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External Costs of Aviation

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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.

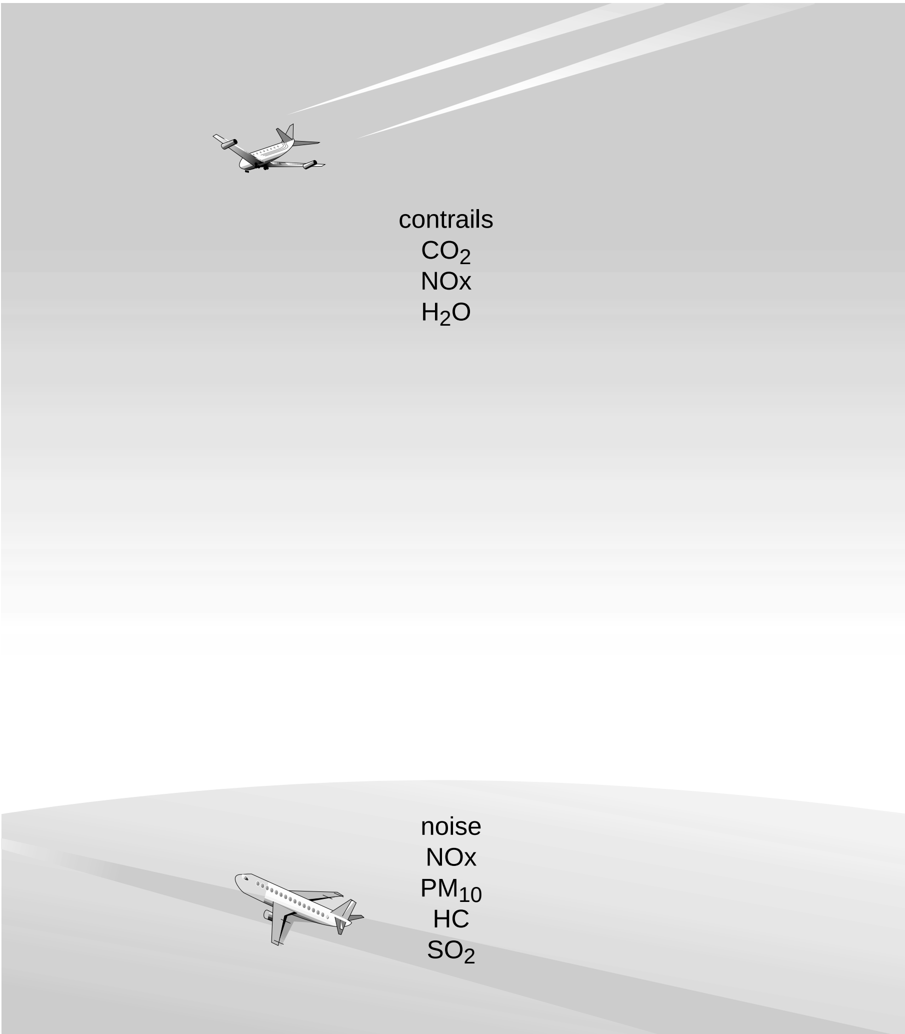
Air transport: benefits and undesired side-effects

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.

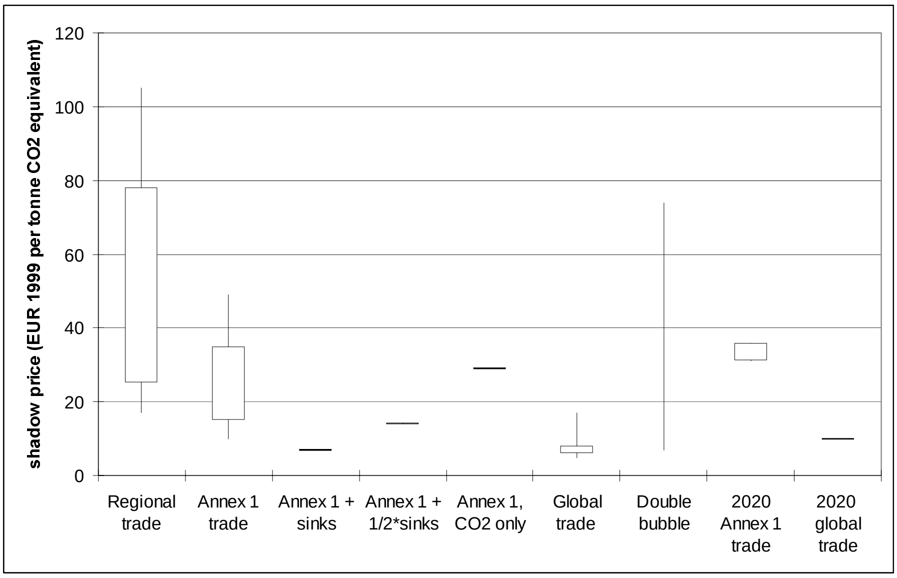
With respect to the damage cost approach, it was found that the social discount rate employed is one of the most important factors governing the calculated CO_2 shadow price (Table 1).

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

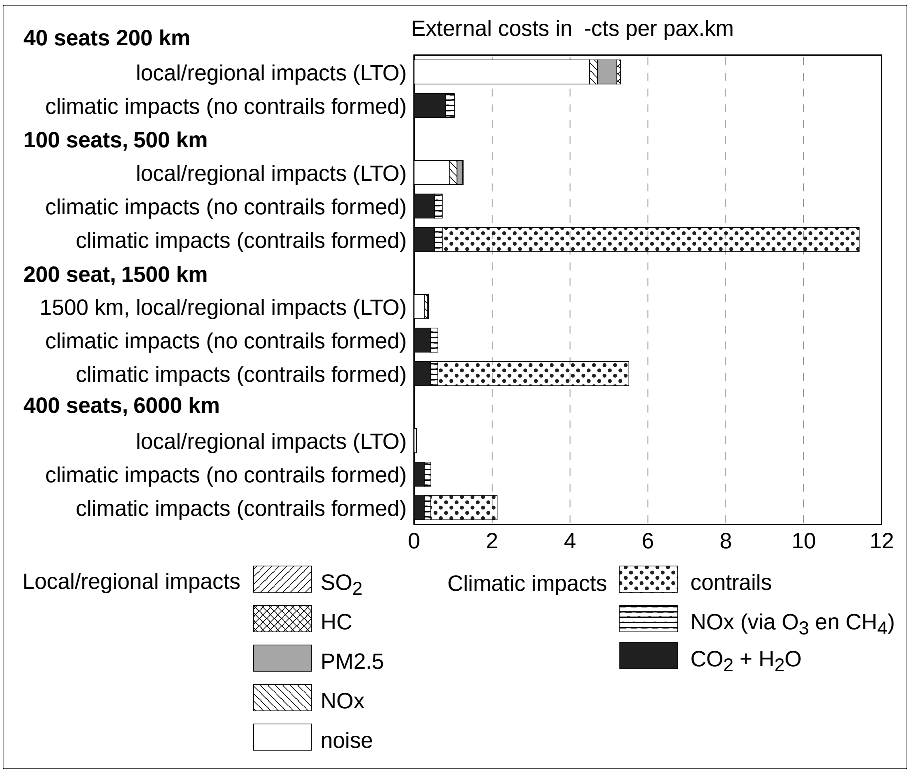
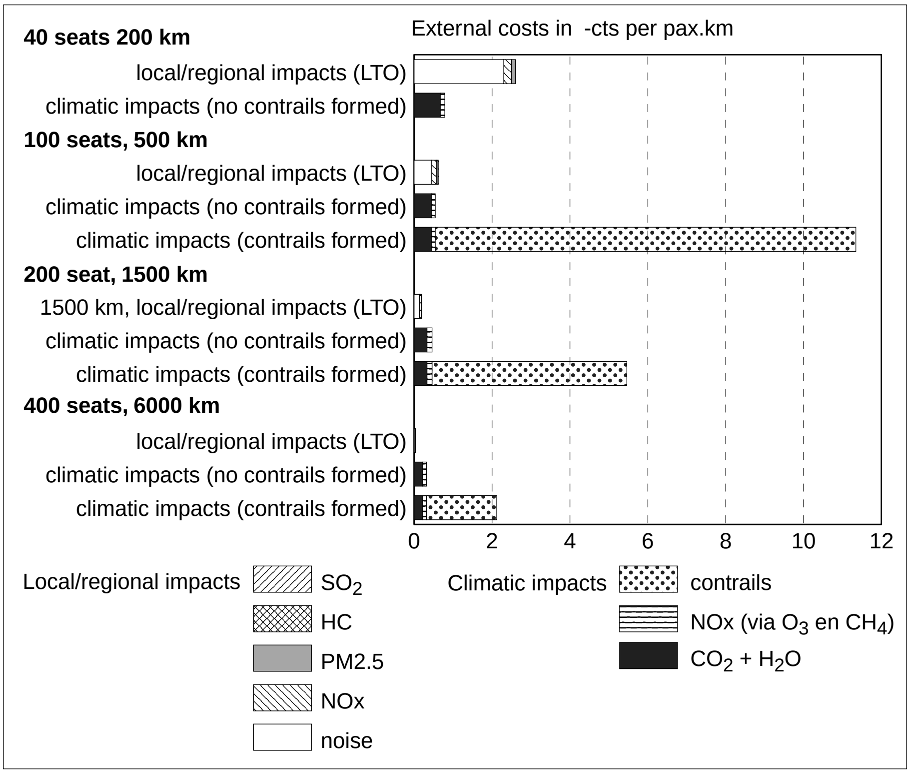


Figure 4 External costs in €ct per passenger-kilometre: state-of-the-art aircraft technology, CO_2 emissions valued at € 30/tonne



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

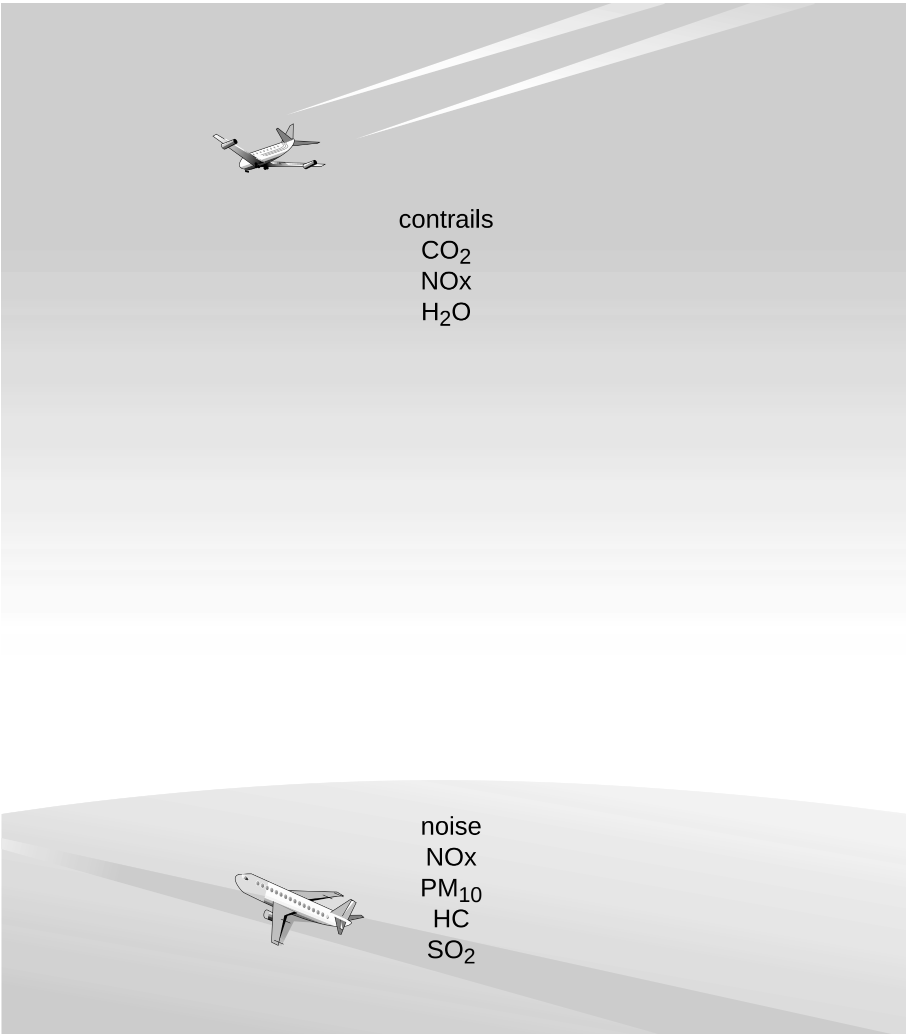
The aim of this report is to quantify – within as narrow ranges as possible – the external costs of air transport, in particular the costs associated with the impacts of climate change, air pollution and noise, and to provide insight into the principal factors determining these external costs. Information 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

[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-

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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:

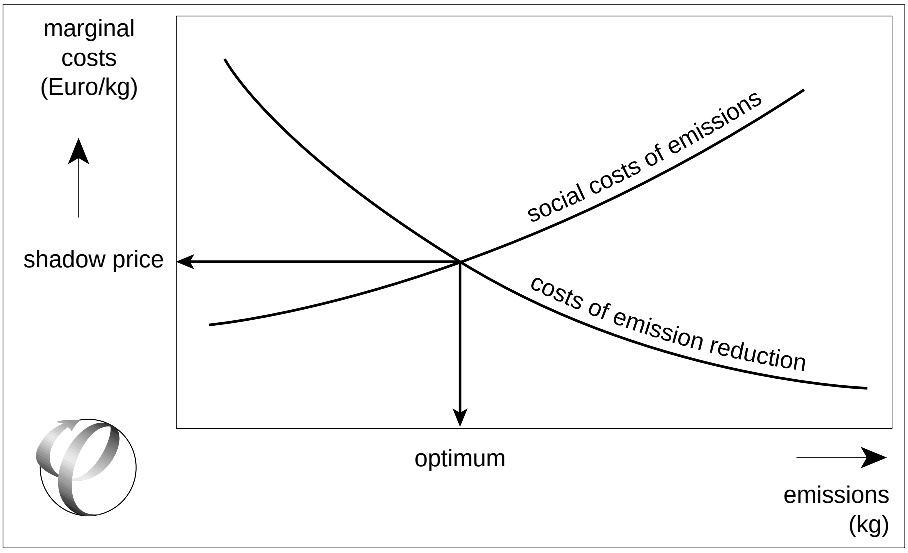
- **Costs of damage/nuisance plus avoidance/adaptation**
  Aircraft emissions of greenhouse gases, pollutants and noise may damage human health, the natural environment, buildings and equipment as well as give rise to nuisance. Accidents are another possible source of social costs (off-site risks). Finally, 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).

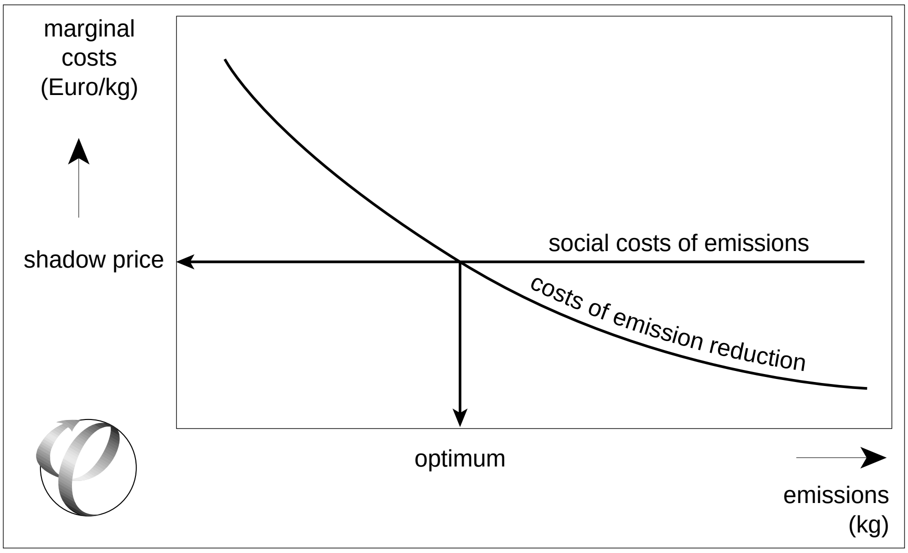
3.3 Valuation methods for environmental effects

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:

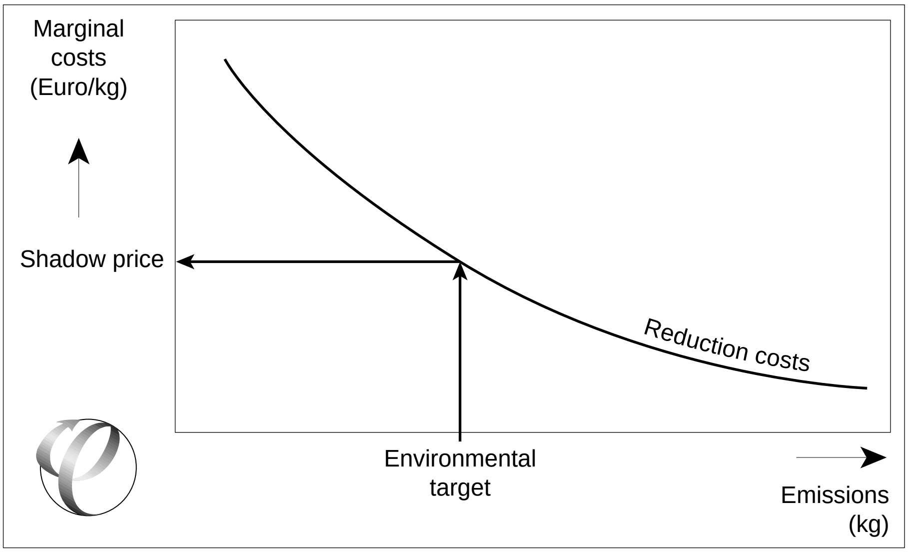
- it is extremely debatable whether respondents are capable of assigning a meaningful value to external effects, as is obvious from the example of global warming and even becoming apparent for (the health effects of) noise. While the method is useful for valuing local effects ('quality of life'), therefore, 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)

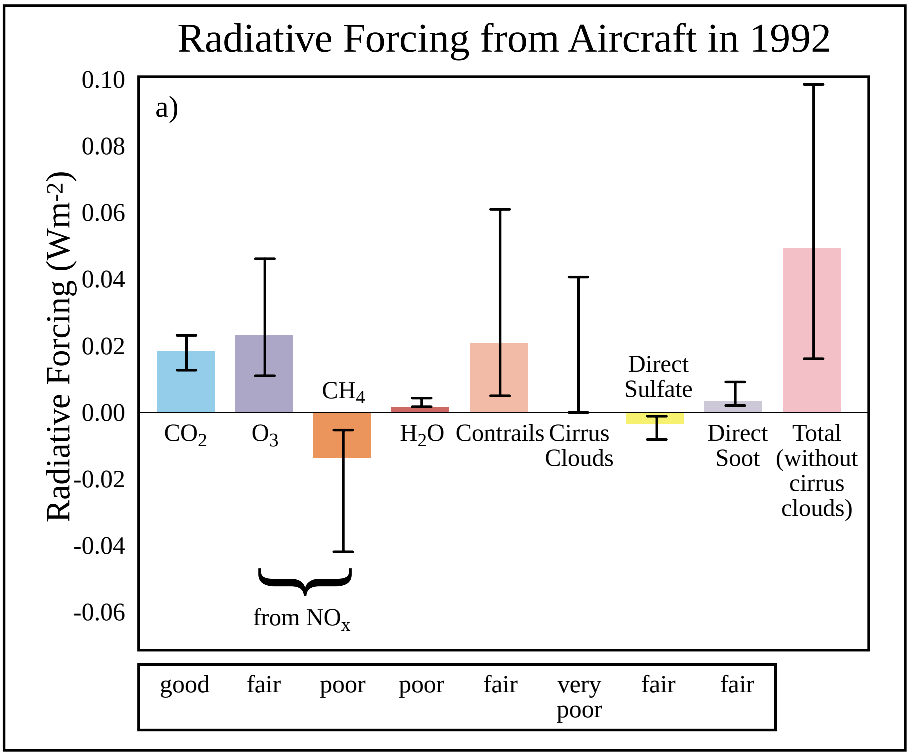
In a report requested by the American White House to help the Administration's ongoing review of U.S. climate change policy, the U.S. National Academy of Sciences confirms the major findings of the IPCC:

> "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

[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/m²)	**+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.

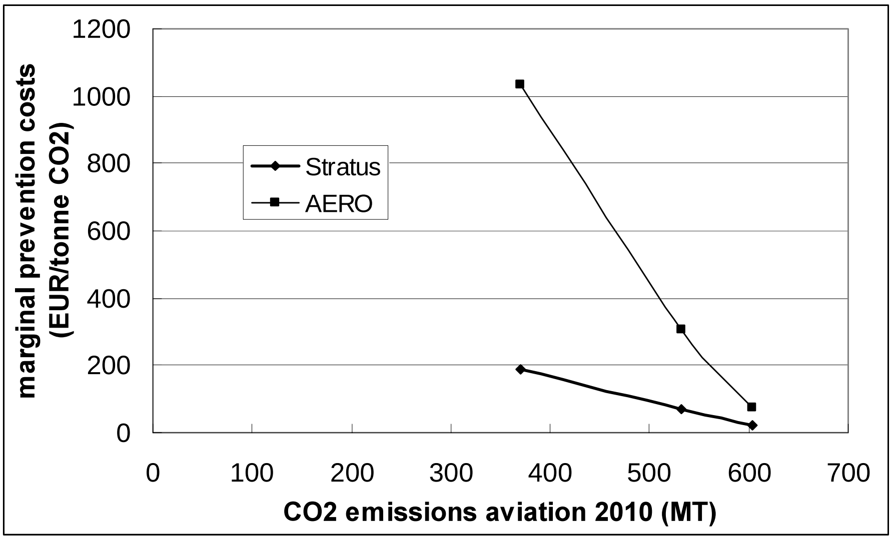
Table 10 Incentive levels at different CO_2 emission reduction targets (expressed both in EUR/litre fuel and EUR/tonne CO_2; $ to € conversion rate 1:1)

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,

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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).

