shall not address these government expenditures.

External costs
Verhoef (1996) sets out three different types of external transport costs. Although these hold for all modes of transport, external effects may differ markedly from one mode to another.

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[6] See, for example, 'Evaluating infrastructure projects; guidance for appraisal' (Dutch Ministry of Transport), and 'Transport and the economy' (SACTRA 1999).

1 External costs resulting from actual transport activities, which can therefore be considered marginal costs: the costs of emissions of hazardous substances, noise nuisance, odour nuisance and public safety, for example. Emissions include nitrogen oxides (NO_X), carbon dioxide (CO_2), hydrocarbons (HC) and particulates (PM_{10}). These costs are at the heart of this study and will also be assessed financially. Odour nuisance and public safety are not treated, however.
2 External costs caused by stationary vehicles, here parked aircraft. These costs are not included in this study. In the case of aviation these will be limited compared with other costs, with the exception of Auxiliary Power Units (APUs) that, when powered with jet fuel, may cause substantial HC emissions at ground level.
3 External costs closely related to the existence of infrastructure: barrier effects, fragmentation of the countryside (with adverse effects on ecosystems and other consequences) and eyesores ('horizon pollution', although some may gain pleasure from the same view). We shall ignore these costs, too, as they are highly variable across different airports and are probably small compared with the other impacts associated with the aircraft using them.

The valuation of external effects will be discussed in Chapters 3 to 5.

Marginal, fixed and social costs
The aforementioned cost items can be further categorised as follows:
- marginal costs: strictly interpreted (short term), these are the additional costs arising from the addition of one aircraft to the skies or at an airport;
- fixed costs: these are costs that are independent, in the medium term, of the amount of mobility, e.g. the costs of building infrastructure;
- social costs are the sum of all mobility costs: internal costs, external costs and government expenditures. Internal costs are not taken into consideration in this report, because the market mechanism enables these costs to be properly allocated to users.

2.5 External costs

2.5.1 Negative external effects

External costs are the costs of negative external effects. These negative external effects arise from the absence of markets for such valuable collective goods as a stable climate, clean air, peace and quiet and public safety. Negative external effects do not form part of private decisions or calculations and are thus not included in private costs or market prices.

In this study we restrict ourselves to a consideration of the following negative external effects:
- climate change due to aviation emissions;
- air pollution due to aviation emissions. with impacts on humans and nature;
- the effects of noise: nuisance, health effects and indirect effects on land use resulting from sub-optimum spatial planning due to zoning.

This study does not consider the impacts of aviation on the stratospheric ozone layer. This is because of the uncertainties surrounding these impacts and the paucity of information for assigning a financial value.

The safety risk, i.e. the risk of crashes and accidents for property, communities and individuals near airports is another negative external effect not considered in the present study. Especially in the case of airports in or near cities, this risk may give rise to significant externalities.

It is widely accepted that aviation is associated with negative external effects. As mentioned earlier, however, the problem for society is not so much the existence of the negative effect as such, but rather the tensions arising from the non-existence of a market. According to Verhoef (1996), the "unresolved tension between the receptor, facing a quantitative constraint on the consumption of the externality, and the supplier, who has no a priori interest in the magnitude of the externality, can only persist provided there is no market on which the externality is traded, caused by a lack of well defined property rights concerning the externality." If the receptor and supplier could directly negotiate about optimum emission levels, this tension would be resolved. We call this internalisation.

2.5.2 Can external costs be estimated?

The challenge of this study is to predict the probable prices ('shadow prices') that would occur if markets existed for clean air, peace and quiet and so on. Two developments facilitate this process.

First, in certain areas like climate change markets are beginning to emerge. Studies on probable shadow prices in this market are now abundant.

Second, there has been considerable progress in the science of establishing shadow prices on the 'imaginary' markets for clean air and peace and quiet. Knowledge on dose-response relationships has greatly improved and there is an increasing consensus on methodologies for valuing these responses, especially health effects. As a result it has become increasingly feasible, after a careful study of the body of literature, to explain the differences found between individual studies, so that small-range estimates can now be provided for specific situations. As long as there are no real markets in existence, however, 'real' prices will never be known. The aim of this study, then, is not to provide definitive answers as to the level of external costs, but rather to present plausible ranges and explain these.

At the same time, though, policy development does not require a precise knowledge of external costs. The primary aim of 'internalisation' policies is to generate efficient market incentives to reduce negative impacts to optimum levels. This implies that, in the short term certainly, the s*tructure* of the incentive being given is at least as important as its *level*. In the longer term, it is easier to adapt incentive levels to the optimum than it is to change the incentive structure.

2.6 Is it useful to add external benefits and costs to yield a 'net' result?

Now that we have described the relevant costs and benefits of air transport, the question is whether it is useful to add these costs and benefits to arrive at a 'net' result.

The answer to this question is simply no. The backgrounds and causes of external benefits and costs are very different, and different instruments and mechanisms are therefore necessary to address them. Even aside from the issue of the extent to which external benefits truly exist, it would be extremely inefficient if the same instruments were used for internalising both external benefits and costs, because the lack of market incentives to reduce costs would persist. Internalising external costs is, in principle, always efficient[7], regardless of the existence of external benefits.

2.7 Efficiency and fairness

Although it is not the principal aim of this study to discuss policies aimed at internalising external costs or fiscal policies, the subject of internalisation of external costs cannot be adequately addressed without describing the links between internalisation, pricing and taxation. In the public debate about aviation charges two arguments prevail and are used in combination: first, external effects need to be reduced and, second, it is only fair that aviation should pay taxes, like road traffic, for example.

2.7.1 External costs: internalisation and efficiency

The first pillar on which this report is built is the issue of the external costs of aviation, which is in essence a problem of economic inefficiency. This economic inefficiency can be resolved by internalising external costs. It should be stated once more that the main aim of such internalisation is to reduce external effects to a 'social optimum', i.e. to a point at which the marginal abatement costs are just as high as the marginal damage costs (see section 3.2).

This means that the aim of internalisation is NOT to reduce emissions and environmental impacts to zero. The cost of, say, reducing the last decibel of noise will certainly be much (if not infinitely) higher than the benefits accruing to society from doing so. It also means that the aim of internalisation is NOT to reduce the volume of aviation, although this is a likely consequence. Consider the case of there being numerous cheap options to reduce noise to almost zero. In this case, internalising the external costs of noise will lead to use of these cheap options and therefore to only limited cost increases and only limited transport volume reductions. In other words, the ultimate volume reduction following internalisation will depend on the magnitude of the external effect and the availability of cheap abatement measures.

Second, it is important to mention that there are other options besides pricing available to internalise external costs. For example, tradable permit schemes and regulation might also be used to achieve internalisation.

Theoretically, the most efficient internalisation options are those in which external costs are reduced to the optimum level in the most efficient manner. Options to reduce external effects may include technological and operational improvements, substitution to alternatives and volume reduction. Classical examples of efficient, market-based policy options are pricing and trading schemes.

An important choice is whether or not internalisation schemes are to generate government revenue. Pricing schemes provide such an opportunity, as do emission charging schemes in which an auction serves as permit distribution mechanism. Emission trading with a 'grandfathering' system of permit distribution does not yield revenues. In principle, the revenue issue is a matter of equity rather than efficiency, since it does not affect marginal pro-

7 Unless the benefits of internalisation in air transport are outweighed by increases in the external costs associated with alternative modes of transport.

duction costs. An advantage of revenue-raising approaches over non-revenue generating alternatives is that the former provide an opportunity to lower distorting taxes such as labour taxes, payroll taxes or VAT (the 'double dividend'). This is where the link with taxation comes in (see next section). From the perspective of economic efficiency, taxes corresponding directly with external effects (e.g. fuel taxes) are to be considered internalisation tools.

Compared with regulation, pricing and trading both have the advantage of flexibility: market parties are all free to implement the abatement options best suited to their particular circumstances rather than adopting standard measures.

Under efficient internalisation policies, all negative effects will be priced according to their marginal social costs and consequently all measures cheaper than the marginal social costs will be duly implemented.

2.7.2 Taxation and fairness

Besides the issue of the external environmental costs of aviation, fair fiscal treatment also plays a key role in the debate on environmental policy vis-à-vis aviation. These issues are often intermixed, however, and it is important to make a distinction as economic efficiency is the main aim of internalisation, while fairness is an important argument in the case of taxation.

It is generally considered fair for all economic actors to be afforded equal treatment, i.e. pay the same taxes for the same goods. A good example is VAT. VAT has no direct relationship with external effects and imposing VAT is therefore not necessarily an efficiency-promoting policy. However, it is generally considered unfair for different VAT regimes to apply to different modes of transport. A more complicated issue is the fuel tax.

The case of the fuel tax

In the case of the fuel tax, the efficiency (internalisation) and fairness (taxation) perspectives are both at stake. From the angle of economic efficiency, fuel taxes can be considered a prime instrument for internalising fuel-related externalities, primarily CO_2 emissions. According to the relevant tax laws, however, most countries regard these road transport taxes not as instruments for achieving part-internalisation of external costs, but as general taxes. This implies that, in the case of road transport, any charges aimed at internalisation would come on top of the existing taxes for that mode of transport. For aviation the consequence of this interpretation is that, on top of efficiency-promoting charges, a general tax could be considered in order to do away with the current tax exemption, as is the case for road transport.

In some countries tax laws adopt a different approach, regarding specific taxes on road transport, such as fuel and vehicle taxes, as (part-)payment for the use of infrastructure and external costs. This implies that the level of additional, efficient pricing will be much lower than in the case of the aforementioned fiscal approach.

Of course, the issue treated is closely related to the ICAO Council Resolution on Charges and Taxes of December 1996. This Resolution strongly recommends that, *inter alia*, "the funds collected should be applied in the first instance to mitigating the environmental impact of aircraft engine emissions", and urges that:

- "there should be no fiscal aim behind the charges;
- charges should be related to costs;
- the charges should not discriminate against air transport compared with other modes of transport".

The interpretation of existing and possible new fuel and vehicle taxes and charges is thus another crucial element in the debate on internalisation and fair fiscal treatment of aviation and other modes of transport.

Fairness and other transport modes
As already mentioned, this study does not attempt to compare current internalisation or fiscal treatment of aviation with the situation for other transport modes. The bulk of the air transport market does not face serious competition from other forms of transport, and besides, such comparisons would require many subjective assumptions to be made.

In short, the aviation (and car) industry often state that it is unfair that they should have to pay full social costs, including external costs, as long as rail transport does not have to pay for its infrastructure. In general, each transport mode points to the perceived or real advantages of the other modes, as an excuse for not having to internalise their own external costs. Here indeed lies a true challenge for decision-makers: to develop a transparent policy that is perceived as fair to all modes of transport.

3 Financial valuation of environmental impacts

3.1 Why financial valuation?

Most economic activities, including air transport, bring with them a range of unintended side-effects, among them emissions contributing to global warming, air pollution and noise. Although these emissions are unwanted by society and therefore lead to social costs, they come with no price tag attached. The economic actors responsible for these emissions therefore have no financial incentive to reduce them and abatement efforts are consequently generally below the social optimum.

Assigning a financial value to emissions may provide better leverage for enhancing the efficiency and rationality of measures to tackle the environmental problems of global warming, air pollution, noise and so on. This chapter discusses the principal methods available for such financial valuation.

3.2 Damage and prevention costs

The social costs of aviation emissions can be divided into two categories:

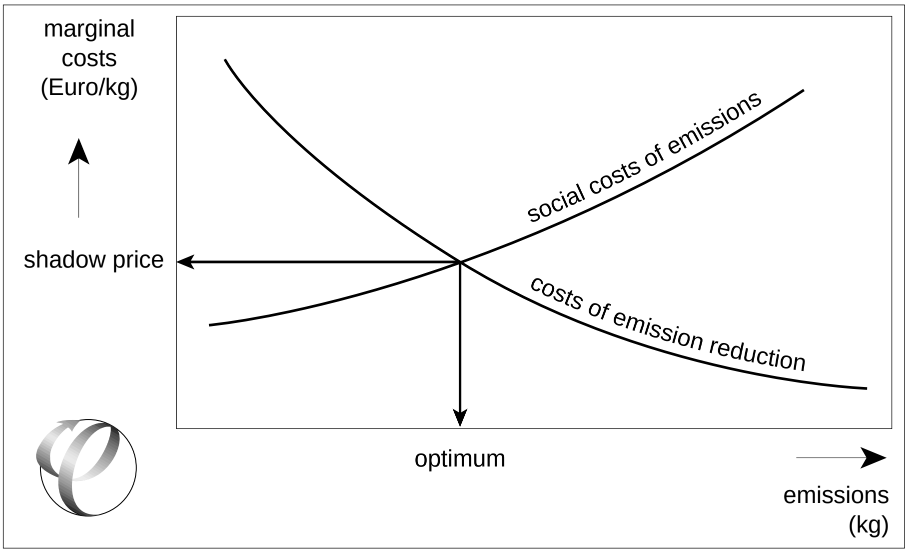
- **Costs of damage/nuisance plus avoidance/adaptation**
  Aircraft emissions of greenhouse gases, pollutants and noise may damage human health, the natural environment, buildings and equipment as well as give rise to nuisance. Accidents are another possible source of social costs (off-site risks). Finally, costs are sometimes incurred in trying to avoid or minimise the damage caused by pollution. Governments may, for example, decide to impose zoning restrictions on land that is subject to excessive noise or off-site risks. These costs can be categorised as avoidance costs of adaptation costs.
- **Costs of abatement and prevention measures**
  For some environmental effects, general (environmental) quality criteria may be laid down in the political decision-making process, i.e. across-the-board emission standards for all sectors of society. Extra emissions occurring under this kind of regime do *not* lead to extra environmental damage, but imply, rather, that somewhere in society additional emission abatement measures are required. Such measures to compensate for e.g. aviation emissions are once again associated with social costs.

Transaction costs, the costs of planning and monitoring the process, play a frequently forgotten but nevertheless often decisive role in the decision-making process.

As already mentioned, at present the social costs of emissions, noise and safety risks are not adequately taken into account in the aviation industry's decision-making processes. When such social, or *external*, costs arise, it means general economic welfare would be improved by taking measures to reduce the particular environmental impact concerned. The situation is illustrated in Figure 6, on the right of the intersection of the two curves.

Figure 6 shows first, as a function of total aviation emissions, the social cost of one extra unit of emission – the cost of health damage due to toxic emissions, for example. The second curve represents the cost of one additional unit of emission *reduction*, which also comes with a price tag. However, the costs associated with emission reduction are not paid by society as a whole, but by airlines, where the scope for effective action lies. This action may take the form of technological measures (using quieter aircraft), operational measures (altering approach corridors) or volume measures (grounding aircraft). The further emissions are reduced by the aviation sector, the greater the costs of additional reduction, assuming that the cheapest measures are implemented first. If little emission abatement action has already been taken, an extra unit emission can be reduced at relatively low cost. If a wide range of measures are already in place, however, and technological options have been exhausted, there comes a time when even very quiet and profitable aircraft will have to be grounded in order to achieve a little extra emission reduction.

