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External Costs of Aviation

by

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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 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.

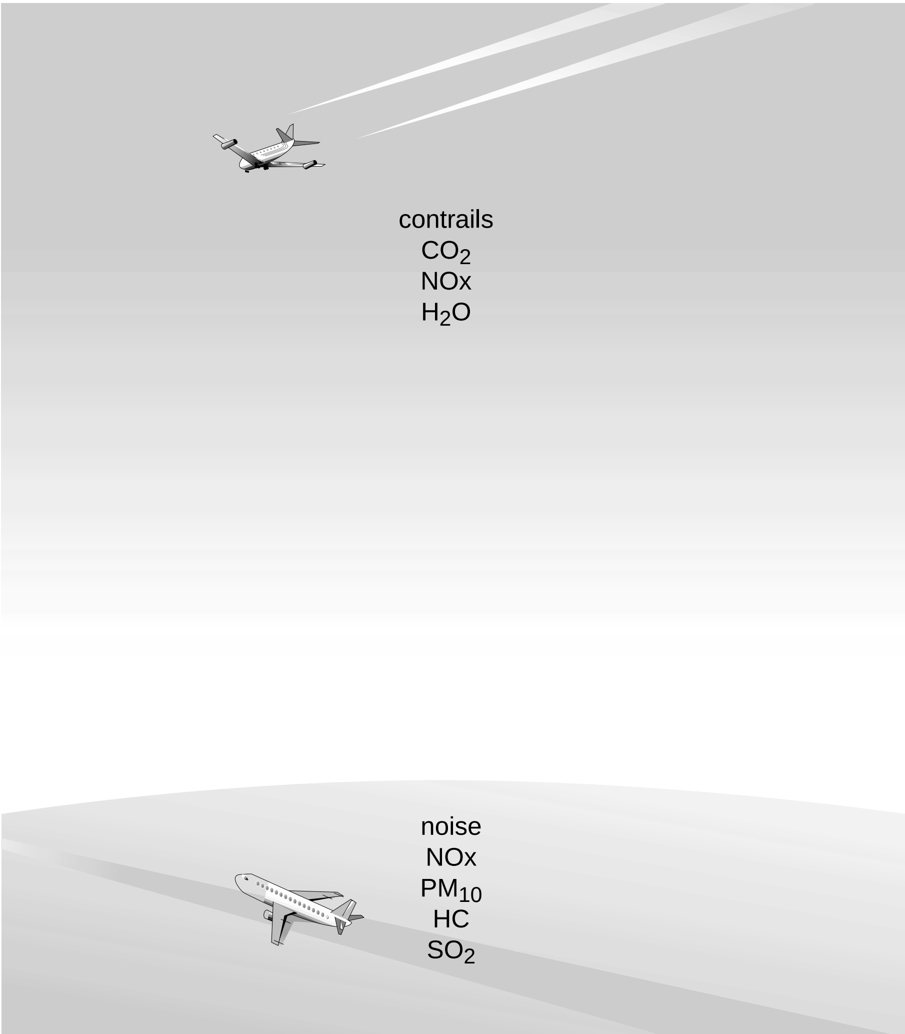
Air transport: benefits and undesired side-effects

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.

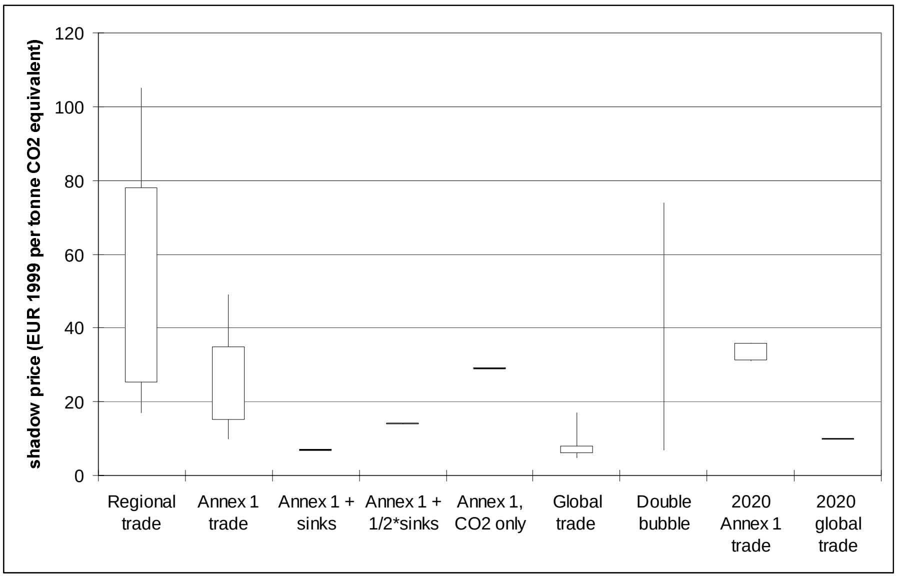
With respect to the damage cost approach, it was found that the social discount rate employed is one of the most important factors governing the calculated CO_2 shadow price (Table 1).