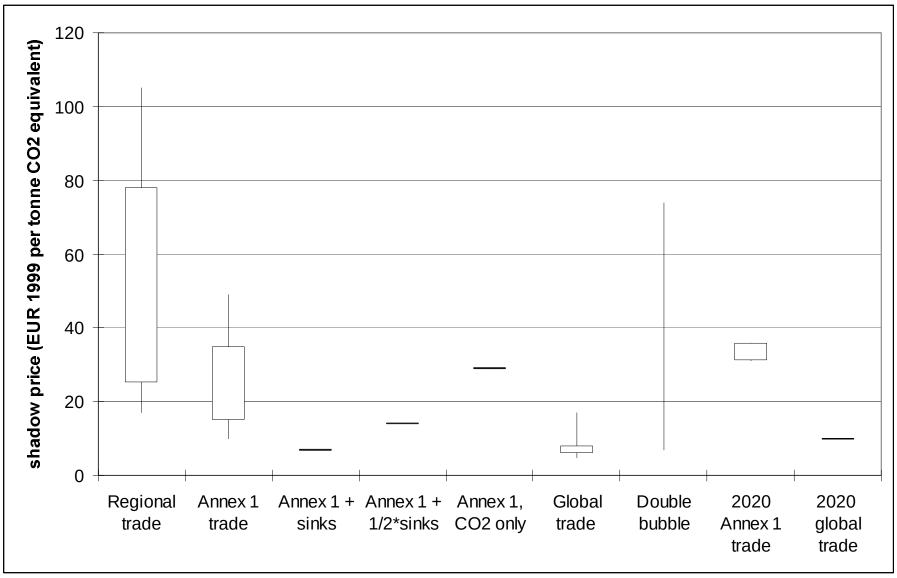
Recently, a debate has started about the issue of *equity-weighting*, i.e. how to aggregate the valuation of impacts across geographical regions that exhibit major disparities in income.[15] Equity weighting always increases cost estimates.

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.

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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-*

[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.

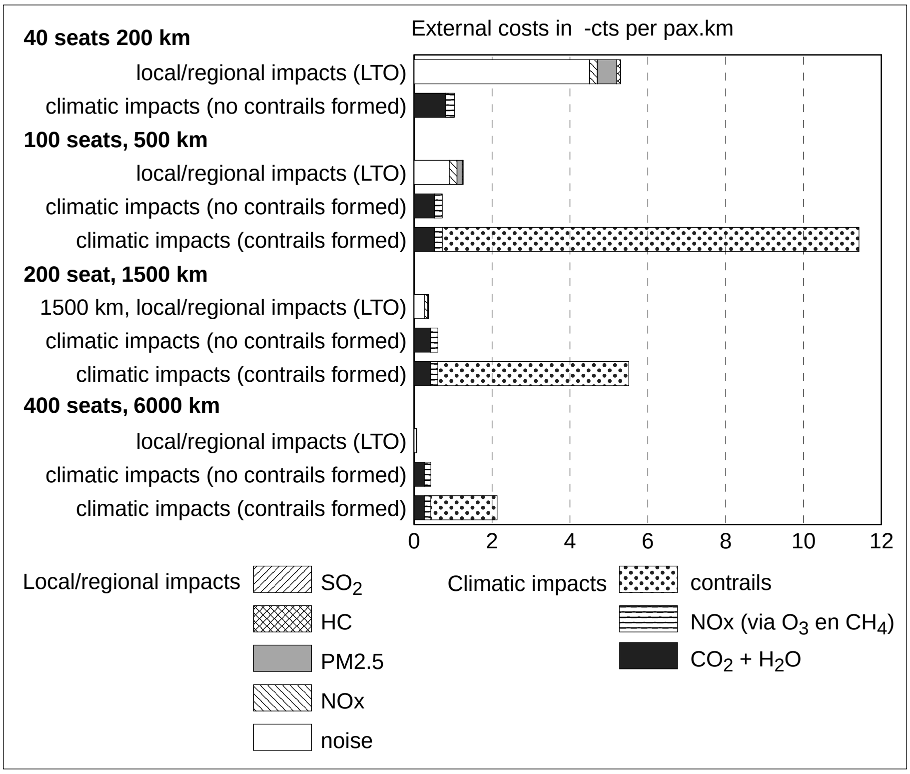
Three different valuations for a tonne of CO_2 emissions have been used: a middle estimate of € 30 per tonne, a low estimate of € 10 per tonne and a high estimate of € 50 per tonne.

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;

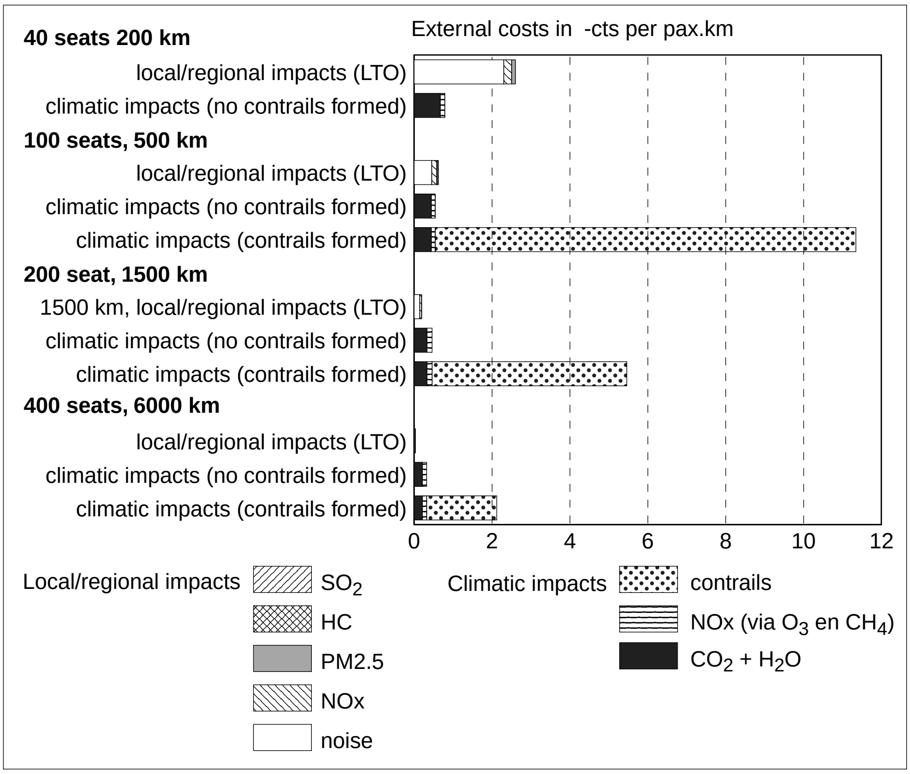
3 there is a 67% probability that the true climatic impact of contrails is between one-third and three times this middle estimate (IPCC 1999, Figure 9);
4 scientific evidence on the climatic impacts of contrails is judged to be 'fair' (IPCC 1999, Figure 9);

- 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 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	0.16	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 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	0.05	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		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	0.27	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

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External costs of aviation

Background report

Delft / Amsterdam

February 2002

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Foreword

Besides numerous benefits to citizens and companies, air transport also brings undesired side-effects such as emissions and noise nuisance. Most of these negative 'external' effects, as they are called, are currently not priced or only to a limited degree. Consequently, the market place creates insufficient incentives to reduce these external effects.

The study 'External costs of aviation', commissioned by the German Umweltbundesamt, aims to contribute to the ongoing international process to create market-based incentives to the aviation industry to reduce the environmental impact of aviation. It does to by assessing, within margins as small as possible, external costs of aviation.

The report at hand is a background report to the study 'External costs of aviation'. It contains four technical annexes.

The first annex, written by CE, contains an overview of the international literature on the valuation of greenhouse gas emissions.

The second annex, written Mr Fransen, describes the dependence of climatic impact of aviation on the occurrence of contrails, and the dependence of contrail formation on operational circumstances.

The third annex, written by CE, contains an assessment of international literature o the valuation of non-greenhouse gas emissions, such as NO_X and SO_2.

The fourth annex, written by CE, contains a short description of the methodology by which emissions and noise are allocated to passenger and freight transport in this study.

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

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External costs of aviation

Annex I: External costs of greenhouse gas emission

Delft, February 2002

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Contents

1 External costs of greenhouse gas emission

1.1 Methods for the valuation of CO_2

The methods for determining the price of CO_2 (per kilogram), are the prevention cost method and the damage cost method.

Below we will briefly describe these two methods and the most important determinants of the differences between these methods. This knowledge is useful when analysing the literature. After that we will judge both methods.

Prevention cost method
The prevention cost method is based on the costs that must be made to reach a predetermined goal. We distinguish two variants:
- one at which a emission reduction goal is enforced to the aviation sector ('closed system');
- in a second possible variant the aviation sector will be included in the Kyoto Protocol; in this variant the sector will have an own goals just like the other Annex 1 Parties, but it will be free to trade emissions according to the mechanisms of the Kyoto Protocol.

In the prevention cost method, the most important variables determining the final shadow price are:
1 The reduction goal to be achieved.
2 The degrees of freedom in trade: is trade possible between Annex 1 countries or even world-wide?
3 The degrees of freedom in the use of 'flexible mechanisms' like emission trade, the Clean Development Mechanism and Joint Implementation.

Damage cost method
Besides the prevention cost method, the literature also pays much attention to the damage cost method. In this method it is tried to establish the regional consequences of climate change, mainly higher water levels and shifts in climatic zones. These changes in the ecosystem damage the economy.
The differences in literature sources that use this approach are mainly dependent on differences in dose-response relationships. Also discount rates play a large role, as damages will most occur in the future. Recalculating damages to net present values implies use of an interest rate reflecting societal preferences of time. This is illustrated in Table 1.

Table 1 Sensitivity of damage costs estimates of CO_2 for interests rates (IPCC 1996)

discount rate	CO_2 shadow price (in € 1999 per tonne)	
	low	high
2%	14	33
5%	1.4	3.3

Some other studies that use the damage costs method to value the damage of CO_2 emissions Nordhaus (1991, 1993) and Fankhauser (1994). Nordhaus calculates in his studies costs of about € 2.7/tonne CO_2, Fankhauser arrives at € 7 - 9/tonne CO_2.

In this study we will only use the prevention cost method to establish a CO_2 price, and we will base our estimates on the Kyoto shadow price, for reasons that have been explained in the main text.

Conversion rates used

In many cases we didn't copy the exact results from the respective sources for the following two reasons:

1 In some cases the results are given in the reduction of one tonne C and in other cases in the reduction of one tonne CO_2; we have decided to present all numbers in prices per avoided tonnes of CO_2. We have multiplied the prices of C with 12/44 where necessary, for the reduction of one tonne C equals the reduction of 44/12 tonne of CO_2.

2 In some cases the results are given in € and in some cases in US $. The basic year for the different data also varies. We've decided to convert all values to €1999. We have used the following conversion table.

Table 2 Conversion rates from $ to €

year	CPI (US, 1989 = 100)	Exchange rates (1 € = .. US$)
1990	105.4	1.40
1991	109.8	1.30
1992	113.1	1.44
1993	116.5	1.19
1994	119.5	1.25
1995	122.9	1.32
1996	126.5	1.28
1997	129.4	1.11
1998	131.4	1.19
1999	134.3	1.07

1.2 Summary of results from prevention cost method

This paragraph presents the CO_2-emission reduction costs found in the literature. A complete review follows later on in this annex.

The ranges of values we've found are presented into four variants:

1 First the variants where the different regions must reach their goal in their own region without trade between the regions.

2 Then the variants where international emission-trading is permitted between Annex I countries.

3 Next a variants where global emission trading is permitted, in other words the maximal variant of CDM.

4 We'll finish with a few examples of values where sinks are permitted, other greenhouse gasses can be reduced or explicitly not, agreement on double-bubble, etc.

1.2.1 Every region it's own

At first we'll give the ranges for the different regions distinguished in the models. Hereby we present the range in the case where the extreme values are being ignored and, between brackets, the whole range.

It further concerns the costs involved for reaching the Kyoto-goals for every region when all reductions must be made in own country.

Table 3 Every region on it's own

Region	Marginal reduction cost (in € 1999 per tonne CO_2)
US	25 – 78 (17 – 105)
EU	40 – 83 (29 – 216)
Japan	29 – 177 (22 – 209)

Sources:

- for the US: 9 literature sources;
- for the EU: 8 literature sources;
- for Japan: 8 literature sources.

This table shows that in all probability the US can reach their goal in their own country in the cheapest way. This is because of the relatively energy-inefficient structure of the American economy, where with the help of energy-savings and 'good-housekeeping' a lot of win-win measures can be taken. Europe is already in a further stage of efficiency-increasing measures, which makes it more expensive to take further measures.

1.2.2 Emission trade between Annex-I countries

When we study the price per avoided tonne CO_2 when emission trading between Annex I countries is permitted, we find the following range of values:

€ 15 – 35 (10 – 49)

This range is based on the results of 10 literature sources.

In this scenario Joint Implementation is permitted, but the Clean Development Mechanism is prohibited.

1.2.3 Global emission trading

In the variant where global emission trading takes place to minimise the total costs to reach the Kyoto-goals, more cheap measurements come available resulting in a lower price.

In this situation there has been assumed that in all models the countries not belonging to Annex I will have emission rights for the forecasted emissions of that country in 2010. This results in an emission ceiling leading to a real market. This variant can be seen as a upper-limit of the opportunities of the CMG-model.

The ranges of values found are (between bracelets is the range without extreme values:

€ 6 – 8 (4.8 – 17)

There were only 4 sources of literature presenting these results.

1.2.4 Some other variants

In the literature analysed we encountered sources which have assessed some extra variants. Below in brief the characteristics with corresponding values:

Table 4 Results sensitive for assumptions

Characteristics	Development shadow price	Reference
Annex I trade + counting all the sinks	22 -> 7	Annex I trade
Annex I trade + counting halve of the sinks	22 -> 14	Annex I trade
Annex I trade + infinite high costs for reduction CO_2 gasses	22 -> 29	Annex I trade
Double-bubble	17 -> 9 (US, Jap. en Austr.) 17 -> 74 (rest OECD)	Annex I trade

Each of these variants was presented by only one source of literature.

Next to these variants model calculations have been made at which the goals of Kyoto have been extrapolated to 2020. We've presented the differences in the prices per avoided tonne CO_2 in Table 5.

Table 5 Kyoto targets also apply to 2020

Source	Prices in 2010 en 2020	Characteristic
McKibben et al. (1999)	17 -> 31	Annex I trade
McKibben et al. (1999)	6 -> 10	Global emission trade
MacCracken et al. (1999)	22 -> 36	Annex I trade

The last two tables show that:
- fully counting of sinks lowers the price of CO_2 with two thirds;
- counting halve the sinks lowers the price of CO_2 with one third;
- infinite high costs for not-CO_2 gasses raise the price of greenhouse gasses with almost one third;
- the effect in implementation of double-bubble differs greatly between the 'bubbles';
- the extrapolation of the Kyoto-goals to 2020 causes higher reduction costs, approximately 60% per tonne avoided.

1.3 Literature studied

The separate sources of literature that are found and analysed are presented below.

Capros, P., en L. Mantzos, 2000, The economic effects of EU-wide industry-level emission trading to reduce greenhouse gasses: results from PRIMES energy systems model, National Technical University of Athens

This study describes the results of model exercises with the PRIMES-model, a partial balance model aimed at the energy markets within the European Union.

Five scenario's to reach the Kyoto-goals within the European Union are being dealt with. This study shows clearly the cost advantages of trading that can be reached.
The five scenario's are:
- every member state reaches his own goal, without trading;
- every sector within a Member State reaches its reduction as is determined for every member state;

- ever member state reaches his own goal where trading between energy producers is permitted;
- ever member state reaches his own goal where trading between energy producers and the energy intensive industries is permitted;
- the European Union reaches the goal, where trading between all sectors in all members states is permitted.

The costs to reach the goals of the EU vary greatly between the different scenario's. Table 6 shows a overview of the scenario's and the marginal reduction costs of the last tonne CO_2 needed to reach the goal.

Table 6 Estimated price per avoided tonne CO_2

Scenario	Marginal reduction cost (in $ 1995 per tonne CO_2)
(I) Every sector within the member state same target as member state	108
(ii) Every member state has a target.	46
(iii) Trade between energy producers	39
(iv) Trade between energy producers and energy intensive sectors.	37
(v) Free trade within the EU	28

This shows that the Kyoto goal of the EU can be reached at relatively low costs if a EU internal emission trading will be set up.

An important assumption in this modelling is that the transaction costs of a emission trading system are set to zero.

CPB/RIVM, 2000, De economische gevolgen van het Kyoto-protocol voor sectoren en wereldregio's (Economic consequences of the Kyoto protocol for setors and world regions), no. 00/31, Den Haag

In this paper the investigators have performed model calculations with the model WorldScan. Goal of this paper was to map especially the economic consequences of the Kyoto protocol, focused especially on the consequences for energy exporting countries and developing countries.
WorldScan is a global general balance model, primarily to describe long term developments. The quotes about the developments in the period 2008-2012 must therefor be carefully interpreted.

The simulations are confined only to CO_2 greenhouse gas and the basic variant is given by the individual reaching of the different goals through the different countries.

The possible cost lowering mechanisms as Clean Development Mechanism, Joint Implementation and the usage of sinks can't be simulated in WorldScan.

Emission trading (between Annex I countries) can be simulated and serves as an alternative variant. In this paper there are no trading limitation simulated though, so in the alternative variant the emission reduction goal can be reached fully by trade between other Annex I countries.

The results of the (two) simulated situations are summarised as follows.

Table 7 Results of the (two) simulated situations

	Marginal reduction costs (in € 1999 per tonne CO_2)	
Region	**Without emission trade**	**With emission trade**
VS	40	15
Japan	29	15
Pacific OECD	32	15
EU	52	15
Eastern Europe	3	15
Former Soviet Union	0	15

ECN/RIVM, 1998, Optiedocument voor emissiereductie van broeikasgassen: inventarisatie in het kader van de Uitvoeringsnota Klimaatbeleid. (option document for GHG emission reduction; inventory in the framework of the Climate Change Execution Paper)

In this publication a overview is presented of the possibilities to reach the emission reduction goal of the Netherlands domestically. An analysis of the results shows that the measures that can and should be taken in the Netherlands (the so-called "basic package") are not the cheapest measures.

A similar analysis is performed by Dings et al. (1999) and this shows that the most expensive measure in the basic package is unequal to the cheapest measure in the extra package. Nevertheless we choose to consider the most expensive measure of the basic package as the marginal costs of the last measure needed in the Netherlands to reach the Kyoto goal.

The costs are roughly € 70 per tonne CO_2. However, this price concerns only the domestic measures and can't be used as a international price to reduce one tonne CO_2. It gives a good view of the possibilities to reach the Kyoto goals domestically.

ECN/AED/SEI, 1999, Potential and cost of Clean Development Mechanism options in the energy sector: inventory of options in non-Annex I countries to reduce GHG emissions

This publication gives a estimation of the possibilities to reach cost savings by the CDM. The table below presents the outcomes of a simple simulation, where a perfect competition market is assumed.

This publication describes a trading system within the OECD, a system where trading between Annex I countries is permitted and a global trading system. This variant can be seen as the extreme variant of CDM.

This resulted in the following outcomes.

Table 8 Results of the simulation

Trade within	**Marginal reduction costs (in € 1999 per tonne CO_2)**
OECD	68
Annex I	21 – 35
Global	4.8 – 18

It has to be noticed that the lower prices in the range will approach the reality the closest. The lower prices will be the result if the so-called ‘no regret' measures will count for reaching the Kyoto goals. The ‘no regret' measures are the measure which will be economic profitable even without strict climate policy.
This separation, between profitable and not-profitable, has been made explicit in this publication.

McCracken, C.N., J.A. Edmonds, S.H. Kim and R.D. Sands, 1999, The economics of the Kyoto-protocol, in: The Energy Journal: special issue, May 1999, p. 25 – 72

With the so-called ‘Second Generation Model" the authors estimated the marginal costs needed to reach the Kyoto goals. These marginal costs represent the costs per tonne CO_2 of the last measure needed to reach the goals. It has been done for 5 scenario's:

1 All region comply with their Kyoto-goal, no trading.
2 Trading is permitted between Annex I countries.
3 Trading is permitted between Annex I countries and CDM is permitted.
4 Not-CO_2 greenhouse gasses are taken into account.
5 ‘Sinks" are permitted in some degree.

Below the resulting prices per avoided tonne of CO_2 for 2010. Between brackets are the values resulting form the model for the year 2020, with the assumption that the Kyoto goals in 2020 are still effective.

Table 9 Resulting prices per avoided tonne CO_2 for 2010

		Marginal reduction costs (in € 1999 per tonne CO_2)				
region	**scenario**	**(i)**	**(ii)**[b]	**(iii)**[c]	**(iv)**[d]	**(v)**[e]
Australia		36 (43)				
Europe		40 (63)				
US		51 (60)	22 (36)	8 (-)	29 (-)	7 (-)
Canada		106 (117)				
Japan		139 (130)				

a When there's no expansion of the nuclear power capacity the marginal reduction costs in Europe can reach up to € 44.
b If Eastern Europe will behave as a monopolist on the market of tradable emission rights, the trading price for this scenario will be higher, namely € 32.
c This price was achieved by allocating non-Annex 1 countries emissions in the reference scenario and subsequently apply global trade. A fictitious market is created, in which indeed scarcity of emission reduction is achieved.
d This price is based on the assumption that the not-CO_2 gases only can be driven back against infinite high costs; when these gasses can be driven back for free, every region can reach their Kyoto goal without costs and the resulting market price for CO_2 will be zero. The price in the second scenario is based on the assumption that the not-CO_2 gasses can be driven back against the same proportional costs as CO_2 can be driven back.
e This price is based on the assumption that all sinks count for reaching the Kyoto-targets, while further trading between Annex I countries is permitted. When only halve of the sinks are counted, the trading price to $ 14.

Table 9 shows that the different assumptions of the filling-in of the Kyoto protocol and its mechanisms have an important influence on the costs the different regions have to make.

Trade between all countries to reach Kyoto targets gives *ceteris paribus* the lowest costs for reaching the goals, namely € 8 per tonne CO_2.

McKibbin,W., M. Ross, R. Shackleton and P. Wilcoxen, 1999, Emissions trading, capital flows and the Kyoto-protocol, in: The Energy Journal: special issue, May 1999, p. 287 – 334

This publication describes the estimation of the costs for reaching the Kyoto targets with the help of the so-called G-Cubed model. This model describes measures and adjustments in several regions and sector in an inter-temporal equilibrium model.