Figure 6 Costs to society (upward curve) and to airlines (downward curve) of one extra unit of emission



From the figure the following conclusions can be drawn:

1 Theoretically there is a social optimum, at a certain emission level, represented by the intersection of the two curves. If airlines reduce their emissions by more than this optimum, they will be implementing abatement measures that cost them more than the benefits accruing to society in the form of reduced nuisance, say. If emissions are reduced by *less* than the social optimum, the converse holds. Thus, the optimum consists neither in zero emissions nor in unrestricted emissions.
2 The social optimum is associated with a ‘price’ per unit emission. It is unwise to implement abatement measures costing more than this price, and equally unwise to reject abatement measures that are cheaper. The optimum therefore represents a situation in which only the cheapest measures required for achieving the optimum are implemented.

Because the social costs of aviation are not currently reflected in the price of air travel or transport, it is more than likely that current aircraft emissions are greater than the optimum (to the *right* of the figure).

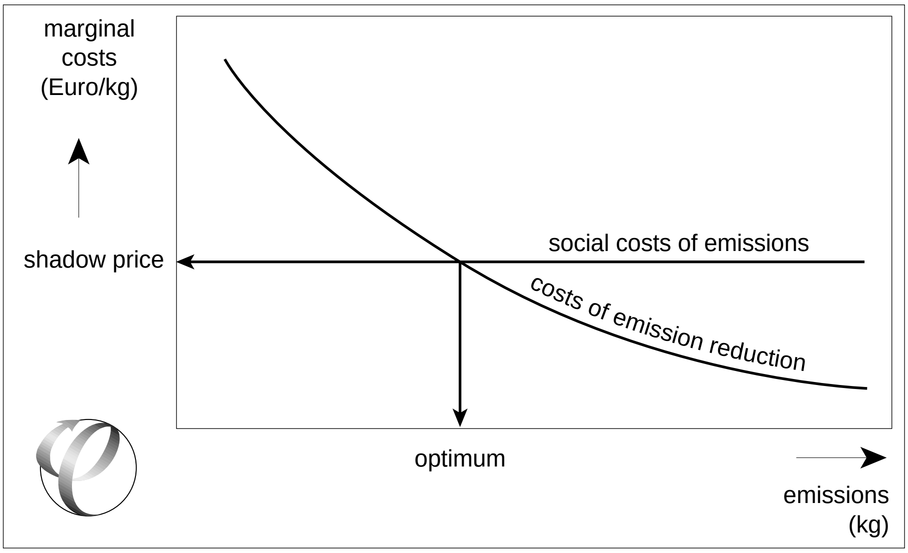
3.3 Valuation methods for environmental effects

The next question is how to assign a suitable price to the environmental effects. Different valuation methods may be applied, depending on whether or not environmental standards are in place for the specific impact concerned. These methods will be discussed in the following sections.

3.3.1 Valuation methods for damage, nuisance and avoidance

If there are no across-the-board emission reduction targets (see Section 3.3.2) in place for the pollutant in question, it is the costs of damage, nuisance and avoidance (in this case, in the form of indirect land use) that determine the social costs of emissions. Several methods are available for estimating these costs. In itself, however, this knowledge is not sufficient for calculating a shadow price, which also requires a knowledge of the curve representing the prevention costs incurred by the emitters (see Figure 6). The simplifying assumption is often made that the total costs of emission damage are proportional to the emission level or, in other words, that the so-called marginal costs remain constant. How reasonable this assumption is will depend on the external effect in question. The advantage of the assumption is that it enables valuation to be undertaken in a single step (see Figure 7).

Figure 7 Assuming constant marginal damage costs for ease of valuation



The following methods are available for calculating the social costs of damage, nuisance and avoidance[8]:

Direct damage cost estimates
This method seeks to make a direct valuation of the damage arising from a given activity, as illustrated by a few examples. A value can be assigned to air pollution damage to agriculture and forestry by valuing the ensuing crop losses. In the case of accidents, an estimate can be made of the victims' lost productive output and medical expenditure. Air pollution damage to buildings

[8] The following discussion is based on interpretation of numerous reports, including Schipper (1999), ECMT (1998), Infras/IWW (2000), CE (1994, 1999) and MuConsult (1999).

can be estimated on the basis of repair costs. From a fundamental viewpoint, this method is undoubtedly the best: if actual damage can be perfectly assessed and valued, this method is superior to the others, each of which has at least one fundamental drawback. At the same time, however, more practical considerations often make application of other methodologies unavoidable.

The first practical drawback of this method is that dose-effect relationships cannot generally be established for each and every material consequence occurring in actual practice. The main reasons are lack of measurement data and statistical problems. There may even be as yet unidentified forms of damage and the method will therefore often leave many items unvalued, as 'items pending', thus providing merely a minimum estimate of lost welfare. Secondly, it is often virtually impossible to value immaterial damage. Damage to nature and biodiversity, as well as psychological damage (in the case of noise and accidents), are notoriously difficult to assess.

Willingness to pay / Willingness to accept via surveys
A second approach is to use 'stated preference' (SP) surveys to establish how much people are prepared to pay to avoid damages ('willingness to pay', WTP) or the compensation they desire to accept damages ('willingness to accept', WTA). One of the strengths of this method is the fact that it covers immaterial as well as material damages. Besides several practical weaknesses (respondents providing 'strategic' answers, major influence of type of question asked), it also has two more fundamental weaknesses:

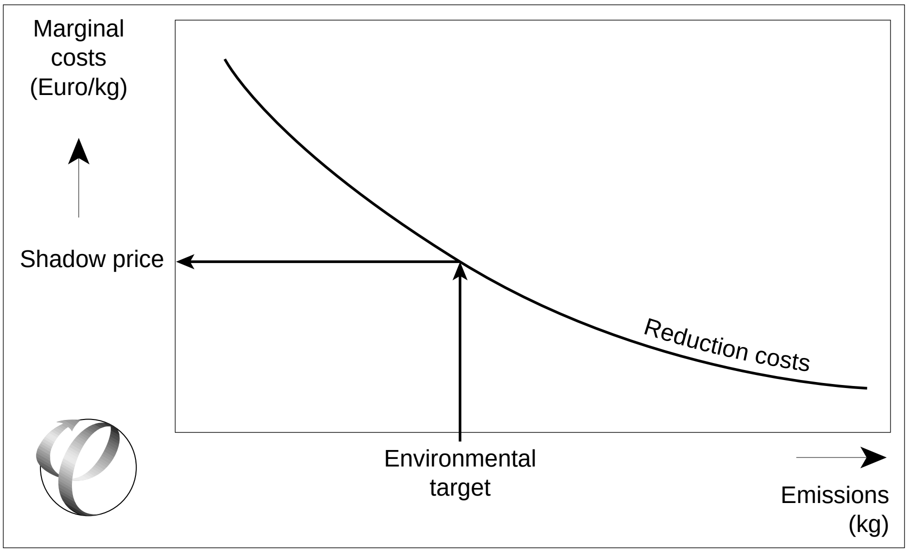
- it is extremely debatable whether respondents are capable of assigning a meaningful value to external effects, as is obvious from the example of global warming and even becoming apparent for (the health effects of) noise. While the method is useful for valuing local effects ('quality of life'), therefore, it is in principle less suitable for global and regional environmental problems;
- the method is usually applied to small groups of respondents who generally seem to be those most concerned about the problem being surveyed. However, the welfare of other people may also often be affected indirectly by the external effect. For example, while aircraft noise is of direct influence on the welfare of local residents, restrictions on land use as well as the noise itself will inhibit people outside the directly affected area from choosing an optimum housing location and raise property prices in unaffected areas.

Willingness to pay / Willingness to accept via changes in market prices
In this 'hedonic pricing' or 'revealed preference' (RP) approach a cost is assigned to external effects on the basis of their observed (revealed) impact on market prices, as when noise and air pollution cause rent and property prices to fall. This method has one fundamental drawback: its limited scope. The potential damage caused by the greenhouse effect, for example, will not be reflected in property prices. Where appropriate, though, this method is probably superior to the survey approach for WTP/WTA, since 'revealed preferences' (i.e. as reflected in market prices) appear to be a more reliable yardstick than 'stated preferences'. There remain several practical obstacles in the statistical assessment and isolation of variables, however.

3.3.2 The prevention cost method

For certain environmental impacts, across-the-board targets for environmental burden are in place for all sectors of society. In these cases, society has weighted – explicitly or implicitly – the costs and benefits of abatement measures. The price of emissions will then be formed by the marginal costs of reducing the impact to the overall target level. If one assumes that society will apply the cheapest measures first to achieve the targets, then an extra unit emission will make it necessary to apply an extra abatement measure of which the costs are equal to the shadow price. This method therefore requires greater knowledge of the shape of the reduction cost curve, i.e. the costs of the abatement measures involved (Figure 8).

Figure 8 Obtaining a shadow price from environmental targets



An important discussion that often arises when the prevention cost methodology is used is whether the across-the-board emission reduction target is 'correct'. Some people may argue that the target is too strict (too far to the left of the graph), others that it is too lax (too far to the right). They have different perceptions of environmental damage and risks, on the one hand, and the economic damage and risks involved in setting different targets, on the other. In effect, the first category would like laxer policies and the second stricter policies.

We feel that this report – which assesses a single, internationally operating economic sector, namely aviation – is not the appropriate place to discuss the correctness of international across-the-board emission reduction targets that have been agreed in a political process. The aim of this report is to establish the costs that arise when the aviation sector emits one extra kg of emissions. If there are across-the-board reduction targets in place, these costs are given by the costs of reducing one kg of emissions somewhere in the economy.

In particular, we would mention a few reasons for not using so-called 'scientific' or 'sustainability' targets when governments have agreed on official targets:

1 Using targets that differ from those politically implemented would lead to inconsistencies in government policy. It is doubtful whether a sectoral

study, such as this one on aviation, is the appropriate platform for questioning policies at a higher level, such as across-the-board emission standards for all sectors of society.

2 Setting a price tag on emissions on the basis of a target different from that holding for the rest of society would lead to inefficiencies. If a more ambitious target were set, it would lead to the aviation sector implementing measures that reduce emissions at higher cost than would have been incurred by other economic sectors. With a less stringent target the opposite would occur.

3 It is highly debatable whether targets can be formulated on a scientific basis alone. Science may be able to indicate the emission levels at which damage and risks become small. However, in virtually all cases, one must weigh the costs of risk reduction against the remaining risks. In some cases, such as global warming, there is also uncertainty involved. There will never be zero risk and there is no clear-cut point at which risks become negligible, tolerable or acceptable, none of which concepts belong in the realm of the natural sciences, but rather require political or normative judgement.

4 If normative judgements are a necessary part of policy target formulation, the democratic decision-making process seems to be the most qualified arena for setting those targets. It will be clear that such issues as the asymmetric influence of certain lobby groups and lack of democratic legitimacy of parties at the international negotiating table may disturb this arena. Still, in the framework of the present study it cannot be judged *a priori* to which side of society's preferences the outcome of such negotiations will tend. Besides, as already stated, the aim of this study is not to contribute to the debate on across-the-board emission standards for all sectors of society, as these are already in place.

Finally, a few practical problems associated with the prevention cost method should be mentioned which should not be overlooked. This is because the establishment of marginal prevention costs requires the shape of the reduction cost curve to be known, as an *ex ante* assessment of possible future measures.

This gives rise to the following problems:

- costs are often overestimated because the *dynamics* of technology development are underestimated. Only measures identified at the time of establishing the cost curve are taken into account, with new solutions unforeseen;
- costs are also often overestimated because in many studies only *technological* options to reduce emissions are considered. If behavioural (operational) changes and volume changes are included in the cost curves, the marginal prevention costs will obviously fall;
- on the other hand, costs are often underestimated because prevention cost curves assume measures to be applied in order of cost-effectiveness. In other words, they assume that a perfect market exists for emission reduction. In reality, the market for emission reduction is often far from perfect, as all kinds of regulations and agreements currently in place hamper actual reduction of emissions across all sectors;
- costs are also often underestimated because transaction costs and comfort costs are often ignored or overlooked. An example of transaction costs is the cost of incomplete information. An example of the existence of comfort costs is the fact that many people do not choose to drive a very fuel-efficient car, although doing so would save them a considerable sum of money.

Finally, we note that damage and prevention costs may not be added to arrive at a ‘final’, 'net' result. The two approaches are complementary, stem from different valuation philosophies and have their own specific pros and cons. If the reader's aim is to obtain an impression of the actual damage arising from one extra tonne of emissions, in the context of negotiations on optimum emission reduction targets, for example, they should use the damage cost approach. If the reader is convinced that one extra tonne of emissions in one place will not lead to extra damage because this will be mitigated by emission reductions elsewhere, they should use the prevention cost approach.

3.3.3 Summary

If NO across-the-board emission reduction targets exist, the most satisfactory approach to environmental valuation is direct valuation of damage, nuisance and avoidance costs. This can be done by establishing dose-response relationships for all relevant effects and valuing each of them individually. If enough data are available to value at least some of the effects, this approach can be used to obtain a good minimum estimate of costs. Indirect valuation methods, such as stated and revealed preference methods, can be applied in cases where environmental effects have a direct and local character, but due note should be taken of their drawbacks. In cases where the environmental effects are long-term and regional or even global in character, stated and revealed preference methods do not seem satisfactory because either too much knowledge is required on the part of respondents (stated preference) or clear relationships with real-market prices are lacking (revealed preference).

If broadly agreed across-the-board emission reduction targets DO exist, the prevention cost method can be applied. This is because in this case the cost of an extra unit of emissions at one location is NOT determined by the damage due to these extra emissions, but by the marginal costs of measures to reduce the same emissions elsewhere. As the costs of measures are all that count here, the debate on whether or not targets are 'correct' (i.e. set at or near the social optimum) is not relevant in this approach. Besides, this report is not the place to discuss the correctness of across-the-board emission reduction targets that have been politically agreed. The most important advantage of this approach is its consistency with politically agreed, across-the-board environmental policies. Its greatest disadvantage is that many people consider these targets either too strict or too lax. Besides, the prevention cost method has several practical drawbacks that makes actual estimation of the costs of measures harder than it may seem here.

The major findings are summarised in Table 3.

Table 3 Principal pros and cons of different approaches to valuing environmental effects

cost category	damage/nuisance + avoidance/adaptation cost approaches			prevention / abatement cost approach
subcategory	direct damage costs (dose-response)	stated preference (SP), CVM, WTP/WTA	revealed preference (RP); hedonic pricing	
main advantage	theoretically satisfying	good at non-material damage	within its scope better than stated preference	consistent with reduction targets defined
fundamental drawback	none	lack of knowledge about effects	limited scope	reduction targets may be ‘wrong’
		limited population		
practical drawback	dose-response relationships for all effects	strategic answers	statistical analysis	dynamics of technological development
	valuation of non-material damage	importance of question type		assumption of perfect markets
				transaction and comfort costs
application recommended	when adequate damage and valuation data are available	for short-term and local effects	for short-term and local effects	for regional/global effects, with agreed reduction targets
		when non-material damages are substantial	when damages are mainly material	

Source CE interpretation of international literature.

Abbreviations:

CVM Contingent Valuation Method

WTP/A Willingness to Pay / Accept

3.4 Definition of types of aircraft and flight

Aircraft types play no significant role throughout most of this study. An important aim of this project is to establish external costs per unit emissions or noise, irrespective of the aircraft causing these emissions.