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

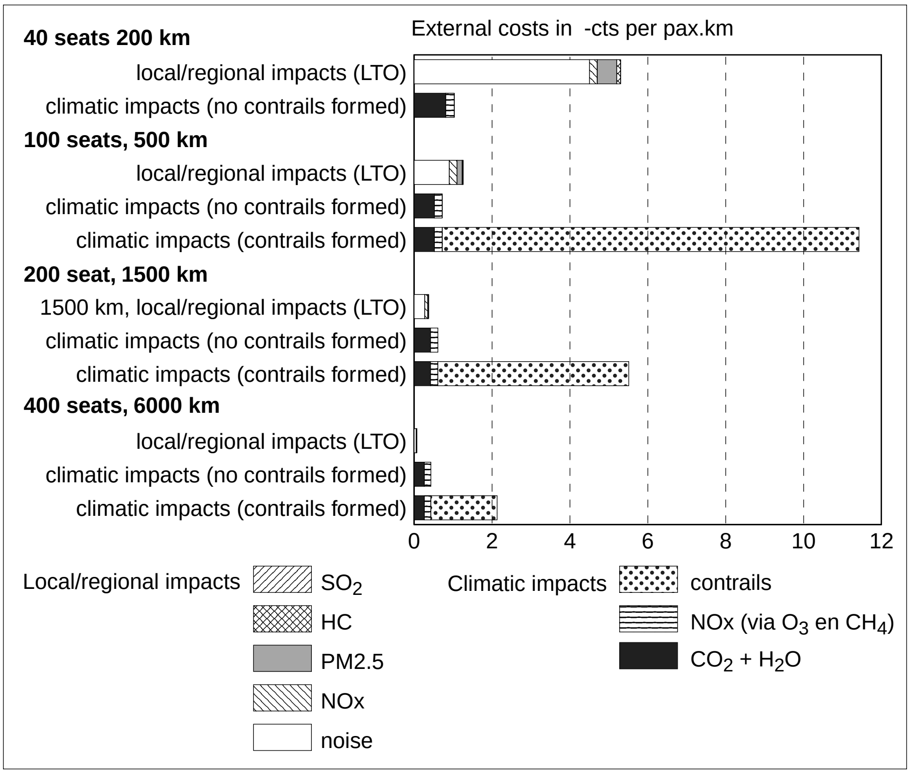
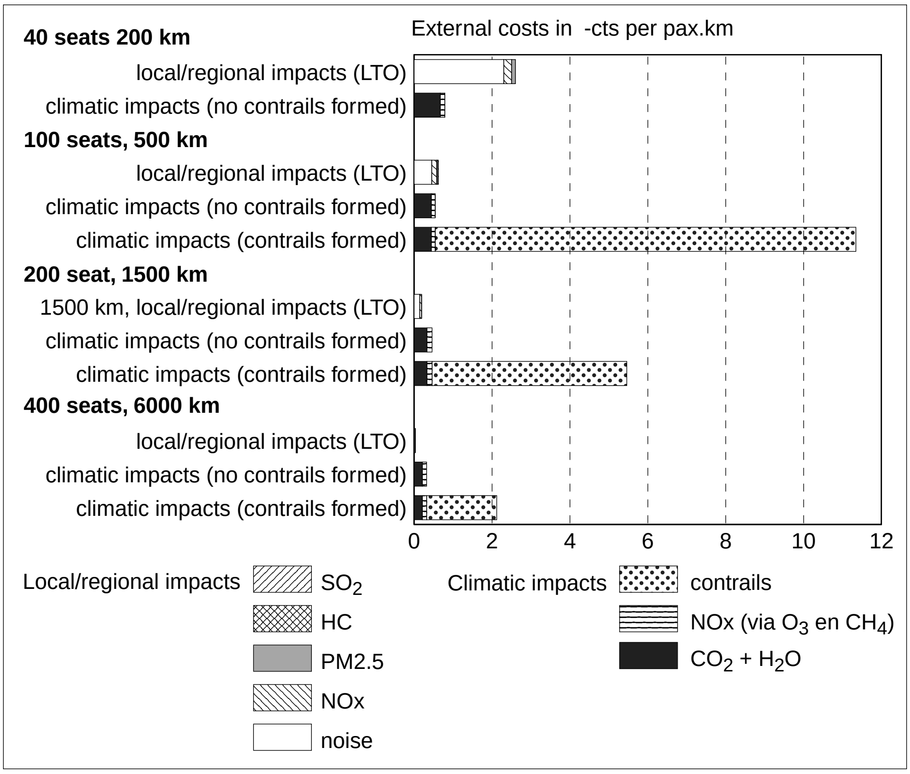


Figure 4 External costs in €ct per passenger-kilometre: state-of-the-art aircraft technology, CO_2 emissions valued at € 30/tonne



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.