In this study five scenarios are calculated:
1 Only the US fulfil the Kyoto goals.
2 All Annex I countries fulfil their Kyoto goals, trade is not permitted.
3 All Annex I countries fulfil their Kyoto goals, trade is permitted between Annex I countries.
4 All Annex I countries reach their Kyoto goals, trade is permitted within two trading blocks 'other OECD' and "other Annex I', while there's no trade permitted between trading blocks.
5 Global trade is permitted where the developing countries not appearing in the Kyoto protocol get their reference emissions assigned.

The model is not capable to consider the reduction of not-CO_2 emissions as well. This approach counts for more models treated in this annex and ignores the relatively cheap reduction measures of other greenhouse gasses.

This model proclaims a strict climate policy in 2000, so the economic actors have 10 years to anticipate on the policy and take action.
We present the resulting prices per avoided tonne CO_2 in Table 10 for 2010 and 2020 (in € 1999).

Table 10 Resulting prices per tonne of CO_2 avoided

<table>
<tr><th colspan="2"></th><th colspan="5">Marginal reduction cost per tonne CO_2 (in € 1999)</th></tr>
<tr><th>region</th><th>Scenario</th><th>(i)</th><th>(ii)</th><th>(iii)</th><th>(iv)</th><th>(v)</th></tr>
<tr><td colspan="2">Australia</td><td>-</td><td>50 (64)</td><td rowspan="4">17 (31)</td><td rowspan="3">9 (19)</td><td rowspan="4">6 (10)</td></tr>
<tr><td colspan="2">US</td><td>22 (27)</td><td>25[a] (29)</td></tr>
<tr><td colspan="2">Japan</td><td>-</td><td>32 (45)</td></tr>
<tr><td colspan="2">rest of OECD</td><td>-</td><td>73 (88)</td><td>74 (89)</td></tr>
</table>

a The difference between this price ($ 25) and the price of 23 in case of unilateral action by the US (scenario 1) can be explained as follows: when all countries have to reduce their CO_2 emissions demand for oil and thus its price will decrease. It will be harder then to achieve the US reduction targets;

b The difference between this price ($25) and the price of $23 in case of one-sided action by the US (scenario 1) can be explained as follows: If all countries must push back.

De price that will result from global trade is about 6 €/ton CO_2 in 2010.

Manne, A.S. and R. Richels, 1999, The Kyoto-protocol: a cost-effective strategy for meeting environmental objectives? in: The Energy Journal: special issue, May 1999, p. 1 – 24

From this article it is hard to judge the assumptions made for modelling climate policy and the resulting costs.

Next prices are mentioned as marginal reduction costs in € 1999 per tonne CO_2:

1 € 78 in case of US unilateral domestic action.
2 € 33 in case of trade between Annex 1 countries and application of CDM.
3 € 22 in case of completely global trade.

The difference between variants (ii) and (iii) the CDM potential assumed; in variant (ii) the authors assume only 15% of total CDM potential can be exploited in practice. This reflects the complexity of CDM. In case of global trade, the full potential of CDM can be exploited.

PEW Center on Global Climate Change, 1999, International emissions trading and global climate change, Arlington, USA

This report gives an overview of advantages of international emission trade for reducing GHG emissions. The researchers assess differences between various models used to assess the effects of GHG emission reduction.

Table 11 below offers an overview of marginal reduction costs as calculated by various models. Reduction costs birth in case of regional and Annex 1 trade are calculated.

Table 11 Differences between models

	Marginal reduction costs per ton CO_2 (in € 1999)									
	SGM		EPPA		GTEM		G-Cubed		OECD Green	
region	no trade	Annex I trade	no trade	Annex I trade	no trade	Annex I trade	no trade	Annex I trade	no trade	Annex I trade
VS	51	22	56	49	105	35	17	10	44	19
Japan	139	22	177	49	209	35	71	10	22	19
Western Europe	44	22	83	49	216	35	47	10	58	19
former Soviet Union	0	22	0	49	0	35	0	10	0	19

Differences are caused by factors as previously described in this annex.

PNNL, 1997, Return to 1990: The cost of mitigating United States carbon emissions in de post-2000 period (no. PNNL-11819)

This publication gives a brief overview of possibilities to reduce costs to achieve reduction targets. For fictive US targets are used instead of the Kyoto targets. We will not discuss the results in detail, also because the results from the Second Generation model used have already been described under MacCracken et al. (1999).

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External costs of aviation

Annex II: The contribution of contrail occurrence to climatic change induced by air traffic

Delft, February 2002

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The contribution of contrail occurrence to climatic change induced by air traffic

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Preface

The environmental effects of aviation give rise to concern on local and global scales. The IPCC Special Report on Aviation and the Global Atmosphere* indicates that in 1992 aviation contributed 2% to the anthropogenic CO_2 emissions, about 1% of the anthropogenic CO_2 concentrations increase since pre-industrial times can be attributed to aviation and the aviation-induced perturbation of the radiative balance is about 3.5% of the total anthropogenic radiative forcing. Without changes in policies, the environmental impact of aviation is expected to increase in the coming decades.

In order to support the development of policies to mitigate the environmental impact, the German Umweltbundesamt commissioned CE Delft, the Netherlands, a study in order to quantify, within the smallest possible range, external costs of aviation resulting from emissions and noise..
Since estimates of the external costs will only be widely accepted if the environmental data and relations underlying these costs are accurate and widely accepted, the relationship between fuel use and emissions by air traffic on the one side and the associated climatic changes on the other side should be given proper attention. It is within this framework that the underlying study has been carried out.

W. Fransen

INTEGRAL Knowledge Utilization

* IPCC, Aviation and the Global Atmosphere. A Special Report of IPCC Working Groups I and III in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer. Penner, J.E., et al., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (1999).

Summary

Emissions from aircraft fuel burn contribute to climate change by perturbing the radiative balance of the Earth-atmosphere-system. All major constituents of aircraft exhaust directly or indirectly perturb the radiative balance irrespective of flight conditions. However, under specific meteorological conditions and depending on propulsion efficiency, emissions of water vapour and aerosol precursors also lead to contrails and aircraft induced cirrus. This adds to the climatic impact from aircraft emissions. In this study an estimate is given for the relative contribution of contrail occurrence to the climatic impact by air traffic. This estimate is represented in the following table:

Perturbation of the radiative balance in W/m^2 for the part of yearly annual flight time during which contrails occur (10% of flight time)		**Perturbation of the radiative balance in W/m^2 for the part of yearly annual flight time during which no contrails occur (90% of flight time)**	
Δ(carbon dioxide)	+0,0018	Δ(carbon dioxide)	+0,016
Δ(ozone) from NO_x emissions:	+0,0023	Δ(ozone) from NO_x emissions:	+0,021
Δ(methane) from NO_x emissions:	–0,0014	Δ(methane) from NO_x emissions:	–0,013
Δ(water vapour):	+0,0002	Δ(water vapour):	+0,002
Δ(contrails):	+0,0200		
Δ(sulfate aerosols) from SO_x emissions:	–0,0003	Δ(sulfate aerosols) from SO_x emissions:	–0,003
Δ(soot aerosols) from C emissions:	+0,0003 +	Δ(soot aerosols) from C emissions:	+0,003
	+0,023		+0,026
total radiative forcing of (0,023 + 0,026 =) 0,049 W/m^2 is in accordance with IPCC (1999) value			

From the information presented in the table, it can be said that the climatic impact of the 10% of air traffic leading to contrail occurrence is of the same order of magnitude as the 90% of air traffic not leading to contrail occurrence. From the same information it can be concluded that air traffic leading to contrails has on average a near eightfold climatic load compared with air traffic that does not lead to contrail occurrence. This conclusion does not account for the climatic impact of additional cirrus induced by these contrails which is likely to enhance the climatic load.

Climate and climate change as referred to in this study

A simple definition of climate is the average weather. A description of the climate over a period (which may be from a few years to a few centuries and for meteorological purposes is typically 30 years) involves the averages of appropriate components of the weather over that period, together with the statistical variations of those components. Thus defined, 'climate' as concept concerns

1) different meteorological components, such as wind, temperature, humidity, cloud coverage, precipitation, et cetera;
2) different types of average values for these components, e.g., daily, monthly, seasonal or annual mean and daily or annual cycle for a single location (e.g., De Bilt), an area (e.g., The Netherlands) or the globe; and
3) variations in these components at different time-scales, e.g., day-to-day and year-to-year variations, including extremes (minima and maxima).

Fluctuations of climate occur at different time-scales, e.g., day-to-day, year-to-year and century-to-century, as a result of natural processes; this is referred to as natural climate variability. In this perspective, climate change refers to the difference between, for instance, one 30-year period and another 30-year period.

Climate change as it is currently in general being addressed within society, is that which may occur over the 21st century as a result of human activities or that which has actually occurred during the past century as a result of human activities. In this discussion, climate (change) has a broader scope and encompasses, for instance, sea level (rise).
For the purposes of the UNFCCC the definition of climate change is "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods".

The climate change that is being addressed in **this report concerns global mean temperature change at the Earth's surface** which may occur over the present and next centuries as a result of aircraft emissions. It is acknowledged that the use of temperature change as a metaphor for climate change gives a first order estimate of climate change only. However, given the aim of this report such a first-order estimate is sufficient.

box 1

Introduction

At some point in the early nineties ICAO, IPCC and WMO agreed to co-operate in order to enlarge the knowledge with respect to the atmospheric effects of aircraft emissions and to study the effect of possible (operational) measures to mitigate these effects. Since then, their knowledge has increased rapidly as manifested by the IPCC Special Report on Aviation and the Global Atmosphere (1999). Due to this better understanding, it is now possible to provide policymakers with some basic information on the sensitivity of the Earth's climate to aircraft fuel use and resulting emissions. Moreover, the many specific studies which have been carried out during the last decade allow us to make some distinction between the different constituents of aircraft exhaust concerning the extent by which they perturb the climatic system. Finally, theoretical considerations, satellite observations, in-situ measurements and results from simulations with tracer and (chemistry-)climate models of different complexity have increased enormously in number and make it possible to give some indication of the dependence of the climatic effects of aircraft exhaust on the prevailing meteorological conditions during cruise.

Aim of the study

This study aims to give the reader an idea of the sensitivity of the climatic system to the occurrence of aircraft induced clouds, known as 'condensation trails' or 'contrails'.
For this, climate effects are linked to aircraft fuel use as well as to the concomitant emissions by linearisation and averaging of many complex relationships between emissions and effects. This is justifiable as long as globally averaged equilibrium situations are concerned. Features of the atmospheric system and current state-of-the-art atmospheric science as encompassed by tracer and (chemistry-)climate models substantially facilitate this approach. For instance, many of the indirect relationships between emissions and effects are numerically represented in physical and chemical models. As these models use well-defined and rather detailed emission scenarios for their calculations of climate changes due to air traffic, the output of these models is used to reach the objective of this study.
In accordance with the formal requirements as presented in the 'Terms of Reference' by the Umweltbundesamt, the study has been based on literature only.

* **External costs** are costs that are not properly addressed by markets, i.e., costs that do not fall on those parties whose choices have caused them but on other parties or on society as a whole. A typical example of an external cost is the degradation of the local environment by emissions and noise from transport.

Radiative forcing in perspective: definition, uncertainties and confidence intervals

A change in average net radiation at the tropopause, because of a change in either solar or infrared radiation, is defined as a radiative forcing. A radiative forcing perturbs the balance between incoming and outgoing radiation. Over time climate responds to the perturbation to re-establish the radiative balance. A positive radiative forcing tends on average to warm the surface; a negative radiative forcing on average tends to cool the surface. As defined here, the incoming solar radiation or the contribution of CO_2 in the atmosphere to the Earth's radiative balance is not considered a radiative forcing, but a change in the amount of incoming solar radiation or the radiative effect of a change in the CO_2 background concentration is.

IPCC (1999) has addressed the uncertainties in estimating aviation's radiative forcing values with confidence intervals and descriptions of the level of scientific understanding of the physical processes, models, and data (see below). The interval and the quality-of-the-science descriptions are, to a large extent, independent measures covering different aspects of uncertainty.

The confidence intervals define a likelihood range which is defined as the 2/3 probability range. The probability range is meant to be symmetric about the mean value. More precise, the probability that the value is less than the lower value is 16%, and the probability that it is less than the upper value is 84%. The range between the low and the high value is equivalent to the '1-sigma' range of a normal, i.e., Gaussian, probability distribution. Derivation of these confidence intervals lies with the expert judgement of the scientists responsible for the values given and include a combination of objective statistical models and subjective expertise (see, e.g., Fransen, 1995).

The confidence intervals given by IPCC combine uncertainty in calculating atmospheric perturbations to greenhouse gases and aerosols with that of calculating radiative forcing. It includes, but is not solely based on, the range of best values from different studies.
The radiative forcing uncertainties from different perturbations have been determined by different methods; potential errors in individual components may not be independent of one another, and the error bars may not represent Gaussian statistics. The uncertainty range for the total is assumed to represent a 2/3 probability range as for the individual components. It is calculated directly from the individual components as the square root of the sums of the squares of the upper and lower values.

Overall, addition of the best values for radiative forcing provides a single best estimate for the total. The uncertainty ranges for individual impacts can be used to assess whether they are potentially major or trivial components and to make a subjective judgement of confidence in the summed radiative forcing.

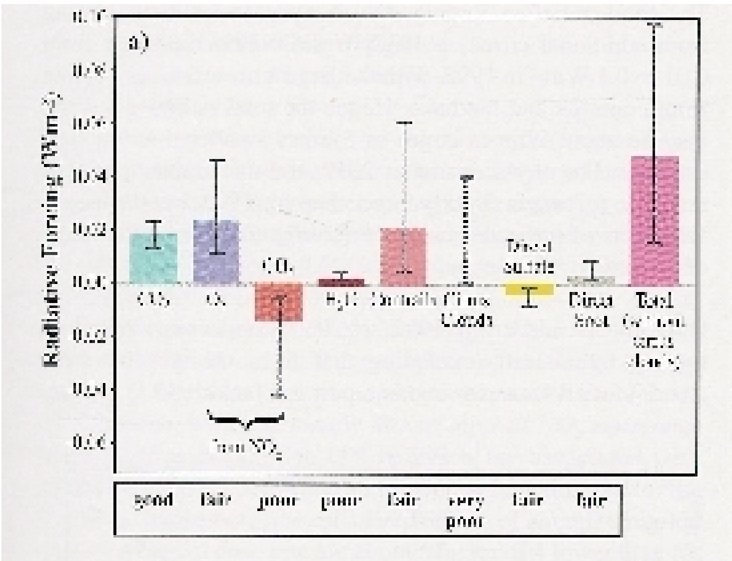

Figure 1. Bar chart of radiative forcing from aviation effects in 1992. Best estimate (bars) and high-low 2/3 probability intervals (whiskers) are given. No best estimate is given for aircraft induced cirrus clouds; rather, the dashed line indicates a range of possible estimates. The evaluations below the graph are relative appraisals of the level of scientific understanding associated with each component.

box 2, adapted from IPCC (1995 and 1999)

The dependence of aircraft induced climatic change on contrail occurrence

Studies with chemical as well as radiative-balance models have used the data from emission inventories that concern aircraft emissions for the situation in 1992 with respect to latitude, longitude, altitude and time in order to calculate the radiative forcing by several radiatively active constituents of aircraft exhaust. All emission inventories under consideration were scaled to an annual fuel use of 160.3 Teragram. The perturbations of the radiative balance have been assessed by IPCC (table 1). Taking the values presented in the table 1, the present-day radiative forcing exerted by aircraft emissions is assumed to be 0,049 Watt per square metre.

Perturbation of the Earth radiative balance due to present-day air traffic

Δ(background concentrations of carbon dioxide CO_2)	+0,018
Δ(background concentrations of ozone O_3) via emissions of nitrogen oxides (NO_x):	+0,023
Δ(background concentrations of methane CH_4) via emissions of nitrogen oxides (NO_x):	–0,014
Δ(background concentrations of water H_2O) in the form of water vapour:	+0,002
Δ(contrails):	+0,020
Δ(cirrus clouds) induced by aircraft:	positive (+), but no 'best estimate' given
Δ(background concentrations of sulfate aerosols) due to emissions of sulfur oxides (SO_x):	–0,003
Δ(background concentrations of black carbon aerosol) due to soot (C) emissions:	+0,003 +
total radiative forcing:	+0,049

Table 1, taken from IPCC (1999)

Table 1 shows that many constituents present in aircraft exhaust directly or indirectly exert an influence on the radiative balance. In all but the cloud cases this influence is exerted continuously during any flight, be it that for some constituents the effects are more dependent on the place where the emissions take place than for others. For instance, carbon dioxide emissions perturb the radiative balance irrespective from when or where these emissions take place. Nitrogen oxides on the other hand, enhance ozone formation in the upper troposphere but may lead to lower ozone concentrations in the stratosphere.

Contrails and aircraft induced cirrus, however, only occur under specific meteorological conditions. Conditions which favour contrail occurrence are restricted with respect to time and place. Consequently, the radiative balance is not during every flight (continuously) perturbed by the occurrence of (persistent) contrails and aircraft induced natural cirrus. As this feature may be relevant in the discussion about external costs, it asks for a closer look at the forcing ranges estimated by IPCC for the perturbation of the radiative balance by contrails and aircraft induced natural cirrus.

The situation in 1992 as present-day situation

IPCC estimates concerning radiative forcing and climate change presented in the special report on aviation and the global atmosphere (IPCC, 1999) have been based on calculations which have used values for the situation in 1992 as input because for that year detailed information - *i.e., with high resolution with respect to place and time* - for fuel use, emissions and flight paths is available. As this report is the only comprehensive assessment with quantitative information on radiative forcing and climate change by aircraft, it has been the basis for this report. Consequently, **the 1992 situation is taken as the present-day situation in this study**.

box 3

Calculated temperature change in perspective: equilibrium and realised climate change

When the radiative forcing on the earth-atmosphere increases, for example due to increasing greenhouse gas concentrations, the atmosphere will try to respond immediately by warming. ‘Try’ as the atmosphere is closely coupled to the oceans, so in order for the air to be warmed by the enhancement of the greenhouse effect (= increased radiative forcing), the oceans also have to be warmed. Because of their thermal capacity, this takes decades to centuries.

In a hypothetical example where concentrations of greenhouse gases which have been steady for decades - *in reality these concentrations fluctuate* - suddenly rise to a new level and remain there, the radiative forcing would also rise rapidly to a new level. This increased radiative forcing would cause the atmosphere and oceans to warm, and eventually come to a new, stable, temperature. A commitment to this <u>equilibrium</u> temperature rise is incurred as soon as the greenhouse gas concentration changes. But at any time before equilibrium is reached, the actual temperature will have risen by only part of the equilibrium temperature change, known as the <u>realised</u> temperature change.

The **temperature changes presented in this report concern equilibrium global mean temperature changes** or committed temperature changes. In theory, these changes will ultimately occur under the condition that future aircraft emissions will be as large as the present day emissions and a new radiative equilibrium is reached. This implies that the results presented in this study apply to a situation in which future air traffic is assumed to show the same emission patterns as today. In reality this will not happen: assuming an unaltered (relative) distribution of emissions, higher emissions will lead to larger increases in radiative forcing and, thus, to larger temperature increases; decreasing emissions to smaller temperature increases.

box 4, adapted from IPCC (1990)

Calculated temperature change in perspective: limits of the radiative forcing concept

In table 1 and figure 1 radiative forcing estimates for various aspects of aircraft-induced perturbations to radiatively active substances are reported. One of the basic ideas behind these estimates is the validity of the concept of radiative forcing as a quantitative predictor for climate change. It is implicitly assumed that contributions from individual perturbations to the change in global mean surface temperature are additive, at least to a first order approximation. The radiative forcing concept requires a constant climate sensitivity parameter λ within the same model for different types and different magnitudes of radiative forcing. This is not always the case (see, e.g., Hansen et al., 1997, and Ponater et al., 1998).

In this report **temperature changes are calculated by multiplying the value calculated for the radiative forcing by aircraft emissions with a climate sensitivity factor of 0.6° Celsius per Watt per square metre**. It should be noted that calculations performed by recent climate models (IPCC, 1996) suggest a climate sensitivity factor for climate change due to anthropogenic emissions at the Earth’s surface of about 0.8° C/Wm^{-2}.

box 5, adapted from IPCC (1999)

Contrail formation and persistence

Condensation trails or contrails are line-shaped clouds, composed of ice particles, that are visible behind the engines of jet aircraft during cruise. Contrails are a normal effect of jet aviation. They often form in clusters within regions that are cold and humid*. Depending on the temperature, pressure and amount of moisture in the air at cruise altitude, contrails evaporate quickly (if humidity is low, temperature is high or both) or persist and grow (if humidity is high, temperature is low or both). In the latter case, newly formed ice particles will continue to grow in size by taking up water (vapour) naturally present in the atmosphere ‘surrounding’ the aircraft flight path. The typical atmospheric residence time of a persistent contrail is about one day (see below). This is substantially shorter than the atmospheric residence times of greenhouse gases directly or indirectly emitted by aircraft which range from weeks (ozone) to centuries (carbon dioxide).
<u>Persistent</u> contrail formation requires air that is supersaturated with respect to ice; ice nucleation requires 30% supersaturation on the average. For persistent contrail formation 15% of supersaturation with respect to ice is often enough as the additional water needed is emitted by the aircraft in the form of vapour. This also explains the regions in which aircraft induce persistent contrails but which are otherwise free of clouds.
Eventually, the line-shaped contrail may transform into a cirrus cloud. Bakan et al. (1993, 1994) assessed long-term changes of contrail cloud cover over Europe and the eastern part of the Atlantic as well as contrail life-time from satellite data. They concluded that 2% of the contrail areas, i.e., regions with a group of contrails and a typical diameter of thousand kilometres, could be followed by satellite for less than about 6 hours, 62% for more than one day and 24% for more than two days.

