Universitat Autònoma de Barcelona

Negative externalities of airports: quantitative description and analysis

Memòria del Treball Fi de Grau

en

Gestió Aeronàutica

realitzat per

Oriol Gómez Castelao

i dirigit per

Liana Napalkova

Escola d'Enginyeria

Sabadell, juliol de 2020

UAB
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La sotasignada, ***Liana Napalkova***,

professora de l'Escola d’Enginyeria de la UAB,

CERTIFICA:

Que el treball al que correspon la present memòria
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NAPALKOVA -
DNI Y1986704R

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LIANA NAPALKOVA
DNI Y1986704R
Date: 2020.06.29
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Signat:

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Externalidades negativas de los aeropuertos: descripción cuantitativa y anàlisis; Externalitats negatives dels aeroports: descripció quantitativa i anàlisi; Negative externalities of airports: quantitative description and analysis

Autor: Oriol Gómez Castelao

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Tutora: Liana Napalkova

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- Català: soroll, emissions, externalitats dels aeroports, quantificació d'externalitats, correcció d'externalitats, Aeroport d'Amsterdam-Schiphol
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- Anglès: noise, emissions, airport externality, monetary valuation, externality quantification, externality correction, Amsterdam Airport Schiphol

Resum del Treball Fi de Grau

- Català: Aquest treball descriu una visió completa i actualitzada de les externalitats dels aeroports i analitza la seva correcció i quantificació tal i com s'aplica en la Unió Europea. En primer lloc, les externalitats del soroll i les emissions s'identifiquen i expliquen a través de les seves fonts i efectes negatius, després els mètodes de quantificació i mesures de correcció. Finalment, la correspondència entre valuació monetària i política de correcció s'explora per mitjà d'un *case study* sobre el soroll a l'Aeroport d'Amsterdam-Schiphol.
- Castellà: Este trabajo describe una visión completa y actualizada de las externalidades de los aeropuertos y analiza su corrección y cuantificación tal y como se aplican en la Unión Europea. En primer lugar, las externalidades del ruido y las emisiones se identifican y se explican a través de sus fuentes i efectos negativos, después los métodos de cuantificación y medidas de corrección. Finalmente, la correspondencia entre valuación monetaria y política de corrección se explora mediante un *case study* sobre el ruido en el Aeropuerto de Amsterdam-Schiphol.
- Anglès: This thesis describes a comprehensive and up to date vision of airport externality and analyses quantification and correction as applied in the European Union. First of all, the externalities of noise and emissions are identified and explained through their sources and negative effects, then quantification methods and correction measures. Finally, the correspondence between monetary valuation and correction policy is explored through a case study on noise in Amsterdam Airport Schiphol.

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I. Introduction

State of the art

Aviation has been for a century not only a means of transportation, but a vessel for economic enterprise and wealth generation, and an enabler of transactions that would otherwise be impossible. With it, however, come adverse effects: increased noise and the worsening of local air quality are the most notable among them, leading to a concealed but pernicious cost on the society that lives around airports. Since this cost is not reflected in the free flow of the market, it receives the name of externality, and its identification, quantification, and correction has been a matter of intense study for the last five decades.

Progress has been made in the identification of the harmful effects derived from noise and air quality, linked to ailments such as sleep disturbance, circulatory disease or respiratory problems, though much ground is yet to be treaded. ICAO and other regulatory bodies are only recently catching up with an increase in stringency that may account for particulate matter effects, and WHO and the EU have dedicated considerable effort to research of epidemiological nature. This first step allows for the advancement of quantification methods, which rely in explaining the intangible and invisible in monetary terms. Whether through the appraisal of the health costs, or through the direct estimation of the market price associated to the externality, quantification methods have become increasingly popular in literature in a parallel fashion with the growing concern among regulators to address these matters. From this urgency emerges the necessity to adequately prevent and correct these costs, from approaches of regulatory, technical, operational, or economic. This pressure, in turn, results in positive industry trends, namely the development of quieter, cleaner aircraft that are becoming prevalent in modern-day skies, such as the Airbus 320neo family.

The growing concern is ever more prevalent within the European Union, whereupon citizens increasingly frequently make decisions not only based on private economic interest, but also under their environmental implications. The case of Amsterdam Airport Schiphol is of peculiar interest due to the historic challenge posed by making one of the busiest airports in the continent a suitable place to live, while ensuring that externality correction policy satisfies all stakeholders. The critical situation of the airport, at present exceeding its capacity cap established nearly two decades ago, merits further attention as a modern example of the relative importance of quantification methods to frame this balance between the government, airport management, airlines, and the community.

Objectives

The goal of this thesis is twofold. One, to examine noise and emission externalities in depth, to form a comprehensive vision of their sources and negative effects, and then to understand quantification and correction as applied in the European Union. Two, to examine Amsterdam Airport Schiphol as current example of how this knowledge is applied, and to discuss whether current policy aligns with quantification methods and the general EU approach towards externality correction.

In order to reach these objectives, it is of paramount importance to construct a sufficient body of knowledge that, in the first place, leads to a deep understanding of what constitutes an externality cost, and through which mechanisms this cost is inflicted on society. Proceeding from this basis, quantification methods are of ultimate importance, and their procedures must be closely examined through literature review in order to reproduce and analyse the findings of studies concerning the case study. Additionally, correction measures are the last of the elements to form a coherent argumentation in the case study, and so are to be reviewed from the standpoint of European Union policy. This should as a result allow the compilation and summary of available information from a variety of sources, which cannot be easily found currently in the comprehensive terms that conform the first goal of this thesis.

The analysis of the case study, focusing on Amsterdam Airport Schiphol as an example of relevant European airport, will be then justified by all this prior collection of knowledge, and will integrate the information and methodologies seen beforehand. It should then be possible to study Schiphol's current situation first, and then proceed with a review of associated literature examining noise externality costs. The reproduction of their calculations and a cohesive explanation of their findings would not be possible without the previous theoretical work. Finally, exploring noise correction measures applied by the airport authority will provide the basis for an evaluation of how they relate to the current situation, and to enunciate recommendations on how new policy would better resolve the cost of externality from the point of view of quantification methods.

Motivation

Noise and emissions take central importance amid the prevalent attention that the negative environmental effects from aviation receive in the present day, and more so in the case of the European Union. Quantification methods represent a valuable economic tool, but their importance in determining the decisions of policymakers is not manifest. Thus, examining this relation supposes an innovative point of view which may support future consideration.

The novelty of this thesis lies first in the lack of cohesive compilation of all available information on noise and emissions externality costs, mainly due to the multidisciplinary character of the fields involved: while this is inherently an economic concept, other disciplines such as engineering (technological solutions and advancement of the state of the art), physics (noise measurement and modelling), chemistry (emission studies), health sciences (epidemiological studies linking health effects to costs), and naturally economy and aeronautical management. This is, in truth, the character of the Aeronautical Management Degree, and decisions in the sector of aviation must always stem from adequate multidisciplinary knowledge. It must be noted however that an economic scope has been adhered to within possible measure as to ensure the coherence of chapters towards the concluding elements presented in the case study. To compile and explain all of these factors, even in a summarised manner, constitutes the theoretical motivation of this thesis.

Novelty is further reinforced, however, by a practical study of the case of Amsterdam Airport Schiphol, notorious in the last decade for its pioneer approach towards community involvement in addressing noise externality, and for its controversial operational cap limiting its competitivity within the EU. It is also the motivation of this thesis to examine how monetary valuation is produced, and whilst applying these same techniques would be impossible due to their scope and practical limitations, calculations should be reproduced and interpreted to draw conclusions about the current situation of Amsterdam Airport Schiphol. It is therefore one of the aims of this thesis to practically demonstrate how the current situation of Schiphol is a product of its own correction policies, and to which degree these should be influenced by economic measures derived from externality quantification methods.

Methodology

The theoretical construction of this thesis is based on the gathering of information chiefly from academic and institutional sources, though supporting data bases and sources have been consulted due to the complexity and diversity of the fields involved. Research on all topics of relevance has been reviewed with due care paid to its recency and relevance within their fields, and particular attention has been dedicated to those studies that hold the most importance in quantification method description and case study analysis. Relying on a reduced number of sources has been avoided in all possible situations, but due to the presence of many previous meta-studies and the citation of previous research, this has not always been possible. A specific section has been dedicated in the chapters pertaining to noise and emissions to explain the metrics and units of measurement employed in the industry, justifying its use in this thesis.

The tool utilised for calculation and the reproduction of the figures offered by authors has been Microsoft Excel, although data presentation has been enhanced in some cases with the aid of image editing software. In all cases where a foreign currency was used in the results, adjustment for inflation for said currency has been done and conversion has followed applying current currency exchange rates into euro. Unless otherwise indicated, data presented is taken as obtained by the original authors.

Structure

The thesis is comprised of a total of ten chapters excluding this introduction, of which the first eight present theoretical and practical content and the last two play a supportive role. Chapters are ordered numerically as indicated by Roman numerals, starting from the count of two. The thesis contains a total of 112 pages.

The first chapter, *Airport impact upon society*, is of introductory character and seeks to explain the economic benefits and costs associated with airport activity, their magnitude, and their reach, as well as their estimation. The concept of negative externality is also explained, which forms the theoretical core of this thesis. Then proceed two chapters dedicated to *Noise* and *Emissions*, the first two main forms of externality caused by airports. These chapters contain a brief review of the definitions, metrics, and units used when referring to noise and emissions, a summary identifying sources that lead to their generation, and a profound description of their negative effects in accordance with current research. The next chapter, *Externality quantification*, has as its goal to adjust the economic concepts seen in chapter *II* with the more technical definition of the negative effects of externality seen in chapters *III* and *IV*. Dedicating a section to noise and another to emissions, the use of distinct methods is explained and justified, to then explore two noise methods in particular, hedonic pricing and contingent valuation, due to their importance in the case study and their stronger economic basis, and some of the calculations present in research are reproduced. From this follows a final theoretical chapter, *Correcting externality*, that aims to offer an overview of different measures focusing on the correction of noise and emission externality respectively.

Lastly, chapter *VII* is dedicated to the case study of noise externality in Amsterdam Airport Schiphol. Opening with a description of its current situation, a research analysis of three main studies is done afterwards by a reproduction of their figures and a summary of their findings. This is followed by a review of externality correction policy, and finally a commentary to reflect on how measures are linked with valuation and to which degree policies are quantitatively driven, as well as to formulate recommendations. The last two chapters, *IX* and *X*, contain a list of sources and gather annexes respectively.

II. Airport impact upon society

Aviation is, intrinsically, a sensitive and volatile sector, offset by high risks, and characterized by an often-tenuous equilibrium among stakeholders. However, aviation can also be held as an economic sector in the national and supranational levels that is ever-growing, well-supported by public investment and development, and historically promising in its long-term forecasts. According to ICAO's own figures(1), the growth of air transport industry has on average overtaken GDP growth for the last two decades, and has shown rapid recovery from crises that made demand plunge considerably, sometimes for a span of years, such as the 9/11 terror attacks on US soil, the SARS epidemic, or the world recession of 2008.

Within this context of sustained historical growth, airports have evolved dramatically since the inception of civil aviation in the interwar period. What once were a diversity of airstrips and scattered airfields originally destined for exclusive military use gave way to a model that aimed to support the economic development, lengthening of the supply chains, and commercial input and output of the metropolitan areas immediately adjacent to the airports. The degree of connectivity provided was increasingly important after aviation began to occupy first a prime position as a strategic sector within a national frame, and later one of competitivity in an international ambit, where metropoles were linked to one another and fed from minor stations thanks to the attachment of the airports to the logistic area they aimed to support. This role was not only maintained, but reinforced, after the liberalization era in the US and Europe led to a rise of demand and an unprecedented affordability of air transport that involved the necessity of expanding airport capacity in accordance(2).

Naturally, these areas, however densely populated initially, began to experience growth of their own, not only due to urban expansion from the capitals, but also as a consequence of the induced impact upon the surrounding vicinity: the infrastructure supporting the airport itself, of growing capacity and therefore surface area, stimulates the mesh around it, which includes job creation, land usage, real estate construction, network capillarity, and the development of complementary activities. The considerable public investment needed to habilitate the land, build infrastructure that is safe and secure, regulate traffic and operation of such infrastructure by private parties, enable adequate ground access, and lastly offer other incentives such as tax-free fuel or funding for joint projects(3) attests to the great return that is expected from an airport as a long-term concept. Not in vain, the resulting stimulus translates in a positive manner in the local, regional, and national ambit, through impacts traditionally categorized as direct, indirect, induced, and catalytic(4, 5).

Benefits

Aviation is the only mean of rapid worldwide transportation, and its importance for global business is paramount: it generates economic growth, creates jobs, and facilitates trade and tourism internationally. In 2016 this industry represented 3.6% of global GDP, and supported a total of 65.5 million jobs, 10.2 million of which were direct; those figures do not account, however, for the enabling of other business activities, the value provided by the speed and connectivity of air travel, the stimulus to domestic tourism and trade, or the appeal offered for foreign direct investment. In terms of tourism alone, of 1.4 billion international tourists in 2018, over half of them travelled by air to reach their destination, translating into 37 million jobs in the tourism sector supported by aviation. Lastly, air transport plays a key role in articulating global trade and electronic commerce thanks to its speed and consistency in markets under increasing Just-In-Time pressure: goods worth a total of USD 6.8 trillion were displaced in 2018, a 35% of the world's traded goods by value but only 1% in terms of volume(5).

Aviation as a generator of wealth and employment is defined, as mentioned above, first through its own activities and supply chains (direct and indirect impacts) and then as an enabler of other industries (induced and catalytic impacts). In this framework, every person employed in aviation or in tourism generated by this sector sustained another 6.4 jobs elsewhere worldwide, and for every 1 USD of gross value added directly created by aviation, USD 3.8 of economic activity was supported elsewhere worldwide. The direct impact of aviation stems from the sector itself, by serving passengers directly at airlines, service providers, or airports themselves, in areas such as check-in, catering, or cargo, but it also directly reflects on the manufacturing sector that produces the aircraft that form the basis of most of this activity. This direct generation of wealth was in 2016 estimated as USD 704.4 million (at an average of USD 69 000 per worker per year, three and a half times the average across world economy)(5, 6), and yielding an occupation of 10.2 million jobs. Downstream industries supplying airport activities, such as fuel suppliers or construction companies, have alternatively resulted in an indirect impact of 11 million jobs in 2016 and USD 238 billion of global economic activity. Induced impact, on the other hand, is an effect of the spending of the incomes of the aforementioned direct and indirect employees that supports jobs in other sectors (for instance, retail, consumer goods, or service industries such as banks or restaurants), amounting an approximate of USD 454 billion(5). Air transport is effectively a key gear of many other industries that rely on it as a transport link, leading to what is called catalytic impact: just-in-time delivery systems, international investment into regions, or networking and collaboration among global organizations forms a connectivity mesh that helps countries participate in the worldwide economy by letting business operate efficiently and attract high-quality employees. This last form of impact is difficult to quantify, although it has been pointed out to respond for EUR 427 million of European GDP in 2013(4).

Other, more qualitative benefits entail the developmental impact on a regional level, attracting and concentrating industries through a better connectivity and access to international markets, and the airport's role as a logistic centre supported by a high quality labour pool, good ground accessibility, and the presence of related industry, sometimes coalescing in the form of business parks. Similarly, it's difficult to evaluate in economic terms the great aid air travel signifies in the integration of remote or isolated territories for national entities, invaluable to vertebrate service and communication networks, as well as to retain skilled workforce in places that would be otherwise handicapped in offering an adequate quality of life for residents, such as islands or land far removed from the urban centres. As an essential service, air transport may be the only possible means of bringing humanitarian aid during emergencies, and the only affordable and practical way for many citizens to access education, enhance their leisure opportunities, or broaden their cultural horizon.

Costs

The costs derived from the exploitation of aviation, particularly those sourced in airports, start at the sizeable economic investment and tight regulatory oversight required to ensure that air transport infrastructure operates in accordance with international standards of reliability, safety, security, and performance. Therefore, the development of a policy that encompasses not only the airport itself and its role as a service provider, but also wider national interests, lies within the responsibilities of governing bodies, which are also in charge of its economic and financial performance. The latter is characterized by large and long-lasting expenditure in financing and maintenance costs, and must strike a balance between the pricing of airport services to ensure self-sustainability and the avoidance of monopolistic abuse and accounting for the domestic and international dimension of demand. The area dedicated to this sort of activity is immobile and strongly dependant on the present and future availability of space, shaping regional policy on a national level for a long time, and requires careful adaptation to characteristics such as the wealth of the population, polymodal transport links, geographic specifications, and the degree of economic regulation(7). The national entity is also better able to minimize capital cost thanks to its possibility guaranteeing debt, and its risk management capacity is facilitated by its advantage allotting contingent liabilities.

Airports, in parallel with other structures of the aviation sector, have been traditionally contemplated as a national asset, and governments have been reluctant on ceding control over to private enterprises that might not uphold the best interest of consumers and investors for the short- and long-term(8). Another factor to consider, as will be discussed at length below, is the serious negative impacts aviation (concentrated chiefly as airport activity) has upon society in the form of externality, which if not offset by firm regulation and checks by policymakers, would go unattended seeing as local well-being cannot be guaranteed by the spontaneous self-limitation of a market that in this case is idiosyncratically national and international. This doesn't exclude private participation, however, generally sought due to the need to facilitate investment in large-scale improvement programs, capacity expansion, or new airport construction, and that allows for larger financial autonomy, the prosecution of commercial objectives, and even full for-profit management by private firms with or without public limitations. In 2017, 31.1% of Europe's airports were privately participated to some degree, the largest proportion among all regions worldwide, yet they accounted for 75% of all passenger traffic in the continent(9). Regional airports are often owned and funded by local governments due to its low commercial viability and essential role for the economy of the region, whereas private investors are found predominantly at larger airports.

