

External costs of aviation

Executive Summary

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Report

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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 for the aviation industry and its clients 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 so by assessing, within margins as small as possible, external costs of aviation.

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

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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 CO₂ 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 that 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

Air transport brings, besides numerous and sizeable benefits to citizens and companies, also undesired and damaging side-effects to people living near airports and to the local and global environment.

The market place is generally well-equipped to account for the benefits of transport, in this case aviation. This is not the case with the undesired 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 the effects.* External effects cause economic inefficiencies because efficient economic decisions are only taken if ALL social costs and benefits are taken into account.

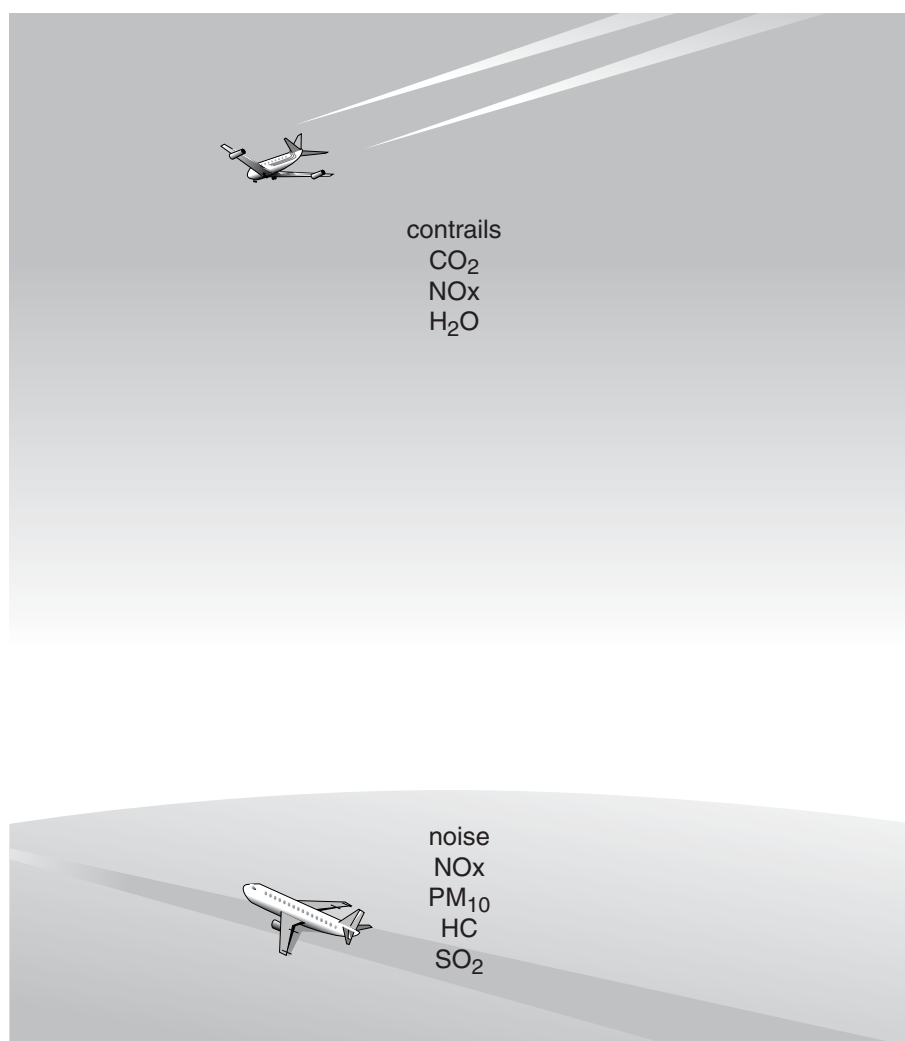
Therefore, in all transport modes policies are currently being considered to bring costs that are currently 'external' to the market, such as costs of noise and climate change, into the transport market. The aim of such actions is not to reduce the negative impacts to zero, nor is it to reduce the volume of transport. The aim is to provide market-based incentives to the transport market to reduce negative impacts to a socially optimal level.