Implications of the relative brevity of contrail occurrence

An estimate of the percentage of annual air traffic fuel use actually responsible for the perturbation of the radiative balance by contrails allows a distinction between situations with and without contrail formation. Using the results by Gierens et al. (1999) that 13,5% of flight time of commercial aircraft occurs in air masses that are ice-supersaturated with a mean supersaturation of 15%, it is assumed here that in three quarter of this flight time persistent contrails actually occur and that these contrails are responsible for the perturbation of the radiative balance which the IPCC (1999, 2001) has estimated at 0.02 Watt per square metre. Under the assumption that flight time relates linearly to flight kilometres, this implies that 10% of aircraft flight kilometres are responsible for the radiative perturbation by contrails.

* see, e.g., the aircraft contrails factsheet from EPA (2000) for a simple introduction into contrail formation processes, or Schumann (1996) for an introduction into the physics behind contrail formation.

Present-day occurrence of contrails and aircraft induced cirrus

- Based on simple estimates, Ponater et al. (1996) calculate that 0.04% of the Earth's surface is covered by contrails, but as much as 0.56% of the area covered by frequently used flight routes.
- Sausen et al. (1998) obtained the actual present day contrail coverage by multiplying the calculated potential contrail coverage of 16% with the fuel use according to the DLR inventory after normalisation (figures 2 and 3). The maximum cover is about 5% over the eastern part of the US; the annual global mean value is 0.09%.
- The visual inspection of satellite images of central Europe suggests that, on the average, 0.4% of the area is covered by contrails when contrails are defined as high clouds that are line shaped (Schumann, 1990). Similarly, Bakan et al. (1993, 1994) derived from seven years of satellite images of the Eastern Atlantic and Western Europe region an annual mean contrail cover of about 0.5% with regional maxima in the North Atlantic Flight Corridor of more than 2%. Both studies did not account for aged contrails which have grown to such a large size that they are no longer line shaped, nor for other 'natural' clouds which have been produced by water vapour and aerosols emitted earlier by aircraft. Hence the numbers provided should be regarded as lower limits of contrail coverage.

box 6

Potential coverage by contrails and aircraft induced cirrus

Humidity measurements by commercial aircraft show that - *during flights between Europe, North and South America, Africa and Asia* – 13,5% of flight time was in air masses that were ice-supersaturated with a mean supersaturation of 15% (Gierens et al., 1999). As a supersaturation of 15% is enough for persistent contrail formation, these results imply that contrails potentially form during 13,5% of flight time. **This value is used in this study**. Similar results have been produced via independent methods.

- Contrail clusters observed in satellite data indicate that air masses which are cold and humid enough to allow the formation of persistent contrails cover 10 to 20% of the area over mid-Europe and parts of the US. This range is consistent with the fraction of air masses expected to be ice-supersaturated at cruise altitudes on basis of the Schmidt-Appleman criterion. (Mannstein et al., 1999; Carleton and Lamb, 1986).
- Based on the ECMWF analyses for the years 1991 to 1994, Brockhagen (cited in Brasseur, 1998) found that up to 6% of the area of the globe at cruise altitude pass the criteria for persistent contrails. This implies that if aircraft were flying everywhere, 6% of the planet would be persistently covered by contrails.
- Using 11 years of ECMWF data, the coverage by air masses suitable for contrail formation is found to have a global mean value of 16% by Sausen et al. (1998). Sausen concludes that since this value is comparable to the global mean coverage of cirrus clouds, i.e., 23% over land and 13% over the oceans (Warren et al., 1986 and 1988, cited in IPCC, 1999), the amount of high cloud cover (persistent contrails, aircraft induced cirrus and natural cirrus) could almost double if aircraft flew everywhere.

box 7

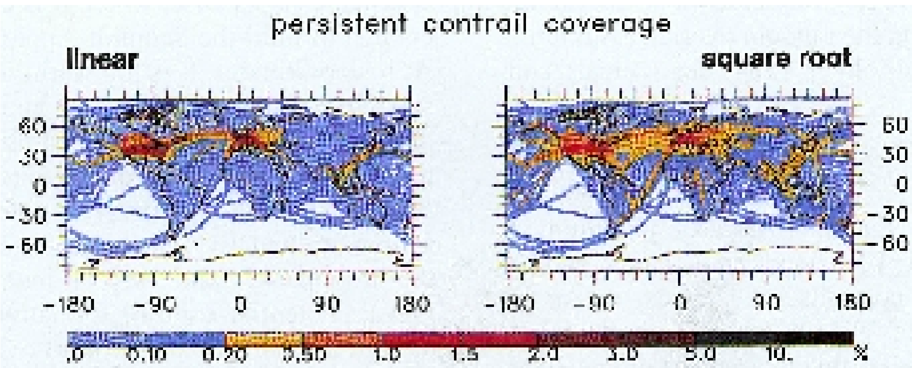

Figure 2. Annual mean contrail coverage for the years 1983-1993 as obtained for two different statistical methods by which the fuel consumption is weighed: linear (left panel) and square root (right panel) weighing. Calibration produces a mean value of 0.5% for the region extending from 30° W to 30° E and from 35° N to 75° N for both linear and square root weighing. Figure taken from Sausen et al. (1998).

If the situations with contrail formation (accounting for 10% of flight time) and without contrail formation (90% of flight time) are applied to the IPCC estimates, the following values are obtained:

Perturbation of the radiative balance in W/m^2 for the part of yearly annual flight time during which contrails occur (10% of flight time)		**Perturbation of the radiative balance in W/m^2 for the part of yearly annual flight time during which no contrails occur (90% of flight time)**	
Δ(carbon dioxide)	+0,0018	Δ(carbon dioxide)	+0,016
Δ(ozone) from NO_x emissions:	+0,0023	Δ(ozone) from NO_x emissions:	+0,021
Δ(methane) from NO_x emissions:	–0,0014	Δ(methane) from NO_x emissions:	–0,013
Δ(water vapour):	+0,0002	Δ(water vapour):	+0,002
Δ(contrails):	+0,0200		
Δ(sulfate aerosols) from SO_x emissions:	–0,0003	Δ(sulfate aerosols) from SO_x emissions:	–0,003
Δ(soot aerosols) from C emissions:	+0,0003 +	Δ(soot aerosols) from C emissions:	+0,003
	+0,023		+0,026
total radiative forcing of (0,023 + 0,026 =) 0,049 W/m^2 is in accordance with IPCC value			
	table 2		*table 3*

The calculation makes clear that contrails exert a large perturbation of the radiative balance compared to all other perturbations by constituents of aircraft exhaust (except maybe nitrogen oxides), both in an absolute sense (see table 1) as well as in a relative sense (this table). An aircraft flying under meteorological conditions favouring contrail formation has an environmental load which is per kilogram of fuel use about eight times larger than the load of an aircraft flying in an area where the ambient conditions do not favour contrail formation. This leads tot the conclusion that the climatic impact of the 10% of air traffic leading to contrail occurrence is about the same as the 90% of air traffic not leading to contrail occurrence.

It is acknowledged that breaking down a value with a large associated uncertainty range will lead to values with a significantly larger uncertainty range. In the context of the study this has been considered acceptable because the larger uncertainty range does not distract from the idea that the radiative balance of the Earth’s atmosphere is very sensitive towards contrail occurrence. Indeed, it can be argued from a more fundamental perspective that a larger uncertainty range ‘per se’ does not imply that the ‘real value’ is larger or smaller than the value calculated.

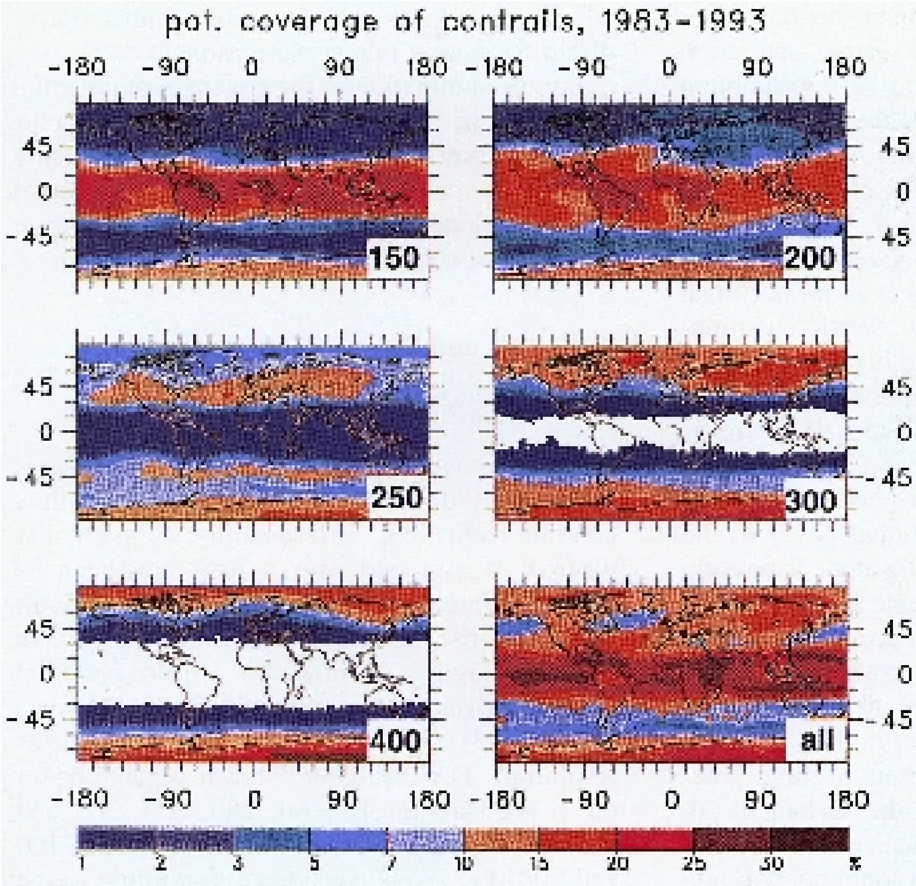

Figure 3. Annual mean potential contrail coverage at various altitudes and as a total coverage for the layer between 100 and 500 hectoPascal. Figure taken from Sausen et al. (1998).

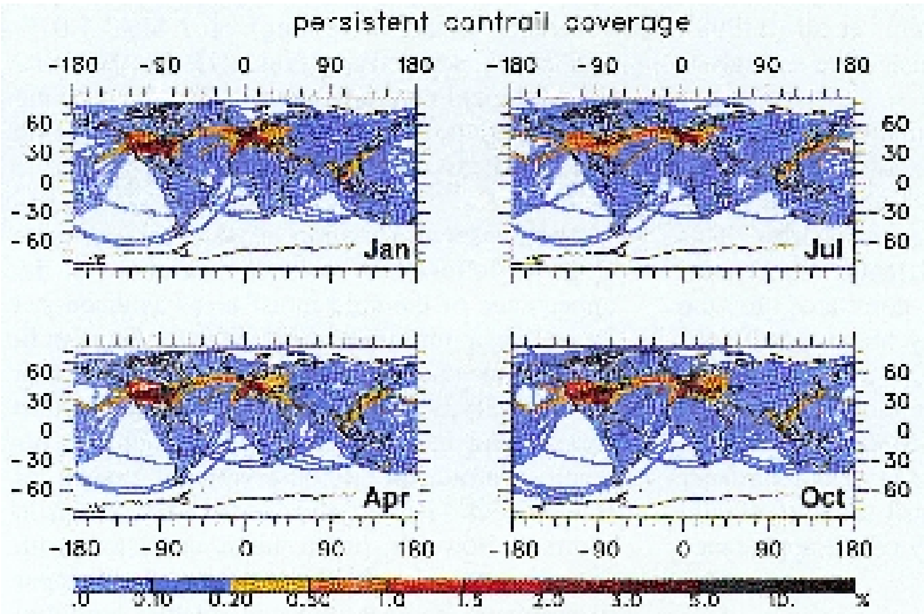

Figure 4. Seasonal variation of the present day contrail coverage obtained by weighing of fuel consumption. Figure taken from Sausen et al. (1998).

Aircraft induced cirrus

Cirrus clouds are high-level clouds which occur as detached, white fibrous clouds, often with a silky sheen. They naturally form high in the troposphere. Air traffic may induce (additional) cirrus. Ageing aircraft exhaust, consisting of a mixture of soot and sulfate aerosols, may lead to the nucleation of ice crystals and, hence, the formation of cirrus clouds in conditions where no clouds would have formed in absence of air traffic (Kärcher et al., 1998). Aircraft may also indirectly increase the occurrence of natural cirrus without any contrail formation through the addition of water vapour, soot and sulfate particles. In addition, aircraft may either increase or decrease this occurrence by inducing vertical motions and turbulent mixing. Finally, aircraft emissions may change the properties of existing natural cirrus clouds. Soot emissions, for example, have been found to double the ice particle concentration of already existing cirrus, thereby changing their optical properties.
IPCC (1999) considers the status of understanding with respect to aircraft induced natural cirrus as ‘very poor’. However it was able to assess a range of radiative forcing due to ‘additional aviation-induced cirrus clouds’ of 0 to 0.04 Watt per square metre. This is in line with results by Meerkötter et al. (1999) who state that the indirect radiative forcing due to contrail induced particle changes in natural cirrus clouds may be of the same magnitude as the direct effect of additional high cloud cover from contrails.
As the formation conditions of persistent contrails and (aircraft induced) cirrus are related (Sausen et al., 1998, and references cited therein), it can be said with some confidence that the meteorological conditions favourable for contrail formation (temperature, relative humidity and pressure) are comparable with the conditions favourable for cirrus formation. In other words: there is a higher probability that additional cirrus clouds will form in areas where contrails form than in areas where contrails do not form. The opposite does not seem to hold though. Schröder et al. (2000) concluded that observations and model results suggest that contrail formation is only weakly, if at all, affected by existing cirrus clouds.

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External costs of aviation

External costs of LTO emissions

Delft, February 2002

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Contents

1 External costs of LTO emissions

1.1 Introduction

For the valuation of emissions other than CO_2 different methods are used. The aim of this annex is to survey the recent estimates of the valuation of environmental effects of aviation. The effects that we have incorporated in this survey are the following:

- NO_x (in itself and via ozone);
- PM_{10};
- $PM_{2.5}$;
- HC, volatile hydrocarbons;
- SO_2;
- CO.

We have searched for studies that value these emissions. We have only sought for valuation of ground level effects, for being able to value the environmental effects of landings and take-offs (LTOs).

In this paragraph, we present the literature sources we have found with their results. To the extent possible, we have also presented the main assumptions and important remarks.

We first present the overview of the findings in paragraph 1.2, with the main conclusions we draw from them. In paragraph 1.3 we then present the full survey. For some literature sources we had to make some additional calculations to arrive at a unit cost, i.e. a cost per kilogram pollutant. We have presented our own calculations in separate text boxes in order to keep the description of the sources as objective as possible.

The one modification we have done for each of the sources is in the currency, because different sources use different currencies and different base years for these currencies. To provide a consistent overview we present all figures in one currency, namely in $€_{1999}$. For the conversion of the different currencies we have used the following conversion table.

Table 1 Conversion factors from $ to €, CPI-numbers

Year	CPI (US, 1989 = 100)	CPI (EU, 1989 = 100)	Exchange rate (1 € = .. $US)[1]
1990	105.4	104.1	1.40
1991	109.8	108.4	1.30
1992	113.1	112.4	1.44
1993	116.5	116.0	1.19
1994	119.5	119.1	1.25
1995	122.9	121.8	1.32
1996	126.5	124.8	1.28
1997	129.4	126.8	1.11
1998	131.4	128.2	1.19
1999	134.3	129.6	1.07

[1] This exchange rate is the end-of-year exchange rate.

In case the original numbers in the report are denoted in another currency, we have given the relevant exchange rate.

1.2 Overview of findings

Qualitative conclusions

From the literature analyses, the following conclusions can be drawn:

- the knowledge about damage costs from other than greenhouse gas emissions has been much improved the last years. Especially on the area of health effects of transport pollutants much progress has been made. Dose-response relationships have been improved, dispersion models as well, and the valuation of (years of) life (lost) is subject to much less controversy;
- the increase in knowledge on these health effects has led to increasing valuations of practically all emissions, lead to a better understanding of variations in valuations, and thus a lower spread of various results if the factors behind the variations are taken into account. For example, several studies show that in an area like the Paris inner city a gram of $PM_{2.5}$ emission leads to several Euros of health damage, and that in sparsely populated areas this is more something like 1 Euro cent. This shows that prices of emissions are very dynamic depending on the circumstances, and that with further scientific insight prices are more likely to increase further than to decrease;
- much of the health effects focus has been shifted to ultra-fine particles ($PM_{2.5}$). Extensive analysis in the framework of the ExternE programme and the WHO study of 1999 shows robust and significant dose-effect relationships. As a result, air pollution related costs from road transport, especially those of vehicles equipped with diesel engines, are dominated by the health effects of these particles;
- the most relevant health effects besides those of $PM_{2.5}$ come from nitrates and ozone;
- carbon monoxide, 1.3 butadiene, benzene, and benzo(a)pyrene, other pollutants being suspected in the past, seem not to give rise to significant health effects. Either exposure or human sensitivity is relatively low;
- it should be said, however, that possibilities to monetise values like biodiversity and the health of forests, still fall rather short compared to possibilities to value health effects;
- health *damage* costs alone already generally seem to be higher than *prevention* costs that are based on the marginal costs of achieving *politically* agreed targets like the NECs[2]. Due to this phenomenon, combined with the progress made on the valuation of health effects, the prevention cost methodology is becoming a less popular tool for emission valuation.

Quantitative conclusions per pollutant

In this paragraph we present the overview of estimates we have found. We present the results in five tables.

We first present in four tables overviews of the values found per emission (NO_X, $PM_{2.5}$, HC, and SO_2). For every emission, results from damage cost studies and prevention cost studies are distinguished. Furthermore, we try to explain ranges and we present differences between valuations for emissions emitted in urban areas and in rural areas.

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[2] Theoretically, marginal prevention costs that are necessary to achieve environmentally sustainability targets are equal to marginal damage costs in the optimum).

In the fifth table the results are aggregated and averaged for use in this study.

Damage costs
Recent (ExternE) insights come to damage cost estimates of 12 €/kg NO_X, which includes the damage of the ozone formed out of NO_X. This value is an average and varies between a presented range of 1.9–21 €/kg across the European countries in the study. The range can mainly be explained by differences in health impacts due to differences in exposed population.

The ExternE programme takes a wide range of impact categories into account:
- human health;
- crops;
- timber;
- building materials;
- ecological systems;
- non-timber benefits of forests.

Although the valuation of damage to ecological systems is uncertain, the resulting marginal damage cost per kg NO_X seems to cover most relevant impacts.
Furthermore and the valuation of mortality is quite high. The value of a statistical life, which is used throughout ExternE, is € 3.2 million. This implies that there is no distinction between a life lost, which would have otherwise been lost 1 day later or a life lost, which might otherwise have lasted for tens of years. Some people have therefor suggested to use the Value of Life Years Lost, which presents the discounted value of the expected amount of life years lost. If this valuation methodology were used, the average value presented in ExternE would be lower.

IIASA et al. (1999b) present damage costs as well, in which they distinguish estimates with the 'Value of a Statistical Life' methodology and the (lower) estimate with the 'Value of Life Years Lost' methodology. The estimate using the Value of Life Years Lost for mortality impacts is € 9, the other is 15 €/kg.

SIKA (1999) arrive at a marginal social cost of 9 €/kg NO_X as well for the Swedish case.

The last recent damage cost estimate for NO_X is provided by COWI (2000) and they make a distinction between damage in rural areas and in urban areas. They arrive at 11 €/kg NO_X in rural areas and 12 €/kg NO_X in urban areas.

Prevention cost
Recent work on the estimation of the prevention cost per kg of NO_x can be found in the studies, which were done by IIASA to calculate the costs of achieving the NECs (National Emission Ceilings). The NO_X ceiling implies a 55% reduction of NO_X emissions in Europe in 2010, relative to 1990. Using this ceiling as a basis, IIASA arrives at a marginal social cost of reducing NO_X of 4.7 €/kg.

The reduction target is the most important factor determining the marginal cost in the prevention cost method. Ågren (1999) states that the National Emissions Ceilings, although more ambitious than the targets proposed in the so-called Gothenburg Protocol, still fall short of meeting the environmental targets as set in the Fifth Environmental Action Plan. Those targets are defined as the targets that need to be achieved in order to have no exceeding ever of the critical loads, for both human health and vulnerable biodiversity. In order to achieve those ‘sustainability’ targets, the prevention costs will most probably be higher than 4.7 €/kg.

Kågeson (1993) presents prevention costs for NO_x as well and he arrives at a marginal social cost of 4.8 € 4.8/kg. This marginal social cost is the result of calculating the cost of the last measure, which was needed to achieve a 50% reduction in NO_x emissions in Europe in 2000, relative to 1985.

The level of NO_X emissions did not change too much in Europe between 1985 and 1990, so we can conclude that the cost curves in Europe did not change too much either. Kågeson notes that the targets he used to calculate the marginal social costs needed to be seen as interim targets as well.

Total

The conclusion is that with respect to NO_X, the damage cost approach leads to higher marginal social costs than the prevention cost approach based on marginal costs to achieve politically established emission reduction targets. This suggests that reduction targets should be stricter in order to achieve maximum welfare. Therefore, we will base our final estimate of the NO_X emission value on damage instead of prevention costs. We also differentiate for rural and urban effects.

Table 2 Overview of literature on the valuation of NO_X emissions in €1999, including indirect damage via ozone

sources on **damage costs**	average	range	rural	urban	comment
ExternE (1999)	12	0.9-21			mainly depends on population density
ExternE transport (1999)		4-25	4-13	7-25	
IIASA (1999b)	12	9.4-15			depends on valuation of life lost
SIKA (1999)	9	7.7-10	7.4	7.7-10	Swedish case, depending on population
COWI (2000)	11		11	12	basis for estimate could not be found
IVM (1999)	4.4	0.6-32			Dutch case, only health impacts via nitrate and ozone
sources on **prevention costs**					
IIASA (1999a)	1.5-3.3				depending on scenario, targets probably not sustainable
IIASA (1999c)	4.7				
CE (2000)	5.5		5	7	based on Auto Oil standards
Kageson	4.8				1985-2000 reduction targets

$PM_{2.5}$ / PM_{10}

Damage cost

Because the most important determining factor of PM_{10} is human health we only deal with the damage cost estimates. These damage costs crucially depend on the amount of people living in a certain area. Two sources are the most relevant for this study:

- the ExternE projects with its numerous spin-off reports;
- the WHO (1999) study used by INfras/IWW (2000) as this gives new information about the dose-response relationships.