Nevertheless, aviation authorities, as well as national bodies, do acknowledge that such negative externalities need correcting. As to adequately compensate the effects upon society, identifying and measuring this impact has become the focus of much of the research in the regulatory levels, and has made it possible for incentives to shift in the industry as well; for instance, building and operating quieter engines is motivated by restrictions and tax pressure, as well as public awareness. While some of the aforementioned harmful consequences are the result of the emplacement and construction of the airport and associated projects, others are a direct result of its activity. In a similar way, the social costs of airport may find its origin not only in the day-to-day flight operations, but also in ground operations serving them, in airport terminal operations, in the ground accesses to the airport, or even in projects derived from it.

Negative externalities

A negative externality is understood as a portion of the cost associated with a good's or service's production borne by individuals that have no influence on the decisions involved in that production. This is considered an inefficiency in the market, where the volume of production exceeds the desirable amount, and the parties bearing the cost are not part of the transaction(10). In the case of the aviation sector, airports as air traffic hubs reunite a large part of the environmental cost associated with the economic transaction. An airport's impact is not only limited to foreseeable local effects of construction and expansion, but also on the environmental issues caused by its operation.

Land take, landscape and wildlife impact, as well as social costs to nearby communities are derived from airport planning when establishing new infrastructure, such as in the case of capacity increase through the building of runways or terminal facilities. On the other hand, noise, air pollution, and waste and energy management, are direct effects of its operation that have an impact absorbed by society, characterized most importantly by the surrounding areas. By large, the most salient externalities European regulators have tried to correct have the first two: noise is a very perceptible and easily quantifiable environmental effect, and concerns over air pollution have increased in regulatory levels in the last decades due to increasing awareness over greenhouse emissions and air quality. Both are currently regulated both at international (ICAO Annex I and II, as well as European Union Directives), national (studies and surveys funded by governments), and local levels (airport environmental plans and reports).

As externalities are understood as the detriment in the welfare of those who are not represented in the economic activity that causes that detriment, it could be inferred that a lack of well-defined property rights is in fact the root of the problem, as it prevents the existence of a market for these external effects. Such is the case of airports: individuals living in its vicinity do not have clearly defined property rights that may entitle them to quiet peace and clean air, and the definition of such rights is not possible due to the characteristics of airports as explained before. Therefore, a price mechanism (based on *cost price*, or shadow price) that may distribute the cost of the damage across those partaking in the economic activity causing it is one of the solutions to compensate social damage. In the case of aviation, identifying and measuring this externality is key to establish a corrective account on those air passengers choosing to fly, thus compensating the costs on residents affected by noise and emissions(11).

In conclusion, while benefits and project costs for airport operation, construction and expansion may be appraised with relative ease (except perhaps in the case of the catalytic benefits), it is not possible to plainly account for environmental costs, particularly beyond Environmental Assessment Studies. The reality of aviation benefits is, therefore, consubstantial with externality costs, which are perceived only by a part of society. These costs will be characterised further.

III. Noise

Possibly the most obvious form of negative externality incurred by airport activity, noise is an obvious and bothersome environmental impact that leads to a decrease in the well-being and quality of life of those living in the proximity of airport facilities, and even to serious health problems. In this chapter a description of noise externality will proceed starting by the definitions and units of measure involved, continuing with an identification of the sources that will be later key to understanding corrective policy, and finally understanding the nature of the negative effects associated with it.

Noise pollution finds its root cause both in the aircraft themselves and in other auxiliary systems during ground operations, but the largest contributor is the noise generated in runways during take-off and landing and on their approach and departure. Noise annoyance is a subjective effect, and so different factors have an influence on how it is perceived by the community, such as the statistically measurable cumulative effect in the long term, as well as the concentration of noise in night hours. This unwanted sound is produced due to the passage of air against aircraft structure or through its power plants, causing noise from the friction as well as pressure disturbances that propagate to an observer on the ground below(12).

Definitions

An important distinction needs to be considered between the subjective "annoyance" perceived by the affected community and a more physical appreciation of acoustic pressure; while the latter can only be measured, the former needs to be interpreted. Conciliating both magnitudes requires definitions that rely on numerical operations and depend on exposure, time, audibility, and maximum value. Human hearing responds to a wide range of frequencies (20 Hz to 20 kHz), but aircraft noise certification is studied at 50 to 10 kHz and in ⅓ octave bands(13). For comparative purposes, four metrics are used in literature as to quantify noise annoyance:

- Sound Pressure Level (SPL) and decibel (dB): the decibel is a relative unit that expresses the ratio between two sonic pressure values, taking into account a reference value as a threshold. As it follows a logarithmic scale, a noise source producing 50 decibels is 10 times louder than another one producing 40 decibels.

- As the human ear does not perceive different frequencies equally and is more perceptive towards mean values, these units are generally weighted to better approximate them to auditive reality. The A-weighted decibel attempts to offer this more realistic approach by filtering lower and higher frequencies, conserving those frequencies that are more harmful for the ear. For reference, an airport terminal generates noise in its interior in the order of 60-65 dBA(14).

- Maximum sound level (L_{max}): as aircraft are in motion, their noise levels vary over time, increasing on the approach and decreasing as it flies away. Therefore, the maximum sound level is the largest value in dB or dBA that the noise source reaches at a given time, though it does not account for its duration(15, 16).
- Average sound level (L_{eq}): the total sound energy measured over a given period of time offers a mean value in dBA(16).
- Sound Exposure Level (SEL): the magnitude or level of the event generating the sound, as well as the duration, is compressed into what is known as SEL. This offers a good assessment of environmental noise in a single value measured in dB or dBA(16).

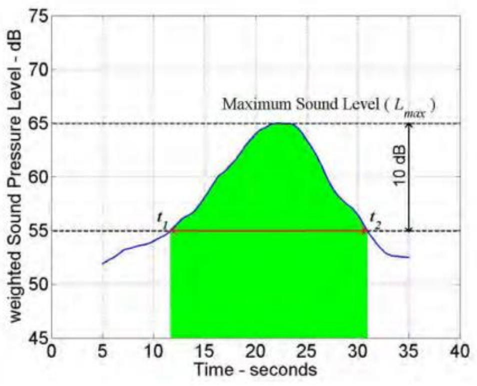


Image 1: Sound Exposure Level is determined as the logarithm of the integral of the surfaced comprised by the time period where sound pressure from a sound event is above a threshold level. In the image, this threshold is 55 dBA. L_{max} value of 65 dB may also be observed [Source: (16)]

- Day-night average sound level (L_{den} or DNL) and night average sound level (L_{night}): it is the sound pressure level averaged over the year that includes penalties for the annoyance caused at night hours, accepted by the European Union for assessing noise impact. 10 dB are added to the A-weighted sound levels during night-time and 5 dB during evening due to lower background noise leading to increased noticeability of aircraft noise. L_{night} is the sound pressure level averaged over the year for the night time period only(17). What comprises this time period may vary from country to country (for instance, in Sweden it is taken as 2200-0700, whereas for Spain it is 2300-0700)(15).

- Effective Perceived Noise Level (EPNL): it is an international metric used for certification of commercial aircraft as described in Annex 16. It is measured in EPNdB. It is a complex variable resulting from the location of the source (flyover, lateral, or approach) and correcting factors for tone and duration of the flight(18).

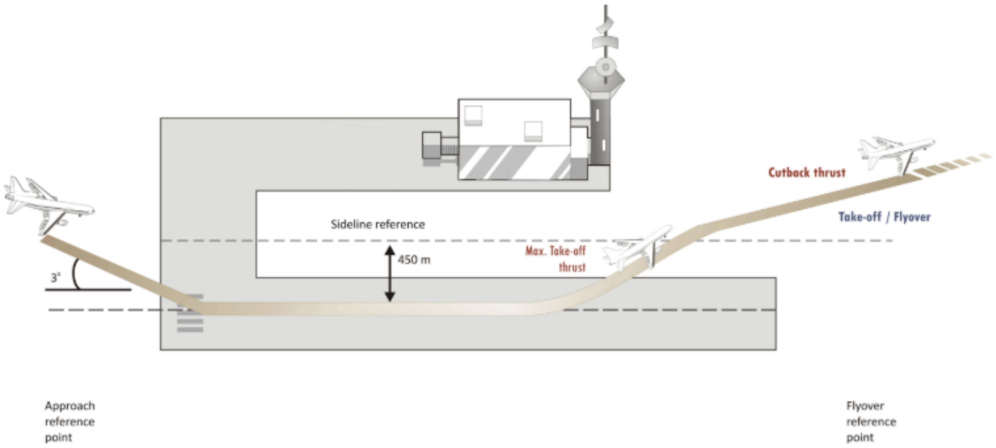


Image 2: ICAO's procedure for aircraft noise certification. Three different measurement points (approach, side-line, and take-off/flyover) result in an EPNL figure that must meet certification standards of the latest update of Chapter 16 Volume I [Source: (19)]

The recording devices employed to measure those metrics are set at specific locations to capture arrival and departure both laterally and positionally, and have a lower bound to discard background noise(14). Computing noise levels at individual locations of interest make it possible to draw noise exposure contours based on metrics like L_{eq}, in terms of lines connecting points at a same dBA level, going from 57 dBA to 72 dBA at 3 dB intervals(20). Long-term effects consider those same L_{eq} measurements over a 24-hour period with the corrective addition of 10 dB at night to obtain L_{den}, set generally at ≥ 55 dBA(14).

Noise sources

The causes of airport noise can be located firstly in the aircraft itself and its movement, and secondly in other systems and machinery that is essential for airport operations. As for the first of these sources, it is generally assumed for theoretical noise modelling, backed up by empirical studies and tests, that each component of the aircraft responsible for a considerable noise contribution can be treated independently, calculating the resulting noise at one frequency by summing all the components at the same frequency(14). For that matter, these components can be further classified as belonging to either propulsive (engines) and non-propulsive (airframe), and they both depend on operational conditions and configuration. Further, corrections must be made taking into consideration equipment on the aircraft such as noise shielding, and factors outside the airplane like ground topography. The propagation from these noise sources however has an impact at long distances, up to several kilometres, travelling through layers of the atmosphere that are in turn affected by changes in density, pressure, temperature, humidity and wind conditions(21).

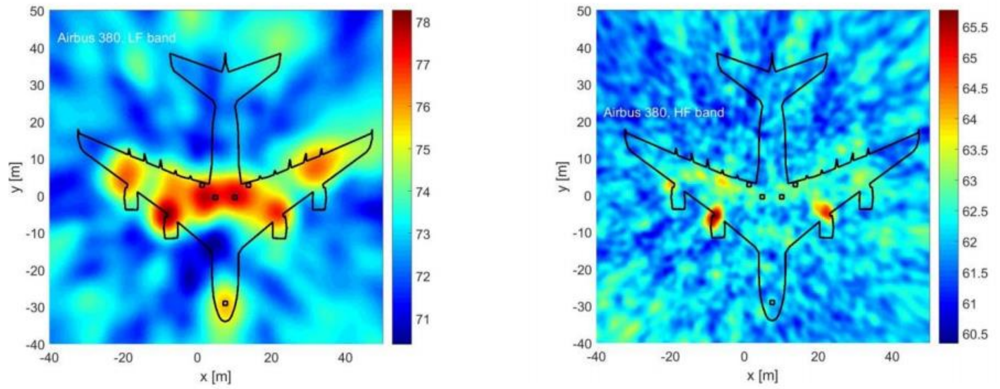


Image 3: Noise plots for the low (left) and high frequency (right) bands of an Airbus 380 four-engine aircraft. The aircraft contour is indicated by a black line and the position of the main and nose landing gear is denoted by the squares [Source: (22)]

Airframe noise can be understood as the result of friction and turbulence between the air and the moving airplane, an effect that increases with speed, and whether or not landing gear and high-lift devices are deployed. Understanding non-propulsive components, particularly landing gear and high-lift systems, as a noise source was first tackled experimentally by gathering empirical data, and within the last two years, following a more physics-based approach through the modelling of turbulence(23). High-lift devices, such as flaps and slats, are mechanisms on the aircraft wing destined to increasing lift, and in turn, generate large turbulences that generate noise. In the case of flaps, located in the aft profile of the wing, vortexes form on its edges due to air flow separation caused by pressure gradients, leaving a trail of acoustic disturbance. Slats, which are located on the wing's frontal profile, behave slightly differently, creating not only vortex turbulence but also mechanical oscillation leading to cavity noise, mainly due to its positioning. Lastly, landing gear is on its own an important noise source particularly on approach, when their contact with the air flow is larger. The effect of the large aerodynamic wake is coupled with its interaction with the bay that hosts it, as well as with the wing (sitting above it) and with flap configuration. Additionally, the effect of the tyre on the ground often exceeds 90 dB, and leads to lower-frequency noise that is transmitted over long distances. As for noise caused by the fuselage, it is generally considered negligible, at 10 dB below high-lift device noise(14).

Beginning with the early days of jet propulsion, the main source of noise was associated with the mechanisms of the jet nozzle itself until the development of turbofan technology, allowing for increased propulsive efficiency and reducing it to a similar noise footprint as compressor noise. Engine noise finds its origin in the sound of moving parts, as well as the air coming out of the engine at high speeds and interacting with air flow resulting in turbulence. In a similar method as the one applied for airframe noise, propulsive noise is studied as the composite of the individual elements that make up the engine; due to their synergy and joint action however, engine noise can be simplified as divided between tonal noise generated by the regular rotation of turbomachinery blades, and broadband noise caused by pressure fluctuations associated with turbulence(14). Fan noise is the leading contributor of noise in most flight conditions, though it is more directional (more notable in front of the fan), and depends on technical aspects of the engine like fan compression ratio, diameter, blade number, rotational speed, or temperature gradient across the engine. Tip Mach speed resulting from rotational force, when reaching supersonic values, translates into a characteristic *buzzsaw* noise. Advanced design of fan blades and rotor–stator arrangement, as well as acoustical lining concepts have been able to reduce this impact to a certain degree(24).

As for jet noise, it has been widely studied since the 1950s, with technology moving forward from gas turbine engines into turbofan engines with increasing by-pass ratios, introducing a layer of moderately fast-moving cold air between the hot exhaust and the still air to perform more quietly. Jet noise comprehends noise from the engine core (the rotating machinery, i.e. compressor and turbine stages, combustor noise (from the combustion itself and from the hot gas exhaustion in the turbines and the nozzle), and turbine noise, particularly notable on approach; all of this components are hard to separate in their noise contributions, however, as they work in solidarity. In the particular case of propellers, still in common use particularly in short-range aircraft, noise is characterized by a broadband component and a discrete frequency; the latter is the result of the “thickness noise” generated when the blade displaces the air mass depending on its thickness, and a “loading noise” that is the acoustic disturbance from the aerodynamic loading, or how much air weight is lifted by unit area(14).

Another relevant factor among propulsive noise is the usage of thrust reversers, which consists in the re-direction of air from the fans to deflect it out from the side of the engine, creating an elevated amount of drag to help decelerating the aircraft right after landing. As the friction with the air is very large, it has a considerable impact on the noise generated during landing, estimated as an increase of up to 10 dBA on average (from 75 dBA to 85 dBA)(25). Similarly, auxiliary power units or APU, used to energize the aircraft when an external power unit cannot be supplied on the ground, contribute to airport noise in the form of combustion noise. While highly dependent on aircraft type, APU noise is considered to have a notable impact in the 250-350 Hz range(26). Both reverse thrust and APU usage are not directly limited by ICAO, JAA or even FAA regulations, and generally respond to an airport-based approach; it is worth noting however that Annex 16 does limit ramp noise around the aircraft to 85 dBA and of 90 dBA in the immediate vicinity.

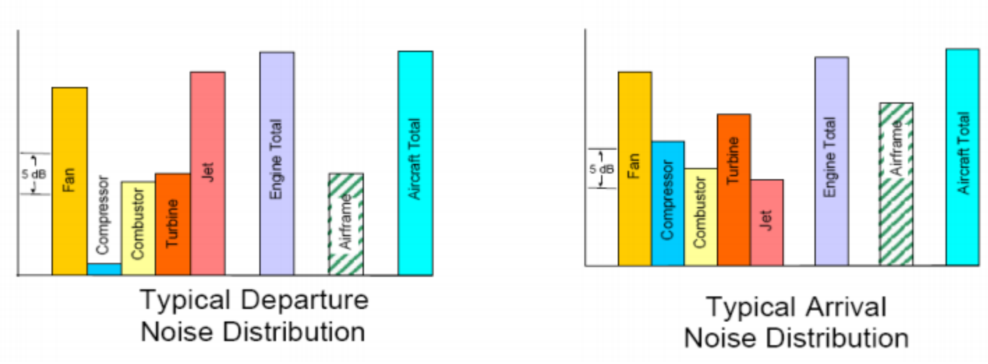


Image 4: Importance of noise sources during departure and arrival, as identified by ICAO [Source:(27)]

Negative effects

Noise exposure, whatever the source, is linked to public health as well as satisfaction and well-being(28). According to the World Health Organization, between 1 and 1.6 million DALYS (Disability Adjusted Life Years, the number of years lost due to ill-health, disability or early death) are lost annually to the negative effects of environmental noise over the health of those exposed in high income western European countries, of which 903 000 account for sleep disturbance, 654 000 to noise annoyance, 61 000 to heart diseases, and 45 000 to cognitive impairment in children(29). These negative effects manifest for long-term exposure beyond certain thresholds, and there is considerable evidence demonstrating an impact on the aforementioned issues (sleep disturbance, community annoyance, hypertension and cardiovascular diseases, and children's cognition and learning) as well as the collectives more badly affected by them (remarkably, children, the elderly, persons with hearing impairments, night-time workers, and infirm and rehabilitating persons)(30). Other conditions such as tinnitus and effects on pregnancy and birth still lack sufficient research basis for a clear association with aircraft noise.