Air transport is no exception; both at ICAO and EU level options are being sought to achieve this goal. In the development of such policies, knowledge about the size and structure of these costs is important.

Following from this, the aim of this study is to quantify - within ranges as small as possible - external costs of air transport, particularly climate change, air pollution and noise, and to give insight in the most important factors determining these external costs. The report is written from a global perspective when the climatic impact of aviation is concerned, and from a European perspective when local and regional environmental effects (LTO cycle effects) are concerned. This study does not contain a description or assessment of policy options. Also, safety risks are not assessed and valued in the report. An overview of impacts assessed is given in Figure 1.

Figure 1 Environmental impacts of aviation considered in this report



Financial valuation of environmental impacts

There is a lot of discussion as to what degree it is possible to financially value environmental impacts.

It is first important to note that environmental impacts can lead to *real* economic costs, although these costs are generally not clearly visible in statistical and financial overviews. Examples include higher hospital bills, decreased productivity of people and land, costs of mitigation measures (clean-

ing, insulation, ...), costs of zoning, et cetera. For a total environmental cost assessment, all these costs should be added, for an average cost approach they should be divided by the amount of environmental impact.

However, the aim of this report is not to establish figures for the total costs of the environmental impact of aviation. It is to support the development of policies to reduce the environmental impact of aviation 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.

Fundamentally, two different approaches exist for marginal cost estimation, or to assign a *shadow price* to certain amount of environmental impact.

The first possible approach is by assessing the costs of **damage / nuisance** plus **avoidance / adaptation** that result from an extra unit of impact. Direct damage costs can be estimated via direct dose-response relationships, questionnaires (revealed preference) or via changes in market prices (stated preference). Avoidance or adaptation costs are costs to avoid exposure to environmental impacts without reducing the actual impacts themselves, for example the costs of installing zones around airports. In marginal cost assessments, avoidance costs should be added to the direct damage costs: increased exposure will lead both to more direct damage and to more avoidance behaviour.

A second - fundamentally different - approach, the so-called **prevention or abatement** cost approach, can be considered when across-the-board emission reduction targets exist that are politically agreed upon and respected. In this case, one extra unit of emission does not lead to extra damage or avoidance costs. In this case, extra emissions lead to extra abatement measures - at some place in the economy - to bring the emission level down to the target agreed upon. In such cases, the costs of emissions can therefore be represented by the marginal costs to reduce emissions to the target agreed.

By their different nature, damage and prevention cost approaches do not necessarily lead to the same shadow prices. Only when the target agreed upon is set at the theoretically optimal level, shadow prices based on damage and prevention costs are the same. Both the damage and prevention cost approaches have their specific pros and cons that are treated in more detail in the main text. Per environmental aspect studied, an appropriate choice on valuation methodology should be made.

Estimating costs of climatic impacts from aviation

Estimating a shadow price for CO₂ emissions

As a start of the economic valuation of the climatic impact of aviation, a cost estimate of a tonne of CO₂ emission was established by a compilation of both damage and prevention cost assessments.

Using the damage cost approach, it was found that the social discount rate used is one of the most important influences on the CO₂ shadow price. See Table 1.

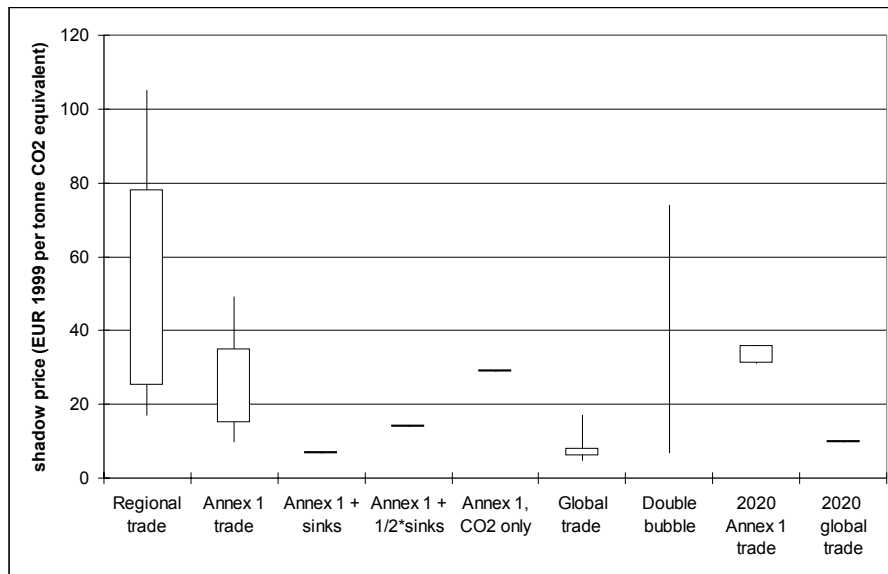
Table 1 Central estimates of the marginal cost of CO₂ emissions in often-quoted international literature, as a function of the discount rate. Extreme values omitted. The values are in € 1999 per tonne of CO₂ emitted between 2000 and 2010