In ExternE, a practical approximation formula has been derived: the damage cost of $PM_{2.5}$ per kg is about equal to 10 + 122*population density (in 1.000 people per km^2). One should, however, take care that transport is linked to human activity, and that therefore most transport emissions are released in areas that are more densely populated than the national average. For example in the Netherlands with its 450 inhabitants per km^2 the damage costs are higher than 10+122*0.45 = 65. For example, IVM (1999) comes, on the basis of the ExternE approach, to 130 €/kg, whereas Infras/IWW (2000) comes to 174 €/kg. In the Paris city centre, the health costs of a kg of $PM_{2.5}$ even amount to several thousand Euro.

As the relevant impact of $PM_{2.5}$ emission is human mortality and morbidity, and as scientific knowledge about the damage of PM_{10} emission has been greatly improved, and dose-response relationships seem to be well-established, the prevention cost approach seems not suitable any more for the valuation of this emission.

Table 3 Overview of literature on the valuation of $PM_{2,5}$ or PM_{10} emissions in €1999

source on damage costs	average	rural	urban	comment
Infras/IWW (2000)	73-194			national averages across EU, based on WHO study
ExternE transport (1999)		18-200	200-2000	depends mainly on population density, high value = Paris, low = Dutch average density
SIKA (1999)			85-915	Swedish case, high value = Stockholm centre
COWI (2000)		24	90	basis for estimate could not be identified
IVM (1999)	130	18-150	200-942	$PM_{2.5}$ from 'low source' (transport), Dutch case

* practically all transport PM emissions fall in the range of smaller than 2.5 micron; therefore the '2.5' estimates seem to fit best the transport emission cost estimates.

VOC/HC

Damage cost

For VOC/HC there exist not too many recent estimates. ExternE leads to estimates of 4-9 €/kg. The higher estimates apply for cities like Stuttgart and Barnsley. For the Paris city centre the value explodes to 33 €/kg. SIKA (1999) presents for the Swedish case the same range of values many to take urban effects into account: € 4-9. COWI (2000) presents a value of 2.7 €/kg.

Prevention cost

IIASA (1999c) calculates the marginal social cost of a kilogramme, but this modelling is not too sophisticated, because most measures that reduce VOC/HC, also reduce NO_x. Therefor, in general all costs are allocated to either one of the pollutants. This results in almost identical prevention costs for VOC/HC as for NO_x. The value IIASA (1999c) presents is € 4.6 per kilogramme.

Total

From the different estimates it seems best to use the value of € 4 as the marginal social cost per kilogramme. The COWI estimate is lower than the other two, and also Bleijenberg et al. (1994) presented an estimate of € 5.

Table 4 Overview of literature on the valuation of HC emissions in €1999

sources on damage costs	average	range	rural	urban	comment
ExternE transport (1999)		3.9-33	4	4-33	depends mainly on population density, high value = Paris
SIKA (1999)		3.6-8.9	3.6	4.1-8.9	Swedish case, depending on population density, 8.9 = Stockholm centre
COWI (2000)	2.7		2.7	2.7	basis for estimate not clear
sources on prevention costs					
IIASA (1999a)	1.5-3.3				depending on scenario, targets probably not sustainable
IIASA (1999c)	4.6				
CE (2000)	5.5		5	7	based on Auto Oil standards

SO_2

Damage cost

Recent (ExternE) insights come to damage cost estimates of 8.5 €/kg SO_2. This value is an average and varies widely across the European countries in the study. The presented range is € 1.5-15.5.

The resulting marginal damage cost per kilogram SO_2 seems to cover all relevant impacts. However, the damage to ecological systems is uncertain.

Other damage estimates come from IIASA (1999b), which presents € 3.5 per kilogram, and Kågeson (2000) who presents a value of € 3.3 as an absolute minimum. The recent COWI-study (2000) calculates values for rural areas (€ 5.5) and urban areas (€ 9.5).

Altogether, it seems that the ExternE-value in general is too high and from the other studies we conclude that the value from Kågeson (2000) and IIASA (1999) can be best used as the lower bound.

Prevention costs

Recent work on the estimation of the prevention cost per kg of SO_2 can again be found in the studies, which were done by IIASA to calculate the costs of achieving the NECs.

The estimate for marginal social cost of a kg of SO_2 which we could derive from IIASA (1999c) was 1.5 €/kg. This value is based upon the target set in the National Emissions Ceilings. This target boils down to a 78% reduction of SO_2 emissions in Europe in 2010, relative to 1990.

It is important to note that this value seems very low, compared to the damage cost estimates. An important factor determining the marginal cost using the prevention cost method is the target. About this target Ågren (1999) makes the following remark: the National Emissions Ceilings are more ambitious than the targets proposed in the so-called Gothenburg Protocol, but they still fall short of meeting the environmental targets, set in the Fifth Environmental Action Plan. Those targets are defined as the targets that need to be achieved in order to have no exceeding ever of the critical loads, for both human health and vulnerable biodiversity.

In order to achieve those 'sustainability' targets, the prevention costs will most probably be higher than 1.5 €/kg. Kågeson (1993) presents prevention

costs for SO_2 as well and he arrived at a marginal social cost of € 1.6 per kilogramme. This marginal social cost is the result of calculating the cost of the last measure, which was needed to achieve a 60% reduction in SO_2 emissions in Europe in 2000, relative to 1985.
However, Kågeson (1993) also calculated the marginal social cost of a reduction of 80% in 2000 relative to 1985. The value he found there was € 3.2 which is substantially higher, whereas this target still cannot be seen as a sustainable level of SO_2 emissions.

Total
When we compare the results from damage cost studies and prevention cost studies, the gap is fairly small. Both the damage cost estimates from IIASA (1999b) and SIKA (1999) can serve as a lower bound, which is € 3 per kilogramme. This value is quite similar to the highest prevention cost estimate.

Table 5 Overview of literature on the valuation of SO_2 emissions in €1999 per kg

sources on **damage costs**	average	range	rural	urban	comment
ExternE (1999)	8.5	1.3-16			variation across EU Member States
ExternE transport (1999)			6.8-8.5	10-50	mainly depends on population density
IIASA (1999b)	3.5				depends on valuation of life lost
SIKA (1999)	3.3		3.3		Swedish case, minimum estimate
COWI (2000)	7		5.5	9.5	basis for estimate could not be identified
sources on **prevention costs**					
IIASA (1999a)	1.2				variations between countries, targets probably not sustainable
IIASA (1999c)	1.5	0-5			
CE (2000)	3		3	3	based on Auto Oil standards
Kageson (1993)	1.6-3.2				depending on reduction targets

Table 6 Overview of middle estimates from the recent European literature for the valuation of NO_X, PM_{10}, HC and SO_2, per kilogram emitted, based on damage costs

	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

1.3 Full survey of literature

The following literature has been found on the valuation of emissions other than CO_2. For each source we shortly describe the method that is used, and the assumptions that are made. Finally the results are presented.

Infras/IWW, 2000, External costs of transport: accident, environmental and congestion costs in Western Europe, UIC, Zürich/Karlsruhe/Paris

Method: damage cost

The impacts that are distinguished are the following:

- human health;
- materials and buildings;
- agricultural crop losses;
- forest damages[3].

Health: the method is based on WHO (1999), based on PM_{10} as the leading indicator and a value of statistical life for people affected by air pollution of € 0.9 million. The results from WHO for Austria, France and Switzerland were extrapolated by Infras/IWW by using the weighted PM_{10} and NO_X emissions in different countries. This is done as follows.

Infras/IWW extrapolated the health impacts found by WHO (1999) (PM_{10} as leading indicator, countries Austria, France and Switzerland) to the EU Member States. As for other countries data on PM_{10} concentrations are not widely available Infras/IWW have followed an indirect approach. As NO_X emissions in all EU Member States are well known, they defined a correlation between PM_{10} concentrations and PM_{10} and NO_X emissions in France, Austria and Switzerland, and use this correlation to establish PM_{10} concentrations for the other European countries considered. A correction for non-exhaust PM_{10} emissions was necessary in order to properly fulfil this task.

[Addition by CE: dividing the health costs by transport particulate emission estimates leads to an approximate health costs of approximately 100 € per kg of particulate emitted (urban/rural average for France, Austria and Switzerland). An important factor behind the health impact of PM_{10} emitted is population density; this amounts 107, 96 and 172, for France, Austria and Switzerland respectively. As a first order estimate, one can put a population density correction factor on the PM_{10} shadow prices, as exposure per unit of emission is approximately linearly dependent on population density]

The health costs account for an average 81% of external costs from air pollution in the countries under consideration.

Crop losses: the costs that were computed for Switzerland (Infras/Econcept/Prognos, 1996) are used to calculate the same costs for other European countries. The formula that is used is as follows:

Crop losses = α * (NO_X emissions/country area) * agricultural production
with $\alpha = 0.0037$ [m^2/ton]

On average these costs amount to 1% of external costs from air pollution in the considered countries.

Building damages: the methodology used to calculate these costs is similar to the one used for crop losses. The costs computed in Infras/Econcept/Prognos (1996) were scaled to other European countries using NO_X exposure levels and building surface. The exposition levels are estimated by dividing the emissions by the country area and the building surface is estimated using population. The following formula results:

Building damage = β * (NO_x-emissions/country area) * building surface * PPP
with $\beta = 0.322$ [€/tonne].

3 This last category is only included in the sensitivity analysis.

On average these costs account for 18% of external costs from air pollution in the considered countries.

Addition by CE: using the data on emissions as provided in the Infras/IWW report for the EU-countries, we have calculated the average cost per kilogram PM_{10} for the EU-countries. The average cost is equal to the marginal cost, because the dose-response functions are linear: at a certain location, each kilogram is assumed to have the same impact. This resulted in Table 7.

Table 7 Overview of average and marginal damage costs per kg of PM_{10} emission

Country	**Marginal social cost (in €$_{1999}$) per kilogram of PM_{10}**
Austria	104
Belgium	143
Denmark	162
Finland	111
France	107
Germany	135
Greece	74
Ireland	109
Italy	129
Luxembourg	194
Netherlands	174
Norway	146
Portugal	73
Spain	78
Sweden	121
Switzerland	172
United Kingdom	140

From the table we see that the marginal social costs of PM_{10} in the European countries considered varies between 73 and 194 €/kg. The main variables determining this value are population density and society's purchasing power parties, mainly defined by income.

Comparing the results with those from the ExternE bottom up approach
In Infras/IWW the authors also make a comparison between the top down approach (WHO) and the ExternE bottom up approach. Infras/IWW states that there are significant differences in these two approaches; WHO leads to higher damage costs than ExternE. However, the study does not directly compare unit values per kg of PM_{10} emission following from both methodologies.
Comparison by CE of bottom up and top down damage estimates per passenger or tonne kilometre in the Infras/IWW study leads to the conclusion that the top down values used by WHO are, on average, 2 to 3 times higher than the bottom up values as estimated following the ExternE approach. This conclusion is in line with the results of both studies as discussed in this annex.
Infras/IWW explain this difference as follows:

- the dispersion models for health costs: Whereas the top down approach, based on the WHO study (1999) uses a particulate based modelling, including as well particulates from tyres and clutches, the ExternE model (see above) is basing their models on exhaust emissions of transport and dividing it into a regional and a local part;

- the adjustment of VSL for health costs: Whereas the WHO-study based on a VSL of 1.4 M€, ExternE bases its assumptions on a VSL of 3.2 M€. The adjustment factors are different however;
- the building damages, based on estimations of a shortage of renovation cycles or damages to cultural buildings are not considered explicitly within the ExternE model. Their approach for material damages might therefore be an underestimation.

Comparison of the health impacts with the two approaches shows that the average values based on the WHO study are similar to the results of ExternE. The uncertainty can therefore not be explained by uncertainties in the dose-response functions.

COWI, 2000, Civil aviation in Scandinavia – an environmental and economic comparison of different transport modes, Lyngby, Denmark

Method: damage cost

The damage cost categories that have been included are the following[4]:
- morbidity;
- premature mortality;
- reduced farming and forestry yields;
- dirty and corroded buildings.

This study has calculated the marginal external costs of emissions. Using dose-response relationships, they arrived at the following values.

Table 8 Damage costs estimates according to COWI (2000)

Pollutant	Marginal social cost (in $€_{1999}$) per kilogram	
	Rural area	Urban area
NO_X	11	12
particulates	24	90
HC	2.7	2.7
SO_2	5.5	9.5
CO	0	0

There is no further information available on the specific functional form of the dose-response relationships that were used.

CE / TNO, Early introduction of cleaner petrol and diesel fuel in the Netherlands; analysing emission reduction potentials and cost effectiveness ['Vervroegde introductie van schonere benzine en diesel in Nederland: een analyse van emissiepotentieel en kosteneffectiviteit'], Kampman, B.E., J.M.W. Dings, R. Gense, E. van de Burgwal, Delft, 2000

Method: overview of estimates of shadow prices used.

This study in general uses shadow prices used previously in (CE 1999) and (CE 1997). The estimates for NO_X, HC and SO_2 are based on marginal prevention costs based on (CE 1994) and for NO_X and HC additionally on the costs for complying with the newest EU vehicle emission and fuel standards. With respect to PM_{10} emission a new damage cost estimate is used based

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4 Damage to the global climate is also considered in this study, but we will go into that, in the section on valuation of greenhouse gases.

on WHO (1999| and Infras/IWW (2000). CE (2000)[5] is used additionally in order to split the damage cost estimate for PM_{10} into a rural and an urban component.

The following marginal social cost estimates are used in CE (2000).

Table 9 Marginal costs estimates used in (CE 2000), based on both damage and prevention costs

Pollutant	Approach	Marginal social cost (in €$_{1999}$) per kg	
		Rural area	Urban area
NO_x	prevention	5	7
PM_{10}	damage	35 – 70	150 – 300
HC	prevention	5	7
SO_2	prevention	3	3

European Commission, DG XII, ExternE – Externalities of Energy, 1999 (**http://externe.jrc.es/overview.html*****), Brussels, Belgium***

Method: damage costs

Model: for each pollutant an impact pathway is defined. This means that for each pollutant all possible impacts are taken into account, the exposure levels are identified (how many people are exposed to what concentration for example), the effects are modelled (how many people will die premature for example) and these effects are valued (what is a life lost worth for example). This approach has been followed for all different impacts as far as possible.

The methodology has thereafter been worked out for all EU-countries. The study has focused on the production of energy in different forms. This means that the values should be seen as values that arise for emissions at ground level.

The impact categories have not all been taken into account, but the larger ones have. In the eventual estimate of the damage the following cost categories arise:
- crops;
- timber;
- building materials;
- human health;
- ecological systems;
- non-timber benefits of forests.

Alternative techniques have been developed for valuation of the last three 'goods', the main ones being hedonic pricing, travel cost methods and contingent valuation. For the other goods, it was possible to use the market prices, for timber, crops and so.

5 This source is not included in the list of references, because it does not provide shadow prices. It does however provide information on the effects of emissions of particulates on concentration levels in rural and urban areas. Information in |CE 2000| has been used to calculate the difference in marginal social costs in rural areas as opposed to urban areas. This had led to a ratio of 4.5 which means that the marginal social cost in rural areas has been found by dividing the value for urban areas by 4.5.

For each of the pollutants SO_2, NO_x (including the damage through ozone formation), and PM_{10} the damage costs are identified.

On the ExternE website, the results are given for each country separately. We will here present only the ranges found across Member States and the average value found by applying a weighed average according to each member state's population.

We would like to emphasise that the damage costs, as given in ExternE are strongly dependent on the exposure levels and thus strongly fluctuates not only *between*, but also *within* countries.

Table 10 Damage costs across the EU Member States of NO_X, SO_2 and PM_{10} emissions according to the ExternE study

Pollutant	Marginal social cost (in €$_{1999}$) per kg	
	Medium estimate	Range
NO_x	12	2.1 – 21
PM_{10}	14	2.1 – 198
$PM_{2,5}$	23	high estimate: 75
SO_2	8.5	1.1 – 16

IER, *External costs of transport in ExternE*, with contributions by IER, ETSU, IVM, ARMINES, LIEE, INERIS, IEFE, ENCO, IOM, IFP, EEE, DLR, EKONO, 1999

In the transport section of the ExternE research several transport cases have been researched. In this overview study some of these cases are summarised in terms of MEUR per km driven. The values are shown in the able below. Consequently, they are recalculated to units per kg of emission by using emission factors as stated in the German case study (IER 1998, Transport externalities due to airborne pollution in Germany - application of the ExternE approach, Bickel, P. et al., Stuttgart, 1998), and modification factors for these emission factors mentioned in the report.
Furthermore we assume that ozone damage is for 50% caused by HC emissions and for 50% by NO_X emissions.

This approach leads to the results in Table 11.

Table 11 Damage estimates (vehicle use only) for diesel passenger cars in agglomerations, urban areas and extra-urban areas, given as 'best estimate' in 1995 m€/vkm, and recalculated to 1999 €/kg of pollutant

	agglom-erations	urban areas			extra-urban areas		uncer-tainty*
	Paris	Stuttgart	Amsterdam	Barnsley	Stuttgart-Mannheim (motorway)	Tiel	
primary pollutants							
$PM_{2.5}$	534.09	50.43	78.60	97.40	18.77	29.50	B
SO_2	0.93	1.12	0.71	0.80	0.60	0.32	A/B
CO	0.02	0.003	0.003	0.005	0.001	0.0004	B
Cancers	4.02	0.54	0.57	1.25	0.18	0.22	B
secondary pollutants							
Sulphates	0.59	0.82	1.30	0.63	0.68	1.10	B
Nitrates	18.18	9.14	2.70	2.82	7.24	3.80	B?
Ozone	1.29	0.96	0.90	0.93	0.78	1.20	B
damage costs per kg of pollutant							
$PM_{2.5}$	4,800	640	620	560	240	180	B
NO_X	26	17	5.7	7.4	14	4.7	B
SO_2	54	14	11	20	9.1	7.2	B
HC	36	7.8	5.5	9.3	4.3	4.2	B

* A = high confidence (a factor 2.5 to 4); B = medium confidence (a factor 4 to 6); C = low confidence (a factor 6 to 12); „?" = evidence is weak

It can be seen that the majority of externalities is caused by $PM_{2.5}$ and nitrate.
A study by NTNU/DNV (Environmental performance of transportation -a comparative study, Magerholm Fet, A. et al., IØT-Report nr. 3/2000), is referred to ExternE damage costs functions expressed in EUR per kg of pollutant per 1,000 inhabitants per square kilometre.

$PM_{2.5}$: 10 + 122 * pop
nitrates:2.1 + 6.4 * pop

World Health Organization, 1999*, Health Costs due to road traffic-related air pollution: an impact assessment project of Austria, France and Switzerland,* prepared for the WHO ministerial conference on environment and health, London, June 1999

Method: damage cost

Model: establishing dose-exposure-response relationships between emissions PM_{10} and human health effects.

This study uses a dose-response modelling exercise. The impact of emissions of PM_{10} on human health is measured for Switzerland, France and Austria. PM_{10} is not considered to be the only air pollutant, but from other studies it seems to have the strongest correlation with health impacts and it is used a indicator for urban air pollution.

The following health effects were included in the assessment:
- total mortality based on cohort studies[6];
- respiratory hospital admissions;
- cardiovascular hospital admissions;
- chronic bronchitis in adults;
- acute bronchitis in children;
- restricted activity days in adults;
- asthma attacks in children and adults.

A potentially important health effect that is not included is acute mortality.

The dose-response modelling has been done according to the following impact-pathway:

emissions → concentration → exposure → immission → health response (mortality/morbidity) → costs

Some important remarks on the dose-response relationships are the following:
- all air pollution-related health effects are only considered for the age groups assessed by epidemiological surveys and above the lowest assessed exposure level of 7.5 µg/m^3 PM_{10};
- WTP is used for monetary valuation;
- only PM_{10} has been assessed (the annual average concentration is taken as an indicator for urban air pollution).

The monetary valuation used for (some of the important) health effects is as follows:
- € 0.9 million per prevented fatality (total mortality costs >70% in 3 countries);
- € 0.21 million per prevented case of chronic bronchitis (74% of morbidity costs);
- € 94 per restricted activity day avoided (22% of morbidity costs).

WHO states that the most recent empirical values for the willingness to pay of a risk reduction of fatal road accidents applied is € 1.4 million. WHO corrects this value to € 0.9 million to consider the lower willingness to pay of the higher average age class of air pollution related victims.

Unfortunately, the results are not recalculated into values per unit of emission. This was done by Infras and IWW (2000) as previously discussed.

SIKA, 1999, *Översyn av samhällsekonomiska kalylprinciper och kalkylvärden på transportområdet*, SIKA nr. 6, Stockholm (summary sent in a memo by *Kågeson, P., 'Calculation values used by Swedish State Agencies in the transport sector'*

Method: damage cost

This memo provides the English summary of values used in Swedish transport policy. The values have been calculated in SIKA (1999)[7]. The values

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6 Increase in premature mortality is only considered for adults older than 30 years of age. Furthermore, the results from the cohort studies only detect long-term impacts, so acute mortality is not included in the analysis.

7 The full reference of this publication is: SIKA, 1999, Översyn av samhällsekonomiska kalylprinciper och kalkylvärden på transportområdet, SIKA nr. 6, Stockholm.

are agreed upon by the state agencies for the different modes of transport (road, rail, water and air), the Swedish Environmental Protection Agency and the Swedish Institute for Transport and Communications Analysis (SIKA). They are used in cost-benefit analyses.

The values for NO_X, SO_2, VOC and PM_{10} are based upon the damage cost method. The total damage arises from local damage, as well as regional and global damage. The cost categories that have been included are the following:

- human health;
- damage to forestry and crops;
- material damage.

For the calculation of total (marginal) damage cost the two values can be added. The following table presents the ranges in regional values, local values and total values that are used in Sweden.

Table 12 Marginal damage costs for Sweden, based on SIKA (1999)

Pollutant	Marginal social cost (in €$_{1999}$) per kilogram		
	regional damage	local damage*	total
NO_x	7.4	0.3 – 2.9	7.8 – 10
PM_{10}	0	85 – 915	85 – 915
HC	3,6	0.48 – 5.3	4.1 – 8.9
SO_2	2.1	1.2 – 26	3.3 – 28

* Mainly depending on population density; figures reflect differences between North-Sweden and the Stockholm city centre

Ågren, C., 1999, Getting more for less: an alternative assessment of the NEC Directive, Air pollution and Climate series 13, T&E 99/9, Brussels

Method: prevention cost method

This study presents a critical review of IIASA et al. (1999a,b). This study does not present new estimates for the marginal costs for each pollutants, but it presents (lower) estimates for the total costs needed for meeting the National Emission Ceilings (NECs) in the different EU-countries.
We will describe the main points of criticism under the heading of IIASA et al. (1999a,b).