In the presentation of the results, however, it is important to translate the costs to several types of aircraft. We distinguish four different passenger aircraft, ranging from 40 to 400 seats, and two flight distances, 200 and 6,000 km. We also distinguish two technology levels: ’market-average’ and ’state-of-the-art’ technology. We make no reference to aircraft complete with names and makes; the main purpose of this study is to present typical values for specific aviation markets.

Freight is a special issue. Most freight is transported in combination with passengers and is generally transported over long distances. KLM and Lufthansa’s average freight transport distance is about 6,000 km. For the freight analysis we have therefore taken a combination flight of 6,000 km as our reference. For this distance flight, external costs will have to be allocated to passengers and freight separately. The methodology used for this purpose is described in Annex V.

We shall consider the following cases:

Passenger transport:

- aircraft with about 40 seats flying about 200 km (typical of short-distance domestic transport);
- aircraft with about 100 seats flying about 500 km (typical of short-haul intra-EU transport);
- aircraft with about 150 seats flying about 1,500 km (typical of longer-distance intra-EU air transport);
- aircraft type with about 400 seats flying about 6,000 km (relevant for intercontinental travel).

The characteristics of freight transport are entirely different from those of passenger transport. Freight is moved over much longer distances, and about three-quarters of the world's freight is carried in passenger aircraft. For the freight analysis we therefore consider the freight part of the 400-seater at 6,000 km.

We distinguish two aircraft classes with respect to environmental technology (emissions and noise). The technical and environmental profiles below are based on a model fed with inputs from a wide variety of sources (Janes 2001, CE 1997c, CE 2001b, IPCC 1999, Lee 2000, ICAO 2001).

Table 4 Technical characteristics of aircraft analysed, both market-average and state-of-the-art technology

type	typ. distance (km)	MTOW* (tonnes)	maximum payload (tonnes)	seats (#)	pax (#)	freight (tonnes)
1: 40 seats, 200 km	200	17	4.5	40	20	0
2: 100 seats, 500 km	500	52	12	100	65	1
3: 200 seats, 1,500 km	1,500	110	24	200	140	2
4: 400 seats, 6,000 km	6,000	395	72	400	320	25

* MTOW: Maximum Take-Off Weight

Finally, in order to gain an impression of the relative magnitudes of the external costs, we have also quantified several economic characteristics of the aircraft. Both airport-related and flight-related costs have been taken into account.

Table 5 Economic characteristics of aircraft analysed, both market-average and state-of-the-art technology

type	landing charges		return ticket price	
	€/LTO	€/pax	€	€cts/pax.km
1: 40 seats, 200 km	200	10	100	25
2: 100 seats, 500 km	1,000	15	200	20
3: 200 seats, 1,500 km	1,500	11	300	10
4: 400 seats, 6,000 km	4,000	9	800	6.7

* MTOW: Maximum Take-Off Weight

Table 6 Environmental characteristics of today's market-average aircraft

type	fuel consumption		emission indices (g/kg fuel)					
	kg/LTO	kg/km in non-LTO ('cruise') phase	CO_2	SO_2	NO_X		$PM_{2.5}$	HC
					LTO	cruise	LTO	LTO
1	130	1.0	3.15	0.6	8	7	1	5
2	730	2.1			10	9	0.4	2
3	1,500	5.1			14	12	0.2	1
4	3,100	11			18	15	0.2	1

Table 7 presents the figures for the emission characteristics of a 'state-of-the-art' aircraft. Compared with a market-average aircraft, it has a 20% lower Specific Fuel Consumption (SFC), 20% lower NO_X and SO_2 emission index (EI) in grams per kg of fuel burnt and 70% lower PM_{10} and HC emission indices.

Table 7 Environmental characteristics of state-of-the-art aircraft

type	fuel consumption		emission indices (g/kg fuel)					
	kg/LTO	kg/km in non-LTO ('cruise') phase	CO_2	SO_2	NO_X		$PM_{2.5}$	HC
					LTO	cruise	LTO	LTO
1	110	0.84	3.15	0.6	6	6	0.3	1.5
2	590	1.7			8	7	0.1	0.6
3	1,200	4,1			12	10	0.1	0.3
4	2,500	8,9			15	12	0.1	0.3

4 Valuing greenhouse gas emissions

In this chapter we describe the methodology used in this study to value the climate change impacts of aviation. First we provide a brief, general overview of the current status of climate science, subsequently focusing our attention on aviation and on contrail formation in particular. Then, in section 4.4, we provide a short review of global policies to reduce greenhouse gas emissions, which then serves as input for actual valuation, from section 4.5 onwards.

4.1 The IPCC 'Third Assessment' and 'Aviation' Reports

In recent years scientific knowledge on the possible impacts of greenhouse gas emissions in general and aviation emissions in particular has improved substantially. This is reflected in the IPCC's 1999 'Special Report on Aviation and the Global Atmosphere' and its 'Third Assessment Reports', published in 2001.

As reported in the latter, "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities. (…) Most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations. (…) Emissions of CO_2 from fossil fuel burning are virtually certain to be the dominant influence on the trends in atmospheric CO_2 concentration during the 21st century. (…) The globally averaged surface temperature is projected to increase by 1.4 to 5.8°C over the period 1990 to 2100." (Report from Working Group 1, Summary for policymakers)

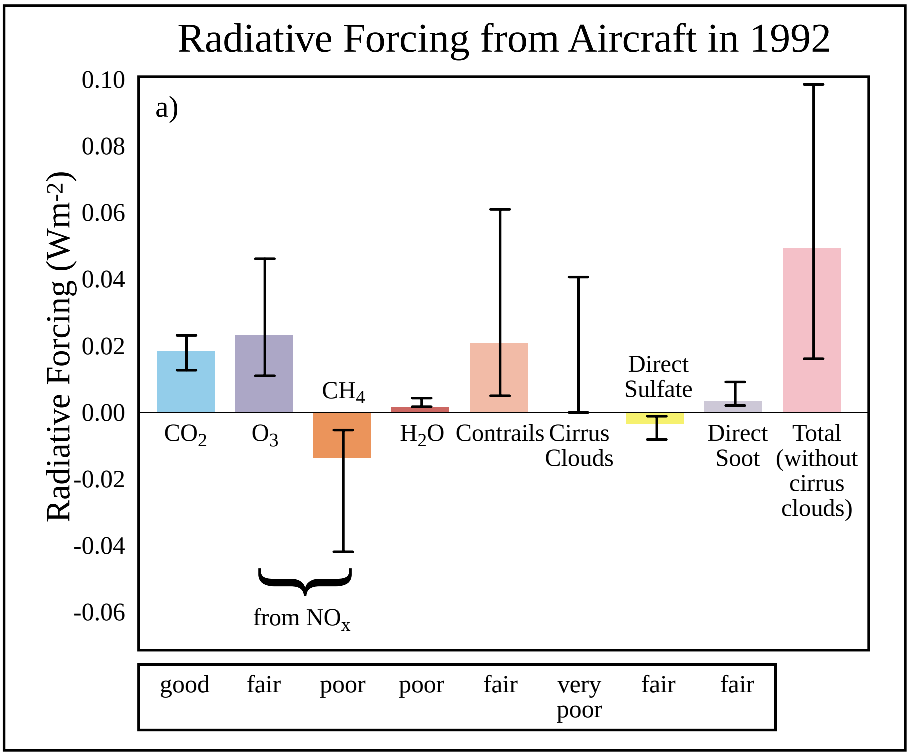
In a report requested by the American White House to help the Administration's ongoing review of U.S. climate change policy, the U.S. National Academy of Sciences confirms the major findings of the IPCC:

> "The committee generally agrees with the assessment of human-caused climate change presented in the IPCC Working Group I (WGI) scientific report, but seeks here to articulate more clearly the level of confidence that can be ascribed to those assessments and the caveats that need to be attached to them. (…) The IPCC's conclusion that most of the observed warming of the last years is likely to have been due to the increase in greenhouse gas concentrations accurately reflects the current thinking of the scientific community on this issue."

The former report, issued in May 1999, describes the likely global environmental impact of aviation in the base year 1992 and in the future. The report estimates that aviation's contribution to anthropogenic radiative forcing amounted to about 3.5% in 1992 and would, in a reference scenario, amount to 5% in 2050. In absolute terms forcing in 2050 would be 3.8 times as high as in 1992. The band width is rather broad: the lower and upper scenarios considered give a factor of 1.5 less to a factor of 3 greater than that for the reference scenario, ranging from 2.6 to 11 times the value in 1992.

One of the key graphs from this report is reprinted below.

Figure 9 Impact of aviation emissions on the earth's radiative balance and hence on the forced greenhouse effect, in 1992 (IPCC 1999)



Radiative forcing (RF) is defined here as the degree to which emissions change the radiative balance of the atmosphere. Global mean RF is approximately linear to change in equilibrium mean surface temperature and is therefore a good proxy for the global warming potential of emissions.

The bars indicate the best estimate of forcing, while the line associated with each bar indicates a confidence interval: based on current scientific understanding, there is a 67% probability that the true value lies within this range. The confidence intervals are largely independent of the level of scientific understanding ('poor', 'fair', etc.)

Ozone (O_3) is not a direct emission but is formed by atmospheric reaction, triggered by NO_X. The lifetime of the potent greenhouse gas CH_4, on the other hand, is shortened as a result of NO_X-emissions.

Table 8 presents the figures numerically, for calculations, and adds the figures for 2050.

Table 8 Perturbation due to aviation emissions of the radiative balance, in W/m^2, for the 1992 situation and a 2050 reference scenario, according to IPCC (1999)

perturbation due to	1992 middle estimate	2050 reference scenario, middle estimate	level of scientific understanding
CO_2	+0.018	+0.074	good
O_3 (from NO_X)	+0.023	+0.060	fair
CH_4 (from NO_X)	-0.014	-0.045	poor
stratospheric H_2O	+0.002	+0.004	poor
contrails	+0.02	+0.10	fair
cirrus	p.m. (0 - 0.04)	p.m. (0 - 0.16)	very poor
sulphate aerosols	-0.003	-0.009	fair
soot aerosols	+0.003	+0.009	fair
Total	**+0.049 + p.m.**	**+0.193 + p.m.**	

p.m.: *pro memoria,* 'item pending'

As the graph and table show:

- in the middle estimate of the reference scenario, total radiative forcing due to aviation will increase by a factor 3.8 between 1992 and 2050;
- emissions of NO_X lead to changes in tropospheric ozone (O_3) and methane (CH_4). On a globally averaged basis, these two effects have opposite signs: the net globally averaged impact on radiative forcing of O_3 is about half that of CO_2. IPCC (1999) states that "Changes in tropospheric ozone mainly occur in the Northern Hemisphere, while those of methane are global in extent so that, even though the global average radiative forcings are of similar magnitude and opposite in sign, the latitudinal structure of the forcing is different so that the net regional radiative effects do not cancel." This implies that in certain regions and circumstances, the external costs of aviation might be higher than calculated in this study, while in others they might be lower;
- the globally averaged impact of stratospheric H_2O emissions is about 11% of that of CO_2 and its share in environmental impact is likely to decrease somewhat;
- the globally averaged impact of persistent contrails is much more uncertain but, according to best estimates, comparable to that of CO_2. Moreover, the climatic impact of contrails is likely to grow faster than that of CO_2: between 1992 and 2050 a factor 5 increase is expected. Contrail formation can be accurately predicted for given atmospheric temperature and humidity conditions;
- the impact of the cirrus clouds that sometimes result from persistent contrails is known with even less certainty, but might be substantial, as upper estimates give twice the impact of CO_2 alone;
- the effects of sulphate aerosols and soot aerosols cancel; sulphate aerosols cool the earth and soot aerosols warm it, both at a rate of about 15% of that of CO_2 emissions;
- the total radiative forcing due to aviation, according to the middle estimate and excluding cirrus clouds, is about 2.7 times (2 to 4 times) as high as that due to CO_2 alone. In the 2050 scenario this factor is likely to remain fairly stable (2.6).

This implies that, according to current understanding, the prime concerns with respect to the climate impact of aviation are: emissions of CO_2, contrail formation and emissions of NO_X. In the following sections, which explain the methodologies used for valuing the climate impact of aviation emissions, we consequently focus principally on CO_2 and NO_X emissions and contrails. We do not value sulphur or soot aerosol emissions, as their contribution is relatively small, there is wide variation in emission factors and the chemistry is complex.

4.2 Impacts of NO_X emissions

As Table 8 shows, in 1992 the contribution of NO_X to the global climate change impact of aviation was about 18%. The forcing is the net result of the warming effect of ozone (O_3) and the cooling effect of methane (CH_4) lifetime reduction. Although the absolute radiative forcing resulting from NO_X emissions is predicted to increase, its contribution to total radiative forcing is expected to decrease to 8% in the 2050 reference scenario.

Ozone concentrations in the upper troposphere and lowermost stratosphere are expected to increase in response to NO_X increases and decrease in response to sulphur and water vapour increases. An aircraft's NO_X emission is therefore the first factor influencing ozone formation. Another important factor for these processes is the lifetime of NO_X, which is of the order of days in the upper troposphere and about a week in the lowermost stratosphere. Finally, ozone production also depends on the background NO_X concentration. At higher altitudes increases in NO_X may lead to decreases in ozone. Much scientific work is still required to clarify the exact processes and influences at work.

We here value the environmental impact of NO_X as follows:
- we use differentiated emission factors for different aircraft types;
- we work with globally averaged environmental impacts per kg of NO_X emission.

4.3 Impacts of contrail formation

In this report we give particular focus to the issue of contrails. This is for two reasons: their substantial contribution to the overall radiative forcing due to aviation, and the specific and fairly well-predictable operational circumstances under which they are formed. This section is based largely on a paper by Mr W. Fransen written specifically for this project (Annex II).

The contribution and formation of contrails
In Figure 9 we saw that in 1992 the contribution of contrails to radiative forcing due to aviation was about 40%. This climatic impact is caused primarily by so-called 'persistent' contrails: contrails that do not evaporate rapidly but evolve into more extensive contrail cirrus. Formation of contrail cirrus requires air that is about 30% ice-supersaturated. Recent humidity measurements show that about 14% of flight time occurred in air masses that were supersaturated with a mean value of about 15% (IPCC 1999, p.88). Other sources (IPCC 1999, p. 91) mention that 10 to 20% of the air masses over mid-Europe, or a global mean of 16%, would be cold and humid enough to trigger persistent contrail formation[9]. It is not accurately known at what degree of supersaturation additional aircraft water vapour would trigger contrail formation. If we assume that in 70% of this 'critical' flight time contrails are indeed formed (Fransen, 2001), then all radiative forcing from contrails (about 0.02 W/m^2, see Table 9) would occur during roughly 10% of flight time. It is interesting to note that contrail formation depends largely on

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[9] These figures immediately indicate potential maximum contrail coverage if flight paths were to span the entire qlobe.

the number of aircraft kilometres flown, irrespective of aircraft size, while other environmental effects are more dependent on fuel burn.

Table 8 also shows that in the future contrail formation might increase more rapidly than fuel burn. This is due to a number of factors. Exhausts will probably become cooler as a result of increased engine efficiency; a higher percentage of flight time may take place in the upper troposphere; and the number of aircraft km flown per kg fuel burnt will probably increase. This is why in the reference scenario (2050) contrail formation is expected to increase by a factor of about five, while radiative forcing from other impacts is expected to increase by a factor of about four.