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

Using the prevention cost approach, the only international reduction target that has been politically agreed upon is the Kyoto protocol. Separate emission ceilings for the aviation sector have also been considered but have not (yet) been agreed upon; prevention cost estimates following from this approach are substantially higher than those following from the Kyoto protocol and can be found in the main report.

Figure 2 gives an overview of results from prevention cost studies that were finished before the Conference of the Parties (COP) meetings in Bonn and Marrakech.

Figure 2 Overview of marginal prevention costs of a tonne of CO₂ equivalent under the Kyoto Protocol, under several assumptions with respect to the scale of trade, mechanisms, and timeframe



Ranges in the *lines* represent the extremes found in the literature; ranges in the *boxes* represent the range omitting them most extreme values found in the literature.

- 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.
- CO₂ only: infinite prevention costs of non-CO₂ 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, high for the second.
- 2020: Kyoto targets apply to 2020 as well.

It can be seen that the order of magnitude of shadow price estimates from the damage and prevention cost approach are not very much different. Both range from around € 5 to over € 100 per tonne of CO₂. The Bonn and Marrakech agreements on sinks will certainly push the shadow prices following from the prevention cost approach down 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 upward.

In this broad range of estimates, we chose to work with a middle estimate of € 30 per tonne, and to apply sensitivity analysis with € 10 and € 50 per tonne, respectively.



Contrails and other non-CO₂ climate impacts

The full climatic impact of aviation emissions was in 1992, according to an IPCC middle estimate, 2.7 times as high as that of CO₂ alone. Besides CO₂ emissions, primarily contrail formation and NO_x emissions are important phenomena.

Formation of contrails has been given specific attention in this study. This is for two reasons: its substantial contribution to aviation's overall radiative forcing, and the special and quite well-predictable operational circumstances in which they occur. It is assumed in this study that contrails are, on average, formed during 10 % of flight kilometres. Furthermore, it is assumed that the formation of contrails is not correlated with other environmental impacts from aviation. Finally, the possible additional impact of cirrus formation from persistent contrails is omitted. With these assumptions, we have differentiated the climatic impact of average flights that do, and do not, cause contrails. See Table 2.

Table 2 Global average perturbation of the radiative balance in W/m², differentiated for situation without and with contrails, under the assumptions stated below the table, based on 1992 data and the 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 ₂ O, 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

From the table we can see that, under the assumptions mentioned, 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)¹. For an average contrail-inducing flight kilometre, the climatic impact of the contrail *alone* is about eleven (11) times that of CO₂ *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 column provide insight in the additional impact of contrails, and come probably closer to real situations.

The climatic impact of NO_x emissions comes from two completely different processes: net production of tropospheric ozone and a net reduction of methane. Both mechanisms have different chemical background and occur under different circumstances. Although, strictly speaking, both mechanisms should be valued separately, we chose here for reasons of simplicity to work with a global average net result. Subsequently, non-LTO NO_x emission has been valued at € 1.2, 3.6 and 6.0 per kg, respectively. With these valuations a W/m² of radiative forcing caused by NO_x emissions is valued identical to a W/m² forcing caused by CO₂ emissions. The climatic impact of sulphur and

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

soot aerosols has not been financially valued because at a global level both effects cancel.