Living within a daytime aircraft noise path has also been tied to a reduction of perceived well-being for levels over 55 dBA, with repercussions on life satisfaction, self-esteem, happiness, affect balance, and increased anxiety “equivalent to around half the effect of being a smoker for some well-being measures”(31). After the 1999 report on environmental noise by WHO cited before, the European Union elaborated a directive based on its guidelines in 2002, enacted by members states through national policy and action plans, and drawing strategic noise maps at L_{den} 55 dB and L_{night} 50 dB(29). The total population residing inside those two noise contours for the 47 major European airports were 2.58 and 0.98 million people respectively in 2017(17). WHO Regional Office for Europe has been publishing new guidelines regularly since then, strongly recommending reducing noise levels produced by aircraft below L_{den} 45 dB and L_{night} 40 dB due to proven adverse health effects in its 2018 report; it is estimated that around 3.2 million people were highly annoyed by aircraft noise, and 1.4 million suffered from high sleep disturbance in 2017 around the 47 major airports. The number of people exposed to more than 50 aircraft noise events exceeding 70 dB per day was estimated to be 1 million in 2017 for the same airports, a 60% more than in 2005(32) [See Annex 1 for WHO Community Noise Guidelines – Source: (33)].

Noise also has a negative effect upon wildlife, though studying these effects on wild animals on their own environment and under natural conditions is challenging. Additionally, sensitivity to noise sources, such as aircraft, ground operations, or airport accesses, is highly variable among different species, and it is difficult to isolate with certainty the impact of noise from those of others such as visual disturbance and emissions. The growth of urban areas applies pressure on the protection of natural habitats, however, and so concern about wildlife disturbance has increased for the last two decades. As it is currently understood, both birds and fish have been observed to suffer the effects of noise to a measurable degree. Nevertheless, the case of fish concerns sonic boom cases (although not yet conclusively linked as having a harmful effect) from supersonic aircraft, which currently do not operate in commercial conditions in the European Union; other airborne sound is reflected on water surface with only a small fraction penetrating the air-water boundary. The behaviour of reptiles, amphibians, and invertebrates is still too poorly studied for any conclusive statements to be made on the matter(34).

Birds are especially affected by noise, notably grassland and woodland birds. These animals have their breeding and feeding habits altered by noise, and it encourages unnecessary energy expenditure when moving towards or away from the sound source, which may expose them to predators. Besides their feeding habits, this disturbance also affects their breeding success, and some species are noted by changing migration patterns as a consequence of it. Studies have established a relationship between a lower bird population density and noise level; sound levels above 50 dBA could be considered negative at distances of 1000 m. It is worth mentioning that physiological consequences are not well researched yet, and that population density alone is not a determinant indicator of habitat quality(35).

Cardiovascular diseases

According to WHO's Global Health Observatory data for the Global Burden of Disease, ischaemic heart diseases are the leading cause of death both in developed and developing countries in 2016, accounting for 22.8% and 9.4% of total deaths respectively, of which 13.5% of deaths are attributable to high blood pressure (hypertension)(29, 36). The auditory system is the human inlet for acoustic information, which is then processed by different brain structures; consequently, repeated biological response conditions the nervous and endocrine system's activity. Chronic noise stress may then dysregulate the homeostatic equilibrium of the organism, impairing natural recovery processes and decreasing the body's regulatory capacity. Health effects of chronic noise stress begin to appear in the long term, estimated in the range of 5 to 15 years(37). Cardiovascular disease as mentioned in this section includes ischaemic heart disease, hypertension (high blood pressure) and stroke. Both laboratory and empirical studies of non-auditory effects of noise have been conducted for decades, pointing out to short-term effects such as short-term changes in circulation and blood pressure, heart rate, cardiac rhythm and vasoconstriction, as well as stress hormones affluence(29).

Pathological studies point out associations between raised blood pressure and continuous day-round noise levels above 55 dBA and peaking at 72 dBA, and linked exposure to aircraft noise above 50 dBA with an increase of 20% in the risk of hypertension(37). More comprehensively, the HYENA study (HYpertension and Exposure to Noise near Airports) found that a 10 dBA increase in L_{night} was associated with a 14% additional risk for high blood pressure, as well as an increased likelihood of usage of hypertension medication. Other evidence comparing populations around London-Heathrow living under noise levels below 51dB in the day-time and those exposed to noise levels over 63dB in the day-time had a 24% higher chance of a hospital admission for stroke, a 21% higher chance of a hospital admission for coronary heart disease; and a 14% higher chance of a hospital admission for cardiovascular

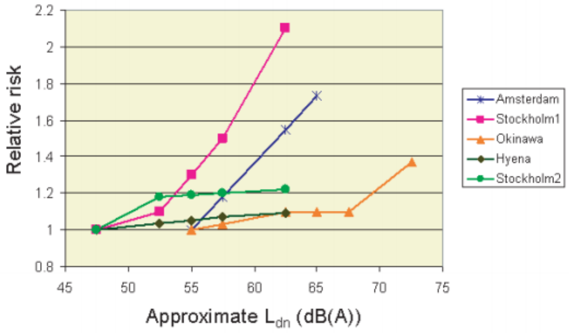


Image 5: Association between aircraft noise and the prevalence or incidence of high blood pressure according to related literature [Source: (29)]

disease(33). Lastly, a study around Cologne-Bonn Airport found correlations between hypertension medication prescription and night-time noise signifying a 27% more frequent prescription in women exposed to continuous aircraft noise levels of 40 to 45 dBA, and a 66% significantly more often at 46 to 61 dBA (whereas for men, 24% at 46 to 61 dBA).

Annoyance

Noise annoyance may be considered as an adverse effect on health going by WHO's definition on health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity(38). Annoyance is a notorious community matter that describes negative reactions to noise such as disturbance, irritation, dissatisfaction and nuisance, and stress-related psychosocial symptoms such as tiredness, stomach discomfort have also been linked to this problem. While the definition given above is broad, noise annoyance is a legitimate environmental issue affecting the well-being and quality of life of the population exposed, and some factors such as fear, sensitivity or anger do not respond directly to sound levels(33) [See Annex 2 for WHO's estimates on DALY loss attributable to air traffic noise – Source: (29)].

This negative effect is generally described by means of community surveys based on internationally standardized annoyance scales, appreciating responses in a 0 to 10 grade as "annoyed" (50% or more in the scale) or "highly annoyed" (72% or more); this method will be described in further detail below due to its importance in valuation of externality cost. The European Commission's 2002 study associated exposure to aircraft noise at 60dB L_{den} to a 38% of the population reporting being "annoyed" and a 17% being "highly annoyed", while at 65dB L_{den} it was associated with 48% of the population reporting being "annoyed" and 26% being "highly annoyed"(39). These figures have increased since, however, as pointed out by other studies. A 2006 study in the vicinity of Frankfurt Airport established that 64% of the population sampled were highly annoyed by aircraft noise, with a 25% of the residents claiming to be annoyed at levels above 53 dBA L_{den}. Interestingly, the lower bound for aircraft noise-related annoyance has been getting lower since the first studies, with 25% of those polled reporting annoyance decreasing 8 dBA between 1960 and 1995, and another 8 dBA lower in the 2006 study(37). The reason for this decrease can be attributed to sensitization to long-term stress over the years, as well as more thorough methodological analysis.

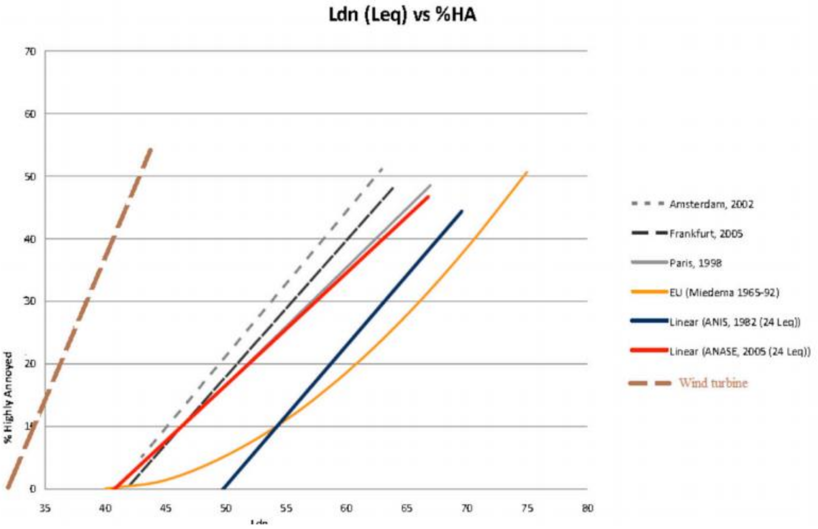


Image 6: Annoyance curves showcasing the relationship between those highly annoyed and noise level in L_{den} (dBA). There is a historical recess in the threshold for noise annoyance, showing increased sensitivity towards noise. Data compiled by ICAO 2016 Environmental Report [Source: (40)]

Sleep disturbance

According to WHO, sleep disturbance, one of the most common complaints raised by populations exposed to aircraft noise, is considered the most grievous non-auditory effect of environmental noise exposure due to the epidemiologic links between limited sleep and negative health outcomes such as obesity or diabetes. Alertness and performance during the day, as well as quality of life and good health, can only be guaranteed by undisturbed sleep for several hours. The human auditory system is constantly watching the environment for noise stimulus, responding naturally with changes in sleep structure or increases in heart rate and breathing that, if substantial, can lead to an increase in health issues. Environmental noise may reduce the restorative power of sleep by the repetition of stimuli leading to sleep fragmentation, which if recurrent can affect waking psychomotor performance, memory consolidation, creativity, risk-taking behaviour, signal detection performance and risks of accidents(29). Repeated arousals deteriorate sleep quality by delaying sleep onset, causing early awakenings, limiting sleep depth and REM sleep, and increasing time spent in superficial sleep stages. The elderly, children, shift-workers, and those who are ill are considered at higher risk for noise-induced sleep disturbance(33).

Methods to estimate the impact of aircraft noise in sleep disturbance consist both in self-reporting in epidemiological studies using surveys as well as polysomnography, a widespread sleep analysis technique that allows for the recording of electroencephalogram (EEG) and other physiological variables. Polysomnography allows for the identification of sleep cycles lasting from 90 to 110 minutes, with individuals experiencing from 4 to 6 of such cycles per night; there is evidence that aircraft noise affects time spent in different sleep cycles, reducing slow-wave sleep (NREM stage 4) and REM sleep and increasing NREM Stages 1, 2 and 3(29). A laboratory study for Frankfurt Airport using polysomnography concluded that a curfew on flights in the 23:00-05:00 time frame led to a healthier sleep structure and to small changes in sleep cycles(33). It has also been established that SPL contemplating L_{max} as low as 33 dBA induce physiological reactions during sleep (proving that the organism is able to differentiate these noise events from background noise), although this figure is well below the limits set for policy and regulation(41). According to the WHO Europe Night Noise Guidelines, the target value for nocturnal noise exposure should be 40 dB L_{night} to protect both the public and vulnerable groups [See Annex 3 for health effects linked to nocturnal noise exposure as described by WHO – Source: (29)].

Psychological health and cognitive effects in children

Drawing from the conclusions of studies linking aircraft noise with community annoyance, it has been suggested that long-term exposure to aircraft noise could have an influence in psychological health. Evidence for this correlation is not as abundant as for other health outcomes such as cardiovascular disease, though the effects of noise in the cognitive development of children has been a matter of research for decades(33). Despite the lack of detectable organic damage, noise has been linked to a deterioration of central processing and language tasks like reading comprehension, attention, and certain memory performances, manifested also through the results in standardized tests. Studies of epidemiological nature focus on establishing a correlation between chronic exposure to noise disturbance and underperformance in cognitive capacities, while discarding confounding factors such as those of socioeconomic nature(29).

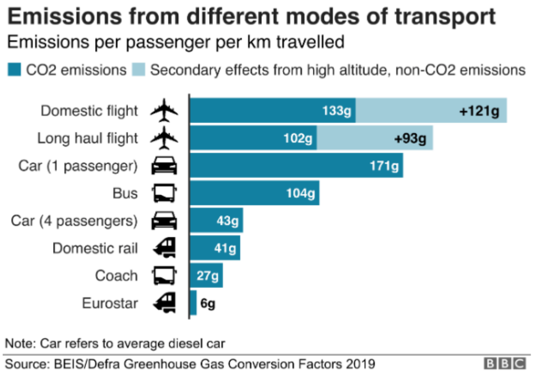
A remarkable study in the field was published in 1998 following the 1992 relocation of Munich Airport, reflecting its effects on the health and cognition of children aged 9 to 11 years. Deficits in long-term memory and reading comprehension disappeared after children ceased to be exposed to high noise exposure and led to further development of these capabilities, proving that this hindrance could be reversed(42). Another more recent but equally important study known as RANCH (Road traffic and Aircraft Noise and children's Cognition & Health) focusing on children aged 9 to 10 from schools around London Heathrow, Amsterdam Schiphol, and Madrid Barajas found correlations between aircraft noise levels and reading comprehension: such skills fell below average at around 55 dB L_{eq} and a 5 dB increase was associated with a 2-month delay in reading age in the UK, and a 1-month delay in the Netherlands(43). Finally, despite the lack of research on the psychological health of adults, the already mentioned HYENA study pointed out that 10dB increases in L_{eq} and L_{night} levels were associated with a 28% and 27% increase in anxiety medication use respectively. While no association was found for anti-depressant and or sleep medication use, a sub-study concluded that salivary cortisol levels (a hormone detected in higher values for people with depression) were 34% higher for women exposed to aircraft noise >60dB L_{eq}, compared to women exposed to less than 50dB L_{eq}(33).

As a concluding statement, it can therefore be stated that negative effects of noise, while pervasive, may be perceived and gauged mainly from the community annoyance caused. Health effects present themselves in solidarity, but some of them are not easily noted by individuals exposed to them. Correct measurement and identification of these effects leads to policy groundwork, which in turn helps in corrective measures being undertaken.

IV. Emissions

Airports, and aviation at large, intrinsically produce air pollutants due to the nature of air travel, which is dependent on combustion engines to power the aircraft. The effect of this emission is twofold: in the first place, air quality in the vicinity of the airport is affected by the concentration of particulate matter and gases; in second place, the release of greenhouse gases produces an aggregate effect on global warming and ocean acidification, upon which environmental focus has been put in the last few decades. Both effects are solidary to the activity of airports, which, as explained, has been growing considerably and leading to further concern about its negative impact on health and the environment. This chapter will discuss, in a similar fashion to the previous chapter dedicated to noise, the definition of all relevant pollutants that result in emissions' negative effects, to follow with an identification of the sources and finally an extensive research review to describe negative effects and their importance.

Aviation represents a 2% of all human-induced carbon dioxide emissions, and 12% of carbon dioxide emissions from all transport sources, behind other types of transportation such as road transport(5); yet, if averaged across kilometres travelled and passengers displaced, aviation ranks as the worst contributor to this form of emission, with figures of 90-100 grams per passenger and kilometre flown depending on aircraft type and route length(44, 45). The sources of the emissions are not only found in aircraft engines, however, and other aircraft systems, ground support equipment servicing aircraft, and inbound and outbound ground traffic related to the airport are also relevant agents that must be accounted for.


Emissions from different modes of transport

Emissions per passenger per km travelled

Note: Car refers to average diesel car

Source: BEIS/Defra Greenhouse Gas Conversion Factors 2019

Image 7: CO2 emissions associated with each mode of transport. Aviation tops the list, with very important secondary contributions to greenhouse effects [Source: (46) with data from (47)]

Definitions

As mentioned, aircraft engines work through the combustion of hydrocarbon fuels (kerosene), which upon completion releases carbon dioxide, water vapour, and sulphur dioxide as products; this combustion, while being of very high efficiency in modern engines, still gives rise to other combustion products such as carbon monoxide and particulates. These compounds are therefore not just gaseous, but also comprise hydrocarbon and aerosol particles containing organic and inorganic components with volatile and semi-volatile properties(48). Annex 16 Volume II of ICAO aims to identify and rate these emissions for aircraft certification, and European legislation, namely Directive 2008/101/EC. The main pollutants involved in these emissions, affecting not only global warming and acidification but also leading to local air pollution, are the following:

- Carbon dioxide (CO_2): the resulting product from the complete combustion process found in the engines, carbon in fuel combines with the oxygen in air to form carbon dioxide. This gaseous emission has been linked to greenhouse effects when dispersed in the atmosphere, as it absorbs infrared light and heats up concentrating energy near the surface and lower atmospheric layers, making it difficult for energy to reach the upper atmosphere(49). Carbon dioxide contributes to global warming through this process, and is particularly harmful as it lingers in the atmosphere for thousands of years(50). Another repercussion is ocean acidification, a regular increase in the pH of oceans due to the dissolution of carbon dioxide on the surface of masses of water turning into acid components, which poses serious danger to biosphere(51). As mentioned, this is the largest form of emission from aircraft at 163 million tonnes by 2017, making aviation the most polluting form of transport in terms of carbon dioxide(44).
- Nitrogen oxides (NO_X): they comprise nitric oxide (NO) and nitrogen dioxide (NO_2). These gaseous emissions are formed when air, containing nitrogen, passes through high temperature and high pressure combustion, leading to NO oxidizing and forming NO_2, which is acidic and highly corrosive. NO_X may further react with ammonia to form nitric acid vapor, or with volatile organic compounds to form ozone, both considered highly toxic and damaging to lung tissue(52). Similarly to carbon dioxide, NO_X are also greenhouse gases, leading to the formation of ozone in lower atmospheric layers that absorb infrared radiation. Besides this global effect, local effects in air quality are of considerable concern due to serious health impacts linked to increased susceptibility to respiratory diseases; high NO_X levels may also damage foliage and decrease plant growth, its deposition may lead to soil and water acidification, and are also suspected to contribute to photochemical smog(53). WHO recommends that exposure for humans does not exceed an annual mean of 40 µg/m^3, and that levels of 30 µg/m^3 are

not exceeded for vegetation(54). Levels of NO_X due to aviation as of 2017 amounted to 839 thousand tonnes, making it the second largest form of emission. In 2015, aviation accounted for 14% of all EU transport NO_X emissions, and for 7% of the total EU NO_X emissions(44).