Additionally, the circumstances under which contrails form show some correlation with those under which aircraft-induced cirrus clouds are formed. However, knowledge about such additional cirrus formation from aircraft is still very poor (IPCC 1999). We shall therefore not take additional cirrus formation into account in our calculations.

Predictability
Although it is beyond the scope of this report to assess mitigation measures, an important reason for the particular attention afforded to contrails here is that "contrail formation can be accurately predicted for given atmospheric temperature and humidity conditions" (IPCC 1999, p.67). Contrails form mainly in the upper troposphere at mid-latitudes, where the atmosphere is sufficiently cold and humid (IPCC, 1999). By avoiding these regions, then, contrails can – at least in part – be avoided. This would generally require lower cruise altitudes in the subtropics and higher cruise altitudes in polar regions. However, critical regions could also be avoided by means of horizontal flight path deviation. The most important trade-off to be considered when avoiding contrails is the NO_X emission, which is much more critical at higher than at lower altitudes.

Regional variations in radiative forcing from contrails
Ice-supersaturated air masses prone to contrail formation are to be found in the upper troposphere, typically at altitudes of 16 km in the tropics and 10 km at mid-latitudes. This figure of 10 km is a typical aircraft cruising altitude. Besides, radiative forcing from an assumed 100% contrail coverage is highest in the tropics and lowest in polar zones (IPCC 1999, p.101). Finally, contrail formation in Asian zones and in the Southern Hemisphere is much lower than in Europe and the US. Combining these factors, by far the greatest amount of radiative forcing from contrails occurs in Europe and the United States.

Differentiating for a situation with and without contrails
We conclude this section by distinguishing between the radiative forcing caused by aviation in a situation with and without contrail formation. In doing so, we make two important assumptions: that contrails are formed during 10% of flight time (as argued above) and that contrail formation is not correlated with the other environmental impacts of aviation.

Table 9 shows the results for average flights.

Table 9 Global average perturbation by aviation of the radiative balance, in W/m^2, differentiated for a situation with and without contrail formation, under the assumptions stated below the table, based on 1992 data

perturbation due to	average situation (with assumed 10 % probability of contrails for each km flown)	situations **without** contrails (about 90% of flight time)	situations **with** contrails (about 10% of flight time)
CO_2	+0.018	+0.0162	+0.0018
O_3 (from NO_X)	+0.023	+0.0207	+0.0023
CH_4 (from NO_X)	-0.014	-0.0126	-0.0014
H_2O	+0.002	+0.0018	+0.0002
contrails	+0.02	0	+0.02
sulphur aerosols	+0.003	-0.0027	+0.0003
soot aerosols	+0.003	+0.0027	+0.0003
total	**+0.049**	**+0.026**	**+0.023**
flight km 1992 (bln)	**20.7**	**18.63**	**2.07**
per flight km (picoW/m^2)	**+2.4**	**+1.4**	**+11**

This table is based on two main assumptions:

- contrails are formed during 10% of flight time, corresponding to 10% of flight kilometres (see text);
- the other climatic impacts of aviation emissions are not statistically correlated with contrail formation.

Based on a total of 20.7 billion flight kilometres [IPCC 1999, p.302].

From this table the important conclusion can be drawn that, under the two key assumptions made, the contribution of the 10% of contrail-inducing flight time is comparable to the 90% of flight time that does not lead to contrails. We can convert the figures to units per average flight hour, assuming a linear relationship with flight kilometres. We then see that, under the given assumptions, the total average climatic impact of a contrail-inducing flight kilometre is about eight (8) times the *total* average impact of a flight kilometre that does not induce contrails (11 vs. 1.4). For an average contrail-inducing flight kilometre, the climatic impact of the contrail *alone* is about eleven (11) times that of CO_2 *alone* (0.02 vs. 0.0018). As already mentioned, the factors of 8 and 11 apply to 1992 and do not include the highly uncertain impacts of additional cirrus cloud formation.

A final important step is to take into account that "the amount of persistent contrail cover may depend mainly on the number of *aircraft* triggering contrails and less on *fuel consumption*" (IPCC 1999, p.107, emphasis added). In contrast, other environmental effects are related more directly to fuel consumption than to number of aircraft. The factor of 8 therefore applies to average aircraft. Consequently, for aircraft burning more fuel than average (i.e. large aircraft) this 'contrail multiplier' will be less than 8 and for aircraft burning less fuel than average (small aircraft) it will be greater. Average aircraft emit about 22 kg of CO_2 per km (IPCC 1999, p.302). Using the factor 11 presented above, this implies that the *extra* climatic impact of an aircraft km inducing contrails compared with the same km not inducing contrails is the equivalent of 11 times 22 kg = about 240 kg of CO_2 per aircraft km.

This implies that in order to assess the total climatic impact of an aircraft km causing contrails we must calculate the climatic impact of the emissions of that aircraft per kilometre, including the effects of NO_X, sulphur and soot but excluding contrails, and then add the climatic impact of 240 kg of CO_2 per aircraft km.

Summarising, in this paragraph a relatively simple methodology has been presented which makes it possible to differentiate the average IPCC figures from Figure 9 for situations in which contrails are formed and for situations in which they are not. Of course, several simplifying assumptions had to be made in order to achieve such differentiation. We chose to do so because contrails are such a 'binary' phenomenon (either they are formed or not) and their impact is relatively large.

The advantage of the differentiation presented in this section is that the 'average' radiative forcing given in the IPCC report and summarised in Figure 9 and Table 8 is never actually achieved on an individual flight and is therefore in fact always 'wrong'. The differentiated numbers probably come closer to real flight situations.

4.4 Greenhouse gas emissions reduction policies

The global community has committed itself to tackling the climate issue in a series of treaties. In Article 2 of the 1992 Framework Convention on Climate Change, the ultimate objective is formulated as follows: "...to achieve stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system within a time-frame sufficient to allow ecosystems to adapt naturally to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." The convention was signed by 177 nations and entered into force in 1994.

In the Kyoto Protocol, subsequently adopted on 10 December 1997, the general terms of the Climate Treaty are translated into concrete, binding targets. Under the terms of the Protocol the most developed nations are to reduce their greenhouse emissions by an average of over 5% by 2008-2012 compared with 1990/1995 levels. No firm targets have yet been set for developing nations, nor for international aviation and shipping. The Kyoto Protocol provides for the use of 'flexible mechanisms' such as emission rights (tradable by countries that have pledged to reduce their greenhouse emissions), JI (Joint Implementation) and CDM (the Clean Development Mechanism). These mechanisms are designed to ensure that once the Kyoto protocol has been ratified an international market price for greenhouse emission abatement will settle out.

In subsequent negotiations in Buenos Aires, The Hague, Bonn and Marrakech the Kyoto Protocol was further elaborated. Although the US retreated from the protocol in March 2001, ratification has since come closer owing to agreement being reached on 'sinks' and penalties. EU Member states have committed to ratify the Protocol by Rio + 10 (second half of 2002). The future will show whether the global community, including or excluding the US, will finally be able to commit itself to the targets agreed upon in 1997 and take appropriate measures to achieve them.

4.5 Damage and prevention cost approach

In this section we assess the four options for valuing greenhouse gas emissions presented in Section 3.3: the direct damage cost approach, the stated and revealed preference approaches, and the prevention cost approach.

4.5.1 Damage cost approach

Over the last decade a number of direct damage cost studies have been performed (viz. Ayres/Walter 1991; Nordhaus 1991; Hohmeyer/Gärtner 1992). These studies aim to economically assess the balance of direct costs and benefits of the impacts of climate change. In the course of time the level of sophistication of socio-economic assessments of climate change impacts has improved significantly and the studies have also come to include a greater number of impact categories. We shall therefore use the results of these studies as one of the inputs in our assessments.

Revealed preference (RP) methods, such as hedonic pricing (see Section 3.3) are not suitable approaches for valuing greenhouse gas emissions. The impacts of these emissions are indirect, they occur on a global scale and in the long term, and they will therefore not show up clearly in price differentials for goods or services. Stated preference (SP) techniques require people to be very well informed about the effects of the emissions in question. Given the complex nature of the climate change problem, this is not something one could reasonably expect from non-experts.

4.5.2 Prevention cost approach

As we have seen, an alternative valuation approach becomes available once emission ceilings have been established. In that case, extra emissions in one place do not lead to extra damage but to extra costs to reduce emissions elsewhere. The costs of extra emissions are then represented by the marginal coats of prevention and/or abatement measures.

As discussed earlier, in the case of greenhouse gas emissions the global community may commit itself definitively to targets that more or less fix aggregate emission levels. These agreements do not currently cover international aviation – nor, indeed, international shipping – although this might become the case at some future date. In the case of aviation being included in the agreements via a so-called ‘open trading system’, the costs of an extra unit of CO_2 emissions will be determined by the marginal reduction costs of CO_2 under the Kyoto Protocol. Besides, there is a possibility that the aviation sector itself will adopt emission targets. In this case the aviation sector will face a separate emission ceiling not necessary similar to the targets of the Kyoto Protocol. We discuss both possibilities here.

Prevention cost based on Kyoto compliance costs
The most obvious approach would seem to be to take the equilibrium price resulting from the Kyoto Protocol as an estimate of the shadow price of aviation greenhouse emissions, for two reasons.

First, it is to be assumed that the international aviation and shipping sectors will also somehow align themselves with the general commitments of the industrialised nations. The ICAO is currently examining the scope of charges, tradable emission rights and voluntary agreements for controlling aircraft emissions. Whatever system is adopted, it should preferably value the marginal cost of emission reduction in the aviation sector just as high as in other sectors. Failure to do so would give rise to an economically inefficient situation. Without suitably stringent reduction targets on the part of the aviation sector, expensive abatement measures would have to be taken around the world with the sector still leaving various less costly control options unimplemented. If, conversely, the aviation sector is too stringent in the targets it adopts, the abatement measures involved may be more expensive compared with other measures not implemented elsewhere[10].

Second, the global community has committed itself to targets vis-à-vis desired (long-term) environmental quality, implying limits to global greenhouse emissions *including* aircraft emissions. Even if the aviation sector adopted no restrictions at all, then, additional aircraft emissions would not ultimately lead to increased levels of greenhouse gases. The only consequence would be that other sectors and sections of the global community would be obliged to adopt additional abatement measures. The price of these extra measures will be the same as the aforementioned international equilibrium trading price[11].

Although the share of aircraft emissions in global greenhouse emissions is growing and by no means negligible, the international trading price for greenhouse emissions is unlikely to be affected significantly by the aviation sector entering the emissions market. Regardless of sectoral efforts, then, the shadow price of aviation greenhouse gas emissions (per unit of CO_2-equivalent) will be close to the international trading price arising after ratification of the Kyoto Protocol.

The reduction targets presented in the Kyoto Protocol are the result of political compromise. They may be considered the best proxy for society's current 'willingness to pay' to reduce the risks attaching to climate change, until such time as a new compromise is reached. They represent a first step towards striking a balance between reduction costs on the one hand and the remaining damage and risks accruing from climate change on the other.

On the other hand, it will be clear that the Kyoto Protocol represents no more than an interim target. As the IPCC's Third Assessment Report (Working Group 1) states: "Reductions in greenhouse gas emissions and the gases that control their concentration would be necessary to stabilise radiative forcing. For example, for CO_2, the most important anthropogenic greenhouse gas, carbon cycle models indicate that stabilisation of atmospheric concentrations at 450, 650 or 1,000 ppm *(current concentration about 370 ppm, addition CE)* would require global anthropogenic CO_2 emissions to drop below 1990 levels, within a few decades, about a century, or about two centuries, respectively, and continue to decrease steadily thereafter." However, the IPCC makes no pronouncements on desirable emission reduction paths or timeframes. In this study, we cannot estimate the impact of future agreements on marginal prevention costs, as neither the agreements nor information on measures are available.

Besides, it should be noted that the retreat of the US from the ‘post-Kyoto’ negotiations makes the prevention cost approach less credible, as this approach is based on an internationally agreed emission reduction target. On the other hand, the US has stated that the Kyoto Protocol will remain "the only game in town".

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[10] A system based on the same marginal emission reduction costs across the board will probably lead to the aviation sector reducing its greenhouse emissions by proportionally less than other sectors of society, because its abatement options are relatively expensive.

[11] Many shadow prices for greenhouse gas emissions are reported in the literature, calculated on the basis of estimates of the ensuing damage. As explained in Chapter 1, these figures should not be used for the purpose of valuing aviation greenhouse emissions, but only to establish *global* targets. Once such targets are in place, additional aircraft emissions no longer lead to extra damage, but to additional compensatory measures.

Prevention cost based on separate emission ceiling for aviation

ICAO CAEP/FESG

The ICAO Committee on Aviation Environmental Protection (CAEP) is currently evaluating the potential role of a range of market-based options (MBOs) for limiting carbon dioxide emissions from the aviation sector. In order to support the MBO Working Group 5, the ICAO CAEP Forecasting and Economic Support Group (FESG) uses three tools for the analysis of the MBOs: the FAA model[12], the AERO model and a specially developed model (Stratus Consulting, 2001).

Among other aims, the AERO and Stratus Consulting models were used to analyse the fuel tax level that would result if the following CO_2 emission reduction targets were to be achieved:

- 25% reduction in emission growth between 1990 and 2010;
- 50% reduction in emission growth between 1990 and 2010;
- 5% reduction of 1990 emission levels.

Table 10 shows the estimated fuel levies required to achieve each of these emission reduction targets. It should be noted that the Stratus Consulting model assumed a far greater supply-side effect than the AERO model.

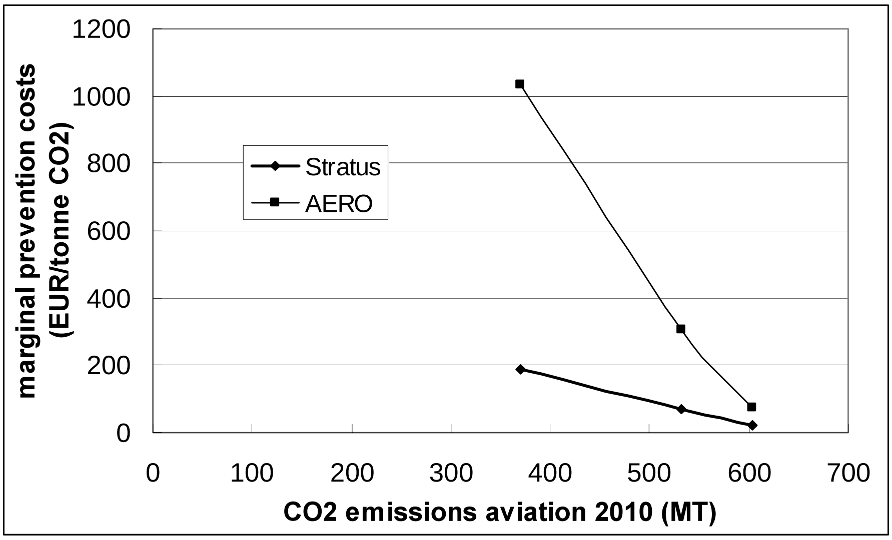
Table 10 Incentive levels at different CO_2 emission reduction targets (expressed both in EUR/litre fuel and EUR/tonne CO_2; $ to € conversion rate 1:1)

emission reduction	Stratus Consulting		AERO	
scenario	EUR/litre	EUR/tonne CO_2	EUR/litre	EUR/tonne CO_2
-25% of growth	0.06	23	0.19	76
-50% of growth	0.18	71	0.77	308
-5% of 1990 level	0.47	187	2.58	1,032

These results are illustrated graphically in Figure 10.