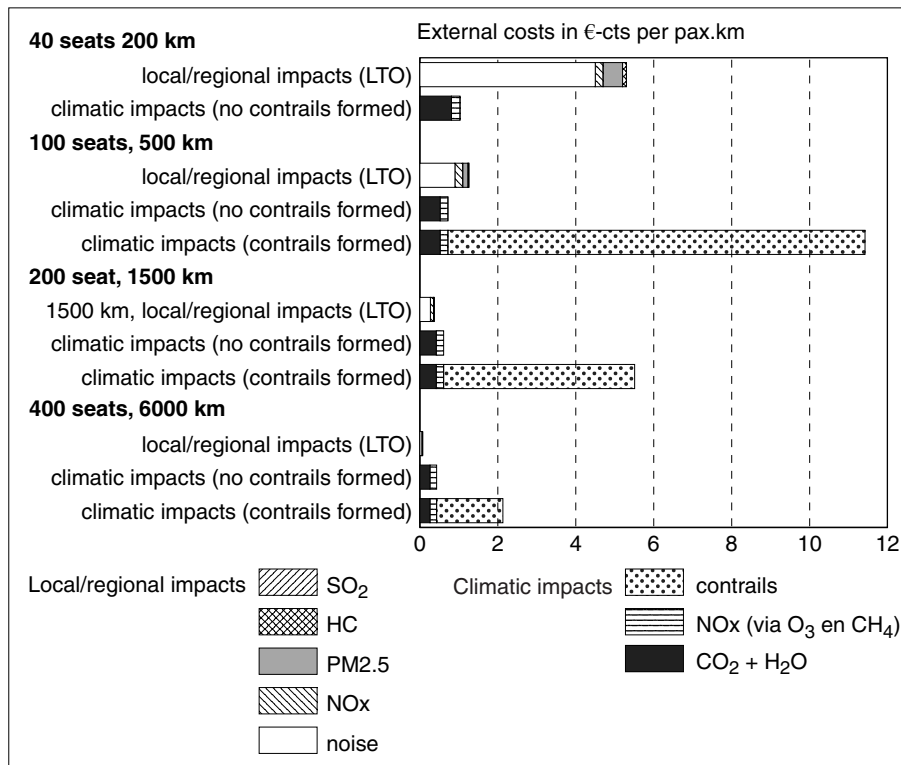
Estimating costs from noise and LTO emissions

With respect to the non-climate impacts of aviation, the LTO-related costs of noise, NO_x, PM₁₀, HC and SO₂ emissions have been assessed. The marginal costs of these emissions have been established using the damage plus avoidance cost approach. After extensive literature analysis, it appeared that, once corrected for population density, most of the shadow prices per unit of 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 of noise contours around airports. With respect to emissions, the most important cost item is damage to human health.

Results

Below follow the results that follow from the methodological principles and choices as explained. We calculated external costs for two technology levels namely fleet average technology and state-of-the-art technology. Other variants calculated but not shown in this summary include variants with a lower valuation per tonne of CO₂ equivalent (€ 10 and € 50 respectively)². Results for the 'fleet average' variant are presented in Figure 3