- Volatile organic compounds (VOC): they include a wide range of chemicals of organic nature, notably hydrocarbons (abbreviated HC, and consisting of compounds such as methane or benzene), as well as halocarbons and oxygenates. These compounds are characterized by being colourless, odourless, and vaporizing at room temperature. They result from incomplete fuel combustion, remaining unburnt and combining in the process to form other hydrocarbon structures(52). They are hazardous even at low levels particularly for long-term exposure, leading to very diverse health issues depending on the compound(55). Recommended levels vary from 5 $\mu g/m^3$ in the case of benzene to 2.25 $\mu g/m^3$ in the case of 1,3-Butadiene(54). 57 thousand tonnes of HC were produced by aviation in 2017(44).
- Particulate matter (PM): it includes both organic and inorganic substances, either solid or liquid in state, resulting from incomplete combustion and aerosols from condensed gases, generally referred to as soot. Common components are sulphate, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water(54). These particles are described by their size in micrometres (for instance, PM_{10} would refer to those smaller than 10µm), in all cases small enough to be inhaled(52). PM have some of the worst impact on human health, gravely affecting air quality and leading to increased morbidity and mortality to those exposed, even at low concentrations. PM_{10} can penetrate deep into lung tissue, and $PM_{2.5}$ are able to penetrate the lung barrier and enter the bloodstream. WHO recommends annual mean values of 10 $\mu g/m^3$ for $PM_{2.5}$, and 20 $\mu g/m^3$ for PM_{10}(54). 53 thousand tonnes of PM were liberated into the atmosphere in 2017 due to the activity of air transport(44).
- Carbon monoxide (CO): in conditions of temperature exceeding optimal combustion temperature, or low oxygen concentration, carbon monoxide is released as a by-product of the process of combustion of carbon in the fuel. Carbon monoxide has serious health effects as it bonds to haemoglobin in blood and reduces oxygen absorption by blood cells, which may cause intoxication and organic failure, or milder symptoms such as fatigue and nausea(56). Maximum exposure is indicated at 10 mg/m^3 as the daily 8-hour mean. In 2017, 108 tonnes were produced due to aviation activity(44).
- Sulphur oxides (SO_X): small quantities of sulphur are found in all petroleum fuels, generally at concentrations of 300–1100 ppm in aviation(48). During combustion, sulphur combines with oxygen to produce sulphur oxides (chiefly SO_2 or sulphur dioxide),

which may then contribute to secondary particulate matter formation, and even precipitate in the form of acid rain after combining with water to form sulphuric acid(52). The latter effect can severely damage the ecosystem through the acidification of soils and water with further impact to aquatic life and deforestation, and causing material damage to infrastructure. SO_2 can also affect humans as an irritant and lead to respiratory infections, and more serious health effects if combined with PM. 20 µg/m3 is the annual mean value for vegetation and humans(54).

- Other emissions of gaseous nature (water, ozone): other gaseous pollutants are released either directly or indirectly during combustion, though their importance by amount is not comparable to the aforementioned compounds. In the case of water (H_2O), it is produced as a result of combustion in the form of vapour, though at high altitude and under certain atmospheric conditions this can have an impact towards the greenhouse effect after condensing in what is known as *contrails.* These releases have been associated with the formation of cirrus, which may have warming effects that are not yet fully studied conclusively(57).

  On the other hand, ozone (O_3) is generated mostly through photochemical reactions from NO_X and VOC, and is responsible both for greenhouse effects and air quality issues. It causes health issues such as the irritation of the eyes or throat and lung and heart problems, and it can cause both natural and material damage due to its corrosive properties(58). Levels of 100 µg/m3 for an 8-hour mean are not to be exceeded more than 10 times per year.

Other complex chemical reactions may occur as these emissions mix with the atmosphere, leading to new particles or increase concentrations of pre-existing particles, resulting in broader exposure. For example, NO_2 contained in the plumes leads to the formation of nitric acid (HNO_3), which through interaction with atmospheric ammonia generates ammonium nitrate particles (NH_4NO_3) and oxidation reactions with hydrocarbons in gaseous state, leading to other organic compounds in the form of aerosol particles(52).

Pollutants can be classified also according to their transformation after being generated in the source. Under this classification, we find those generated immediately after exiting the combustor (such as CO_2, NO_X, or CO), those generated downstream from the engine in the hot exhaust plume (SO_X, VOC), and those that result from mixing with the atmosphere, after cooling down (PM, ozone, H_2O, some VOC). Hot combustion gases cool down when mixing with ambient air, where gases like heavy hydrocarbons condense to form aerosol particles; in the exhaust plume, some molecules undergo chemical reactions, which aggregate to form larger particles (PM)(52).

Emission sources

As mentioned above, aircraft are not the only source of aviation emissions, as airport road access also constitutes a notable contributor to local air quality and greenhouse gas emissions, as well as ground support equipment (GSE), generally reliant on combustion engines and located within the airport premises to service aircraft and ground operations. Additionally, normal flight operations also include other sources such as APU(Auxiliary Power Unit) usage on the ramp, or the release of particulate matter during landing and take-off. Other miscellaneous sources are important but are not unique to airports and may be encountered in other large infrastructures, such as maintenance work, fuel storage facilities, and construction projects.

The principle by which aircraft operate is based on the propulsion provided by combustion engines, or in other words, the release of chemical energy stored in hydrocarbon-based fuel in the conditions of adequate oxygen supply, high temperature, and high pressure. Air intake is indispensable to provide this oxygen supply (containing oxygen and a majority of nitrogen), initiating the combustion of the fuel (kerosene, a hydrocarbon molecule or C_nH_m, with sulphur components) injected from the tanks into the engine. Ideally, combustion releases carbon dioxide, water, and sulphur oxide along with air; realistically however, NO_X, HC, CO, soot, and SO_X are emitted in addition to those combustion products(59). These emissions are produced during departure (taxi, take-off, and climb-out) and arrival (final approach, landing, and taxi) generating a local effect in terms of air quality. During cruise and other stages of descent and climb, local effects are not as notorious due to emissions dispersing atmospherically, contributing mainly to greenhouse effects. ICAO certifies engines based on NO_X, CO, HC and smoke, under standards of the total quantity of pollutants emitted in a landing-take-off cycle, divided by the maximum sea level thrust and plotted against the engine pressure ratio at maximum sea level thrust(60). Engine efficiency (how much thrust is applied) is responsible for the amount of VOC and CO, a situation common on approach when engines are working at reduced power. Similarly, the APU utilized on approach, taxi, or on the stand generate similar pollutants to those released by the main engines, representing between 40 and 50% of total GSE emission of CO and NO_X(61).

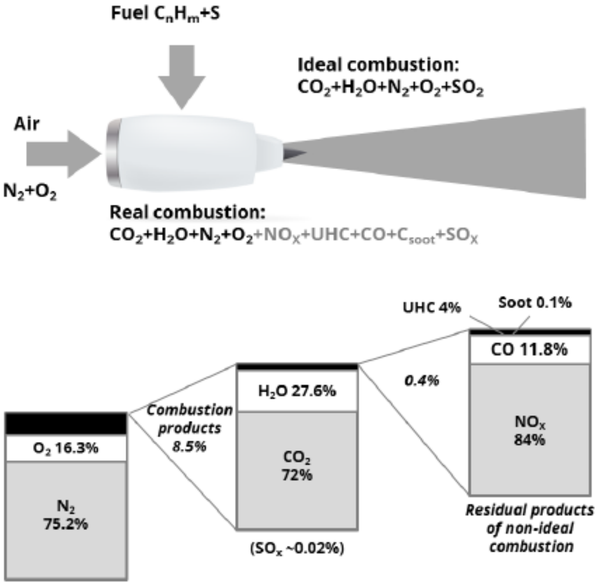


Image 8: Emissions resulting from aircraft engines are a consequence of the release of combustion products and the reactions among them and with the air [Source: (59)]

Ground support equipment are very distinct in nature, and rely on internal combustion engines very unlike those used in aviation. They consist of many different vehicles such as belt loaders, pushback trucks, tractors, cabin service trucks, step-cars, or even emergency service vehicles. In most cases save for those where an electric power system is present, GSE use gasoline or diesel as fuel, with an emission pattern very different from aircraft engines and resembling that of common road traffic(62). This includes CO_2, CO, NO_X, PM and HC, which along with power output dictate European emission standards. Ground access vehicles are those accessing the airport on roadways mostly for delivering airport passengers and employees, comprising private vehicles, shuttles, public transportation and others. Gasoline, diesel, compressed natural gas and electric engines can be found among them, and they are subject to national regulations for private vehicles. Emissions are not too different from GSE, and modelling their impact has been an important subject of study the last two decades to estimate total CO, NO_X and HC output(63).

Aircraft tyres are designed to endure a large amount of friction to both accelerate the aircraft during take-off and to decelerate it during landing. This intense wear of the tyres, particularly during landing, results in particulate emissions that can be either coarse or in the form of PM, and closely related to the weight of the aircraft. The same can be said for brake wear, also relevant during landing(64). Fuelling and fuel handling may also cause VOC and HC emissions, which due to the large amount of operations can be significant in global airport data.

While very rare, fuel dumping (requiring the emptying of fuel tanks to reduce risk of ignition during emergency landing) can also lead to the release of large quantities of unburnt fuel into the air, with associated VOC and HC emissions; aircraft in these situations are expected to dump fuel at altitudes and over locations where no risk is posed to the population, where these components would evaporate before reaching the surface(64).

Aircraft and airfield maintenance (cleaning, repairs, painting, de-icing), fire practice, waste disposal, power plant electricity production and heating, as well as construction, are also sources of CO_2, NO_X, VOC, PM, and other emissions of diverse nature such as dust and smoke. Under most metrics however, these sources do not contribute in great measure to local air quality and greenhouse emissions to the extent of aircraft operations, road traffic or GSE activity(65).

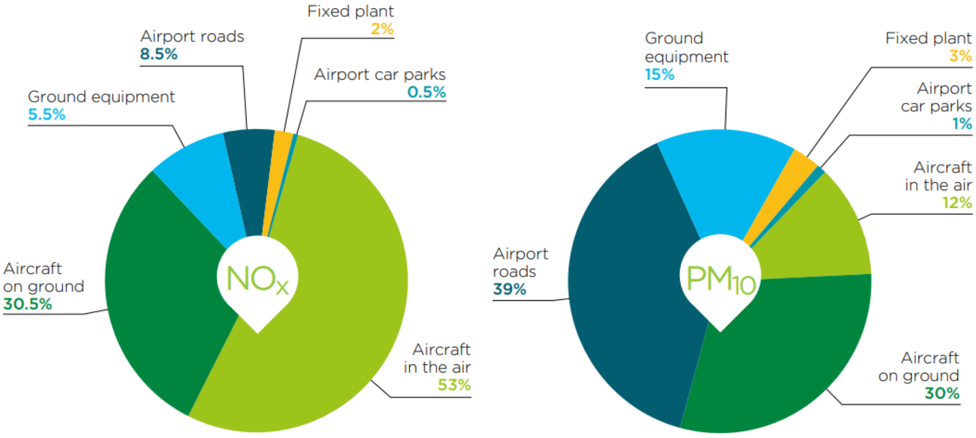


Image 9: On-airport emissions for NO_X and PM_{10} based on emission inventories for London Gatwick (2010) and London Heathrow (2013) [Source: (65)]

Negative effects

The effects of emissions that find their source in the aviation industry are not distinct from those of other sources. As seen, in the case of aviation the form and volume of those emissions is very distinct, however, from those of the car industry and plant generation, and are bound to very different regulation (for instance, maximum sulphur content for automotive diesel and gasoline is set at below 10 ppm, whereas the limit for aviation fuel remains at 3000 ppm and linked to a lump “smoke factor”(48). As discussed, the impact translates directly into the environment through two major effects: greenhouse effect and the consequential global warming, and the decrease in air quality mainly in the vicinity of airports. The former is well-studied and comprises a large variety of indirect and induced effects, the quantification of which is complex and outside of the scope of this study, as the characteristics of global warming have a much larger scale encompassing a multitude of stakeholders non-related to aviation and would require in-depth separate analysis. Climate change impacts of CO_2 and contrails account for 39% of air quality damages per unit aviation fuel burn(66).

Air quality is affected by the concentration of pollutants particularly in the vicinity of the airport area and on a regional level, leading to a deleterious impact on the health of people, animals, and vegetal life. Other less-studied effects contemplate eutrophication (an excessive mineral deposit in water which generates vegetal overgrowth) and building deterioration and the permanence of odours(53). Aircraft emissions have been estimated to cause 16,000 premature deaths a year from impaired air quality, with its impact being 1.7 to 4.4 times higher than the climate impact per unit of fuel burn(66, 67). The most important contributors to human health are NO_X/NO_2, PM, and ozone at the ground level(68). The legal framework for air quality stems from the EU Air Quality Framework Directive of 1996, with subsequent legislation addressing the threats identified in it.

Particulate matter is the pollutant that inflicts the worst burden on human health when inhaled. PM_{10} (particles with a diameter of 10 µm or less) can penetrate deep inside the lungs, and $PM_{2.5}$ particles (particles with a diameter of 2.5 µm or less) can be even more damaging due to their ability to trespass from lung tissue into the bloodstream, leading to both acute and chronic effects such as cardiovascular and respiratory diseases (including lung cancer). Other ultrafine particles (PM_1 and $PM_{0.1}$) may act as inflammation and act as carriers for toxic substances that damage the genetic information in cells(68, 69). The association between PM_{10} and $PM_{2.5}$ concentration and increased mortality or morbidity has been quantitatively established, with no threshold under which the effects do not follow correlation. Besides cardiovascular and lung disease, growing ambient PM concentration has been linked to an increase in lower respiratory symptoms and reduced lung function in children, and chronic obstructive pulmonary disease and reduced lung function in adults(70). Long-term effects on health become apparent at annual means of 10 µg/m^3 ($PM_{2.5}$) and 20 µg/m^3 (PM_{10}), whereas short-term effects are noteworthy at daily means of 25 µg/m^3 ($PM_{2.5}$) and 50 µg/m^3 (PM_{10}); these are the guidelines indicated by WHO, noting that health effects can be expected at annual mean concentrations ranging 11–15 µg/m^3 ($PM_{2.5}$). In Europe, short-term mortality effects have been shown to increase at a pace of 0.46% per 10 µg/m^3 of PM_{10} daily mean concentration(71). Worldwide, in a 20 km range from the airport, PM2.5 is reported to cause 5000 premature deaths per annum, 38% of which occur in European airports(67). A different model within the same confidence interval estimates 3600 premature mortalities each year, 3210 of which due to cases of cardiopulmonary disease and 390 due to increases in cases of lung cancer(72).

Nitric oxides (NO_X) and nitrogen dioxide (NO_2) in particular have a direct impact on human health, animals and plants, as well as generating other particles such as $PM_{2.5}$ and, in the presence of ultraviolet light, low-level ozone. Both short-term and long-term effects are relevant. Short-term concentrations are toxic above an hour mean of 200 $\mu g/m^3$ and have been shown to cause significant inflammation of the airways, with high concentrations resulting in severe pulmonary damage in healthy humans, while exposure of persons with pre-existing chronic respiratory conditions such as asthma may lead to sudden respiratory responses. Long-term exposure to NO_2, defined by WHO at 40 $\mu g/m^3$ yearly mean, has been associated with increased respiratory symptoms, which are more commonly observed in conditions of indoor exposure(73). Similar concentrations have been reported to affect animals. NO_2 is generally employed as a marker for NO_X presence, although attributing the individual impact of NO_X exposure is a difficult task experimentally due to its weakening effects magnifying the impact of other, but correlated pollutants(71). In the case of vegetation, NO_X are absorbed in a manner akin to CO_2 through epidermal cells, where they dissolve to form nitrite and nitrate, and then incorporated into organic compounds after being further reduced into ammonia; however, high concentrations of NO_X cause necrosis of vegetable tissue, particularly in the long-term, and if high enough may stifle growth(73). An annual mean of 30 $\mu g/m^3$ is recommended by WHO. Other biological consequences upon the ecosystem are unbalances in biomass, eutrophication and in the most severe case, acidification. Lastly, material damage caused by NO_X, while not yet quantified and isolated from other pollutants, is linked to the stimulus of microbial activity on surfaces.

Ozone may be present in lower atmospheric levels rather in the upper atmosphere due to a photochemical reaction with NO_X and VOC emissions, its concentration consequently increasing in sunny days(54). As a powerful oxidant, ozone is very reactive with cellular components and biological materials, causing particular damage to the respiratory tract: inflammation, morphological, biochemical, and functional changes, and decreases in host defence functions are known effects on humans and animals. Aside from reducing lung function and causing lung diseases, ozone is responsible for triggering asthma episodes(74). At an 8-hour mean of 160 µg/m3 lung inflammation has been detected in those exercising outdoors, whereas for concentrations in excess of 240 $\mu g/m^3$ for a same time period significant health effects are considered likely, with an increase in attributable deaths of 5–9% relative to exposures at background levels (set at 70 $\mu g/m^3$). WHO sets the recommended value at 100 $\mu g/m^3$ 8-hour mean(54). Exposure of vegetable life to ozone causes leaf injury, growth and yield reductions, and altered sensitivity to biotic and abiotic stresses that is relatively well-researched in Europe. Damage to materials is notable in those of organic nature (such as rubber or textiles), but indirect and synergistic effects upon inorganic materials are also important when in association with other pollutants such as SO_2 and NO_X(74). Premature deaths associated with ozone generation from aviation have been identified as amounting to approximately 2100 per year worldwide(67).