[12] A spreadsheet model of the aviation sector developed by the Federal Aviation Administration of the USA.

Figure 10 Marginal prevention costs in aviation sector for year 2010 under a 'closed' CO_2 trading system, or kerosene charge, following from Stratus and AERO models



European Union
The European Union has adopted objectives and targets for environmental quality in order to ensure that all citizens of the Union enjoy suitably satisfactory environmental conditions. The EU has also agreed on "reduction targets" for the Union as a whole, viz. the Kyoto commitment. Sector-specific targets are still very much uncharted territory at the EU level, however, despite most member countries having already adopted some kind of objectives and targets specific for their own transport sector. In addition, setting quantitative environmental targets for individual sectors may not serve cost-effectiveness and fairness because there is no assurance that emissions will be reduced in the cheapest possible way, and the marginal prevention costs of individual sectors will differ.

A Joint Expert Group on Transport and Environment of the European Commission has looked at the scope for setting environmental targets at the sectoral level. The Expert Group reported to the Commission that, for reasons of subsidiarity, objectives and targets that will bind Member States to commitments at the sectoral level are unlikely to be agreed and are therefore not further discussed in their report. Given this position of the Expert Group and the current early stage of the debate on setting sectoral environmental targets, we conclude that it is unrealistic to expect introduction of such targets at the EU level in the near future.

4.5.3 Conclusion

In this study we shall base estimates of CO_2 shadow prices on assessments arrived at in both damage cost and prevention cost studies. It should be noted once again, however, that both methods have their pros and cons. With the prevention cost method, applying a specific target for aviation may have practical advantages and it ensures that aviation emissions will be reduced. On the other hand, it may lead to higher costs (unless the target is set at such a level that the marginal abatement costs are equal to those under the Kyoto Protocol) and involves the subjective choice of a specific aviation target.

Therefore, in this study we have supplemented the CO_2 damage estimates with a prevention cost estimate based on the Kyoto target, although the protocol represents an interim target only and the US has retreated from the protocol. Note that this prevention cost assessment does not imply a judgement as to whether or not the Kyoto target has been set 'correctly'.

It is important to state that, for maximum economic and environmental efficiency, in the approach adopted here all the relevant climate change impacts of aviation must be valued using this shadow price, not just the six gases included in the Kyoto Protocol. This means that the climate change impacts of contrails, NO_X emissions, etc. (see earlier sections) will also be included in the valuation.

4.6 Valuation of CO_2 emissions

In this section we review published estimates of the damage and prevention costs associated with CO_2 emissions. In Section 4.6.3 we draw conclusions from these overviews. All values have been converted to € of 1999.

4.6.1 Overview of CO_2 damage cost estimates

Here we present quantitative estimates of the marginal damage costs of greenhouse gas emissions. Many studies into these damage costs calculate the total economic costs (expressed as the annual percentage loss of world GNP) that would arise if CO_2 concentrations in the atmosphere were to rise to twice their pre-industrial value, a figure taken because the IPCC assessment of climate change focuses mainly on this value. Estimating damage costs is highly complex and uncertain by nature, because of the major uncertainties in dose-response relationships, especially in the long term, the wide variety of possible impacts and the unpredictable additional risk of extreme climatic response.

Of greatest interest in policy applications are generally the *marginal* costs of emissions, i.e. the costs associated with emission of one additional tonne of CO_2. In most studies a linear damage cost curve is assumed; in other words, average damage costs are assumed equal to marginal damage costs. In 1995 Working group III of the IPCC reported on the basis of then available estimates a range of between € 2 and € 50 per tonne of CO_2 (converted to € of 1999 and emissions between 2000 and 2010).[13] Since 1995 new cost estimates have become available. The most important work in this respect is that carried out under the ongoing ExternE project, launched by the European Commission in collaboration with the US Department of Energy in 1991, and evaluating the external costs associated with a range of different fuel cycles. In the ExternE project a low and high value are recommended of about € 20 and € 56 per tonne of CO_2, respectively.

On the one hand, the wide range of marginal cost estimates (see Table 11) reflects differences in methodology and scientific uncertainty. On the other,

[13] The original range reported by the IPCC of \$5 to \$125 per tonne of carbon emitted between 1991 and 2000 has been translated to 1999 prices and adjusted for the fact that existing studies generally yield estimates of social costs that increase with time.

though, it reflects differences in political choices regarding issues of fairness between generations and between geographical regions. This is illustrated by the various rates at which future damage is discounted to obtain present values. For example, damages having a value of € 100 in one hundred years' time will have a net present value of € 13.8 if a discount rate of 2% is employed, compared to just € 0.3 if a 6% discount rate is taken. While some economists deduce discount rates from actual savings and interest data, other economists advocate lower discount rates on the basis of considerations of intergenerational equity. To appreciate the importance of the discount rate for damage cost estimates, consider Table 11, which shows the various middle cost estimates found in the literature as a function of discount rate.

Table 11 Middle estimates of marginal cost of CO_2 emissions in often-cited international literature, as a function of social discount rate; values in € 1999 per tonne of CO_2 emitted between 2000 and 2010

Discount rate:	0%	1-2%	3%	5-6%
IPCC review (1995)	2-50			
Ayres and Walter (1991)		10 – 12		
Cline (1992, 1993)		50	4-9	3
Peck and Teisberg (1993)				4 – 5
Maddison (1994)				3
Fankhauser (1994)		17		3
Nordhaus (1991, 1994)				2
Plambeck and Hope (1996)		127	13	8
Nordhaus (1999)				2
ExternE project (1999)	20-56			
Eyre et al. (1999) [a] Tol (1999)	104 (47)	56 (24)	20 (7)	8 (3)

[a] Eyre *et al*. and Tol estimates are for the period 1995-2004; in parentheses, estimates excluding *equity weighting*, a topic discussed in the text.

Although many commentators stress the uncertainties surrounding these cost estimates, the reference is generally to the possibility of the true costs being *under*estimated:

- Much debate focuses on the question of whether considerations of intergenerational equity dictate that a *lower* discount rate should be employed than 5-6%, a figure deduced from actual savings and interest data. There is virtually no debate on whether a *higher* discount rate should be used. In addition, related to the discount issue is the importance of the time scale considered: medium-term estimates based on 'only' 30 years yield lower damage costs than long-term estimates for 100 years or even longer, certainly when low discount rates are used[14].
- The middle cost estimates do not include the risk of 'climate catastrophes' or 'surprises': theoretically conceivable effects with a low probability but high social costs. It is these low-probability but high-consequence scenarios that drive much of the international concern about climate change. IPCC (2001) mentions the following examples of climate catas-

[14] On the other hand, uncertainty grows with the time scale taken: the longer the period considered, the broader the uncertainty ranges of the results.

trophes: significant slowing of the ocean circulation that transports warm water to the North Atlantic, large reductions in the Greenland and West Antarctic Ice Sheets, accelerated global warming due to carbon cycle feedbacks in the terrestrial biosphere, and releases of terrestrial carbon from permafrost regions and methane from hydrates in coastal sediments.

- Most studies provide only a first-order assessment of total global warming damage using a simple enumerative approach, viz. total damage as the sum of individual damage categories. Some studies focus only on individual consequences such as sea level rise (Ayres/Walter 1991) or agricultural impacts (Cline 1991). Higher-order effects are not included. For example, if global warming causes agricultural output to decline, no consideration is given to higher-order effects such as economic losses in the food industry or mass starvation. At the same time, though, the possibility cannot be completely excluded that the social costs of climate change are *lower* than expected (Mendelsohn *et al*., 1996).

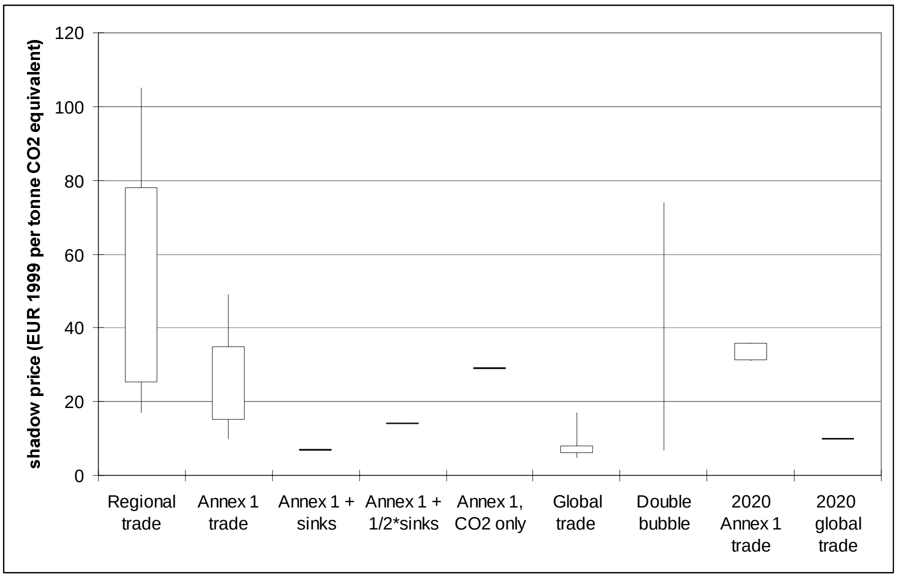
Recently, a debate has started about the issue of *equity-weighting*, i.e. how to aggregate the valuation of impacts across geographical regions that exhibit major disparities in income.[15] Equity weighting always increases cost estimates.

4.6.2 Overview of 'Kyoto' CO_2 prevention cost estimates

In this section we present quantitative estimates for the marginal prevention costs of greenhouse gas emissions under the Kyoto Protocol. The values are based on the review of the international literature presented in Annex I. The results are shown in Figure 11.

[15] In short, equity weighting can be seen as the *intra*generational counterpart of discounting. Expected increases in income may constitute a reason for discounting costs arising in later years. For the same reason, costs occurring in low-income countries may be valued higher than costs occurring in high-income countries. For this debate, see Fankhauser *et al*. (1997), Tol *et al*. (1996, 1999), Azar (1999), and Azar and Sterner (1996).

Figure 11 Overview of marginal prevention costs of one tonne of CO_2-equivalent under the Kyoto Protocol, under several assumptions with respect to scale of trade, mechanisms, and timeframe



The ranges given by *lines* represent the extremes found in the literature, those in the *boxes* the ranges omitting the most extreme values found in the literature.

- regional trade: only trade *within* EU, US and Japan permitted;
- annex 1 trade: JI (Joint Implementation) permitted (trade between all Annex I countries);
- global trade: JI + CDM (Clean Development Mechanism) permitted, to be considered a variant with maximum use of Clean Development Mechanism;
- (1/2*)sinks: (half of) sinks may be used in addition to JI;
- CO_2 only: infinite prevention costs of non-CO_2 greenhouse gases;
- 'double bubble': trade permitted in two bubbles: one US/Japan/Australia, the other all other Annex 1 countries. Lower value represents costs for the first bubble, higher for the second;
- 2020: Kyoto targets apply to 2020 as well.

From this figure the following conclusions can be drawn:

- the flexibility allowed under the Protocol goes a long way to explain the variations in valuations found;
- the financial consequences of the EU policy statement that Parties should strive to achieve 50% of their commitments by means of domestic measures have not yet been studied;
- maximum flexibility would lead to valuations of below € 10/tonne CO_2-equivalent, minimum flexibility to values about 10 times as high;
- stretching the Kyoto target to 2020 would increase reduction costs substantially. Stricter targets would obviously increase costs further.

4.6.3 Conclusions on CO_2 valuation

The principal conclusions to be drawn from this section are:

- there is major variation in the results of both damage and prevention cost studies;
- in the damage cost estimates, the social discount rate is a very important explanatory factor for these differences. Some deduce discount rates from actual savings and interest data, while others advocate lower discount rates on the basis of considerations of intergenerational equity. The lower the discount rate, the higher the shadow prices found;
- in the prevention cost approach, the shadow price of emissions is determined by 'autonomous' developments such as economic growth, the

reduction target and the costs of available and permitted measures. Including the aviation sector in the Kyoto protocol ('open trading system') would lead to much lower shadow prices than in the case of aviation having to reduce emissions itself by a comparable percentage. For lack of an agreed separate reduction target for aviation, we have chosen to use the 'Kyoto' compliance costs as a basis for prevention cost assessment;

- the ranges of estimated damage and prevention costs are comparable: from several € to roughly € 100 per tonne of CO_2.

Eliminating the extreme estimates of several € and € 100 per tonne of CO_2, in this study we shall use working values of € 30 per tonne of CO_2 as a middle estimate and € 10 and € 50 in sensitivity analyses.

4.7 Valuation of NO_x and H_2O emissions

Although the climatic impact of emitting one kg of NO_X or water vapour can vary substantially under local and regional atmospheric conditions, we have chosen to work with globally averaged impacts of NO_X and H_2O emissions from aircraft relative to the impact of CO_2.

To arrive at a value for NO_X and H_2O, we must first establish the relative emissions of CO_2 and H_2O.

Table 12 Overview of 1992 and 2050 scenarios from [IPCC, 1999] in terms of fuel, CO_2, NO_X and H_2O emissions, radiative forcing and the relative radiative forcing impacts of these emissions

	fuel consumption	CO_2	H_2O	NO_X
1992 situation				
1992 emissions ('NASA-1992' scenario, in Mtonnes)	160.3	506	202	1.92
radiative forcing (W/m^2)		0.018	0.002	0.009
globally averaged radiative forcing per kg of emission, relative to 1 kg of CO_2 emission		1	**0.28**	**132**
2050 situation				
2050 emissions ('FESGa tech 1' scenario), in Mtonnes)	471	1488	593	7.15
radiative forcing (W/m^2)		0.074	0.004	0.015
globally averaged radiative forcing per kg of emission, relative to 1 kg of CO_2 emission		1	**0.14**	**42**

From this table we can conclude that in the 1992 situation on average one kg of water vapour emitted caused 0.28 times the radiative forcing impact of one kg of CO_2; for NO_X this factor was 132. In the 2050 situation the relative importance of CO_2 has increased, leading to lower relative valuations of NO_X and H_2O emissions.

Application of the 1992 multiplication factors from Table 12 yields the values shown in Table 13.

Table 13 Valuation of NO_X and water vapour emissions, based on their relative impacts compared with CO_2 in 1992

Emission	CO_2 factor (previous table)	Valuation		
		low	medium	high
CO_2 (€/tonne)	1	10	30	50
NO_X (€/kg)	132	1.3	4.0	6.6
H_2O (€/tonne)	0.28	2.8	8.3	14

4.8 Climate impact per aircraft type

The final step is to calculate the external costs of different aircraft and flights, as given in Section 3.4. We do so by multiplying the emission factors of the different aircraft types from Section 3.4 by the values given in Table 13.