IIASA, DNMI and RIVM, 1999a, Economic evaluation of a directive on National Emission Ceilings for certain atmospheric pollutants: part A, Cost-effectiveness analysis, Laxenburg, Austria/ Oslo, Norway/ Bilthoven, The Netherlands

Method: prevention costs

Model used: RAINS (Regional Air pollution INformation and Simulation), focussing on NO_x, SO_2, NH_3 and VOC. For these pollutants emission control options are identified and costs have been determined. The associated costs include investment-related and operating costs. All investments in emission reduction are annualized using a discount factor of 4%.

Not all emission control options are incorporated in the model, only the major ones for the economic activities that contribute the most. For NO_x and VOC, only the emission control options (and emissions) are given for stationary sources. The omission of control costs of mobile sources introduces an uncertainty in the results.

In the remainder of this description we focus on the emissions ceilings for 15 European countries (EU-15) and the corresponding abatement measures and costs. IIASA et al. also present figures for non-EU-countries in Europe, but these figures are not as reliable and do not show up in the summarizing tables in the report.

Different scenarios have been used, with one central scenario in which the emissions of different pollutants in the EU overall are reduced as follows, compared to the emissions in 1990:
- NO_x: -55%
- VOC: -60%
- SO_2: -78%

These reductions are the results of minimising the costs to achieve environmental targets. These environmental targets arise from the acidification and ozone-exposure strategies that was also adopted in the UN/ECE Convention on Long-range Trans-boundary Air Pollution, where for all areas a target of a '60% gap closure' of excess sulphur deposition was established. However, IIASA states (p. 96) that the targets used in its report will not be sufficient to meet the environmental long-term targets (the no-damage levels) everywhere in Europe within the next one or two decades.

Three scenarios are used:
1. A base case 'central' energy scenario, which leads to a 9% increase of CO_2 emissions between 1990 and 2010.
2. A 'low CO_2' scenario' which uses the agreements as set in the Kyoto Protocol, which boils down to a cut in CO_2-emissions by 7% in 2010 relative to 1990. This leads to a large reduction in abatement costs for NO_X and VOC, and a cut of 28% in overall costs to achieve the environmental targets for NH_3, NO_X and VOC in Europe.
3. A 'low NH_3-scenario' which is based on a 10% cut in livestock all over Europe, following an expected change in the Common Agricultural Policy. This 'new' base case, which is purely hypothetical, results in lower costs for SO_2-measures. The effects on costs of measures to reduce NO_x and VOC are small.

Table 13 Derivation of *average prevention costs* from IIASA (1999a) in three scenarios (all figures relative to the reference scenario)

	central	low CO_2	low NH_3
NO_X reduction (ktonne)	927	856	607
HC reduction (ktonne)	1,547	1,312	1,470
NO_X + HC reduction costs (M€)	4,508	2,567	5,538
average NO_X + HC prevention costs in €/kg	2.2	1.5	3.3
SO_2 reduction (ktonne)	1,050	1,368	827
SO_2 reduction costs (M€)	861	994	782
average SO_2 prevention costs in €/kg	1.0	1.0	1.2

As we mentioned under the heading of Ågren (1999), the results of this IIASA-study have been criticised. The main points of criticism in this study are the following:

- the level of ambition is fairly low: although the environmental targets in the central scenario have been strengthened in comparison with the Gothenburg Protocol, the level of ambition is low compared to the first reading of the European Commission. The targets are not sufficient to achieve the objectives laid down in the Fifth Environmental Action Plan. The long-term aim is that critical loads for both human health and vulnerable biodiversity should never be exceeded;
- the costs of achieving the NECs are overestimated because of:
  - the energy scenario which serves as the input for the future emissions is not based on meeting the agreements of the Kyoto Protocol;
  - only end-of-pipe measures are included in the list of measures that can be taken to achieve the environmental targets set, whereas fuel switching and energy and transport efficiency measures have been ignored. This method thus excludes measures that might be achieved a zero cost;
- technological improvements (including cheaper technology) is not taken into account.

Ågren (1999) presents no other average prevention cost estimates, but presents the cost consequences of and an alternative energy scenario, which brings CO_2 emissions in 2010 down with 15% relative to 1990. In this scenario, the overall costs of meeting the NEC-directive come down from the € 7.5 billion (see IIASA, 1999a) to € 2.7 billion.

IIASA and AEA Technology, 1999b, Economic evaluation of a directive on National Emission Ceilings for certain atmospheric pollutants: part B, Benefit Analysis, Laxenburg, Austria/ Culham, United Kingdom

Method: damage cost

Model used: ALPHA, permits analysis of the effects of sulphur/nitrogenous pollutants and ozone on public health, materials, crops, forests, ecosystems and visibility.

Not all categories are quantified in detail, and so the authors emphasize that the benefits, which are presented in the report, are a 'subtotal'. For different policy scenarios in order to achieve reductions in NO_x, SO_2, NH_3 and ozone the emission reductions and benefits are calculated.

The scenarios differ in targets set for the different pollutants.

The larger part of the benefits comes from lower mortality and morbidity. The results therefor crucially depend upon the method used to value these health impacts. Two possibilities are explored in this study, the Value of a Statistical Life (VOSL) and the Value of a Life Year lost (VOLY).

The main difference between these two approaches is the fact that in the case of VOSL each life year lost is valued at the same price, whereas the VOLY-approach uses different values for a life year lost for a young adult and a life year lost for an elder person.

The results for the different policy scenarios are almost identical when looking at the damage cost per tonne NO_X, SO_2 and NH_3 reduced. We therefor only present the average for NO_X and SO_2 below.

Table 14 Marginal damage costs of NO_X and SO_2 found in IIASA (1999b)

Pollutant	Marginal social cost (in €$_{1999}$) per kilogram	
	Low estimate (using VOLY)	High estimate (using VOSL)
NO_X	9.4	15
SO_2	3.5	6.9

Ågren (1999) points out that the following benefits have not been quantified:

- less acidification of soil and water;
- less euthrophication;
- fewer effects on biological diversity;
- less long-term risk for lowered forest productivity;
- reduced direct health effects of NO_2 and VOCs;
- less damage to historical buildings and monuments.

IIASA, 1999c, Further analysis of scenario results obtained with the RAINS model, Laxenburg, Austria

Method: prevention costs

Model used: RAINS (Regional Air pollution INformation and Simulation), focussing on NO_X, SO_2, NH_3 and VOC. For these pollutants emission control options are identified and costs have been determined. The associated costs include investment-related and operating costs. All investments in emission reduction are annualized using a discount factor of 4%.

This report presents for each country the marginal social costs to achieve the environmental targets on acidification and ground-level ozone as put down in the Seventh Interim Report to the European Commission. These targets are the as follows for the EU as a whole:

- NO_X: -55%
- VOC: -60%
- SO_2: -78%

The marginal prevention costs can vary widely between countries (each country has its specific environmental targets) and between economic sectors. In Table 15 below we present two figures: an 'average' marginal prevention cost and a range of marginal prevention costs. In both figures the highest prevention costs across economic sectors are taken as a reference. The ranges presented are ranges of these marginal costs across countries; the 'average' figures represent the averages across these countries.

IIASA presents in table 1.7 of its report the following marginal prevention costs.

Table 15 Marginal prevention costs according to IIASA (1999c)

Pollutant	Marginal social cost (in €$_{1999}$) per kg	
	Average over all countries	Range per country over all sectors
NO_X	4.7	0 – 13
VOC	4.6	0 – 11
SO_2	1.5	0 – 5.0

***IVM 1999, Monetising the benefits of environmental policy: an exploratory investigation* ['Monetarisering van baten van milieubeleid: een verkennend onderzoek'] (in Dutch), Kuik, O.J., C. Dorland, and H.M.A. Jansen, Institute for Environmental Studies (IVM), Amsterdam, 1999**

Method: damage cost

This literature survey attempts to estimate the benefits of environmental policy for the Netherlands. In most cases the estimates are based on European studies on dose-response relations and other underlying data.

The following categories of potential effects are discerned:
- climate change;
- human health;
- material damage;
- agricultural damage;
- nature and biodiversity.

The emissions that are taken into account are PM_{10}, $PM_{2.5}$, NO_X, and CO_2. For these emissions the impact on the different categories are determined and monetised. The authors distinguish between 'high sources' and 'low sources'. Most industrial sources are considered 'high sources', whereas transport is considered a 'low source'.

Furthermore, the authors stress that the impact of a pollutant differs largely between locations. Even for a small country like the Netherlands, this results in a factor 10 difference between high and low estimates. However, in their study they only present the value for an average location in the Netherlands. For 'high sources', this average location is Amsterdam, for the 'low sources' the arithmetic average of emissions on different locations in The Netherlands is used to 'define' the average location.

In the results, the distinction between 'low' and 'high' sources has been made as follows: for low sources, i.e. mainly traffic, the particulate matter emissions are taken as particulate matter with a diameter smaller than 2.5 micron ($PM_{2.5}$). For high sources, the particulate matter consists of particles with a diameter smaller than 10 micron (PM_{10}).

The resulting marginal social costs that were found in IVM (1999) are presented below.

Table 16 Marginal damage costs found in IVM (1999)

Pollutant	Marginal social cost (in €$_{1999}$) per kilogram	
	Medium estimate	Range
NO_X (via nitrate)	2.9	0.4 – 21
NO_X (via ozone)	1.6	0.2 – 11
NO_X (total)	4.4	0.6 – 32
PM_{10} ('high source')	12	1.6 – 85
$PM_{2.5}$ ('low source')	130	18 – 942

The most important benefits from environmental protection that IVM (1999) finds are human health benefits. These benefits can be monetised following different methods. The medium estimate in the table above and the associated range are determined with a fixed monetary value for the risk of premature death, specifically k€ 150 for a 1-year reduction of lifetime from acute mortality and k€ 50 for a 1-year reduction of lifetime from chronic mortality.

The authors note that the intervals presented, reflect uncertainties in atmospheric dispersion, in numbers of exposed population and in exposure-effect relationships. The authors have also compared their estimates with a number of international studies[8] that go into the damages avoided by environmental protection and they conclude the following from their comparison:

- the medium estimates for PM_{10} and NO_X are similar with other international sources;
- the medium estimate for $PM_{2.5}$ is near the upper bound of the estimates found in the international literature; this is mainly due to the fact that in other studies the exposure-effect relationships for ‘low sources’ and thus for $PM_{2.5}$ are not modelled at the same level of detail as is done in Kuik et al.

ECMT, 1998, Policies for internalisation of external costs, ECMT/OECD. Paris, France

This study draws heavily on CE (1994) and CE (1997) and therefor this study is not worked out further.

Delucchi. M.A. 1996-1998, Report series 'The annualized social cost of motor-vehicle use in the United States based on 1990-1991 data', University of California, Institute of Transportation Studies, 1996-1998:

- 1998, The annualized social cost of motor-vehicle use in the United States 1990-1991, summary of theory, data, methods, and results; Report #1 in the series, June 1998.
- 1997, The valuation of non-monetary externalities Report #9 in the series, June 1998.

IWW et al., 1998, Entwicklung eines Verfahrens zur Aufstellung umweltorientierter Fernverkehrskonzepte als Beitrag zur Bundersverkehrswegeplanung, Karlsruhe, Germany

Method: damage costs

This study goes into the damage caused by NO_X, VOC and diesel particulates.
For the following categories the damage has been investigated for Germany for the year 2010:

- health;
- materials and buildings;
- forests;
- crops and animals.

Finally, acute health impacts and damage to crops are valued in terms of *average* damage costs per kg of pollutant. In Table 17 the results are shown.

[8] Most of the sources they mention have been covered elsewhere in our overview of the literature.

Table 17 Estimates of average damage costs of pollutants in Germany in 2010, according to IWW et al (1998)

Pollutant	Average social costs (in €$_{1999}$) per kg		
	total	of which health	of which crops
NO_x (via ozone)	0,23	0,16	0,07
HC (via ozone)	0,30	0,20	0,1
Diesel particulates*	37 (in urban areas)	-	-

* Based on Planco, Berücksichtiging wissenschaftlicher Erkenntnisfortschritte im Umweltschutz für die Bundesverkehrswegeplanung (BVWP, Schlussbericht im Auftrag des Bundesministeriums für Verkehr, 1995

Note: the study gives no indication on the base year used, but some figures suggest that all monetary values are denoted in DM_{1995} and the exchange rate to the ECU used in the report itself is one ECU to 1,85 DM. We use this value as well and correct for CPI developments between 1995 and 1999.

The estimates presented may serve as an underestimate for the marginal damage per kg, because:

- not all impact categories have been monetised; only acute health damage and damage to crops is included;
- the values present average instead of marginal damage costs.

CE 1997, *Optimizing the fuel mix for road transport*, Dings, J.M.W. et al., Delft, May 1997

Serves as a basis for CE (2000); therefore see CE (2000).

IPCC, 1996*, Climate change 1995: economic and social dimensions of climate change,* contribution of Working group III to the second assessment report of IPCC, UNEP/ WMO

Overview of different damage estimates: the following ranges are taken from IPPC (1996) in which the social costs of air pollution are mentioned to incorporate the second order benefits of CO_2 reductions.

Table 18 Estimates of marginal damage costs of pollutants in IPCC (1996)

Pollutant	Marginal social cost (in €$_{1999}$) per kilogram				
	UK	UN ECE*	Norway	US	US
source	Pearce (1994)	Pearce (1994)	Alfsen et al. (1992)	Ottinger et al. (1990)	Scheraga and Leary (1994)
NO_x	0.2	0.7	2.2 – 44	2.8	0.1 – 1.4
particulates	30	30	2.9 – 39	3.8	0.5 – 16
SO_2	0.5	0.9	0.7 – 11	6.7	0.4 – 2.6

* Damage done by a tonne of UK emissions to Western and Eastern Europe, including UK (UN ECE region)

ITS 1996, The full costs of intercity transportation, a comparison of high-speed rail, air and highway transportation in California, Levinson, D. et al., Institute of Transportation Studies, Berkely, 1996

This study used health cost estimates from various sources from 1977 to 1990. Due to its lack of more recent estimates we do not consider this study.

IWW/Infras, 1995, External effects of transport, UIC, Karlsruhe/Zürich/Paris

We do not go into detail for this study, because it is a similar study as the one, which has been finalised in 2000. We therefor use the update (see Infras/IWW, 2000).

Bleijenberg, A.N., Van den Berg, W.J. and G. de Wit, 1994, The social costs of traffic, literature overview, CE, Delft

Method: literature survey

This study provides an extensive survey of existing literature on the valuation of the external effects that occur with transport. The literature deals with WTP-studies, damage cost estimates and prevention cost estimates.

Table 19 Overview of marginal social costs estimates in (Bleijenberg et al., 1994)

Pollutant	Marginal social cost in €$_{1999}$ per kilogram		
	Low	Medium	High
NO_X	1.0	5.0	6.4
HC	1.9	5.0	7.3
SO_2	0.43	1.0	3.7

In these values the results from IOO (1993) have not been included because they were much lower than the values that other studies presented. This is due to the fact that IOO (1993) has not put a value on the deterioration of agricultural land, nature and forest land and leaves aside the damage to buildings.

The following studies were included in this literature survey:
- Grupp, 1986;
- Quinet, 1990;
- Dogs and Platz, 1990;
- Klaasen, 1992;
- Teufel et al., 1993;
- Kågeson, 1993;
- Neuenschwander et al., 1992;
- Maibach et al., 1992.

We have not analysed these sources separately in our study, except for the study by Kågeson (1993).

Pearce, D.W., 1994, Costing the environmental damage from energy production, mimeo, Centre for Social and Economic Research on the Global Environment (CSERGE), University College London and University East Anglia, Norwich

This study has been included in the literature survey of IPCC (1996). We therefor do not present the results separately.

Scheraga, J.D. and N.A. Leary, 1994, Costs and side benefits of using energy taxes to mitigate global climate change, in: Proceedings of the 86th Annual Conference, National Tax Association, Washington DC, USA

This study has been included in the literature survey of IPCC (1996). We therefor do not present the results separately.

Teufel, D., P. Bauer, G. Bekez, E. Gauch, S. Yäkel, T, Wagner, 1993, Ökologische und soziale Kosten der Umweltbelastung in der Bundesrepublik Deutschland, Umwelt un Prognose Institut, Heidelberg, Germany

This study has been included in the literature survey by Bleijenberg et al. (1994). We therefor do not present the results separately.

Kågeson, P., 1993, Getting the prices right, European Federation for Transport and the Environment

Method: prevention cost

Environmental targets for SO_2 and NO_X have been established, denoted in emission reduction in 2000 relative to levels in 1985. The targets are different for the different European countries and for each country high and low targets have been set.

IIASA has constructed national abatement curves and the resulting estimates for the marginal social cost of SO_2 and NO_X have been calculated. The following table presents the results for both pollutants and the different targets.

Table 20 Marginal prevention costs according to Kågeson (1993)

Pollutant	Marginal social cost (in €$_{1999}$) per kilogram		
	Target (relative to 1985)	Medium value	Range
NO_x (including ozone)	- 50%	4.8	3.2 - 6.4
SO_2	- 60%	1.6	0.47 - 3.9
SO_2	- 80%	3.2	0.47 - 21 1.2 - 5.8[9]

Note: the value in the report are in DM$_{1985}$; to arrive at €$_{1999}$ we have used the following conversion factors: 1 DM$_{1985}$ equals 1,2 DM$_{1993}$, exchange rate in 1993 is 1 € = 2 DM and eventually we have used the CPI to come from €$_{1993}$ to €$_{1999}$.

Kågeson also mentions that the marginal social cost for NO_X is also applicable for VOC. The IIASA model is not suit to capture targets for VOC separately and construct the abatement cost curve. Therefor, Kågeson suggests to use the value found for NO_X simultaneously for VOC.

Alfsen, K.H., A. Brendemoen and S. Glomsrød, 1992, Benefits of climate policies: some tentative calculations, Discussion paper no. 69, Norwegian Central Bureau of Statistics, Oslo, Norway

This study has been included in the literature survey of IPCC (1996). We therefor do not present the results separately.

9 Range excluding the extreme cases of Germany (€ 0,47 per kg) and Sweden (€ 21 per kg).

Klaassen, G., 1992, Marginal and average costs of reducing nitrogen oxides and sulfur dioxide emissions in Europe – A contribution to internalizing the social costs of transport, T&E, Brussels, Belgium

This study has been included in the literature survey by Bleijenberg et al. (1994). We therefor do not present the results separately.

Maibach, M., R. Iten and S. Mauch, 1992, Internalisieren des Externen Kosten des Verkehrs, Fallbeispiel Agglomeration Zürich, INFRAS, Zürich, Switzerland

This study has been included in the literature survey by Bleijenberg et al. (1994). We therefor do not present the results separately.

Neuenschwander, R., and F. Walter, 1992, External costs of transport: an overview, Ecoplan, Bern, Austria

This study has been included in the literature survey by Bleijenberg et al. (1994). We therefor do not present the results separately.

Umwelt Bundesamt, 1991, Advantages of environmental protection/ Costs of environmental pollution: an overview of the research programme Costs of environmental pollution/ Advantages of environmental protection, UBA, Berlin, Germany

This set of information sheets provides an overview of different costs (of environmental pollution) and benefits (of environmental protection) that arise in Germany. Categories such as human health, biodiversity impacts, material damage were included, but the costs and benefits have not been related to units of pollution. Therefor, this study is not relevant to our research.

Dogs, E. and H. Platz, 1990, Externe Kosten des Verkehrs, PLANCO Consulting – GmbH, Essen, Germany

This study has been included in the literature survey by Bleijenberg et al. (1994). We therefor do not present the results separately.

Ottinger, R.L., D.R. Wooley, N.A. Robinson, D.R. Hodas and S.E. Babb, 1990, Environmental costs of electricity, Pace University Center for Environmental and Legal Studies, Oceana Publications, New York, USA

This study has been included in the literature survey of IPCC (1996). We therefor do not present the results separately.

Quinet, E., 1990, The social costs of land transport, OECD, Paris

This study has been included in the literature survey by Bleijenberg et al. (1994). We therefor do not present the results separately.

Grupp, H., 1986, Die sozialen Kosten des Verkehrs, in: Verkehr und Technik, 1986/9, nr. 10

This study has been included in the literature survey by Bleijenberg et al. (1994). We therefor do not present the results separately.

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External costs of aviation

External costs of noise emission

Delft, February 2002

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Contents

1 External costs of noise emission

Effects of noise

The effects of noise from transport are increasingly studied. Within this study, we distinguish the following categories:

1. Effects on human well-being, which can be assessed via WTP/WTA studies and via property price decrease (hedonic pricing) studies.
2. Effects on human health, of which knowledge is gradually coming available.
3. Effects on indirect land use; governments put restrictions on land that is too heavily affected by noise.

The three effects can be added as higher noise levels in the long term lead to lower property values, more health costs, and more indirect land use.

Noise standards

There is an abundance of noise standards in Europe, and currently attempts are being undertaken to establish EU-wide standards. Currently national standards vary between 40 and 65 dB(A) for day-time noise (average: 52) and 40 and 55 for night-time noise (46 average). Scientist on average recommend 50-55 dB(A) as threshold value for day-time noise, and 40-45 dB(A) as threshold value for night-time noise (Infras/IWW 2000).

1.1 Overview of studies

Infras/IWW, 2000, External costs of transport: accident, environmental and congestion costs in Western Europe, Zurich/Karlsruhe

Method: two methods that have been used internationally are reviewed in this study. These two methods are:

a the willingness to pay for different noise levels (WTP);
b the actual health risk of noise (damage cost method).

The first method measures the willingness to pay (WTP) for the reduction of noise levels. These data on willingness to pay are given in relative terms, i.e. relation to the income per capita. This results in linear relations between the (acceptable) noise level and the per capita income. Infras/IWW reviewed 5 studies:

- Pommerehne (1986);
- Soguel (1994);
- Iten (1990);
- IRER (1993);
- Weinberger (1990).