Colourless and manifested through a sharp door, sulphur dioxide inhaled in high enough concentrations is an irritant that can affect the respiratory system and lung functions, and irritate the eyes and induce asthma attacks. Inflammation of the respiratory tract causes coughing, mucus secretion, and aggravation of asthma and chronic bronchitis as well as increasing the likelihood of other respiratory tract infections. Hospital admissions for cardiac disease, as well as mortality rises, have been associated with peaks in SO2 levels(54). Organic responses to SO2 are quite rapid (within minutes), with short-term effects manifesting at concentrations above the 10-minute mean of 500 µg/m^3 recommended by WHO. Long-term exposures (over 24 hours) are still under debate due to the co-dependence with PM concentrations, and an impact on mortality has been observed at daily concentrations ranging f 5–40 µg/m^3 (similar to the prudent long-term boundary set by WHO at 20 µg/m^3)(71). On vegetation, degradation of chlorophyll, reduced photosynthesis, raised respiration rates, and changes in protein metabolism appear due to leaves taking up the sulphur from the environment. The annual mean value suggested by WHO for crops is 30 µg/m^3 and 20 µg/m^3 for forests. SO2 also plays the most important role among pollutants in material corrosion, both by directly depositing as sulphates on the surface and through increased acidity when dissolving in rain droplets(68).

Other pollutants such as CO and VOC are known to have a negative impact on health and are acknowledged by European Air Quality legislation, though the contributions of aviation for their concentration are not well researched. Carbon monoxide reacts with haemoglobin and reduces the oxygen-carrying capacity of the blood and impairs the release of oxygen to extravascular tissues, resulting in toxic effects that become evident in organs and tissues with high oxygen consumption such as the brain, the heart, the exercising skeletal muscle, and the developing foetus. WHO standards set the maximum recommendable concentration at 10 mg/m^3 for an 8-hour period(75). As for VOC, 1,3-butadiene, acrolein, and benzene seem to be of biggest concern due to their carcinogenic potential and linkage with developmental abnormalities, although only benzene is present in European Air Quality directives(76). This compound has been extensively researched, and its chronic exposure linked to bone marrow depression, gene mutation, and leukaemia. Out of 1000 workers subject to an exposure of 3.2 mg/m^3 over 40 years, roughly one case of cancer could be attributed to benzene. No safe level of exposure is recommended by WHO due to its carcinogenic effects(77).

As seen, emissions are different from noise in the sense that exposure is not as easily detected by those who suffer it, particularly not in lower concentrations that are still proven to be harmful in the short- and notably the long-term. This, as will be seen further into this thesis, results in particularities in the way the externality is quantified. Policies for the correction of emissions externality must account for the sources seen and for the concentrations that lead to negative health effects in order to be effective.

V. Externality quantification

The following chapter is organised first as an introductory overview of the economic concept of externality as a continuation from the first chapter, and then focuses on how methodology adapts to the disparities present in the quantification of emissions and noise. As will be seen, there is an important dichotomy in their valuation, which gives rise to diverging methods that will also be explored independently (hedonic pricing and contingent valuation).

The motivation for the quantification of externality, done in monetary terms, arises from the same economic reasoning as the concept itself. In first place, seeking a monetary measure for the benefit or cost that is not directly contained in the price value of a service or product is a good way to reflect the strength of feeling for the environmental impact. In second place, environmental quality can be guaranteed through monetary measures sufficiently large to compensate this cost, describing costs and benefits through terms expressed in currency that are commonly understood by both regulators and the public. Furthermore, monetization permits comparison with other monetary benefits when determining fund allocation. Whether funds are being used for house insulation, reduce PM emissions, or some other expenditure, preserving and improving the environment always carries monetary cost and resource dedication, requiring a cost-benefit analysis (CBA) to understand to which extent it is socially worthwhile to carry out such measures(78).

CBA consists in the idea that weighing the advantages and disadvantages of an action is possible and supports decision-making, doing so by employing money as a comparing tool(79). Total economic values must also account for context: attributes such as irreversibility (the possibility that the asset might be eliminated with no chance of regeneration), uncertainty (potential costs in the future might be a consequence of the asset being eliminated), and uniqueness (for instance, in the case of endangered species). This combination of attributes is very important in the case of the impact of the aviation industry, given that it takes, as seen, a considerable toll on human health and the ecosystem; decision-making may then act cautiously and opt for limiting development for the sake of preservation, such as in the case of opening a new runway or applying noise curfews(78). Formally, the basic rule for the decision on a development project considers the cost of the project, its benefits, and the Total Economic Value (TEV) lost by executing the development:

$$\mathrm{TEV} = \mathrm{B_D} - \mathrm{C_D} - \mathrm{B_P}$$

Where B_D refers to the benefits of development, C_D to the costs of development, and B_p to the benefits of preserving the environment by not developing the area. TEV, the Total Economic

Value, will advise to not go ahead with the development if negative, and to do so if positive. B_D and C_D might be relatively simple to measure, as they depend on inputs traded in a market, with observable prices, but such is not the case for B_p, the total value of the asset left as a natural environment. TEV, which is in conclusion a measure of B_p, is not so simply measured as it has no associated commodity that may be traded in the market(78).

For the purpose of the economic measurement of environmental costs, two approaches exist in the market, classified in literature as direct and indirect. The former aims to measure the money value of environmental gains (better levels of air quality, a higher quality of life in airport vicinity, etc.) through the monitoring of a surrogate market or by employing experimental techniques, depending on whether the approach relies on revealed or stated preference. In both cases, the methods attempt to recreate a market in which the environmental cost or benefit of the economic activity is represented. Revealed preference looks for an existing market in which goods or factors of production are bought and sold, observing the environmental benefits or costs as attributes of those goods or factors; under this perspective, air quality or noise annoyance are attributes of purchasing house properties. A stated preference approach, on the other hand, simulates a market through the expression of hypothetical valuation by respondents if real improvements were to be made, making these hypothetical valuations as real as possible to gather realistic data(78, 80). The most salient methods for direct valuation seen in airport-level studies are hedonic pricing and contingent valuation, and will be described further below.

Indirect procedures do not aim to measure revealed preferences for the environmental good in question, but rather calculate a dose-response relationship between the cause of environmental cost and the effects of such a cost, and only then measuring the preference for that effect. This dose-response method is particularly common in the case of emissions, where pollution can be linked to a detriment on health, material deterioration, or effects on ecosystems and vegetation. Nevertheless, the indirect approach does not establish willingness to pay (WTP) for the environmental benefit or the willingness to accept (WTA) compensation for the environmental damage suffered, but instead estimates the relationship between the dose and the non-monetary effect, and ultimately apply WTP measures taken from direct approaches(78, 81). Since WTP is determinant to establish internalization measures (that is, the correction of the externality cost in monetary terms) in either case, and dose-response approaches are characteristically much more specialized in the effect they seek to measure (whether epidemiological, ecological, or pertaining to any other technical studies), it strays from the focus of this document. Indirect methods of valuation will be studied only in descriptive detail when concerning corrective measures, and specifically in the case of emissions.

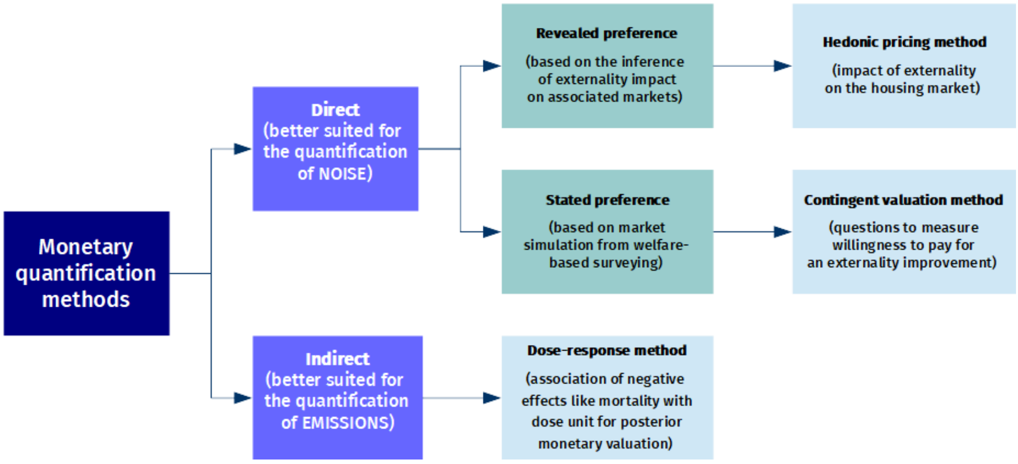


Image 10: Conceptual map summarising methodology dichotomy for externality quantification studies

Emission quantification

To measure the diversity of effects generated by poor air quality and greenhouse emissions on human health and the environment, both scientific and economic information is necessary. Correlations must be established between the nature of the relationship between concentrations of each pollutant and the associated health and environmental impact, the population exposed to the emissions has to be determined, and the value placed by the public on each of those impacts must be outlined. As mentioned, the strongest evidence points towards a clear relationship with an increase in mortality and morbidity, particularly shown through hospital admissions, though there is more recent evidence measuring long-term exposure to pollutants such as PM and ozone. Important parameters are differences in aircraft operations, engine types, emission rates and airport congestion, as well as a distinction first between ground level pollution and cruise-level impact, and second between landing-take-off emissions (which affect local air quality) and cruise stage (characterized for their greenhouse effects) for an individual flight.

The dose-response technique is the most comprehensive method to value the cost resulting from aircraft engine exhaust pollutants, consisting in linking adverse consequences to air emission levels. Estimating the environmental costs of damage to human health, vegetation, buildings and climate change and global warming in monetary terms depends on the cost of the effects for each dose of a given pollutant; there is a high degree of uncertainty towards evaluating the damage, however, due to the wide range of monetary impacts, and so the unitary values are averaged from a range. Those pollutants with a larger unit social costs are PM, SO_2, NO_X and HC, though CO_2, while having a lesser unit social cost, is emitted in much larger amounts. Particularly for the case of emissions with a greenhouse effect (CO_2, NO_X, and H_2O), the impact is measured in terms of radiative forcing (RF), which intends to capture the change in average net radiation in upper tropospheric levels resulting from a change in greenhouse gas concentration. This metric, measured in watts per square meter (W/m^2), has been evaluated constantly since preliminary studies in 1999, and is followed closely by EU policymakers in Environmental Reports(44, 82). For global warming purposes, temperature response is calculated after determining RF, which is done explicitly for CO_2 following the relationship between carbon-cycle models and fuel data, and either directly or indirectly for other gases, scaled for fuel data and climate chemistry models. The total RF effects of aviation were last evaluated in 2005 at 78 mW/m^2 including aviation-induced cloudiness, a 4.9% of the total RF increase for that year. 40% of this overall aviation RF is attributed to CO_2, the rest being generated by remaining greenhouse effect emissions (44, 83–85)

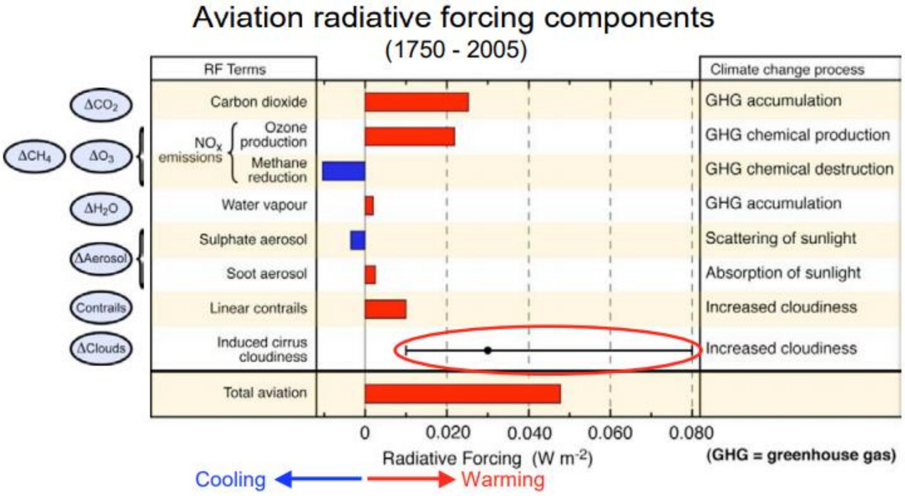
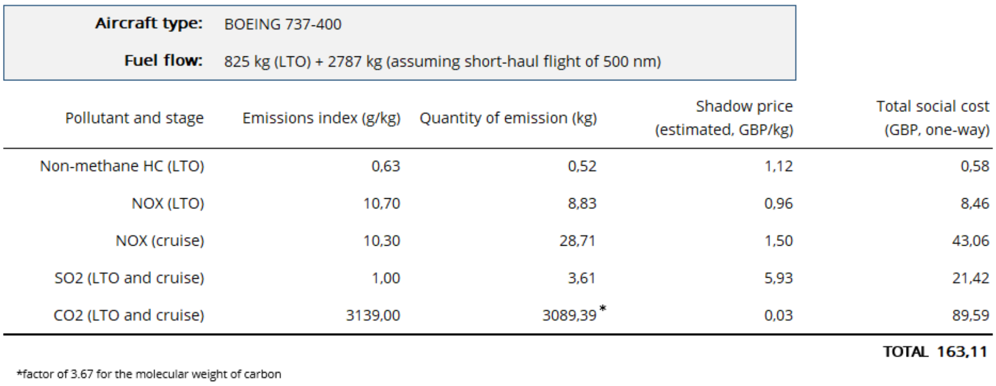


Image 11: RF values from aviation emissions and their impact on climate change [Source: (85)]

As explained, epidemiological studies are essential the magnitude of the health impact of air quality and establish correlation. The current state of the art indicates that pollutants such as PM, ozone, and NO_X have the higher clearly demonstrated impact on human health, while others such as VOC still require further study for the concentrations generated by aviation. The mortality, morbidity, and reduced quality of life are parameters that can lead to monetization, though with a large degree of uncertainty in many cases. Specifically for aircraft as an emission source, once cost per unit of pollutant has been defined, the total social costs can be calculated through a bottom-up approach, with the following inputs(60, 81):

- Time for different flight modes (in minutes), which are outlined by ICAO in Annex 16 Volume II as take-off (0.7 min), climb-out (2.2 min), approach (4.0 min), idle (26 min), and cruise (depending on flight distance and aircraft speed).
- Fuel flow (kilograms of fuel per second) also in accordance with ICAO standards.
- Emission index (grams of pollutant per kilogram of fuel) for different flight modes and each pollutant. HC, CO and NO_X are included in ICAO engine emissions databank, but for SO_2, PM and CO_2 data from scientific research is necessary.
- Unit social costs (monetary unit, such as euro, per kilogram of pollutant), as per current scientific data [See Annex 4 for estimated social costs per pollutant as of 2005 – Source: (81)].

An illustrative example provided by Pearce and Pearce in 2000 in their widely cited study posits the following situation(86):



Aircraft type: BOEING 737-400
Fuel flow: 825 kg (LTO) + 2787 kg (assuming short-haul flight of 500 nm)

Pollutant and stage	Emissions index (g/kg)	Quantity of emission (kg)	Shadow price (estimated, GBP/kg)	Total social cost (GBP, one-way)
Non-methane HC (LTO)	0,63	0,52	1,12	0,58
NOX (LTO)	10,70	8,83	0,96	8,46
NOX (cruise)	10,30	28,71	1,50	43,06
SO2 (LTO and cruise)	1,00	3,61	5,93	21,42
CO2 (LTO and cruise)	3139,00	3089,39*	0,03	89,59
				TOTAL 163,11

*factor of 3.67 for the molecular weight of carbon

Image 12: Explicit calculations for the procedure followed by Pearce and Pearce to estimate the environmental tax to be charged to a Boeing 737-400 in a short-haul flight of 500 nm [Source: elaboration from data found at (86)]

The calculations have been reproduced by assuming the accuracy of the data given by Pearce and Pearce. For the purposes of this example, the authors considered a Boeing 737-400 flying a short-haul route (500 nautical miles) with a given estimated consumption for LTO cycle (which comprises take-off, climb-out, approach, and landing, as well as taxi) and cruise. For the studied pollutants, the categorization discriminates between those for those two phases of the flight, as emission rates depend not only on the proportion of thrust applied but also on engine revolutions (for instance, the largest part of CO emissions occur when engines idle during taxi). Emission indexes are strictly monitored by ICAO, as their output must comply with emission regulations in order to endorse engine certification. The quantities result from the product of those indexes and fuel consumption, while shadow prices arise from the dose-result valuation derived from the state of research at the time. The product of these amounts totals 163 GBP in the year of the study (2000), which when adjusted for inflation would equal to 276 GBP today (or 308 EUR)(87). This would be the *air pollution tax* applied for a one-way, short-haul flight for this aircraft.

A similar study could be conducted for any engine currently operating and found in the last update of the ICAO Aircraft Engine Emission Database. For example, the latest B737 model, the B737 MAX 9, sports LEAP-1B engines, which is reported in the 2019 release as consuming an average of 378 kg of fuel per LTO Cycle. From this fuel combustion, 7.534 kg of NO_X are emitted(88). According to a later dose-result study, NO_X have an average impact of 10.1 EUR/kg in 2005, or 14.3 EUR/kg today when adjusted to inflation(81). Therefore, the air pollution tax associated with the cost of the NO_X generated by a B737 MAX 9 executing a single LTO cycle would be estimated as 107.7 EUR. Estimating the quantity of emission for cruise conditions is more complicated, but good simulation methods exist to correlate emissions of a given pollutant with thrust rates(66).