Table 14 Financially valued greenhouse gas emissions per aircraft-km, in € 1999, based on a shadow price of € 30 per tonne CO_2-equivalent

	average case, contrails during 10% of flight km	€/km in which NO contrails are formed	€/km in which contrails are formed*
40 seats, 200 km	N.A.*	0.21	N.A.*
100 seats, 500 km	1.2	0.48	7.7
200 seats, 1,500 km	1.6	0.90	8.1
400 seats, 6,000 km	2.62	1.9	9.1

* It should be noted that on short trips it is highly unlikely that contrails will be formed during a substantial proportion of flight time. These flights are generally at altitudes too low (temperatures too high) for contrail formation, and no 'contrail' figures are therefore presented for the 200-km trip. Again we state that the figures that include contrail formation are only indicative and designed primarily to illustrate the relative importance of contrail formation.

These figures can be translated to figures per passenger trip and per passenger-kilometre. To this end we have employed the load factors presented in Table 4 and the allocation to passenger and freight transport presented in Annex V.

Table 15 Financially valued greenhouse gas emissions per passenger-km and per (single) passenger trip, in € 1999, based on a shadow price of € 30 per tonne CO_2-equivalent

	Average case (contrails formed during 10% of flight km)		NO contrail formation (90% of flight km)		contrail formation* (10% of flight km)	
	€cts per pax.km	€ per pax single trip	€cts per pax.km	€ per pax single trip	€cts per pax.km	€ per pax single trip
40 seats, 200 km	N/A	N/A	1.0	2.1	N/A	N/A.
100 seats, 500 km	2.1	8.9	0.72	3.6	11.5	57
200 seats, 1,500 km	1.1	16	0.61	9.2	5.5	82
400 seats, 6,000 km	0.60	35	0.43	25	2.1	126

(NB: Figures corrected for amount of freight transported.)

The most important parameters determining the external costs of greenhouse gas emissions are:

- Whether or not contrails are formed. The external costs of trips that do cause contrails are substantially higher than those of trips that do not: roughly a factor 5 to 15.
- The shadow price per tonne CO_2-equivalent. Estimates may vary by a factor 5, depending on the assumptions regarding the reduction target and the permitted mechanisms.

In addition, the level of aircraft technology of course influences the specific emissions per km and trip and thus external costs.

In quantitative terms, under the stated assumptions external costs are calculated to lie within a range of 0.5 to 1 €ct per passenger-kilometre, increasing substantially, by a factor 5 to 15, during flight kilometres in which contrails are formed. The external costs incurred during these kilometres may rise to levels of one-third to one-half the price currently paid for flying these kilometres.

5 Valuing noise and air pollution

5.1 Introduction

In this chapter we treat the valuation of non-greenhouse gas emissions and noise emissions having impacts at a local or regional level. More particularly, we consider the valuation of noise emissions and emissions of NO_X (oxides of nitrogen), PM_{10} (fine particulate matter with a diameter of less than 10 microns), HC (hydrocarbons) and SO_2 (sulphur dioxide). CO is not expected to pose major problems in the future and is therefore not considered here.

First, in Section 5.2, we shall treat the valuation of noise emissions, moving on in Section 5.3 to the valuation of the specified LTO emissions.

5.2 Noise nuisance

5.2.1 Impacts of noise nuisance

Noise has been defined as 'unwanted sound' and as such it reduces the amount of the scarce good 'peace and quiet', which is not generally traded in the market[16]. In addition, the costs of noise nuisance are not generally included in the decision-making of the actor causing the nuisance. As such it is an external effect. Transport noise is an extremely complicated case because of the large number of 'polluters' and the large number of victims.

Typically, one can distinguish tree types of damages resulting from noise:
1 Nuisance effects, which make people want to pay for not being confronted with noise.
2 Damage costs like health effects, currently the subject of numerous studies.
3 Land use effects, a special form of adaptation or avoidance costs; in many cases governments establish *'cordons sanitaires'* around large noise sources such as airports. This restricts optimal use of land, and thus leads to costs, but does not reduce noise.

5.2.2 Valuing noise nuisance

Nuisance effects
Nuisance effects are valued in two ways:
- via 'hedonic pricing' (HP) studies that reveal the impact of noise on property prices. This has the advantage of potentially great accuracy;
- via 'stated preference' (SP) techniques in which people are asked about their willingness to pay for a quieter environment or their willingness to accept more noise.

16 Schipper (1999).

It is sometimes argued[17] that the lower prices found in HP studies should not be considered damage but rather a form of 'compensation' for people who have chosen to live in the vicinity of an airport. Some people also argue that airports increase property prices because people and firms are willing to pay more for proximate access. Neither argument is sound.

Noise reduces the amount of the scarce good 'peace and quiet'. Therefore, noise at a certain location will increase the cost of living at peaceful and quiet locations, although the property at such locations does not provide any additional benefits compared to a situation without noise. Therefore, noise leads to a net decline of welfare and thus to social costs. These social costs are external to the market as long as the parties causing them – airlines and probably also air traffic control agencies – do not take them fully into account in their decision-making.

The increase of property prices near airports results from the accessibility benefits provided by airports. They are a perfect example of the benefits of air transport being processed via market transaction in the economy, as described in Chapter 2, but they provide no grounds for government intervention.

Avoidance costs: land use effects

Avoidance costs from noise nuisance come into play when governments choose to limit direct noise damage and nuisance by implementing zoning plans. In these *cordons sanitaires* land use is restricted; for example, it may not be permitted to build new houses[18]. Such a *cordon sanitaire* leads to welfare losses. It increases scarcities; it makes it impossible to make optimum decisions on land use within this area and indirectly it also limits choices elsewhere. The big difficulty in assigning a value to this loss of welfare is the definition of the 'optimum' spatial planning that would have resulted without the noise nuisance and attendant restrictions. Three Dutch studies have tried to do just this for the case of Schiphol Airport, each in their own way. These studies are described in Annex IV.

Health effects

Noise has been shown to have potentially damaging effects on the stomach, bowels, heart and blood circulation. A large number of qualitative and several quantitative studies have been conducted, as described in Annex IV.

Double counting?

An important question now is whether the four possible approaches are fully complementary, or whether some results can be added without risk of double counting.

First, let us consider the hedonic pricing and stated preference (HP and SP) approaches to nuisance valuation. In principle, SP can also be used to value the non-material damages of noise. However, in the case of aircraft noise it is plausible that all the non-material damage experienced by people is reflected in property prices – except for the nuisance experienced by those living elsewhere. As this last category is likely to be small, the HP method and SP method are not complementary, i.e. the results cannot be added.

A second, more intriguing question is whether the nuisance costs may be added to the welfare loss from indirect land use represented by the *cordon sanitaire*. The answer is that they should be added. This is because the *cor-*

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17 For example, by Hartog, J., 'Schiphol, feest voor columnisten', ESB, 27-11-1998.

18 Zoning is also often implemented with an eye to public safety and air pollution. At most European airports, however, noise targets are the most pressing issue.

don – although sometimes considered an instrument for *preventing* noise nuisance – is in fact an instrument for *avoiding* such nuisance. As such it leads to avoidance costs that should be added to the damage to existing property within the noise contours. As stated previously, these costs are not directly visible as they are caused by the scarcity resulting from suboptimum spatial planning. This can be illustrated by two examples.

Consider the case of the noise levels around a given airport increasing by 10%. If policies are consistent, this will lead to two things: more direct damage to the houses in the current *cordon sanitaire* and expansion of the *cordon*, as more houses come to fall within the critical noise zone. Both mechanisms will occur, at least in the long term. Consider, furthermore, the case of a government opting to demolish houses that are heavily affected by aircraft noise. In this case, both the decrease in direct damage costs and the increase in opportunity costs of the *cordon sanitaire* (these people need a new house) should be taken into account. In other words: the people that lived in the houses suffer less noise themselves, but raise the cost of living for people outside the zone.

Third, external health costs should be considered. These can also be added to the losses in property value, as these are two separate items. This can be readily seen by following the marginal approach: more noise will lead both to lower property values in HP studies and to higher external health costs in health studies.

5.2.3 Noise emissions per aircraft type and valuation

Valuation of (marginal) noise is complicated because noise is itself a non-linear phenomenon, its perception is certainly non-linear and its effects are dependent on immission rather than emission. Assessment of the external costs of noise is described in detail in Annex IV.

Estimates for the costs of nuisance have been derived primarily from sources that use HP (hedonic pricing, revealed preference) techniques complemented with sources that use WTP/WTA (willingness to pay/accept, stated preference) approaches. WTP/WTA approaches seem to lead to somewhat higher results than HP approaches.

The costs of indirect land use have been calculated for the case of Schiphol Airport, combining several Dutch case studies on opportunity costs of the land currently restricted by the airport. The ultimate conclusion is that in the case of Schiphol the costs of indirect land use appear to be somewhat lower than the direct costs of noise nuisance.

Although qualitatively there is abundant evidence of noise causing health impacts, quantitative sources on the ensuing health costs are rather scarce. The available quantitative sources have been used.

Finally, the results from all the different approaches have been combined, leading to the following conclusions:
- it appears well possible to make narrow-range estimates of the total external costs of airport noise. HP and WTP approaches supplemented by health costs give a fairly consistent picture of the external costs of noise from European airports;
- the biggest difficulty is the step from total costs to marginal costs per aircraft type. Information on the shape of the cost curve as a function of number of flights is not abundant. The available material suggests that

marginal costs are lower than average costs. We have used an estimate of 50%;
- finally, the relationships between aircraft size, aircraft technology and external costs are hard to establish; airports worldwide use a very wide variety of calculation methodologies. In this study, we have used the relationships between aircraft size and noise nuisance used at Schiphol Airport to establish noise charges there.

Following this methodology we arrive at the following estimates for the marginal noise costs from different aircraft equipped with fleet-average technology and flying to and from airports located in areas with population densities of 500-2,000 people per km^2 (Table 16).

Table 16 Estimates of typical marginal external noise costs of different aircraft at large European airports, in € 1999 per LTO, for fleet-average technology aircraft

	per aircraft	per seat	per passenger
40 seater	180	4.5	9
100 seater	300	3	5
200 seater	600	3	4
400 seater	1,200	3	4

State-of-the-art technology aircraft are assumed to have about 3 dB(A) lower noise emissions than today's average aircraft, a halving of the noise level. The external costs of noise emissions will therefore also be half as high. The results are shown in Table 17.

Table 17 Estimates of typical marginal external noise costs of different aircraft at large European airports, in € 1999 per LTO, for state-of-the-art technology aircraft

	per aircraft	per seat	per passenger
40 seater	90	2.2	4.5
100 seater	150	1.5	2.5
200 seater	300	1.5	2
400 seater	600	1.5	2

5.3 LTO emissions of NO_X, PM_{10}, HC, and SO_2

5.3.1 Environmental impact

This section is devoted to the effects of aircraft emissions at ground level and the first several hundred metres above ground level. It is not readily feasible to define an altitude at which emissions no longer impact upon local and regional air quality. For practical reasons we have chosen to take emissions occurring during the landing and take-off cycle (LTO cycle: up to 3,000 ft = 905 m) as emissions that affect local and regional air quality. The LTO cycle is also used for emission certification of aircraft engines.

Table 18 summarises the effects of the atmospheric emissions occurring in the LTO cycle and covered by the present study. In the valuation of each emission a distinction has been made between emissions released inside and outside built-up areas. This has to do with the health effects of the emissions, which are of course dependent on the size of the population exposed.

Table 18 Environmental effects of atmospheric emissions covered by present study

	Environmental and health effects
NO_X	acidification eutrophication summer smog (ozone) formation health effects (via nitrate, ozone and NO_2) climate change (via ozone*)
PM_{10}	health effects
HC	summer smog (ozone) formation health effects (via carcinogenic substances and ozone) climate change (via ozone*)
SO_2	acidification health effects (via sulphate)

* Climate change effects of ozone are treated in the previous chapter.

5.3.2 Valuation of impacts

Annex III contains an elaborate description of the literature on valuation of the four emissions. In recent years much of the focus in valuing air pollution has shifted to the direct damage cost approach via dose-response relationships. The background to this development can be explained from the conclusions of the literature survey:

- knowledge about the damage costs of air pollution has improved vastly in recent years. Progress has been particularly marked with respect to the health effects of transport pollutants. Dose-response relationships have been improved, as have dispersion models; in addition, the valuation of (years of) life (lost) is now less controversial;
- improved knowledge of these health effects has led to rising valuations of practically all emissions, to a better understanding of variation in calculated values and thus to less spread of results once the factors behind such variation are taken into account. For example, several studies show that in an area like the inner city of Paris a gram of $PM_{2.5}$ emission leads to several € of health damage, while in sparsely populated areas the figure is more like € 0.01. This shows that the prices of emissions are very dynamic, depending on circumstance, and that, as scientific insight grows, prices are more likely to increase rather than decrease;
- much of the focus with regard to health effects has shifted to ultra-fine particles ($PM_{2.5}$). Extensive analysis within the framework of the ExternE programme and a 1990 WHO study, as well as US studies, shows robust and significant dose-effect relationships. As a result, air pollution related costs from transport are dominated by the health effects of these particles, which are quite consistent across the studies found. Although aviation emits only limited amounts of these particles, we have included them in our analysis;
- the most relevant health effects besides those of $PM_{2.5}$ are those of NO_x and ozone;
- carbon monoxide, 1,3-butadiene, benzene and benzo(a)pyrene, other suspect pollutants of the past, do not appear to give rise to significant health effects. Either exposure or human sensitivity is relatively low;
- in contrast to the situation for human health effects, it remains difficult to assign a financial value to impacts on biodiversity and forest health. It should therefore be duly noted that the valuations cited in most studies include several major 'items pending' in this regard;
- *health damage* costs alone already generally seem to be higher than the *prevention* costs derived from the marginal costs of achieving *politically*

agreed targets like the NECs (European National Emission Ceilings) under the UN-ECE Convention on Long-Range Transboundary Air Pollution (LRTAP)[19]. Given this phenomenon, as well as the progress made on valuing health effects, the prevention cost methodology is becoming less popular as a tool for emission valuation and air pollution cost-benefit analysis.

From the synthesis of recent international literature in Annex III the following estimates of shadow prices for the four pollutants have been derived.

Table 19 Overview of middle estimates from recent European literature for valuation of NO_X, PM_{10}, HC, and SO_2, based on damage costs, in € 1999 per kg emitted

	average	urban	rural
NO_X	9	12	7
PM_{10} / $PM_{2.5}$	150	300	70
HC	4	6	3
SO_2	6	10	4

As the table shows, population density plays an important role in the range of valuations found. This can be explained by the fact that the greater part of the financial value of emissions consists of damage to human health, which is of course highly dependent on population density.

Although the health impacts around Swedish and Norwegian airports, for example, are less than those around Heathrow and Charles de Gaulle, for example, we have chosen not to work with 'low' and 'high' estimates, in contrast to the estimates for greenhouse gas emissions. Large airports are generally located in fairly densely populated areas; the areas around Frankfurt, Schiphol and Charles de Gaulle have densities of about 500-2,000 people per km^2. We have chosen to use 'average' values, as large airports are generally located neither in urban nor in rural areas.

5.3.3 LTO emissions per aircraft and valuations

The final step is to calculate the external costs of the different aircraft and flights given in Table 6. We do so by multiplying the emission factors of the different aircraft types from this table by the valuations given in Table 19.