For these studies the gradient is fairly similar: for each incremental dB(A) (on average) 0.11% of per capita income is needed to compensate. Following this approach, Infras/IWW concludes that for determining the total noise cost not the marginal cost per dB (A) is crucial, but the ‘target level’. Below this target level, no costs are put on the noise, above this level the cost increases by 0.11% of per capita income per dB (A). The target level can be estimated from the 5 studies, to be 50 dB (A), i.e. below this level no noise cost is apparent. Infras/IWW have decided to take a more cautious target level, namely 55 dB (A).

Table 1 WTP per person per year per dB(A) reduced in € 1999, according to Infras/IWW (2000), for the case Germany

dB(A)	55-60	60-65	65-70	70-75	>75
WTP	47	142	236	331	425

Additionally Infras/IWW value the health effects of transport noise. Two studies have empirically examined this relationship and the following table presents the results.

Table 2 Increased risk of cardiac infarctions due to transport noise, according to 2 empirical studies

Source	**Location**	**65 – 70 dB(A)**	**70 – 75 dB(A)**	**75 – 80 dB(A)**
Babisch et al. (1993)	Caerphilly, Speedwell	+ 20%	-	-
Babisch et al. (1994)	Berlin	-	+20%	+70%
Value used in Infras/IWW		+20%	+30%	

According to Infras/IWW the values found using the first method (WTP) and the damage cost (for health) can be added.

The values that are given in Infras/IWW cannot be easily translated into marginal cost per unit noise production, because noise is an 'extremely local phenomenon' (Infras/IWW). Therefor, Infras/IWW give some decisive characteristics for determining the marginal cost. These characteristics include the time zone (day and night), the land use (rural, sub-urban and urban) and traffic conditions (relaxed, dense). This exercise is necessary for each noise source separately. Another important factor is the threshold level, which is determined to be 55 dB(A) in this study. This means that the willingness to pay for a reduction in noise at a level of 55 dB(A) is zero. This threshold level is determined from a number of studies.

For the EU-countries, Switzerland and Norway (EUR17) this exercise is done, which results in (total) noise costs of €M 36,540, of which 59% comes from the WTP-approach and 41% from the health costs. Of this, air transport contributes €M 2,513, of which 62% comes from the WTP-approach and 38% from the health costs).
The amount of LTOs in 1995 in the EUR17 was 3.6 mln (table 82); the costs per LTO are thus € 700.
The total number of passengers is 582 mln (167 mln domestic and 415 mln international, table 82). Using a load factor of 50% for domestic and 65% for international transport the amount of seat LTOs is 486 mln; the costs per seat LTO then arrive at € 5.2.

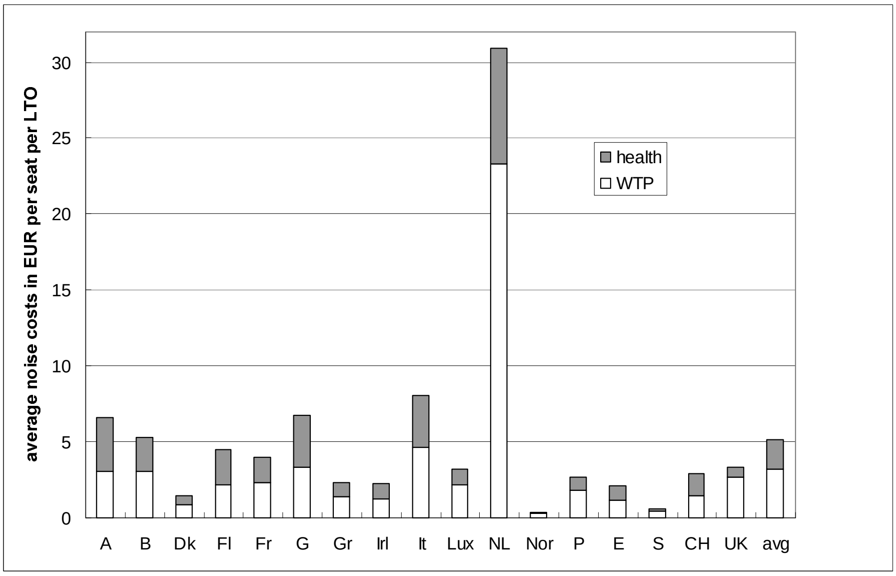
Furthermore, Infras/IWW state that the best estimate of the amount of persons exposed to different noise levels is provided in ECMT (1998).

On the estimation of noise damage from air transport, Infras/IWW states that the marginal cost can be calculated by taking 30 – 60% of the average noise cost.

Table 3 Breakdown of annual noise costs from aviation, according to Infras/IWW (2000), in €, and recalculated to average costs per LTO and seat LTO

country	WTP €M	health costs €M	# LTOs ('000)	# seat LTOs ('000)	costs per LTO €	costs per seat LTO €
Austria	20	23	71.6	6,524	601	6.6
Belgium	29	22	110.9	9,618	460	5.3
Denmark	10	7	118.7	11,629	143	1.5
Finland	13	14	56.5	5,968	478	4.5
France	161	119	498.7	69,829	561	4.0
Germany	300	311	720.7	90,726	848	6.7
Greece	12	8	60.9	8,701	328	2.3
Ireland	9	7	64.6	7,154	248	2.2
Italy	177	131	259.4	38,144	1,187	8.1
Luxembourg	2	1	18.3	931	164	3.2
Netherlands	446	146	145.4	19,154	4,072	30.9
Norway	4	1	132.1	14,273	38	0.4
Portugal	19	9	70.6	10,395	397	2.7
Spain	83	62	407.3	69,681	356	2.1
Sweden	7	2	144.1	14,882	62	0.6
Switzerland	24	24	154.1	16,521	311	2.9
United Kingdom	249	60	559.4	91,903	552	3.4
total	1,566	947	3593	486,032	699	5.2

Figure 1 Estimates of average noise costs in the EU per seat per LTO, based on Infras/IWW (2000)



The extremely high value in the Netherlands is due to the fact that the number of people in the Netherlands that are exposed to airport noise seems to be overestimated.

Marginal costs are on average about 30-60% of this amount, according to Infras/IWW.

Pearce and Pearce *'Setting Environmental Taxes For Aircraft: a Case Study of the UK'*, CSERGE, 2000

This study derived estimates of the marginal willingness to pay (MWTP) for an aircraft 'event' (landing and take-off) for each aircraft type. They started by adopting the NSDI value of around 0.6% per dBA found by Schipper (1999). By applying this NSDI value to the average house price within the Heathrow Airport 57dB(A) daytime contour and by multiplying for the number of resident households, they were able to derive an estimate of overall MWTP for a 1dB(A) Leq reduction in the area.

Table 4 The contour areas and populations of Heathrow Airport

Leq level (dB(A)	area, km^2		% change	population (,000)		% change
	1998	1999		1998	1999	
>57	163.7	155.6	-4.9%	341.0	331.6	-2.8%
>60	94.6	87.5	-7.5%	172.5	175.5	+1.7%
>63	55.4	53.9	-2.7%	82.2	91.2	+10.9%
>66	35.2	35.4	+0.6%	38.5	39.7	+3.1%
>69	28.8	21.9	-3.9%	15.5	13.8	-11.0%
>72	13.1	12.0	-8.4%	4.4	3.9	-11.4%

For comparison: the number of people within the 57 dB(A) contour of Schiphol is about 20,000.

Then, they converted this figure into a daily MWTP. In order to derive estimates of MWTP for the reduction of a daily movement of each aircraft type, they multiplied the impact on Leq (16-hr) of each aircraft type (derived from noise certification data) by the daily overall MWTP figure. Table 5 shows the resulting estimated noise damage costs per aircraft event and per LTO for selected aircraft types (UK£ = € 1.6).

Table 5 Results: external costs in € per aircraft event and per LTO per seat for Heathrow Airport

type	# seats	€ per LTO	€ per seat LTO
A310	220	108	0.5
A340	320	246	0.8
B737-400	150	108	0.7
B747-400	420	538	1.3
B757	200	140	0.7
B777-300	350	172	0.5
B777	350	106	0.3
MD82	150	148	1.0

The resulting figures are rather low compared with the results of Schipper (1999) and with the synthesis at the end of this annex, certainly when the amount of people living within the 57 dB(A) contour is taken into account. The results correspond with the lowest estimates of Schipper that are based on the HP approach.

Jansen, P.G., and D. Wagner, 2000, Lärmbewertungsverfahren für den Bundesverkehrswegeplan: Verfahrensvorschlag für die Bewertung von Geräuschen im Freiraum, F+E-Vorhaben 298 55 269, Stadtplaner AK NW, Köln, Germany

Not relevant for our study, because this study only deals with the costs of preventing noise damage. The study does not go into the desirable amount of prevention, or the damage cost of noise.

Bruinsma, F.R. et al., 2000, Estimating social costs of land use by transport: efficient prices for transport ['Raming maatschappelijke kosten van ruimtegebruik door het verkeer; Efficiënte prijzen voor het verkeer'], Free University, Amsterdam

Subject: valuation of indirect land use by Schiphol Airport.
Method: opportunity cost

This study has estimated the marginal external costs of land-use through different modes of transport. Among these modes is also aviation and Bruinsma et al. (2000) have calculated the external cost of the indirect land use around Schiphol Airport and other (regional) airports in the Netherlands.
As this study intends to fill up the gap of valuation of land use in the CE study 'Efficient prices for transport' CE was asked to deliver comments to a draft version in June 2000. In cases these comments were not included in the final report, we write them down here for clarity.

Land use
Around the airport there are *cordons sanitaires* to restrict damage and nuisance, which generates costs in the form of depressed local property values. The land would be more valuable if it were usable. This implies that even if there is no actual noise nuisance or any off-site accident, there are still real costs associated with noise emissions and the risk of accidents.

The study leads to the following conclusions concerning land use by Dutch airports.

Table 6 Direct and indirect land use by Dutch airports, in km^2

	direct		indirect	
	built-up area	rural area	built-up area	rural area
Schiphol	-	26.8	8.4	222.8
regional airports	--	ca 16.7	3.3	61.9
small airports	-	ca 5.5	5.7	114.8
total	-	49	17.43	399.5

Valuation
The value Bruinsma et al. (2000) put on land-use has been calculated as follows. First, they distinguish indirect land-use in urban areas and indirect land-use in rural areas. We first go into the external cost of indirect land-use in *rural areas* they calculate, after that we describe the external cost of indirect land-use in *urban areas* they describe.

If the restrictions on the land around Schiphol were to be abolished, a part of the land would be used as a built-up area. Bruinsma et al. suggest that not all land would be used for a new function, i.e. not all land would be used for building houses, offices and so on. Bruinsma et al. assume that in non-built-up areas 20% of the land will get a different function, i.e. a change from agricultural area to built-up areas.

Comment CE: our study 'External costs of aviation' focuses on marginal costs, and should thus consider marginal changes. It is highly likely that the marginal use of land that suddenly comes available for new functions would be higher than the Dutch national average of 20%. The Nyfer study (1999) finds that about 53 km^2 could be used, or about 24%.

The difference in property values between agricultural land and land that can be built upon is estimated to be ƒ 50,- (€ 22) (property price per m^2 for built-up areas in the rural area) minus ƒ 5,- (€ 2) (the property price per m^2 for agricultural area in the rural area). This boils down to a difference property values of roughly € 20 per square metre. However, Bruinsma et al. do not take this € 20 to calculate the external cost, because they argue there is a large distributive effect due to which the economic costs of restricted land use are much lower. They argue that therefor, one should not take the price difference between agricultural land and built-up areas in the Netherlands, but instead use the difference between the property price of built-up areas *on an attractive location* and the property price of built-up areas *on a less attractive location*. Arbitrarily they choose a price difference of € 5.
Comment CE: the price difference of € 20 should be used. The distributive effect is not relevant from a national welfare point of view. Restrictions to land use around airports will indeed lead to greater demand for land in other areas. But: the higher prices that result from this do not reflect welfare gains and should thus be considered economic losses.
Consider this case. A person buys a € 2,000 computer at shop A. He would have bought this computer at shop B if it were € 100 cheaper there. Now the computer falls out of the hands of the owner of shop A so that the client cannot buy it there any more. For the client the welfare loss is only € 100, but for society welfare loss equals the full € 2,000. The same reasoning holds true for land that can not be used at one place and will therefor be used at another. The social cost is then equal to the full cost differential of (mainly) agricultural land and built-up areas.

For the indirect land-use in *urban areas*, Bruinsma et al. the methodology is roughly the same, but the figure are different. In case the noise zones of airports lies within built-up areas, a functional change is only assumed to happen for 10% of the land (p.32). The value of land in built-up areas is estimated at € 91 per m^2. Again Bruinsma at al. subtract the value of alternative land of a built-up location (€ 22) and thus arrive at a loss of € 68 per m^2.
Comment CE: again, not the distributive effect is relevant but the substitution effect which would be € 91 - € 2 = € 89 per m^2. (a 30% higher estimate).

Both comments by CE would lead to about a fivefold figure for the valuation of indirect land use outside built-up areas and a 30% higher figure for the value within built-up areas.

To arrive at the marginal social cost per vehicle kilometre the total external costs are discounted to a yearly value (using the real interest rate, 4%, as a discounting factor) and this yearly value has afterwards been allocated to the different types of aircraft.

Bruinsma et al. calculate from these assumptions, coupled to the amount of indirect land-use around the airports the following marginal social cost for indirect land-use by airports. The presentation of the marginal social cost for indirect land-use is given per person- or tonne-kilometre. The total annual costs of indirect land use cannot be directly derived from the report; close analysis suggests an annual cost of €M 8-9. Correction of these figures by CE leads to an estimate of €M 45 per annum.

Table 7 Overview of costs from indirect land use of Schiphol Airport, according to Bruinsma et al., and after modifications by CE

Type of aircraft[1]	**Marginal social cost (in €ct) per person-/tonne-kilometre**		
	Opportunity cost, urban area	Opportunity cost, rural area	Total opportunity cost
acc. to Bruinsma et al.			
aircraft, 150 kilometres	0.08	0.38	0.44
aircraft, 500 kilometres	0.02	0.09	0.10
aircraft, 1,500 kilometres	0.01	0.03	0.04
aircraft, 6,000 kilometres			
- passenger transport	0.00	0.00	0.00
- goods transport	0.00	0.02	0.02
after modifications by CE			
aircraft, 150 kilometres	0.10	2.40	2.5
aircraft, 500 kilometres	0.03	0.43	0.46
aircraft, 1,500 kilometres	0.01	0.13	0.14
aircraft, 6,000 kilometres			
- passenger transport	0.00	0.02	0.02
- goods transport	0.00	0.08	0.08

SEO/ Universiteit van Amsterdam, The shadow price of noise from aviation (in Dutch: De schaduwprijs van geluidhinder door vliegtuigen), not published, preliminary results presented at RLD-research days, March 23rd, 1999 (later published as Chapter 6 in: B. Baarsma, Monetary Valuation of Environmental Goods: Alternatives to Contingent Valuation, Thela Thesis no. 220, Amsterdam, 2000)

Method: non-preference method, implicit valuation through well-being evaluation measured with the use of questionnaires.

This study aims to estimate the effects on well-being from aircraft noise and to find shadow prices both for the social costs of noise nuisance and for isolation (which can be perceived as the costs of noise reduction).

First well-being is formulated as being dependent on a number of variables, among them family situation, income, age, noise nuisance and several other living conditions, such as the isolation of the houses where people live in. Sample data have been obtained using questionnaires for over 16,000 households, of which almost 3,400 responded. The estimations show that well-being is enhanced by the amount of income he or she earns and hampered by aircraft noise, as expected. Subsequently the study investigates equivalent levels of well-being for different levels of noise nuisance. In other words: the study investigates how much *income* a person would require in order to bare a higher level of noise. This gives the implicit shadow price for noise nuisance. By comparing this implicit price for houses with or without isolation and implicit price for isolation is obtained.

The Well-being evaluation method hence determines an implicit shadow price for the environmental good by *assuming* that an increase in noise can be traded off against a higher income.

The results of this approach can be given as follows.

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[1] All 'types' deal with passenger transport, except for the '6,000 km' category aircraft that also carry freight.

Table 8 Shadow prices due to the increase of the noise level of 10Ke (monthly compensations in € to achieve a similar level of well-being)

category of house	Isolation	initial noise level		
		20 Ke	30 Ke	40 Ke
House of € 68,000, € 340 living costs p.m.	no	53	33	23
House of € 204,000, € 680 living costs p.m.	no	162	99	70
House of € 68,000, € 340 living costs p.m.	yes	8.1	5.0	3.5
House of € 204,000, € 680 living costs p.m.	yes	25	15	11

By subtracting the results from the investigation for houses with isolation from those without isolation, an implicit shadow price can be found for isolation. So the implicit shadow price of isolation for a house of € 68,000 laying in the zone of 20 Ke is about € 45 monthly. Interesting is moreover that in this study the additional loss in income due to an increase in aircraft noise diminishes with higher levels of initial aircraft noise: the authors interpret this as an evidence of diminishing marginal disutility as known in the economic literature.

Table 9 Overview of results of SEO (1999)

Ke-value lower limit	corresponding Lden dB(A) value (approx.)	# households*	average monthly compensation per household (€)	total annual compensation (€M)
> 20 Ke	> 49	134,705	52	**84**
> 25 Ke	> 51.5	49,052	35	21
> 30 Ke	> 54	10,041	31	3,7
> 35 Ke	>56.5	5,086	28	1.7
> 40 Ke	>59	3,511	21	0.88

* These numbers do nor correspond very well figures presented elsewhere in this annex; the cause is not clear.

NYFER, Schiphol; sea of space ['Schiphol, zee van ruimte'], Breukelen, 1999

Aim: to establish costs of indirect land use due to cordon sanitaire.

Nyfer calculates that completely moving Schiphol to another location would imply that finally about 80 km^2 of land (out of the total 258 km^2 of the cordon sanitaire) would become available for other functions. This is a net figure including all current water, infrastructure, and recreational areas, and includes reservations for rural activities. The value is well consistent with the estimate of Bruinsma et al (2000), but is criticised in a report by the Dutch CPB 'Towards a more efficient environmental policy', 2000) stating that the real value should be about one third lower. For our purposes, from this amount the direct land use of Schiphol (27 km^2) should be subtracted, leading to a net figure of about 30 km^2 of usable land currently made unavailable by the cordon sanitaire. NYFER estimates the net present value of this land, based on an average rise in land prices of € 90 per m^2, to be about €M 16 to 48 per km^2 depending on the economic scenario. The net present value of 30 km^2 would then amount to €M 480 to €M 1,440. On an annual basis (discount rate 4%) this is € 14 to € 58 mln per annum

Hamelink, P., 1999, *The cost of noise from aviation: a hedonic price study for the Schiphol region* ['De kosten van geluidhinder door vliegverkeer: een hedonische prijsstudie voor de regio Schiphol'], KUB/CE Delft

Method: hedonic pricing

This study used two different approaches, of which one has finally been published.

Approach 1: based on NDIs from international literature
Based on the arithmetic average of 29 primary international hedonic pricing studies, it was concluded that the average fall in house prices (NDI, Noise Depreciation Index) per Ke additional noise exposure on top of 20 is 0.0036. This means that for each additional Ke, the value of a house will drop by 0.36%. It should be noted that the 29 studies are based on a variety of different noise units and conversion to Ke was therefore necessary. Once converted, the results of the 29 studies were remarkably consistent. They yielded 26 NDIs of between 0.17 and 0.63. Three studies had outliers of 1.06, 1.12 and 1.36. The arithmetic average of the 26 'low' NDIs was then multiplied by the numbers of dwellings within different Ke zones at Schiphol, their value and a social discount rate of 4%.

Table 10 Review of dwelling numbers in different Ke zones in 1990

	> 65 Ke	40 – 65 Ke	35 – 40 Ke	30 – 35 Ke	20 – 30 Ke	total
average Ke	65	52,5	37,5	32,5	25	
(average dB(A))	71.5	65	58	55	51.5	)
Ke above cut-off	45	32,5	17,5	12,5	5	
# houses 1990	53	7,012	8,025	36,229	189,908	
deprec. (€/house 1990)	13,608	9,828	5,292	3,780	1,512	
deprec. 1990 (€M)	1	69	42	137	287	536
# houses 1999 (approx.)	40	6,000	7,000	18,000	92,000	
deprec. (€/house 1990)	34,020	24,570	13,230	9,450	3,780	
deprec 1999 (€M)	1	147	93	170	348	759

The average price of a house in the Schiphol area in 1990 was about € 80,000, in 2000 it was about € 210,000. Thus, we arrive at an approximate depreciation of house prices of €M 536 in 1990 and €M 759 in 2000. The latter figure has been multiplied by a 10% discount rate to convert it to an annual amount, in between the 5 and 15% values used in ECMT (1998). This yields a shadow price for the impact of noise at Schiphol of €M 76 per annum. We emphasise that this is merely an initial estimate.

Approach 2: new assessment of house prices
Hamelink conducts a hedonic pricing study on houses located in Amstelveen and Aalsmeer, nearby Schiphol Airport in the Netherlands. The study contains a model describing the sales price of houses in general with variables such as floorspace, number of rooms, year of construction, garden, proximity to the centre, etc. By collecting data from real estate agencies on sales, data have been gathered for 1997 on all houses sold in the two vicinities. By adding variables on noise levels stemming from airplanes to these data, the study can estimate the loss in real estate prices due to noise pollution.

Two measures for noise are examined in this study: Kosten-eenheden (Ke), a Dutch measure which (in short) measures noise levels outdoors weighted by the time of the day, and the LAeq-night, a weighted measure for noise levels indoors at night. Both measures are calculated measures for noise nuisance and are difficult to connect directly to international measures, such as dB(A).

The sample in this study consists of all houses sold in 1997 in the two vicinities, 796 in Amstelveen and 81 in Aalsmeer. The study finds no significant effect of noise on house prices for lower levels of noise, measured in Ke. For higher levels of noise (40-55Ke) there exists a significant negative effect on house prices in Amstelveen (which has the most observations). For lower levels of noise (below 40Ke), this study finds no significant influence on the sale prices. Also for the nuisance because of the night flights, the study finds a significant negative effect on house prices in Amstelveen. For the smaller sample of houses sold in Aalsmeer, the study finds no significant effects.