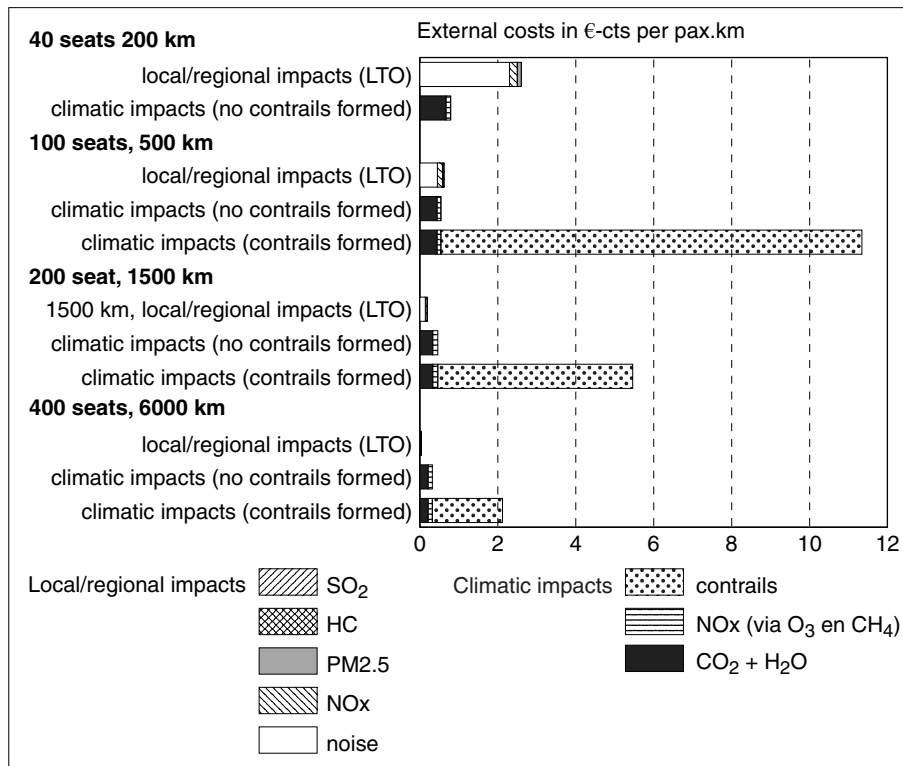
Figure 3 External costs in €cts per passenger kilometre, fleet average technology, CO₂ emissions valued at € 30/tonne



Results for the 'fleet average' variant are presented in Figure 3

² The variants with lower and higher valuation of climatic impact (€ 10 and € 50 per tonne CO₂ respectively) lead to two-third lower and 60 % higher external cost estimates from climatic impacts.

Figure 4 External costs in €cts per passenger kilometre, state of the art aircraft technology, CO₂ emissions valued at € 30/tonne



From these graphs and from the figures presented earlier we can draw the following conclusions:

- For aircraft flying at distances up to a few hundred kilometres, external costs related to LTO emissions are dominant, especially noise costs. This has the following background:
 - the LTO phase with these flights is a substantial part of the journey;
 - these, generally smaller, aircraft have relatively high noise emissions and relatively low NO_x emissions;
 - at these distances aircraft do not reach cruise altitudes where contrails are formed.

LTO impacts from 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 the local and regional (LTO) impacts. For flights over about 1,000 km, external costs of climatic impacts exceed those of LTO impacts (in case no contrails are formed).
- External costs from NO_x emissions can arise from due to climatic impacts of NO_x emissions are approximately half of those of CO₂ and H₂O; the share of NO_x slightly increases with aircraft size due to the higher NO_x / CO₂ ratios of engines applied in these large aircraft;
- The question whether *contrails* are formed or not heavily influences external costs from aviation's climatic impacts. In this report, it is estimated that the climatic impact of a contrail-causing aircraft km with fleet average technology 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 is based on the assumption that contrails are formed in 10 % of global aircraft kilometres;

2. the factor 8 results from a middle estimate of a globally averaged climatic impact of contrails, and there is 67 % probability that the true climatic impact of contrails falls within one third to three times this middle estimate;
 3. scientific evidence on the climatic impacts of contrails is judged as 'fair', hence much work needs yet to be done on this issue.
- We can also express the external costs as calculated in this study as a percentage of ticket prices. If no contrails are formed, total external costs are of the magnitude of about 5 % of average ticket prices at the 6,000 km flight, and about 20-30 % of average ticket prices at the 200 km flight. Naturally, with high-fare tickets this share is lower, and with low-fare tickets, this share is higher. These percentages rise sharply for flights in which contrails are formed during a substantial part of the journey. For example, external costs of flights during half of which contrails are formed amount to roughly about 20 to 25 % of ticket prices paid for such flights.

By nature, studies assessing external costs are a result of numerous methodological choices. This study is no exception. We tried to describe and underpin the most important choices as transparently as possible. We expect therefore that this study is not only a quantitative contribution to the discussion on external costs, but can also serve as an analytical framework for other external cost assessments.