Table 20 Financially valued LTO emissions from the four aircraft types with fleet-average technology considered, in € 1999 per LTO cycle

	NO_X	$PM_{2.5}$	HC	SO_2	total per aircraft	total per passenger*
40 seater	10	20	3	0	33	1.6
100 seater	66	44	6	3	119	1.8
200 seater	186	44	6	5	241	1.6
400 seater	512	95	13	11	631	1.4

* Excluding emissions allocated to freight transported.

19 Theoretically, the marginal prevention costs necessary to achieve environmental sustainability targets are equal to the marginal damage costs at the optimum.

From the table the following conclusions can be drawn:

- NO_X and $PM_{2.5}$ emissions are the dominant factor in the value of aircraft LTO emissions. NO_X is important primarily because of the magnitude of emissions, $PM_{2.5}$ because of its relatively significant health impacts per unit emission;
- the principal assumptions influencing external costs relate to population density around airports and aircraft technology level (the latter especially with respect to $PM_{2.5}$ emissions). Both have been taken here as European averages for large airports;
- the external costs per passenger per LTO cycle are not very sensitive to aircraft size, despite the higher load factor assumed for the larger aircraft (65 vs. 80%). External costs thus vary between about € 1 and 2 per passenger per LTO (i.e. per one-way trip)[20].

[20] This is because large aircraft burn relatively more fuel during LTO and generally have higher NO_x emission indices than small aircraft. During LTO, small aircraft burn approximately 5 times as much fuel as during cruise, while for large aircraft this factor is about 10.

6 Synthesis of results

6.1 Introduction

In this chapter we combine the results of Chapters 4 and 5 to provide an overall review of the external costs of air transport. First, we present and discuss a summary graph of the marginal external costs per passenger-kilometre due to noise, LTO emissions and climatic impacts. This graph is based on the middle variant of this study: fleet-average technology and valuation of the climatic impact of CO_2 at € 30 per tonne. We then move on to discuss the impact of different assumptions regarding level of technology and valuation of climatic impact.

6.2 Summary of assumptions and variants

So that the external cost figures presented in this chapter can be assessed in their proper light, we shall here state once more the principal assumptions and demarcations of scope on which they are based.

Valuations have been made for two different technology levels: 'fleet-average' and 'state-of-the-art' technology, the latter with 20% lower fuel consumption, 20% lower NO_X and SO_2 emission indices per kg of fuel burnt and 70% lower HC and PM_{10} indices per kg of fuel burnt.

The figures for LTO emissions and noise impacts are based largely on the situation at large European airports. They are thus intended to represent a typical average for marginal external costs at large European airports.

Three different valuations for a tonne of CO_2 emissions have been used: a middle estimate of € 30 per tonne, a low estimate of € 10 per tonne and a high estimate of € 50 per tonne.

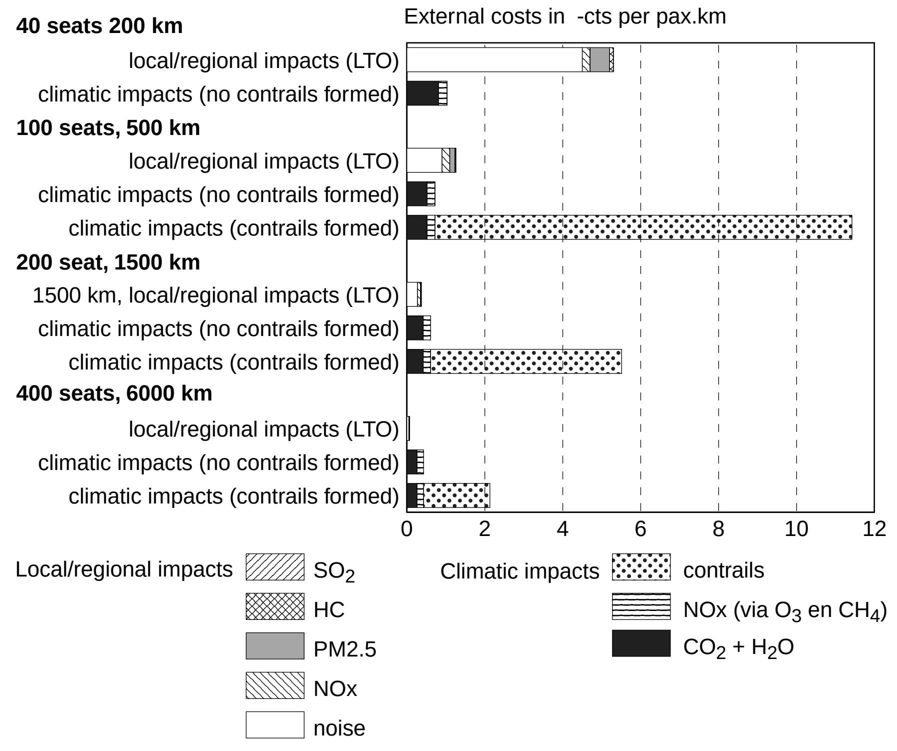
The figures on climatic impact are intended to give an indication of the globally averaged marginal external costs of aircraft operations. The figures have been differentiated for situations in which contrails are, and are not, formed. This differentiation is based on three assumptions:

- the assumption that contrails are formed during 10% of flight time;
- the assumption that the climatic impacts of NO_X and soot are not correlated with contrail formation;
- the assumption that the climatic impact of contrail formation depends on the number of aircraft-km flown, whereas other impacts are calculated on the basis of fuel use and emission indices per kg of fuel used.

6.3 Variant 1: fleet-average technology

In this section we present the external costs calculated under the assumptions stated in the previous paragraph for fleet-average technology and with CO_2 emissions valued at € 30 per tonne, the middle working value adopted in the present study.

Figure 12 External costs in €cts per passenger-kilometre for fleet-average technology and with CO_2 emissions valued at € 30/tonne



From this graph and from the figures presented earlier we can draw the following conclusions:

- for aircraft flying distances of up to a few hundred kilometres, the external costs of LTO emissions are dominant, especially noise costs. This has the following background:
  - on these flights the LTO phase forms a substantial part of the journey;
  - these aircraft have relatively high noise emissions and relatively low NO_X emissions;
  - over these distances aircraft do not reach cruise altitudes, where contrails are formed;
- the longer the trip, the more climatic impacts predominate compared with local and regional (LTO) impacts. For flights of over about 1,000 km, the external costs of climatic impacts exceed those of LTO impacts (if no contrails are formed);
- the external costs of the climatic impacts of NO_X emissions are approximately half those for CO_2 and H_2O; the share of NO_X increases slightly with increasing aircraft size and flight length;
- the question of whether or not *contrails* are formed is a factor weighing heavily on the overall external costs of the climatic impacts of aviation. Assuming that, on average, contrails are formed during 10% of flight kilometres, the climatic impact of a contrail-causing aircraft-km is about eight times as high as an aircraft-km not causing persistent contrails. It should be stressed that:
  1 the factor is based on the assumption that contrails are formed on 10% of global aircraft-kilometres;
  2 the factor is a middle estimate of the globally averaged climatic impact of contrails;

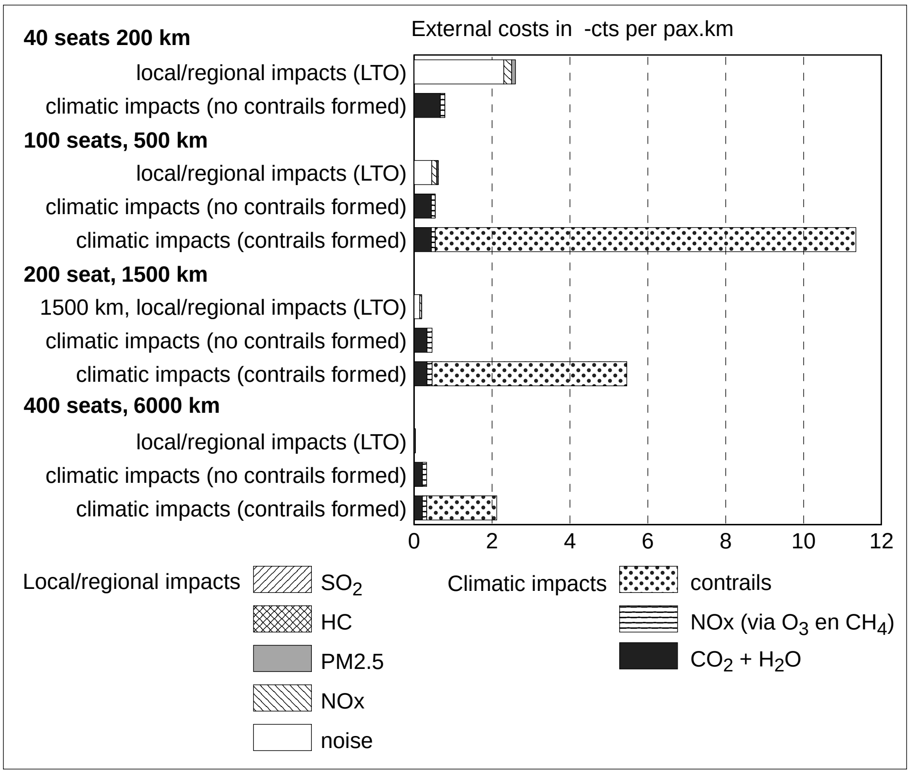
3 there is a 67% probability that the true climatic impact of contrails is between one-third and three times this middle estimate (IPCC 1999, Figure 9);
4 scientific evidence on the climatic impacts of contrails is judged to be 'fair' (IPCC 1999, Figure 9);

- given the fact that the process of contrail formation is scientifically fairly well understood, it would be both attractive and feasible to develop strategies to reduce or avoid contrail formation;
- we can also express the external costs calculated in this study as a percentage of ticket prices. If NO contrails are formed, total external costs are around 5% of average ticket prices for a 6,000 km flight and about 20-30% of average ticket prices for a 200 km flight. Naturally, with high-fare tickets this share will be lower, and with low-fare tickets higher;
- these percentages rise sharply for flights on which contrails are formed during a substantial part of the journey. For example, the external costs of flights during half of which contrails are formed amount to roughly 20 to 25% of the ticket prices paid for such flights.

6.4 Variant 2: state-of-the-art technology

In this paragraph we present the sensitivities of external costs to different assumptions regarding aircraft technology and valuation of climatic impacts. The assumptions are stated in Section 6.2.

Figure 13 External costs in €ct per per passenger-kilometre for state-of-the-art aircraft technology and with CO_2 emissions valued at € 30/tonne



From this figure it can be seen that external costs of local and regional impacts (LTO phase) of aircraft with state-of-the-art technology are approximately half those for aircraft with fleet-average technology.

In the case of no contrails being formed, the external costs associated with climatic impact are also lower, owing to lower CO_2, H_2O, and NO_X emissions. The share of NO_X emissions in the external costs of climate change is slightly lower than in the case of fleet-average technology, as a result of the 20% lower NO_X emission indices. Again, the share of NO_X increases slightly with increasing aircraft size and flight length.

The climatic impact of flight kilometres on which contrails are formed remains essentially unchanged. What cannot be seen from the graph, however, is that kilometres flown with these new aircraft, with thermally more efficient engines, will probably be associated with a somewhat higher probability of contrail formation than the 10% assumed for the fleet-average aircraft. This is due primarily to the fact that more advanced engines have cooler exhaust plumes, which condense more quickly.

6.5 Overview of other results

The variants with lower and higher valuations of climatic impact (€ 10 and € 50 per tonne CO_2) are not shown here graphically. With these alternative valuations the external costs of climatic impacts are 67% lower and 60% higher, respectively, than in the baseline variant.

Concluding this main report, the figures for all the variants and respective cost items are shown numerically in Table 21 to Table 23.

Table 21 Overview of external costs as calculated in this study, with a shadow price for climatic impact of € 30 per tonne CO_2-equivalent

	climatic impacts							local/regional impacts						total		
	CO_2 + H_2O	NO_X		contrails (if any)	*total*			noi-se	NO_X	PM_{10}	HC	SO_2	*total*	km w/o contrails	km with contrails	aver-age
		via O_3	via CH_4		km w/o contrails	km with contrails	aver-age									
fleet-average technology, in € per aircraft-km																
50 seats, 200 km	0.16	0.11	-0.07	N/A	0.21	N/A	0.21	0.9	0.05	0.10	0.0	0.00	1.06	1.3	N/A	1.3
100 seats, 500 km	0.35	0.34	-0.21	7.2	0.48	7.7	1.20	0.6	0.13	0.09	0.0	0.01	0.84	1.3	8.5	2.0
200 seats, 1,500 km	0.62	0.72	-0.44	7.2	0.90	8.1	1.62	0.4	0.12	0.03	0.0	0.00	0.56	1.5	8.7	2.2
400 seats, 6,000 km	1.09	2.01	-1.22	7.2	1.87	9.1	2.59	0.2	0.09	0.02	0.0	0.00	0.31	2.2	9.4	2.9
fleet-average technology, in €ct per pax.km																
50 seats, 200 km	0.81	0.57	-0.35	N/A	1.03	N/A	1.03	4.5	0.24	0.50	0.1	0.01	5.32	6.4	N/A	6.4
100 seats, 500 km	0.52	0.51	-0.31	10.7	0.72	11.5	1.79	0.9	0.20	0.13	0.0	0.01	1.25	2.0	12.7	3.0
200 seats, 1,500 km	0.42	0.49	-0.30	4.9	0.61	5.5	1.10	0.3	0.08	0.02	0.0	0.00	0.38	1.0	5.9	1.5
400 seats, 6,000 km	0.25	0.47	-0.29	1.7	0.44	2.1	0.61	0.0	0.02	0.00	0.0	0.00	0.07	0.5	2.2	0.7
state-of-the-art technology, in € per aircraft-km																
50 seats, 200 km	0.13	0.06	-0.04	N/A	0.16	N/A	0.16	0.5	0.03	0.02	0.0	0.00	0.51	0.7	N/A	0.7
100 seats, 500 km	0.30	0.17	-0.11	7.2	0.37	7.6	1.09	0.3	0.08	0.02	0.0	0.00	0.41	0.8	8.0	1.5
200 seats, 1,500 km	0.49	0.49	-0.30	7.2	0.68	7.9	1.40	0.2	0.08	0.01	0.0	0.00	0.29	1.0	8.2	1.7
400 seats, 6,000 km	0.92	1.22	-0.74	7.2	1.40	8.6	2.12	0.1	0.05	0.00	0.0	0.00	0.16	1.6	8.8	2.3
state-of-the-art technology, in €ct per pax.km																
50 seats, 200 km	0.67	0.31	-0.19	N/A	0.79	N/A	0.79	2.3	0.15	0.12	0.0	0.01	2.55	3.3	N/A	3.3
100 seats, 500 km	0.44	0.26	-0.16	10.7	0.55	11.3	1.62	0.4	0.13	0.03	0.0	0.01	0.62	1.2	11.9	2.2
200 seats, 1,500 km	0.33	0.33	-0.20	4.9	0.46	5.3	0.95	0.1	0.05	0.00	0.0	0.00	0.20	0.7	5.5	1.1
400 seats, 6,000 km	0.21	0.28	-0.17	1.7	0.33	2.0	0.49	0.0	0.01	0.00	0.0	0.00	0.04	0.4	2.0	0.5