The depreciation in real estate prices because of living in the 40-55Ke zone is equivalent to almost 10% of the house prices (€ 14,700 at an average price of € 156,000). The depreciation in prices because of nuisances because of night flights consists of about 9% (€ 13,700).

The study finds that the total depreciation of house prices due to Schiphol Airport noise was €M 106 for all houses with a noise load over 40 Ke, and €M 680 for all houses with a night time load of over 20 LAeq. The €M106 is well consistent with the figure in Table 10, (€M 1+147) given the fact that in this table calculations take place with about 30% higher house prices. This €M 106 is most probably an underestimation because the largest amount of damage costs is found among households that suffer less than 40 Ke.

The conclusion can be drawn that €M 70 seems a reasonable estimate of annual costs of losses of house values die to the noise of Schiphol Airport.

Schipper, Y., 1999, Market structure and environmental costs in aviation: a welfare analysis of European air transport reform, Free University, Amsterdam

Method: literature survey, meta-analysis, mainly on hedonic pricing studies, statistical analysis of noise nuisance

Schipper presents an overview of 32 case-studies on the social costs of aircraft noise, mainly expressed in housing prices. The vast majority of them are hedonic price studies; only 2 studies have used the CVM method.

The hedonic price studies show that the Noise Depreciation Index (NDI), an internationally used standard which shows the price elasticity of noise nuisance (in dB(A)), in general moves between the 0.5 to 0.75%. This indicates that every dB(A) additional noise exposure results in a loss of property values of 0.5-0.75%.

Schipper then asks himself the question whether the results of these 30 hedonic price studies are so homogenous that the results can be transferred to other locations. For this he conducts a 'meta-analysis' on the results of these studies, which is a modern tool to answer such questions. His results show that there is no homogeneity in the results: i.e. the figure of 0.5-0.75% is not consistent without taking into account location specifics (such as income levels, average size of houses, etc.). Subsequently, Schipper identifies two types of variables which explain the variation in the NDI: location specific variables such as the average price of houses near the airport; and study specific variables which explain the differences in methodology of the studies conducted. In general, the study specific variables have more influence on the NDI estimate than the location specific variables. Studies that have not been published in scientific journals tend to find higher NDIs and the discovered NDIs tend to become lower over time. This latter result is somewhat surprising as one would expect that increasing scarcity of 'silence' would result in a higher NDI over time. The most important thing, however, is that the estimate for the NDI which, given all differences in study methodologies, are consistent with the data, is 0.48%: lower than the sample mean of the studies involved[2].

Schipper compares his estimates of the NDI from hedonic price studies with the results from WTP-studies and finds that the results from WTP-studies in general show higher external costs than hedonic price studies.

Subsequently, Schipper conducts a statistical analysis in which OECD data on the number of people living within certain noise contours nearby airports are regressed on the aircraft movements round a number of OECD-airports[3]. Schipper defines noise nuisance as the difference between the exposed noise levels and the background noise. He does not take into account noise nuisance lower than 57 dB(A) Leq.

His results show that the noise nuisance per person increases significantly with the aircraft movements at an airport and diminishes over time. This latter effect may reflect technological improvements in aircraft engines. At this place we only present the estimates for the more recent years, which have a value of 3.9 person-Leq per ACM as a basis. By applying his results to the previous results from the hedonic pricing studies, the cost estimates of an aircraft movement are estimated.

Table 11 Noise costs per aircraft movement (ACM) in 1995 €/ACM from Schipper (1999), taken for data after 1985, not differentiated for aircraft type of population density

Hedonic pricing, avg. house price of € 110,000	1,028
WTP in the USA	4,771

It should be noted that the differences between various aircraft are quite substantial. So will a Boeing 747-200 result in more than ten times higher noise costs than a Boeing 757-200. Finally, it should also be noted that these results are averages from the selected European airports. The total external costs per ACM is of course mainly influenced by the amount of houses located nearby the airport and their respective prices.

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2 However, this figure of 0.48% is not significant. Nevertheless, Schipper uses it subsequently in his study. It should also be noted that such meta-analysis, as conducted by Schipper, are not free of problems. Many studies have not reported their data, as the authors had not expected that their studies could be the object of another studies dealing with their results. See van den Bergh and Button (1999).

3 These data can be found in the Environmental Data Compendia of 1987 and 1993 from the OECD. The airports which have been taken into account are: Copenhagen, Paris, Frankfurt, Dusseldorf, Munchen, Hamburg, Amsterdam, Rotterdam, Maastricht, Oslo, Geneve, Zurich, London and Manchester.

The WTP results refer here to a study of Feitelson et al. (1996) which presented cost estimates using willingness to pay for a certain number of airports in the US. It is interesting to notice that the hedonic pricing studies come to estimates 4 to 20 times lower than those in the WTP studies. Schipper claims that this may be due to the fact that WTP estimates include non-use values or recreational values and the non-committing character of questionnaires through which the WTP is established which results in a much steeper marginal external cost curve.

Table 12 Noise costs per aircraft movement (ACM) in 1995 ECU/ACM from the average European airport from Schipper (1999), differentiated according to aircraft types, and expressed in € per LTO per passenger capacity of the aircraft

aircraft type	capacity	ECU 1995 per take-off		€ 1999 per seat LTO	
	(pax)	average	range	average	range
B737-300	150	555	152-2,577	8	2-37
B757-200	200	150	41-697	2	0.4-7
B767-300	275	297	81-1,380	2	0.6-11
B747-400	420	1170	320-5,430	6	2-28

It can clearly be seen that the valuations per passenger capacity per LTO (=trip) are much lower for the newer aircraft types considered (i.e. B757 and B767).

ECMT, 1998, Efficient transport for Europe, Policies for internalisation of external costs, ECMT/OECD. Paris, France

Method: literature survey

ECMT in their literature survey find no evidence against the assumption that the average and marginal costs of noise changes, measured on the dB (A) scale are equal. This means that the actual noise level does not influence the marginal social cost.

The literature survey is based on a couple of hedonic pricing studies, in which the income characteristics and property prices of houses are used to arrive at an estimate for the social cost of noise. For comparison purposes ECMT has converted all values into a lump-sum value. For this purpose, yearly estimates have been converted to a lump-sum estimate by assuming that persons live in a house for 50 years. Taking a shorter or longer time period does not influence the results substantially. The following studies and corresponding results are presented in ECMT (1998).

Table 13 Summary of studies cited in ECMT (1998)

Study	Lump sum value for a 1 dB (A) noise reduction (in $€_{1995}$)	Remarks
Soguel (1994)	1,044	5% discount
	384	15% discount
	231	25% discount
Colins and Evans (1994)	209	Apartment value: 32,000
	771	Semi-detached house, garden: 60,200
	1,185	detached house: 113,000
Levesque (1994)	809	house value: 44,700
Uyeno et al. (1993)	733	house value: 110,250

From these hedonic pricing estimates, ECMT calculates a shadow price per dB(A) of € 22 per person or € 58 per household per year. When using this value for other countries and sites it is necessary to adjust the figure for Purchasing Power Parities and house values, although the income elasticity of noise valuation is stated to be fairly low.

ECMT furthermore calculates the total costs from transport noise in different European countries by estimating the amount of people living in certain noise bands, i.e. the amount of people that is exposed to a certain level of noise. Noise levels under 50 dB (A) are not valued in monetary terms. The estimate for each of the transport modes under consideration is fully based on the amount of people that are exposed to a certain noise level of a certain transport mode. The external noise cost per kilometre can then be calculated, because there is no evidence from empirical studies that average costs and marginal costs are not equal.

ECMT also presents another method to estimate the external costs of noise from different transport modes. This involves a 'top-down' approach in which the total noise costs from transport in a country are expressed as a percentage of GDP. These estimates only concern noise from road transport and ECMT has also estimated the total external cost from rail transport. Unfortunately, the total external noise costs from air transport are not calculated in ECMT.

Institut für Verkehrswissenschaft, 1991, Kosten des Lärms in der Bundesrepublik Deutschland, UBA-FB 91- 076, Erich Schmidt Verlag Berlin, Germany

Method: combination of damage cost, prevention cost and willingness to pay

The study uses different methods to estimate the social cost of traffic in Germany. However, the cost estimates have not been related to a certain reduction in noise and therefor it is not possible to estimate, in the scope of our study, the social cost per certain noise unit, which can be translated to other airports.

Qualitative summary of the literature
To arrive at a common estimate for external costs from these studies is far from straightforward. Nevertheless, this literature survey can come up with some results:

1 Studies that have estimated the costs of road transport proved not to be useful for estimating aircraft noise because the hindrance from aircraft

noise has a typical peak intensity, largely absent in road transport noise, which can be described as a more general ‘humming’. Proost et al. (1999) have shown that this effect is so substantial that we do not recommend to use figures from road transport to evaluate aircraft noise. This implies that the studies from Proost et al. (1999) and Bleijenberg et al. (1994) are not useful for this study.

2 External costs have been estimated different in most of the studies. This is mainly due to the different valuation approaches that have been chosen. Approaches that are dominant are either the hedonic price method (HPM) or the contingent valuation method (CVM).[4] The disadvantage of the hedonic price method is that it assumes that the true value of external costs may be underestimated. Schipper (1999, p39) concludes that the revealed preference techniques (as hedonic pricing) are only able to uncover a part of the total economic value of environmental goods. For example: the loss in recreational values for non-habitants nearby airports is not counted in hedonic pricing studies. The disadvantage of the contingent valuation method is that this method does not involve a real but a hypothetical transaction. As the filling in of questionnaires has no binding force, the answers may not reflect true market prices. Furthermore the results may be influenced by the amount of people who, under no circumstances, are willing to live nearby the airport. Such unwilling persons may influence the housing market, as housing prices may fall due to a lack of demand for houses nearby airports. Especially when taking into account the happiness of people living nearby airports, as in SEO/Baarsma (1999/2000), an underestimation of the true value of damage may occur.

3 Closely connected to the various methods that have been used for external costs, there exists different definitions of external costs in the various studies. ECMT (1998), Schipper (1999) and Hamelink (1999) have emphasized the loss in property values. SEO/Baarsma (1999/2000) have emphasised the costs of foregone well-being and Infras/IWW has emphasised the general costs (willingness to pay) and the damage costs of reduced health.

4 The disturbance from noise has been measured differently in most studies. The three most used measures of noise are the Leq, the Ldn and the Ke. The day-night average noise level, or DNL, is a 24-hour average (expressed in decibels). Night-time noise, between the hours of 10:00 p.m. and 7:00 a.m. is weighted, i.e., given an additional 10 decibels to compensate for sleep interference and other disruptions caused by loud night-time noise. (The symbol for DNL that often appears in noise monitoring systems is Ldn.) The community noise equivalent level, or CNEL, is similar to the DNL except that it includes an approximate 5 dB "penalty" for evening noise (7 p.m. to 10 p.m.), in addition to the 10 dB penalty for night-time noise. (The symbol for noise equivalent level that often appears in noise monitoring systems is Leq.). The Kosteneenheden (Ke), finally, is a Dutch measure for aircraft noise, which gives the cumulative yearly weighted noise levels. For each time of the day, a different weighting factor is attached to the maximum dB(A) noise levels of an aircraft that passes by. Nightly passages are in this way 5 times more counted than the passages during rush hours. The Ke units cannot

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[4] The HPM establishes a value for external costs through the revealed preferences in associated markets: the price for houses do not only contain components for the quality of the house but also the quality of the environment in which the house is located. Noise nuisance will hence be translated in a lower value of the house than on grounds of the quality of the house could be expected. The contingent valuation method establishes a value for external costs through expressed preferences, for example, with the use of questionnaires. Typical questions are then: “how much compensatory money would you need in order to accept that an airport is located nearby your house”.

be recounted into Ldn or Leq without going into details for every passage that has occurred during a year. This is due to the different calculation methods and to the fact that the Ldn and Leq estimates refer to average noise, while the Ke refers to maximum noise levels.[5] As an extremely rough, and preliminary estimate one may state that the relationship is Leq dB(A) = 39+0.5*Ke. In reality there is no linear relationship between Ke and Leq.

5 The minimum level of noise under which no external effects can be expected differs between the studies. While ECMT (1998) has assumed a minimum level of 50 dB(A), Infra/WWW (2000) has estimated that the minimum level is 55 dB(A) and Schipper (1999) has used a minimum level of 57 dB(A). SEO/Baarsma (1999/2000) have taken a minimum level of 20 Ke (i.e. about 49 dB(A). These substantial differences matter for the estimation of the total external costs.

6 Also the shape of the external damage function is ambiguous from the various studies. Bruinsma et al. (2000) and Schipper (1999) assumed linear marginal cost functions. But SEO/Baarsma (1999) found concave marginal cost functions (i.e. decreasing marginal costs for higher levels of disturbance), and also Infras/IWW state that marginal costs of noise are generally 30-60% of average costs.

7 Finally, the slope of the external cost function can be estimated to lay in between 0.4-0.75%. This implies that every dB(A) increase in noise levels result in an increase in external costs by 0.4-0.75%. Schipper (1999) is the only study, which has attempted to compare various results of the slope of the external cost function, and he arrives at a figure of 0.48% (though it is not significantly different from zero).

Quantitative survey of the literature

Estimates of external costs from Schiphol Airport

Noise damage costs from Schiphol Airport are quite extensively studied. In this paragraph we will show a synthesis of the studies considered earlier in this annex.

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[5] The Dutch government has launched a study project in which during five years both the Ldn and the Ke estimates will be produced for a period of five years to establish a comparison of Dutch figures for aircraft noise with internationally comparable measures.

Table 14 Overview of annual external noise cost estimates results for Schiphol Airport

source	external cost estimate (€M/yr)	remarks
1 estimates with HP (Hedonic Pricing) approach		
Hamelink (1999) approach 1	ca 76	NDIs from literature
Hamelink (1999) approach 2	ca 68	primary HP research
2 estimates with CVM (stated preference) approach		
SEO (1999)	88	WTA, compensation
Infras/IWW	446	all Dutch airports, WTP, we suspect that exposure data have been overestimated.
3 estimates of costs of indirect land use due to 'cordon sanitaire'		
Bruinsma et al, after correction	ca 45	indirect land use from 'cordon sanitaire', no time path
Nyfer (1999), after correction	ca 14-58	indirect land use from 'cordon sanitaire', based on NPV time path 2000-2030
4 estimates of health costs		
INFRAS/IWW	146	all Dutch airports, we suspect that exposure data have been overestimated
	30	indicative correction for health costs from noise from Schiphol Airport
estimates of total external costs (1 or 2 + 3 + 4)		
sources mentioned	100-200	indicative minimum and maximum estimates of external costs from noise from Schiphol Airport

These results show that

- except the Infras/IWW study, CVM and HP approaches show approximately the same order of magnitude;
- the annual costs as a result of the 'cordon sanitaire' seem to be somewhat lower than the damage cost estimates;
- the annual costs resulting from the CVM approach of SEO are the highest values found. This is in line with the conclusions by Schipper (1999);
- the total external costs from noise at Schiphol are about twice as large as the costs that are derived from HP studies.

Based on the methodology for distribution of external costs across different aircraft types from CE (1999) this leads to the following noise costs for different aircraft types.

Table 15 Average noise costs per aircraft type per LTO at Schiphol Airport, based on €M 100-200 of total external noise costs and on the allocation methodology in (CE, 1999)

MTOW (tonnes)	maximum payload	capacity (seats)	typical dist. (km)	noise factor	€ per LTO	€/LTO/seat available	
						average	marginal*
10	3.9	30	150	0.3	140-270	5-9	2-4
50	11	100	500	1.0	450-910	5-9	2-4
70	17	130	1,500	1.3	570-1,130	4-9	2-4
280	48	240	6,000	2.5	1,100-2,300	4-8	2-4

* Marginal costs calculated as 50% of average costs, based on Infras/IWW (2000)

Comparing Schiphol with other airports considered

The number of inhabitants within a radius of 25 km from Schiphol (1,965 km^2) is about 1.8 million people, or about 900 people per km^2. About 8% of this circle is North Sea.

With respect to Charles de Gaulle Airport, within a circle of 25 km radius, more than one half of the city of Paris will be covered (2 million people). The other 75% of the virtual circle adds another 1.8 million people (900 per km^2).

This leads to an estimation of 3.8 million people living within 25 km of Charles de Gaulle Airport, or about 2,000 per km^2.
Frankfurt Airport: the Rhine-Main region, covering major cities like Frankfurt, Mainz and Wiesbaden, has 4.8 million inhabitants. The Rhine Main region is surrounding Frankfurt Main airport and is about 11,000 km^2, which means that the average number of inhabitants is about 431 per km^2.
It can be concluded that Schiphol has a medium position from the point of population density. At Charles de Gaulle the density is about twice that of Schiphol, at Frankfurt it is about half.

Marginal costs of extra aircraft movements
- the external costs of noise per aircraft type per LTO are dependent on aircraft size (MTOW), and even more on aircraft technology level;
- in this study we will base our estimate for the marginal costs on half that of average noise costs (total external costs divided by number of LTOs);
- external costs of noise per LTO are, within a given technology level, more or less linearly dependent on aircraft size in terms of maximum payload, and number of seats (not for freight).

Estimates for the marginal external costs of noise per seat per LTO vary between € 0.2 and € 37, depending on valuation methodology, aircraft technology, and number of people affected. See Table 16.

Table 16 Overview of estimates of external noise costs per seat LTO

	range	average estimate	average or marginal costs?	explanation
IWW/Infras (2000)	0.4-30	5.2	average	low = Norway average high = Netherlands average average = EU average
Pearce and Pearce (2000)		0.3	marginal	B777, Heathrow
		1.3		B747-400, Heathrow
Schipper (1999)	2-37	8	marginal	B737-300, depending on income & location
	0.4-7	2		B757-200
	0.6-11	2		B767-300
	2-28	6		B747-400
CE (2001) (estimate in this annex)		4-9	average	figures apply to Schiphol, to all aircraft sizes, to average technology level

- medium estimates for marginal costs, for an airport with an EU average population density, arrive at about € 3 per seat LTO for aircraft with fleet average technology.

U. S. Standards

Additional literature used
Feitelson, E.I., R.E. Hurd, R.R. Mudge (1996). The impact of aircraft noise on willingness to pay for residences. *Transportation Research* **1D:** 1-14.

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External costs of aviation

Allocating costs to passengers, freight, and aircraft types

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Contents

1 Allocating costs to pax, freight, and aircraft types

In this annex it is discussed how external costs of aircraft movements will be allocated to passenger and freight, in cases both passengers and freight are transported.

Table 1 The characteristics of the four different types of aircraft or market segments, as the case may be, and the distribution of LTO numbers (Landings and Take-Offs, flight movements divided by 2) for scheduled and charter flights to and from airports in the Netherlands in 1997 for these segments

typical distance (km)	MTOW (tonnes)[a]	maximum payload (tonnes)	capacity (pax)	utilisation (%)	number of pax	freight (tonnes)
200 km[c]	17	4.5	40	50%	20	0
500 km	50	12	100	65%	65	1
1,500 km (EU)	110	24	120	70%	140	2
6,000 km ICA[b]	397	72	400	80%	330	25

[a] Maximum Take-Off Weight (empty weight + fuel + load)

[b] ICA: Intercontinental

[c] This segment of the market, as regards characteristics relevant to this study, (MTOW, use of energy, distance, level of capacity utilisation) is defined such that it is representative of domestic flight traffic.

All four types of aircraft have been considered for passenger transport. It can be seen that the difference in *freight* carried between the four is very large. The freight carried varies in the order of 1 tonne for the small types and 17.5 tonnes for the large ones. It is evident from this that most freight is carried in these large aircraft, which generally fly between continents. The average distance for KLM and Lufthansa freight transport, for instance, is about 6,000 km.

Allocation to passengers and freight

For the calculation to be correct, external costs must be allocated to freight and passengers. In aviation it is usual to allow 100 kg per passenger. However, for this study we must view allocation in a broader perspective. It is evident that what are known as *full freighters* have a much higher payload (total maximum permissible load) than those known as *combis*. Thus the full freighter version of the 747-400 has a payload of 129.1 tonnes, whereas the 'combi' version (which can carry 410 passengers) only has a payload (freight plus passengers at 100 kg per person) of 72.2 tonnes. This means that ultimately exactly the same aircraft loses a great deal of its *total* load capacity if it has to be fitted for passengers. Correct allocation requires that the mass of all facilities required for passenger transport be allocated to the passengers. This then results in a representative mass of (129,100 – 72,200)/410 + 100 = 240 kg for one passenger and his or her facilities.

This improved allocation does not affect total costs, but it does mean that air freight is less heavily affected than would have been the case with an allocation of 100 kg per passenger, whilst passenger transport is affected more heavily. Thus for an ICA flight carrying 320 passengers and 25 tonnes of freight it means that the passenger/freight ratio becomes 75/25 instead of 56/44. This adjusted allocation has little effect on passenger transport in smaller aircraft: 100, 97 and 95%, respectively is allocated to passengers instead of 100, 93, 89%, respectively.

A consequence therefore of this allocation method is that it now makes no difference in principle to the outcome for *freight transport* whether a full freighter or a combi is used.

Allocation to aircraft types

This project requires that the costs for infrastructure and noise nuisance be allocated 'top-down' to the four types of aircraft. This was done with weighting factors, which were derived from the current charges for the various types at the airports. For infrastructure costs this means a strong correlation between MTOW and the number of passengers. For noise the proportion of fixed charges was used which Schiphol levies on aircraft over 20 tonnes where airlines do not/cannot submit any dimensional data. These fixed weighting factors depend on (the power of 2/3 of) MTOW and on what is known as the 'k factor' which indicates in which noise class an aircraft is placed in the absence of further information. The same k factor is assumed for all three aircraft types of MTOW over 20 tonnes. For the smallest aircraft (200 km, 17 tonnes MTOW), a weighting factor has been derived based on the prescribed formula for such small aircraft based on the current level of charging of ca. € 10 and the expected future increase is estimated at 30% of that for aircraft of 50 tonnes MTOW. See Table 2.

Table 2 Allocation factors for charges and infrastructure and noise nuisance costs

type of aircraft	infrastructure costs weighting factor	noise costs weighting factor
40 seat 200 km	1	0.3
100 seat 500 km	5	1.0
200 seat 1,500 km	10	1.7
400 seat 6,000 km	25	3.2

It appears that allocation of noise to different aircraft types is practically linearly dependent on the number of seats per aircraft.