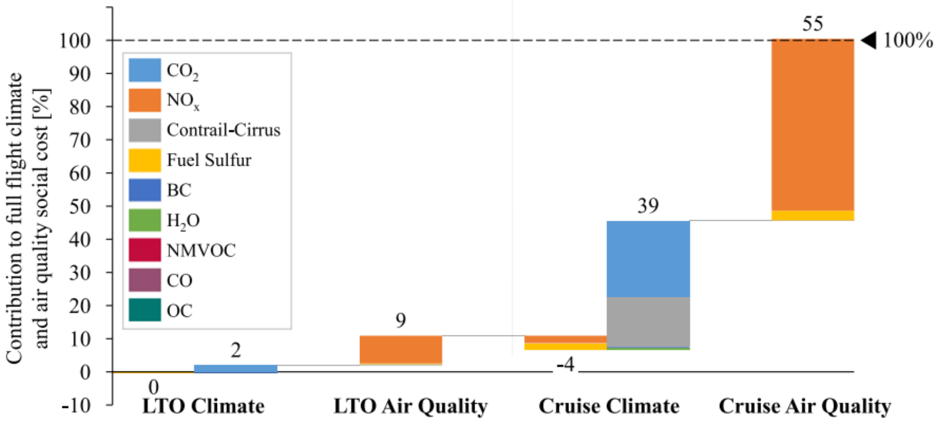


Image 13: Breakdown of climate and air quality social costs for LTO and cruise phases [Source: (66)]

Noise quantification

Noise social costs, unlike those derived from emissions, follow a top-down approach: aggregate noise social cost is first measured, and then allocated to individual flights depending on the real impact generated, obtaining a marginal noise index. The calculation for the noise index is based on the average of the ICAO-certified noise levels (EPNL, in EPNdB) for take-off, side-line, and approach, depending on aircraft and engine combinations. An annual noise index can be aggregated for the composition of aircraft movements per aircraft type and engine combinations, giving rise to the noise social cost per aircraft movement(81). The corresponding environmental tax for noise nuisance is also explained by Pearce and Pearce in the 2000 article through an example similar to that of emission calculations(86).

Acoustic energy in joules for arrival and departure (E_A and E_D) can be determined by knowing the ICAO certification EPNL for a given aircraft engine combination (N_A and N_D):

$$E_A = 10^{\frac{N_A - 10}{10}}$$

$$E_D = 10^{\frac{N_D}{10}}$$

For the B737-400 used as an example, EPDL for arrival is 100.2 dB and for departure 89.1dB (average of take-off and side-line noise as provided by ICAO), which results in 1.047 GJ and 0.813 GJ respectively. The authors take London-Heathrow's data for daily events (departures or arrivals) of B737-400 in 1997, amounting to 157.9 operations per day on average, and factor in the noise levels generated by departures and arrivals(86):

$$E_{daily} = N_{daily}(E_A + E_D) = 157.9\ (1.047 + 0.813) = 293\ \mathrm{GJ}$$

A summation involving all aircraft types (N = 583.5 events) then yields 2824.6 GJ for an average day of 1997 in London-Heathrow. Average daily sound exposure level (SEL) can then be calculated through the following formula(86):

$$SEL_\mu = 10 \log\left(\frac{E}{N}\right) = 10 \log\left(\frac{2824.6 \text{ x } 10^9}{583.5}\right) = 96.85\ \mathrm{dB\ (EPDL)}$$

It is possible to find the marginal noise nuisance caused by the reduction in an event of a B737-400 by deriving the L_{eq} noise level over the number of events. Conversion from average SEL to L_{eq} (for a period of study of 16 hours, or 57600 seconds) is done through the following formula(86):

$$L_{eq} = SEL_\mu + 10 \log(N) + 10 \log(T) = SEL_\mu + 10 \log(N) - 47.6$$

The quantity of noise produced by an event or arrival and departure of a B737-400 on an average day at Heathrow is then found(86):

$$\frac{\partial L_{eq}}{\partial N} = \frac{\partial(SEL_{\mu} + 10\log(N) + 10\log(T))}{\partial N} = \frac{\partial SEL_{\mu}}{\partial N} + \frac{10}{N\ln 10}$$

$$SEL_{\mu} - 10\log\left(\frac{E - E_{A,B734} + E_{D,B734}}{N-1}\right) + \frac{10}{N\ln 10} = 96.84916 - 96.85371 + 0.00745$$

$$= 0.0029 \text{ dB (EPNL)} \xRightarrow{\div 1.35} 0.0021 \text{ dBA}$$

It must be noted that this marginal quantity depends on the existing level of noise, as the result of the derivative will be lower at a noisier airport (higher activity or N).

The externality attributed to one event requires the estimation of daily price depreciation of an associated good; as will be seen below, applying the hedonic pricing method for the housing market offers a good approximation on the marginal willingness to pay for aircraft noise reduction. In the example, this is set as 15 801 GBP (1997), which for the B737-400 would result in the following environmental tax(86):

$$tax_{event} = \frac{\partial L_{eq}}{\partial N} \cdot WTP = 0.0021 \cdot 15801 = 34 \text{ GBP } (1997)$$

This reflects a cost of 34 in 1997 GBP per noise event caused by a B737-400, or 69 EUR today(87).

Much has been done in order to correctly determine exposure to noise in the vicinity of European airports, and as seen, many health studies are not only conducted in laboratories, but also by requesting the participation of the community. The process of measuring noise impact through objective (placement of microphones) and subjective (surveying and collecting complaints) gauges is intimately combined with the process of simulating and predicting environmental noise, which has also seen considerable development in the last decades. Early models and software were based on measured data, but current methods are based on more analytical models; these approaches still suffer from certain inaccuracies in prediction, with new methods constantly being explored. The accuracy of noise simulation is inversely proportional to the complexity of the model, however: individual component analysis, aircraft noise analysis, study of noise events, noise footprints, and finally noise contours are increasingly more complicated and range from models based on physics to those based on empirical observation and finally on experimental database(14). While the former are more centred on aircraft design and certification and flight path design, the latter are the focus of most research for noise zoning policies, land-use decisions, and Environmental Impact Assessments. Calculations imply both atmospheric conditions (relevant in aircraft flight path and noise propagation) and aircraft specific data and airport operational information, resulting in the confection of noise contour diagrams(40).

Noise contour diagrams offer a visual reference of how noise levels vary between locations around the airport region. Besides acoustical parameters, the contours also take into account the number of individuals exposed to a certain noise level, calculated by counting the number of residences between two noise contours and multiplying that by the average number of inhabitants per residence. Generally, this data is grouped in intervals of 5 dBA. The steps followed by this method are:

a) Measurement of noise levels produced by individual aircraft movements at observation points around the airport.
b) Combination of individual noise levels at each of those points, according to the formulation of the chosen noise value.
c) Interpolation and plotting of contours of selected values.

The contours are drawn through the repetition of these calculations at several points around the airport, which are then interpolated across points to form lines (noise contours)(40).

Nevertheless, the reduction of noise at the source is only a measure to counteract the negative effects of noise, or in other words, by reducing the amount of people exposed to it, and the degree at which they are exposed. Calculating actual noise exposure and investigating its linkage with perceived noise exposure are key to the aim of this thesis; the cost estimation of aircraft noise must be necessarily done by correlation with noise exposure, or at least, noise effect on perceived quality of life. As already mentioned, hedonic pricing and contingent valuation are the two most popular methods of evaluation in related literature, following a direct approach [See Annex 5 for a methodology comparison of aircraft emission social cost versus aircraft noise social cost considering their respective inputs – Source: (81)].

Hedonic pricing

The equilibrium price of a house is the present discounted value of the stream of services (rents) provided by the house. These rents reflect the collection of characteristics that make up the house: rooms, location and access, proximity to commercial amenities and other services, and also the environmental quality of the neighbourhood in which the property is located. The difference in price that arises from comparing a noisy house and one that is less noisy, all other factors remaining equal, is the present value of the rental being paid for the difference in noise levels. Thus, it is possible to, in first place, identify how much of this difference is due to particular environmental differences between properties; in second term, to infer the willingness to pay or WTP of the public for quieter conditions, and what the social value of this improvement is. This method is known as hedonic pricing or HP for short(78).

Naturally, in practice houses are not identical to one another, and the effect of noise on house prices must be isolated from other factors. The aim of HP is therefore to summarise this impact of aircraft noise it in what is called Noise Sensitivity Depreciation Index or NSDI. This indicator provides a measure of the percentage change in house price associated with a unit change in noise quantity in terms of dBA L_{eq}. For this purpose, a procedure consisting in a multiple regression technique accounts for all implicated factors with adjusted parameters for their importance, considered over a sample of data taken from similar residential properties over a period of years (time series), a large number of diverse properties at a time snapshot (cross section), or through a methodology comprehending both approaches (pooled data). Given the complexity of controlling the influence of time over the independent variables involved, generally the second method is the most common in literature(11, 78).

The hedonic price function, or P_h, constitutes the dependent variable that must be determined through the HP method. However, two caveats exist for an accurate valuation: first, time is a relevant variable as P_h is a reflection of the stream of expected rental values, so welfare changes in the future have an influence on it; second, the temporary projection of the characteristics of the house is also relevant, so it reflects not only current conditions but also an expected future improvement or worsening of, particularly, environmental conditions. As for the source for the data utilized, it is systematically collected information on sales prices and relevant characteristics as gathered by listing services and tax assessing agencies(89).

Ph depends on explanatory variables that must be included in the analysis to understand their effects. These variables can be structural or property variables (such as size, number of rooms, age…), neighbourhood or accessibility variables (transportation, crime rates, commercial amenities…) or importantly environmental variables (noise levels, air quality, and others). All relevant variables should be included lest the model be inaccurate, and they should carefully be taken as either scalars (e.g. noise contour) or understood as time-dependent variables. Additionally, there is a likelihood of collinearity among variables leading to imprecision in the associated coefficients(78, 89).

A certain amount of relevant variables (expressed as a vector Q_i) should then be able to explain the rental price of a given residential location (R_i) through the use of a linear function $R(Q_i)$. R is related to P_h in the following manner(89):

$$R = (r + t)P_h$$

Where *tax* indicates the property tax rate applied and *r* stands for the discount rate for a stream in perpetuity. Another related concept is the calculation of the welfare changes associated with the price: for a market equilibrium, the sum of the WTP of each affected individual results in the marginal value of the change (or welfare gain or loss) in an amenity, in this case an environmental amenity:

$$w = \sum_{i=1}^{N} WTP_i = \sum_{i=1}^{N} \frac{\partial P_h}{\partial q_i}$$

Where w stands for welfare, q_i is the variable pertaining to each amenity, and N is the number of individuals affected. Welfare change can be used in a cost-benefit analysis to asseverate whether an improvement is desirable by balancing its marginal cost with the expected welfare gain(89).

Hedonic price follows, ideally, a model based on linear multiple regression that obeys to the amenity variables mentioned before; this is the first expression that follows, applied for each house *j* in a period of time *t* and with a *k* amount of variables (q_k)(89):

$$P_{h\ j,t} = \alpha_0 + \sum_{k=1}^{K} \beta_k q_{k,j,t} + \varepsilon_{j,t}$$

Error ε for a house *j* depends on the time period ($\varepsilon_{j,t}$); α_0 designates the linear adjustment coefficient. However, meta-analysis of noise valuation studies, such as the one done by Nelson in 2004, fitting sales prices to a function of noise level (as environmental amenity) and all of the house and neighbourhood characteristics, commonly reach the second expression, a semi-log equation aggregated for all studied houses(90):

$$\ln(P_h) = c_0 + \sum_{i=1}^{I} c_i \ln(Z_i) + c_n \ln(n) + \varepsilon_0$$

In this case, c_0, c_i, and c_n are the different coefficients; Z_i are the non-environmental variables, and n is noise level. This function, describing how changes in noise translate into changes in house prices, is in turn converted into a Noise Depreciation Index (NDI), the percent drop in price that results from each 1 dBA increase in noise(91):

$$\mathrm{NDI} = \left(\frac{\partial \mathrm{P_h}}{\partial \mathrm{n}} \cdot \frac{1}{\mathrm{P}}\right) \times 100 = \mathrm{c_n} \times 100$$

As seen, the price function needs to be derived to attain welfare (or aggregate individual WTP), as on its own it only expresses the equilibrium points between buyers and sellers for each quantity of noise. The demand curve that gives rise to the welfare estimate requires a time series, cross-section, or pooled data approach. Other assumptions need to be made in the calculation of Ph as well: it is assumed to reflect market equilibrium at ideal conditions of consumer information and equilibrium shifts that are instantly balanced, and the function itself is taken as continuous and derivable. On the other hand, a segmentation in the housing market would require additional price functions for each consumer segment[89, 91, 92].

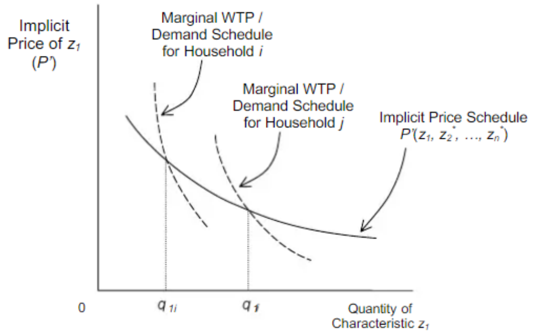


Image 14: The implicit price curve dependant on characteristics z_i aggregates all marginal WTP curves for all the different households studied [Source: (92)]

The HP model is a very useful method through which gauge market impact of the externality cost, but it is hindered by some limitations to correctly estimate welfare effects. First, there is not an infinite range of characteristics for buyers to choose from, as the housing market in a region is finite both in number and in individual housing characteristics, weakening the relation established between individual WTP and the marginal cost of a housing attribute. Second, as the model is based on the consequences of the individuals' choices of residence, WTP for improvements in environmental amenities in other points of the urban area are neglected. Third, it cannot capture behavioural responses such as the known subtle, long-term health effects generated by noise or air quality, of which the dwellers are unaware, and consequently it is not reflected in the estimated WTP. Finally, there is no yardstick against which to measure the reliability of HP studies, as they are inherently non-market valuation methods that can only be compared in terms of consistency of the results in similar contexts, with other estimation techniques (such as contingent valuation), and with empirical experience with the related markets(78).

Contingent valuation

As seen, HP is very effective in its systematic development, but there are many circumstances under which value measures cannot be calculated exclusively from market transactions, as is the case when individuals place value in an environmental amenity that they do not directly use and thus not reflected in the related market commodity. While the approach of revealing preference, as done through HP, is the most common one, the second major set of direct noise valuation methods consists in stated preference studies. These methods find their source of data in the responses of individuals about hypothetical situations ("Would you pay X EUR for Y?", "What is the most you would be willing to pay for Y?", "Which of the following alternatives do you prefer...?"), and values are inferred from their stated responses. The most common of these methods, contingent valuation (CV from now onward) involves questions that yield monetary values for a specified commodity or environmental change, as survey responses should be contingent upon a presented hypothetical scenario(78, 89).

CV aims to obtain a valuation that is close to that of the actual market of the environmental commodity if it existed. A hypothetical market is formed by questioner, questionnaire, and respondent, who should be as close as possible to a real market. The respondent should, additionally, be as familiar as possible with the good to be improved (such as peace and quiet in absence of noise) and with the hypothetical means of payment (such as a local tax). The format that the survey takes can vary significantly depending on the audience and the sort of information that is wanted, but most surveys follow a similar structure(89, 91):

1. Introductory section identifying the general topic and context of the decision the respondent is going to make.
2. Section asking questions concerning prior knowledge about the good and attitudes towards it.
3. Presentation of the CV setting: what the project is designed to accomplish, how it would be implemented, how it would be paid for (payment vehicle), and what would happen under the current status quo if the project were not implemented. This may be accompanied by materials such as charts, photographs, or others.
4. Questions regarding the respondent's WTP to obtain the good’s improvement, or WTA (willingness to accept) to give up on this improvement.
5. Debriefing questions asking why the respondent asked the way they did.

6. Section destined to collect a set of the respondent's characteristics, including attitude (whether the respondent considers himself an environmentalist), demographic data (age, household income, marital status…), and debriefing questions.

Point 4 is the key element of CV studies, as from it welfare metrics (WTP and WTA) can be derived. The procedure is initiated by the questioner’s suggesting the first bid (or starting point price), which the respondent may accept or deny to be willing to pay; in an iterative sequence (bidding game), the price is increased to find at what point the respondent would cease to be willing to pay it. The last accepted bid then becomes the maximum willingness to pay (MWTP). In reverse, the process leads to the WTA value, where bids are systematically lowered until the respondent's minimum WTA is reached(78).

This is known as the open-ended format, among which the bidding game option used to be popular in older literature, but that shifted in favour when starting point bias was revealed as significant in the results. Variations such as offering no starting point bid (asking the respondent to precise what would be a reasonable amount, which adds a different type of challenges) or to show a visual range of values among which the respondent can choose a value, or add their own if such a value is not stated. Regardless of which option is chosen, the open-ended format provides a WTP value (or individual welfare number) for each survey respondent in a straightforward manner. The bid responses can be then regressed on income (M_i), other socioeconomic characteristics (S_i), or variation in the size or composition of environmental changes (ΔQ_i) if so contemplated by the scenario design(89):

$$\mathrm{B_i = B(\Delta Q_i, M_i, S_i)}$$

The more prevalent format however is the dichotomous choice format, also known as single-shot binary discrete choice question. Consists in asking the respondent whether he would pay a certain amount of monetary units for the good (or environmental change); this is normally worded as whether the respondent would vote in favour or against a proposed plan if the X EUR value increase cost his household Y EUR in terms of taxes or higher products. In this format, there is only the choice between "yes" or "no" ("vote for" or "vote against") as if simulating a referendum, though the Y amounts proposed, which constitute the bid value, are varied among respondents. The dichotomous choice format mimics the behaviour of a regular market, where the purchase of the good might be declined or executed depending on its price; the subset of those respondents answering "no" would set their WTP beneath the bid value, whereas those answering "yes" would be above the bid value. Thus it is possible to test the hypothesis that the proportion of respondents who answered "yes" decreases with an increase in the price of the environmental good, which may then be analysed as a discrete choice model to obtain estimates of bid functions(89, 93).