Table 22 Overview of external costs as calculated in this study, with a shadow price for climatic impact of € 10 per tonne CO_2-equivalent

	climatic impacts							local/regional impacts						total		
	CO_2+ H_2O	NO_X		contrails (if any)	*total*			noi-se	NO_X	PM_{10}	HC	SO_2	*total*	km w/o contrails	km with contrails	aver-age
		via O_3	via CH_4		km w/o contrails	km with contrails	aver-age									
fleet-average technology, in € per aircraft-km																
50 seats, 200 km	0.05	0.04	-0.02	N/A	0.07	N/A	0.07	0.9	0.05	0.10	0.0	0.00	1.06	1.1	N/A	1.1
100 seats, 500 km	0.12	0.11	-0.07	2.4	0.16	2.6	0.40	0.6	0.13	0.09	0.0	0.01	0.84	1.0	3.4	1.2
200 seats, 1,500 km	0.21	0.24	-0.15	2.4	0.30	2.7	0.54	0.4	0.12	0.03	0.0	0.00	0.56	0.9	3.3	1.1
400 seats, 6,000 km	0.36	0.67	-0.41	2.4	0.62	3.0	0.86	0.2	0.09	0.02	0.0	0.00	0.31	0.9	3.3	1.2
fleet-average technology, in €ct per pax.km																
50 seats, 200 km	0.27	0.19	-0.12	N/A	0.34	N/A	0.34	4.5	0.24	0.50	0.1	0.01	5.32	5.7	N/A	5.7
100 seats, 500 km	0.17	0.17	-0.10	3.6	0.24	3.8	0.60	0.9	0.20	0.13	0.0	0.01	1.25	1.5	5.1	1.8
200 seats, 1,500 km	0.14	0.16	-0.10	1.6	0.20	1.8	0.37	0.3	0.08	0.02	0.0	0.00	0.38	0.6	2.2	0.7
400 seats, 6,000 km	0.08	0.16	-0.10	0.6	0.15	0.7	0.20	0.0	0.02	0.00	0.0	0.00	0.07	0.2	0.8	0.3
state-of-the-art technology, in € per aircraft-km																
50 seats, 200 km	0.04	0.02	-0.01	N/A	0.05	N/A	0.05	0.5	0.03	0.02	0.0	0.00	0.51	0.6	N/A	0.6
100 seats, 500 km	0.10	0.06	-0.04	2.4	0.12	2.5	0.36	0.3	0.08	0.02	0.0	0.00	0.41	0.5	2.9	0.8
200 seats, 1,500 km	0.16	0.16	-0.10	2.4	0.23	2.6	0.47	0.2	0.08	0.01	0.0	0.00	0.29	0.5	2.9	0.8
400 seats, 6,000 km	0.31	0.41	-0.25	2.4	0.47	2.9	0.71	0.1	0.05	0.00	0.0	0.00	0.16	0.6	3.0	0.9
state-of-the-art technology, in €ct per pax.km																
50 seats, 200 km	0.22	0.10	-0.06	N/A	0.26	N/A	0.26	2.3	0.15	0.12	0.0	0.01	2.55	2.8	N/A	2.8
100 seats, 500 km	0.15	0.09	-0.05	3.6	0.18	3.8	0.54	0.4	0.13	0.03	0.0	0.01	0.62	0.8	4.4	1.2
200 seats, 1,500 km	0.11	0.11	-0.07	1.6	0.15	1.8	0.32	0.1	0.05	0.00	0.0	0.00	0.20	0.4	2.0	0.5
400 seats, 6,000 km	0.07	0.09	-0.06	0.6	0.11	0.7	0.16	0.0	0.01	0.00	0.0	0.00	0.04	0.1	0.7	0.2

Table 23 Overview of external costs as calculated in this study, with a shadow price for climatic impact of € 50 per tonne CO_2-equivalent

	climatic impacts							local/regional impacts						total		
	CO_2+ H_2O	NO_X via O_3	NO_X via CH_4	contrails (if any)	*total* km w/o contrails	km with contrails	aver-age	noi-se	NO_X	PM_{10}	HC	SO_2	*total*	km w/o contrails	km with contrails	aver-age
fleet-average technology, in € per aircraft-km																
50 seats, 200 km	0.27	0.19	-0.12	N/A	0.34	N/A	0.34	0.9	0.05	0.10	0.0	0.00	1.06	1.4	N/A	1.4
100 seats, 500 km	0.58	0.57	-0.35	12.0	0.80	12.8	2.00	0.6	0.13	0.09	0.0	0.01	0.84	1.6	13.6	2.8
200 seats, 1,500 km	1.04	1.19	-0.73	12.0	1.51	13.5	2.71	0.4	0.12	0.03	0.0	0.00	0.56	2.1	14.1	3.3
400 seats, 6,000 km	1.81	3.34	-2.04	12.0	3.12	15.1	4.32	0.2	0.09	0.02	0.0	0.00	0.31	3.4	15.4	4.6
fleet-average technology, in €ct per pax.km																
50 seats, 200 km	1.35	0.95	-0.58	N/A	1.72	N/A	1.72	4.5	0.24	0.50	0.1	0.01	5.32	7.0	N/A	7.0
100 seats, 500 km	0.86	0.85	-0.52	17.9	1.20	19.1	2.99	0.9	0.20	0.13	0.0	0.01	1.25	2.4	20.4	4.2
200 seats, 1,500 km	0.70	0.81	-0.49	8.1	1.02	9.2	1.84	0.3	0.08	0.02	0.0	0.00	0.38	1.4	9.5	2.2
400 seats, 6,000 km	0.42	0.78	-0.48	2.8	0.73	3.5	1.01	0.0	0.02	0.00	0.0	0.00	0.07	0.8	3.6	1.1
state-of-the-art technology, in € per aircraft-km																
50 seats, 200 km	0.22	0.10	-0.06	N/A	0.26	N/A	0.26	0.5	0.03	0.02	0.0	0.00	0.51	0.8	N/A	0.8
100 seats, 500 km	0.50	0.29	-0.18	12.0	0.61	12.6	1.81	0.3	0.08	0.02	0.0	0.00	0.41	1.0	13.0	2.2
200 seats, 1,500 km	0.82	0.81	-0.49	12.0	1.13	13.1	2.33	0.2	0.08	0.01	0.0	0.00	0.29	1.4	13.4	2.6
400 seats, 6,000 km	1.53	2.03	-1.24	12.0	2.33	14.3	3.53	0.1	0.05	0.00	0.0	0.00	0.16	2.5	14.5	3.7
state-of-the-art technology, in €ct per pax.km																
50 seats, 200 km	1.11	0.52	-0.32	N/A	1.32	N/A	1.32	2.3	0.15	0.12	0.0	0.01	2.55	3.9	N/A	3.9
100 seats, 500 km	0.74	0.43	-0.26	17.9	0.91	18.8	2.70	0.4	0.13	0.03	0.0	0.01	0.62	1.5	19.4	3.3
200 seats, 1,500 km	0.55	0.55	-0.33	8.1	0.77	8.9	1.58	0.1	0.05	0.00	0.0	0.00	0.20	1.0	9.1	1.8
400 seats, 6,000 km	0.36	0.47	-0.29	2.8	0.54	3.3	0.82	0.0	0.01	0.00	0.0	0.00	0.04	0.6	3.4	0.9

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List of terms and abbreviations

€, EUR	euro
€ct	euro cent
€M	million euro
AERO	Aviation Emissions and analysis of Reduction Options: model developed by Dutch CAA
$AERONO_X$	EU project to study impact of NO_x emissions from aircraft at altitudes between 8 to 15 km
aerosols	airborne suspension of small particles
anthropogenic	caused or produced by humans
airside infrastructure	infrastructure functioning primarily for airport activity (aircraft and passenger handling, etc.); airports also have subsidiary commercial activities (hotels, shops, etc.) and interface with landside infrastructure (roads, railways, etc.)
ATC	Air Traffic Control
background atmosphere	the atmosphere remote from anthropogenic or volcanic influences
black carbon	graphitic carbon, sometimes referred to as elemental or free carbon
block time	the time elapsing from start of taxi out, at origin, to end of taxi in, at destination
bunker fuels (international)	fuels consumed for international marine and air transportation
CAA	Civil Aviation Authority
CAEP	Committee on Aviation Environmental Protection: environmental committee of ICAO
CBA	cost-benefit analysis
cirrus	thin, high clouds composed mainly of ice particles
contrail	condensation trail: white line-cloud often visible behind aircraft
CO_2	carbon dioxide, the principal greenhouse gas
CO_2, high variant	in this report, sensitivity analysis using a high value for CO_2 emissions (EUR 50 instead of EUR 30 per tonne)
CO_2, low variant	in this report, sensitivity analysis using a low value for CO_2 emissions (EUR 10 instead of EUR 30 per tonne)
CVM	Contingent Valuation Method
distribution	in this report, the extent to which costs and benefits accrue to the same party; pricing based on fair distribution may conflict with optimum or efficient pricing

Dp/F00	the ICAO regulatory parameter for gaseous emissions, expressed as the mass of the pollutant emitted during the landing/take-off (LTO) cycle divided by the rated thrust (maximum take-off power) of the engine
efficiency	in economic theory and in this report, the pursuit of optimum pricing based on marginal costs; cf. 'distribution' and 'fairness'
emission Index	the mass of material or number of particles emitted per burnt mass of fuel (for NO_X in g of equivalent NO_2 per kg of fuel; for hydrocarbons in g of CH_4 per kg of fuel)
energy efficiency	ratio of energy output of a conversion process or of a system to its energy input; also known as first-law efficiency.
environmental cost	financial value assigned to negative environmental effects, based either on the costs of losses or on the costs of prevention
external costs (of mobility)	negative external effects of mobility assigned a monetary value
external effects (of mobility)	effects not taken into account by users in their transport decision; in this report, the following are designated external effects: noise nuisance, emissions, traffic accidents (in part) and congestion
equity	in economic theory and in this report, a second pricing policy consideration alongside efficiency
FAA	United States Federal Aviation Authority
FESG	Forecasting and Economic Support Group of CAEP
greenhouse gas	a gas that absorbs radiation at specific (infrared) wavelengths of the spectrum emitted by the Earth's surface and by clouds. At altitudes cooler than surface temperature, these gases emit infrared radiation. The net effect is a local trapping of part of the absorbed energy and a tendency to warm the planet's surface. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH4) and ozone (O_3) are the principal greenhouse gases in the Earth's atmosphere.
Green Paper	in this report, the European Commission's Green Paper Towards Fair and Efficient Pricing in Transport, 1995, a first step towards a common framework for a European transport pricing policy; see also 'White Paper'
H_2O	water (vapour)
HC	hydrocarbons; in this report, all hydrocarbons
ICA	intercontinental: aviation term

internal costs (of mobility)	social costs already passed on to users by the market mechanism (i.e. already reckoned with in individual transport decisions) and for which government intervention is therefore inappropriate
IPCC	Intergovernmental Panel on Climate Change: worldwide scientific panel established to coordinate international climate change research and publication of results
Ke	Kosten unit: Dutch method for aggregating annual noise nuisance
Ke zone	zone in which aggregate annual noise nuisance exceeds a given number of Kosten units (Ke)
kerosene	hydrocarbon fuel for jet aircraft
Landing/Take-Off (LTO) cycle	a reference cycle for the calculation and reporting of emissions, composed of four power settings and related operating times for subsonic aircraft engines [Take-Off - 100% power, 0.7 minutes; Climb - 85%, 2.2 minutes; Approach - 30%, 4.0 minutes; Taxi/Ground Idle - 7%, 26.0 minutes]
LT	long-term
LTO	Landing and Take-Off: every flight movement at an airport is associated with one LTO cycle; at Dutch airports a flight movement is counted as half an LTO cycle
Mach number	aircraft speed divided by the local speed of sound
marginal costs	additional costs of one extra unit of mobility, one extra vehicle, vessel or aircraft kilometre
MBO	market-based option (levies or trading regimes) for limiting the carbon dioxide emissions of the aviation sector
MIT	Massachusetts Institute of Technology
MSC	Marginal Social Costs
MT	medium-term
MTOW	Maximum Take-Off Weight (aircraft gross vehicle weight, GVW)
NO_X	generic term for oxides of nitrogen (NO, NO_2, NO_3), which contribute to acid rain, eutrophication and tropospheric ozone formation and indirectly to global warming and ozone layer changes
optimum (pricing policy)	in this report, a pricing policy in accordance with efficiency principles, i.e. based on marginal social cost
ozone	a gas formed naturally in the stratosphere by the action of ultraviolet radiation on oxygen molecules; a molecule of ozone is made of up three atoms of oxygen

ozone layer	a layer of ozone gas in the stratosphere that shields the Earth from most of the harmful ultraviolet radiation coming from the sun
passenger-km	passenger-kilometre, unit of passenger transport provision: one person moved one kilometre
pax	aviation term for ‘passengers’
pkm	see 'passenger-km'
PM_{10}	particles of soot less than 10µm in diameter; practically all particles in exhaust fumes
pressure ratio	the ratio of the mean total pressure exiting the compressor to the mean total pressure of the inlet when the engine is developing take-off thrust rating in ISA (International Standard Atmosphere) sea level static conditions
radiative forcing	a change in average net radiation (in W m^{-2}) at the top of the troposphere resulting from a change in either solar or infrared radiation due to a change in atmospheric greenhouse gas concentrations; perturbance of the balance between incoming solar radiation and outgoing infrared radiation
relative humidity	the ratio of the partial pressure of water vapour in an air parcel to the saturation pressure (usually over a liquid, unless specified otherwise)
RIVM	(Netherlands) National Institute for Public Health and the Environment
RLD	Dutch Civil Aviation Authority
SO_2	sulphur dioxide
social costs (of mobility)	in principle all costs, i.e. internal costs, external costs and government expenditure entailed by transport mobility. In this project, with its policy focus, internal costs are not relevant; for this reason ‘social costs’ here designate the external part of government expenditure and the external costs arising from transport mobility
soot	carbon-containing particles formed during incomplete combustion processes
specific fuel consumption	the fuel flow rate (mass per time) per thrust (force) developed by an engine
ST	short-term
stratosphere	the stably stratified atmosphere above the troposphere and below the mesosphere, between about 10 and 50 km altitude, containing the main ozone layer
tkm	see 'tonne-km'
tonne-km	tonne-kilometre, unit of freight transport provision: one tonne moved over one kilometre

tropopause	the boundary between the troposphere and the stratosphere, usually characterised by an abrupt change in lapse rate (vertical temperature gradient)
troposphere	the layer of the atmosphere between the Earth's surface and the tropopause below the stratosphere (i.e. the lowest 10 to 18 km of the atmosphere) where weather processes occur
vehicle-km	vehicle-kilometre, unit of transport: one vehicle moved over one kilometre
vkm	see 'vehicle-km'
VOLY	Value of Life Year lost: mortality valuation method that takes life expectancy into account; generally leads to lower estimates than the VOSL approach
VOSL	Value of Statistical life: mortality valuation method that uses a standard value for a human life, irrespective of life expectancy; generally leads to higher estimates than the VOLY approach
WTA	Willingness to Accept
WTA/WTP	Willingness To Accept/Pay, method of valuing negative external effects based on the willingness of citizens to accept an increase in or pay for a reduction of a certain amount of environmental burden