Under this dichotomy, the individual will respond yes if the associated WTP for an environmental quality q^1 accounting for the subtraction of a cost T on his income M if it is higher than the WTP of an environmental quality q^0 without this cost. The opposite is true if the respondent answers negatively, as seen in the second formula. Formulas also consider individual characteristics (vector S) along with income (vector M), but market prices (P) are assumed to be constant(89):

$$\mathrm{WTP}(q^1, M - T, S) > \mathrm{WTP}(q^0, M, S)$$

$$\mathrm{WTP}(q^1, M - T, S) < \mathrm{WTP}(q^0, M, S)$$

Three advantages distinguish dichotomous choice from open-ended formats: the familiarity of the social context (the take-it-or-leave-it approach to the question), the simplicity of the decision problem by only offering two alternatives (which increases responsiveness among individuals), and incentivizes the honesty of the responders in those cases where they believe answering truthfully will amount to consequential policy changes. It also solves the problem present in open-ended questionnaires of some respondents "protesting" the scenario provided by giving responses equal to zero, very difficult to classify as outliers. Nevertheless, binary choice format also comes at the cost of revealing relatively little information about each survey respondent, requiring much larger samples to characterize central tendencies and determine statistical distribution for the WTP function accurately. Many of these hurdles are overcome by adding a follow-up question after the first dichotomy choice question that may be either dichotomy choice-based or open-ended(89, 93).

Regarding the payment question, presented as well in point 4, it is meant for respondents to answer about their WTP for a proposed plan (or WTA to accept degradation in environmental quality). The responding must understand in depth what the payment vehicle entails, that is, the method through which payments would be incurred by people to fund the provision of the good or the policy that seeks to improve environmental quality. For example, improving air quality might mean a charge to private vehicles accessing the airport; it is up to the respondent to determine how willing he would be to incur in the payment of that fee to secure emissions reductions, and at what price he sets the acceptable amount. Similarly, increase in income taxes or surcharges may be inquired about to finance government programmes that would deliver other improvements in environmental quality, or the maximum increase in the cost of contracting services (such as air fares) offered by firms that may be required to install pollution equipment control(93).

The survey methods are variable. In-person interviews generally achieve the highest-quality WTP data but are also very expensive, whereas telephone surveys, while retaining data quality and lowering the price, do not offer the possibility to describe scenarios at length or involve visual aids. Mail surveys are even less expensive, but completion of the survey indicates likely correlation with the interest (and therefore WTP of the respondent) for the commodity being valued, and limit the ability of the questioner to propose questions based on previous responses(93).

As seen, HP depends on competitive markets in equilibrium, with prices or rents that are not controlled, buyers fully informed of noise levels, and the absence of transaction costs. How informed buyers are on noise level before their purchase of a house is a complicating factor as without that awareness, HP could underestimate the value people place on quiet conditions. There are also many additional factors that are taken into consideration by the buyer in their choice of housing, which are very difficult to control as the market is never infinite in its size or amount of variations. The impact of the assumed form of the price function might also be an issue. This reliance on actual markets is also the strongest advantage of HP and revealed preference methods in general, as they avoid unrealistic behaviour. Stated preference methods avoid the imperfections of markets but also naturally feature susceptibility to strategic behaviour, which influences response from individuals surveyed. For instance, respondents might opine that someone else should bear the cost of an improvement, or might exaggerate their bids to increase policy attention(91).

Lastly, both methods find common problems in the necessity of individuals being fully informed about noise level and its effects. As seen, some of those effects are not well known, leading to bias in the results from over- or under-estimation of their impact. Similarly, what is measured is only a personal value of noise. Economic losses from a delay in a project aiming to increase airport capacity cannot be measured in the same fashion, and are difficult to determine due to the already stated multi-dimensional benefits of aviation (direct, indirect, induced and catalytic). Another important factor is the lack of focus on other properties of land other than homes, which might yield to values with an importance on par with or greater than that of the cost induced upon the housing market (such as vacant land)(91).

As a conclusion, it is possible to state the reasons why indirect methods are more common for air quality externality quantification, whereas direct methods such as stated preference and revealed preference are applied generally for noise externality. In the first case, the effects of emissions are subtle and manifest in the long-term, or through morbidity and mortality effects that are not particularly visible without an epidemiological study that might link the exposure in a certain region to metrics such as hospital admittance for respiratory diseases or lung cancer. This practice is found not just in the case of airport externalities, but also on literature concerning emissions from road vehicles and particularly climate change studies aiming to find monetary values to the damage caused. In the case of noise, however, the annoyance manifests itself in a more conspicuous manner that other more insidious impacts on health; therefore, direct methods are a good way to gauge what is the cost inflicted on the population by a certain noise threshold, the choice of which might be supported by epidemiological or other health studies. Both contingent valuation and hedonic pricing rely on the awareness of the public of the disturbance caused by the externality, and are therefore much more suitable for quantification and its corresponding regulatory solution in the case of airports.

VI. Correcting externalities

The following chapter describes in a summarized manner the most widely applied measures for the correction of the externality cost associated to noise and emissions. Two separate sections have been made to separate those measures addressing noise from those oriented towards emission reduction, and within each of them, a classification has been established in terms of the area upon which they are enforced. Under this classification, different measures are explored, furthering their understanding to aid in the understanding of their goals, means, and expected results.

The correction of externalities, also referred to under the term of *internalization* when monetary, is commonly enforced by the airport manager with the collaboration of national institutions such as the regulatory authority and governmental bodies. In the case of the European Union, correction measures may be designed and executed liberally in pursuing common environmental objectives, as is the case of European Union Aviation Safety Agency (EASA) or the European Commission. EASA is also responsible for formulating recommendations on European environmental strategy, and to coordinating efforts and information across European stakeholders. In the supra-national level, ICAO has acknowledged the need for international consensus on the approach towards externality, as reflected by the Balanced Approach on aircraft noise management and accepting the Committee on Aviation Environmental Protection (CAEP)'s standards to improve local air quality around airports. Likewise, involvement of airlines and other private interests is not uncommon, chiefly due to their role as producers of the activity that gives rise to externality; negotiation and agreement on environmental charges is key to compliance and guaranteeing sustainable growth. Finally, the community, while not involved directly in the decisions involving which measures to apply and how to apply them, is the final receiver of those decisions, and may voice its discontent if the perception is that not enough is done about the negative impact of airports, applying pressure on public institutions(17, 68, 94).

The classification of these environmental measures could be done in several different ways. First, it is possible to discriminate between those measures of preventive nature (trying to ameliorate the downstream effects of the externality before they are produced, such as insulation projects for noise or restrictions on road traffic for emissions), those that are reactive (once the externality is produced, it may be better to curtail or mitigate its effects and resolve possible damage, as is the case with compensations for the community, fines for transgressors of environmental regulation, and noise or emissions budgets) and corrective (aiming to limit the long-term trends of the impact, such as the elaboration of programmes regarding taxes, policies, procedures, monitoring, or authorizations). While this classification is useful in explaining the point of view of those introducing the measures, it does not explain the mechanism through which the measures seek to correct the externality cost on society. Following a similar approach to that of ICAO in its Airport Air Quality Manual, the corrective measures have been classified in accordance to the mechanism that characterizes them: whether this may be regulatory, as in the case of aircraft engine standards; technical, as in infrastructure design; operational, such as take-off and arrival scheduling; or economic, as is commonly seen in environmental taxes. This classification should allow then to understand also the motivation of those designing them and enforcing them, as their character (whether preventive, reactive, or corrective) may vary within each category(95).

Correction of noise externality

Noise is the most noticeable externality of air transport, as has been established in previous chapters, particularly through the perception of aircraft noise annoyance by the surrounding community. Both the regular activity of airports and infrastructure expansion when capacity must be increased lead to negative effects of diverse magnitude. The general international approach to the correction of this externality is ICAO's Balanced Approach to Aircraft Noise Management, adopted in the 33rd Session of the ICAO Assembly in 2011. This approach roughly outlines how to proceed in addressing the noise generated by air operations on an airport-level basis, identifying the problem and all possible noise-related measures through objective and measurable criteria in order to achieve maximum environmental benefit. This approach is further reinforced by EU Regulation 598/2014, which adheres to ICAO's rules and procedures in conjunction with the EU Environmental Noise Directive cited before(44, 96).

The Balanced Approach consists in four main steps(44):

1. Reduction of noise at source. This is done through research studies, modelling, technology programmes and standard setting.
2. Land-use planning and management policies. This process entails not just the planning of infrastructure, but also mitigation procedures (insulation, building codes) and financial aspects (tax incentives and charges).
3. Noise abatement operational procedures. While regarding safety, operational procedures can greatly reduce and redistribute the effects of noise around the airport and its vicinity.

4. Operating restrictions on aircraft. Any restrictions that limit access or reduce the operational capacity of an airport, such as noise quotas, as a last option after considering all the above.

It is to be noted that this approach follows a similar classification to the one given in this thesis, although with the key difference of imposing a priority in the order in which measures must be applied. While points 1 and 2 are characteristically technical and economic, points 3 and 4 take largely an operational and regulatory character.

Image 15 Balanced Approach to Aircraft Noise Management, conceived by ICAO in 2011 and adopted by the EU in 2014. Measures should be applied in numerical order [Source: (44)]

Also, as part of Regulation 598/2014 it is important to note the acknowledgement that the Balanced Approach is not a one-sided flow of policy, but rather a method to strengthen cooperation between all stakeholders. Technical cooperation is required between airport operators, aircraft operators, ground handlers and air navigation service providers; it is critical as well to involve local resident representatives and relevant local authorities, whom are to be consulted and must receive all due technical information. This stakeholder collaboration process receives the term of Collaborative Environmental Management or CEM(97).

The 2019 EU Aviation Environmental Report states that 84% of European airports employed land-use planning processes and the definition of noise zones, a 65% implemented sound insulation schemes for local communities, and that 90% implemented noise abatement operational procedures. Notably, while the last of the four steps should only be used exceptionally, 79% of the airports consulted indicated that employed operating restrictions: on noisier aircraft (78%), night flight restrictions (75%), runway restrictions (48%), noise budgets (18%), and movement caps (18%)(44).

Regulatory measures

Regulatory measures are those that establish mechanisms through legal or normative processes, which include laws, rules, bans, standards, quotas, limitations and the establishment of institutions or platforms to monitor and enforce such mechanisms. Since in many cases the mechanisms may be of different nature, such as in the case of night restrictions, their implementation may be considered technical, operational, or economic instead. This choice has been made considering that the airport manager, as well as public authorities, are ultimately those responsible for setting correction mechanisms of any nature, even if those are executed by third parties (such as the community itself or airlines).

The first measure of strict regulatory character is the establishment of noise budgets or quotas. A given number of decibels L_{den}, L_{night}, or both, may not be exceeded for a time period (generally a year) in certain enforcement points located around the airport surface. Noise load on these points may either be calculated through mathematical means from noise metrics gathered by equipment located elsewhere, or obtained directly by equipment located on the points themselves. This procedure is therefore quite restrictive on day and night operations, as using one runway due to wind conditions may impose a heavier load on it, then obligating to a larger usage of other runways in the future for that time period. Other measures may accompany these noise budgets, which in case of interdiction would aim to correct the causes that led to an excess in the noise load. Measures of this kind are present in airports such as Amsterdam Schiphol and London Heathrow(98, 99).

Another highly effective but costly measure is a cap on the number of operations over a time period or on a specific time frame. Under this sort of restriction, only a given amount of air operations (i.e. landings and take-offs) would be allowed to proceed over a number of years, a year, or for all nights of a year. This imposes a limit on airfield capacity, and demands the application of other measures such as redistribution of capacity on other airfields (intramodal) or a policy oriented to favouring other means of transportation like railway or roadway (intermodal). It also complicates negotiations with stakeholders on capacity elements such as slot assignment. Aircraft movement caps are applied in Amsterdam Schiphol (as a yearly cap effective over a number of years) and London Heathrow (night time) (98, 99).

Slot allocation can also be used to restrict how many operations are carried out during the night-time, a less aggressive measure that results in potentially heavier congestion during the day hours. The effect is a spreading out of operations throughout the night, reducing noise load. In regulated airports, any aircraft without a slot assigned would be denied take-off or landing. For example, in the case of Paris Charles de Gaulle, a maximum of 22 500 slots is granted yearly for the period 00:00-02:59 for departure slots, and 00:30-05:29 for arrival slots, with all unused slots being retired from that figure the next year. London Heathrow follows a similar policy(99).

Lastly, other forms of regulatory enforcement exist to control noise at the source, such as aircraft engine standards set by ICAO. As the authority responsible for aircraft certification, ICAO pursues the goal of progressively increasing the stringency of its noise standards over time in further updates to Annex 16, with manufacturers progressively pushing the state of the art towards quieter engines. In terms of downstream noise management, public institutions play an important role enabling community communication of noise annoyance and information sharing between stakeholders. In the first of these cases, communication must be bidirectional, collecting complaints and queries, but also providing transparency on which measures are being carried out to correct the externality; additionally, bodies to support citizens as part of other measures, such as noise insulation, are part of this regulatory effort(98, 100).

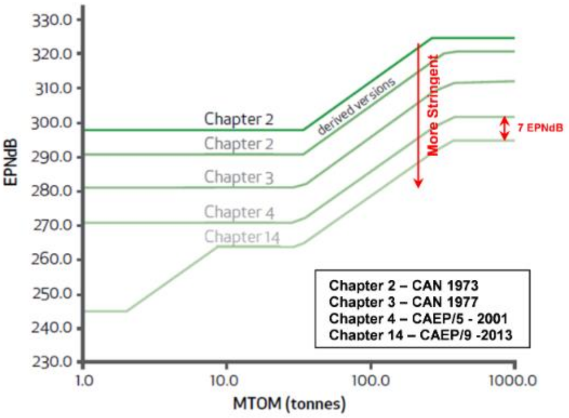


Image 16 Change in EPNL levels allowed for aircraft engine certification as devised by subsequent chapters of Annex 16 Volume I of ICAO. For a same MTOW classification, noise performance has become quieter [Source: (100)]

Operational

Any measures that alter how normal airport operations are carried out can be considered operational. Measures of this nature seek to strike a balance between how speedily, economically, or conveniently operations can be realized and their environmental impact on society, while ensuring that safety standards are observed. Under this classification, operational measures are those that take place starting on approach, landing, taxi, ramp operations, take-off and departure ascent, even if they very commonly find their origin in regulatory mechanisms such as standard operating procedures or airport restrictions. While found in conjunction with them, operational measures are more tactical in their application and less restrictive than regulatory measures, although they may be conceived as part of strategic environmental plans.

Typical measures of this type are those that sets limitations on operational procedures, either within the airport facilities or on arrival and departure, and often depending on the time frame. For sensitive time frames, particularly night-time but not excluding day-time operation, limitations on the use of APU that may imply fines in the case of unjustified use are common, such as in the presence of alternative power supply units. Such a measure requires the technical support of adequate GPU availability in terminal stands, as well as the ease of mobilisation of equipment by ground handlers when required in remote aprons. A similar limitation may apply for reverse thrust on night-time landings; reverse thrust is a usual procedure to aid braking, but its noise impact is also very high, and should not be used unless justified by safety concerns. This measure can be found in many European airports, such as Frankfurt, Amsterdam Schiphol or London Heathrow. The number of engines available for start-up during taxi might also be limited for the same reason, particularly if taxi is very long and for night-time operation, leading to the prohibition of taxiing in some cases (such as in London Heathrow). Engine tests, training flights, and other irregular operations may also be prohibited during night-time(98, 99).

Noisier aircraft, determined by their compliance with ICAO Annex 16 standards under a threshold, may also be banned from carrying out night-time operations, in addition to regular penalties that may apply based on the noise produced. This can be found in a variety of airports in Europe in agreement with what is indicated by the Balanced Approach framework, as an attempt to displace these aircraft from the airspace of congested airports and disincentivise airlines from using them in favour of quieter, newer options(99).

Establishing preferential runways for inbound or outbound traffic, or disabling certain runways depending on the period of the day, is a measure commonly found in many European airports, such as in Zurich, Madrid Barajas, or Amsterdam Schiphol. In the past, exceptions could be made for home base carriers, such as in the case of Frankfurt and its flag carrier Lufthansa, allowing them to land slightly past or before the noise curfew. Preferential runway lists may be made during the day depending on meteorological conditions to ensure operational safety, while accounting for forms of noise control such as noise enforcement points; one or more runways may be allocated for arrivals or departures depending on parameters such as wind gust, while trying to minimize in second term their noise impact. Adequate balance to set preference can be a challenging task for air traffic service providers, as demand peaks at certain points during the day and there may be considerable asymmetry between arrivals and departures. As the number of operations during night-time is inferior, capacity can be disposed of more liberally, and it is possible to close some runways for the traffic, such as in the case of Amsterdam Schiphol or Madrid Barajas. In the case of some airports, such as Frankfurt, night operations are completely forbidden; such a measure can be hard to negotiate with airlines, particularly those with an elevated number of freight operations, as it stiffens and complicates operational scheduling(98, 99).

While the design of noise abatement procedures is highly technical and necessitates advanced simulation software and hardware tools, its application results in changes in operational procedures in the airport level. Flight procedures for approach and departure are critical for economic performance and carefully designed by airlines to optimize fuel burn while maintaining safety standards. At the same time, approach and climb-out phases directly affect the noise footprint of aircraft, where engine noise becomes less important than airframe noise due to much larger friction and turbulence. Tuning the level of thrust, glide path, airspeed, deployment of high lift devices, and gear extension on approach, is a task that involves parameters that may be contradictory and that depends on a correct balance that does not harm economic feasibility, safety, legal requirements (national regulations and ICAO operations), and air traffic management capacity. In terms of approach, a step-down conventional descent contemplates different flight path angles and heights, whereas a Continuous Descent Approach (CDA) in its different alternatives, proposes a more direct, single-angle approach to touch-down. Designing noise abatement procedures for departure must be understood not only in the two dimensions of distance from the airport and altitude, but also in the geographical flight path which should divert in such a way as to minimize noise impact on inhabited areas below whilst ensuring viability for the operators. Specific SID and STAR procedures (instrumental arrivals and departures) can be stipulated for night-time conditions, and deviation from their parameters, as well as from the airways from which they are executed, may become more stringent. These measures have become increasingly popular with the advancement of modelling methods, and are currently applied in airports such as London Heathrow, London Gatwick or Amsterdam Schiphol(99, 101, 102).

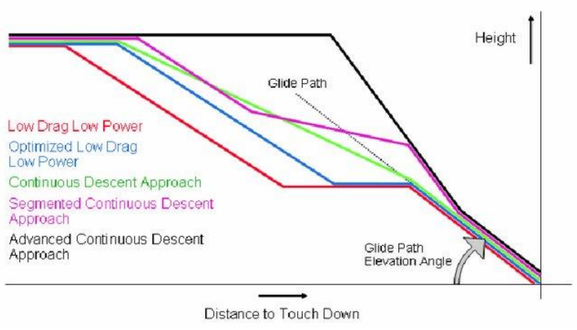


Image 17: Different CDA alternatives [Source: (102)]

Technical

Measures of technical nature consist in any involving technical means for their execution, such as design of facilities and infrastructure, air traffic management of airways and taxiways, projects for noise insulation or technology for the monitoring of noise in the airport area. In the specific case of noise insulation, while done at the request of citizens affected to the regulatory authorities, and applied mostly for economic reasons, their realisation and mechanism are technical to reduce the effect of noise as experienced by the community

As acknowledged by the Balanced Approach, land-use planning and management design is one of the first steps towards noise reduction, introducing land-use zoning around airports. As identified by ICAO, states must minimize aircraft noise through preventive measures that consist firstly in an appropriate choosing of airfield location, away from noise-sensitive areas, and taking advantage of the terrain to protect the community. Adequate measures of land-use planning should be considered not only at the initial stage of any new airport, but also on development projects of an existing airport, such as the opening of a new runway or a terminal building. Additionally, zones must be defined for different noise levels taking into account the population dwelling in them (noise contours) and establish criteria to appropriately use land according to forecasts of traffic growth. This is a prevalent problem in many European airports, where the surrounding urban area exceeded forecasts beyond land planning for forecasted new infrastructure to meet demand. Other forms of land-use that are to be considered are the impact taxiing aircraft from and into runways may have into the surroundings, or sufficiently equipping aprons and stands with GPU support to avoid APU use(103).

Another important manner in which noise impact from air traffic may be controlled is flow management. Dependant on the air traffic service provider, a correct flow management can lead to an improvement in how noise is perceived geographically as well as in terms of intensity. This measure, alternative to stricter forms of regulatory control such as slot allocation or noise budget enforcement points, relies heavily on modelling of noise at the source as well as its dispersion towards the surrounding area. Good synergy can be established between flow management and some forms of operational corrections such as descent and approach procedures or preferential runway lists(104).

Insulation plans stem from the necessity of curtail the cost of the externality caused by noise, under the premise that community perception of noise is much quieter in an insulated building. Insulation is assumed to be a less expensive alternative to economic compensation for individual households, as it should not depend on income or, to a certain degree, on the intensity of the noise perceived. Additionally, funding for projects of this sort may come from the instatement of charges on operations, reinforcing the economic motivation of this measure. Sound insulation plans consist of an identification of all residential units in interest zones, measuring the degree to which they are insulated to determine how much supplementary insulation is needed, and then drawing up a plan that may viably insulate all of the residential buildings to meet acoustic quality standards satisfactorily. If noise zoning techniques determine that certain areas are below noise standards for residential development, strict isolation requirements can be applied for future projects, or even impose a ban of regulatory character on initiating new developments. These projects have been carried out around airports such as Madrid Barajas, Amsterdam Schiphol, or London Gatwick(105).

Finally, noise monitoring is key not only to technical measures to correct externality, but to the strategy chosen by the airport and its execution through measures of different nature. Monitoring solutions are based not only on empirical measurement (microphones that capture the acoustic signal and convert it into an electric signal) but also on data extrapolation from modelling, which may then serve as a baseline to the identification of other possible measures, or to ascertain their effectiveness and make forecasts. Noise monitoring programmes may be found both in the private industry and as part of public monitoring systems dedicated for separate airports or as part of a national network, generally under the supervision of independent public institutions in collaboration with airport management. In the European level, the European Aircraft Noise Measurement System, or EANS, was founded in 2002 as an NGO that today offers free online information about aircraft noise covering 54 airports with 697 noise monitoring stations in 8 European countries, financed through membership fees and donations. Another important institution based on information sharing and benchmarking of noise policies is the Airport Regions Conference, with over 30 members representing nearly 70 million European citizens(44, 99).

Economic

Measures that find their reasoning in regulating or taking advantage of how the market operates are classified here as having an economic character. As seen, while the air traffic market is visible and its transactions can be identified clearly, the effect of externality is not represented plainly; as such, mechanisms such as taxes and charges are applied on the former to result in an effect on the latter. In this case as well as in the others seen before, measures are taken by some form of authority or regulating body, though seeking to attain some form of favourable market balance or direct correction of the externality. These direct forms of intervention can be characterized as compensation and grants aimed to be received by the community within noise zones to improve or guarantee their welfare in face of the externality cost imposed by airport activity.

Airport charges are a common form of taxation aimed at maintaining and improving airport infrastructure. While there are many concepts for these charges, such as for stand parking or power supply usage, the maximum take-off weight (MTOW) of an aircraft dictates how much should be charged per landing or take-off, to represent the deterioration imposed on infrastructure. In accordance with ICAO's Policies on Charges for Airports and Air Navigation Services, noise charges should be applied following these principles(106):

i) Noise charges should be levied in airports experiencing noise problems to recover no more than the costs associated to their alleviation or prevention.
ii) Noise charges should be associated with the landing fee, possibly by means of surcharges or rebates, an be based on certification provisions of Annex 16.
iii) Noise charges should not be discriminatory between users and not be established at such prohibitively high levels as to prohibit the operation of a certain aircraft type.

While these guidelines are adhered to, there is a large degree of freedom as to what degree these charges can be enforced. As a conclusion, noise charges are an addition to MTOW-dependant landing charges on the basis of ICAO noise engine certification standards. While these charges cannot press a certain aircraft type out of operation, they may pursue the goal of displacing noisier aircrafts more and more from the airspace, or at least to render them less profitable for airlines to operate and therefore incentivize fleet renewal.

Taxes paid by users equal to the externality cost caused by their production decisions receive the name of Pigouvian, and intend to make the market take into consideration the full costs associated with the taxed goods in what is known as internalization(107). In this case, the externality cost may be too complex for a completely accurate valuation that may yield to the calculation of an exact tax, but correlation can be made between tax pressure for aircraft based on their noise certification and how aircraft impact the community based on their noise certification. Taxes would then be paid by the market to extract the value of externality, at least partially, and paid by both users (in the form of ticket surcharge or transport fees) and airlines (in the form of reduced operating benefits). Under this logic, noisier aircraft would progressively be pushed out of the market due to a higher tax, while quieter aircraft may be exempt or receive a bonus to reward their use by the part of airlines. This form of 'guided' market self-regulation is economically sound in the sense that can compensate both the damage caused and result in a positive trend for the industry, and as such has been applied in most EU airports in some form. The trend towards quieter operations is further aided by ICAO regulatory standards becoming stricter, as mentioned before(44).

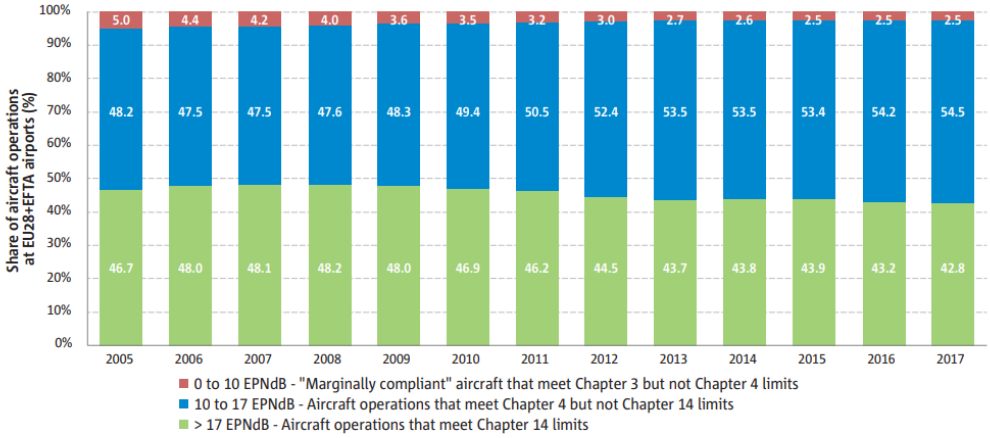


Image 18: Aircraft that do not comply with noise standards set by Chapter 4 of ICAO Annex 16 Volume I have become marginal in EU28+EFTA members. The increase in Aircrafts that do not meet Chapter 14 while meeting Chapter 4 is due to the rising stringency of certification standards [Source: (44)]

Tax revenue acquired from this mechanism may be allocated for compensation of the surrounding community, solely or in aggregation with other budget allotment from governmental institutions. Compensation is relatively simple to calculate as a product of externality quantification, since the factors on which households should be compensated may be surmised from quantification studies (such as proximity, income, or degree of insulation). As proven by studies however, monetary compensation is rarely a better alternative than insulation projects, which have a less expensive implementation cost and manifestly result in better long-term results as far as noise annoyance is concerned. Additionally, since compensation may be dependent on factors other than utilitarian social principles, a household with a larger income would be entitled to a larger compensation due to the larger externality cost experienced, contrary to what may be politically acceptable. Other mechanisms contemplate relocation grants to favour the institution of noise zoning below a certain sound quality threshold to increase the welfare of households affected, or to facilitate the choice to relocate through other means such as tax breaks(81, 86).

Correction of emission externality

Unlike noise, emissions, manifested mainly through the decrease in air quality (though there are other important effects such as global warming), are not as perceptible as noise and are harder to valuate as seen before. Both the negative effects of greenhouse effect gases and those of air quality pollutants may be mitigated through the same measures, as their aim is to diminish the emissions at the source as well as to correct and compensate the externality cost.

ICAO has been developing measures to address emissions from aircraft engines in the vicinity of the airport and from relevant airport sources since the late 1970s, as stipulated in Volume II of Annex 16. Standards have become increasingly specific and tailored to the research on exposure to pollutant concentration, a task undertaken by the technical Committee on Aviation Environmental Protection (CAEP). The adoption of new policies and standards responds to their published Standards and Recommended Practices (SARPs) and their regular revision prior to implementation in Annex 16. One such example is the substitution of the smoke number present currently for engine certification by non-volatile particulate matter (nvPM) concentration and mass in CAEP/11, scheduled for next year. Other provisions address liquid fuel venting and the main gaseous exhaust emissions from jet engines, namely HC, NO_X and CO(108).

Similarly, the ICAO Assembly on its 37th session in 2010 agreed to the adoption of a resolution to aspire to carbon neutral growth from 2020 onwards. ICAO also devises a number of measures to tackle carbon emissions that comprise aircraft technology improvements, operational improvements, sustainable aviation fuels, and market-based measures under the name of CORSIA, or Carbon Offsetting and Reduction Scheme for International Aviation. On the other hand, and as supplementary support to this framework, the European Union has its own Emissions Trading System, which constitutes the cornerstone of EU policy to combat climate change of all sources. Measures concerned will be described in further detail below classified as regulatory, operational, technical or economic(44, 109).

Regulatory

As is the case with noise, competent authorities are increasingly more strict about the application of rules and regulations in order to reduce polluting emissions from the aviation industry, a trend that can be attributed to deeper knowledge about the health effects associated with emissions and broader public perception about them. At the international level, ICAO has established a series of environmental parameters and regulations that must be followed by all airlines as found in Annex 16 Volume II. Certification procedure comprises take-off (at 100% available thrust) for 0.7 minutes, climb (85% available thrust) for 2.2 minutes, approach (30% available thrust) for 4.0 minutes, and finally taxi (7% available thrust) for 26 minutes, generating testbed data by running the engine at each thrust setting. The results offer figures for fuel flow, emission index, and the measured smoke number as seen in previous chapters, which in turn allow for the calculation of emission rate, total gross emissions and values of gram per unit of thrust and the maximum smoke number. While the focus has been set on NO_X reduction, with goals of -45% NO_X emission reduction for 2016 and a -60% for 2026, particulate matter is receiving growing attention and is set to replace smoke as part of certification procedure. As mentioned, ICAO holds regular meetings with other stakeholders such as airlines and manufacturers to regulate emissions for the future, in an attempt to continue a downward trend towards cleaner engine while retaining operability(60, 110).

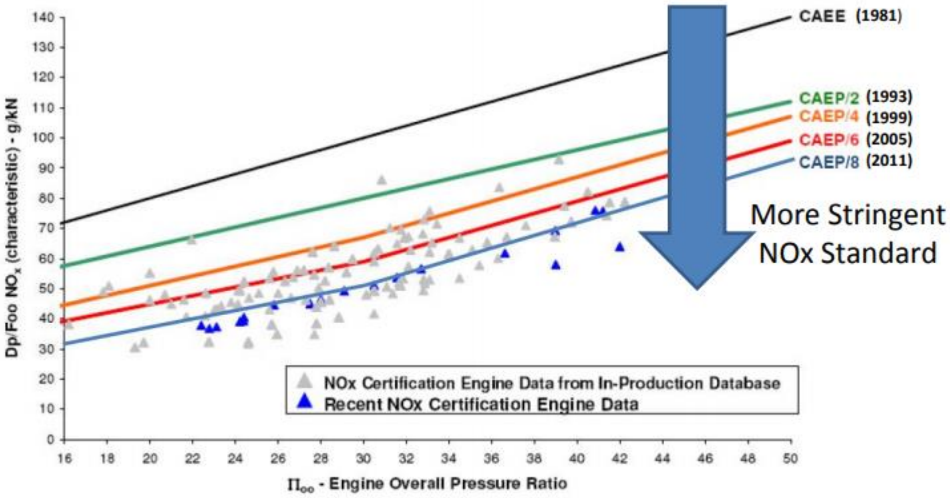


Image 19: CAEP recommendations have become more stringent over time overall, but particularly regarding NOx emissions [Source: (110)]

Other regulations based both on national policy and individual airport policy contemplate the setting of standards for ground support equipment, facilities, and private vehicles. While not as commonly regulated or enforced, GSE standards should contribute to an effort in the modernisation of the ground fleet of ground handlers and service providers, as well as the phasing out of outdated, more polluting equipment. On the other hand, air quality standards for private vehicles are part of broader EU policy and obey to national interests in meeting European goals, but directly affect the impact of ground emissions in the surrounding area. In an analogue way to noise restrictions, other bans or limitations may apply on the local level, such as APU operating restrictions. More importantly, ground side road traffic may be prohibited from idling in airport accesses as to reduce concentrated emissions in the vicinity(53).

Operational

In terms of operational measures, many restrictions can be applied by the airport authority to abate emissions in day to day airport activity. Many of them are similar to those of noise as they strongly depend on engine performance and seek to limit thrust values or periods of operation. Good examples of this form of control are limiting engine start-up prior to push-back based on stand location, to establish single-engine taxiing or a limit on thrust values during taxi, or to make aircraft towing compulsory even in remote stands where aircraft may be able to enter gates under own power. Maintenance procedures such as engine washing can also be mandated to be part of maintenance routines in airports, though there are few examples of such measures being implemented.

Measures of a combined technical and operational character, such as improved approaches and air traffic management are among the most common industry trends to reduce fuel burn, and with it, emissions. Scheduling improvement at the hands of the air traffic service provider, as well as a better optimization of airline timetables and route networks to improve load factor, are also favourable to improving fuel efficiency in the operational level, though they are present as goals rather than concrete measures to reduce operational costs. Other approaches en-route that may be applied by airlines are the limitation of cruise altitude, which would trade an increased flight time and a slight increase in CO_2 emissions for a decrease in high-altitude contrail generation(53, 111).

Aircraft handling and support services can also contribute to lowering GSE emissions by adhering to operational procedures. Following indicated ramp speeds, performing regular equipment maintenance, and avoiding the generation of emissions during refuelling are factors to consider, as well as the responsibility of the airport manager in facilitating access to stands for generators, pneumatic start-up units, and mobile GPUs. As for plant emissions, these may occur during normal operation, in which case low emission procedures should be in place particularly for maintenance; activities such as painting, engine testing, or cleaning may lead to unnecessary releases of pollutants. During construction, a code of construction practice to ensure air quality can contemplate limits on wheel washing or damping down, and the use of covered vehicles for transportation. Finally, many measures can help alleviate ground road traffic emissions, which are quite commonplace in European airports. In particular, alternatives to airport check-in (such as online check-in) are helpful in speeding up the lingering time of cars and other vehicles, and the establishment of preferential lanes for public transportation or the enabling of preferential parking for alternative-fuel vehicles may also aid in day to day congestion(53, 95).

Technical

Global technical advances are a key part of technical measures to allow creating a less polluting environment. In the case of aviation, as an industry strongly reliant in the state of the art of the aerospace industry, numerous technical advances are aiding the trend towards greener future operation and aiding on correcting the impact of emissions in current operations. The first technical measures to address emission externality are not dissimilar to those of noise: land use planning and infrastructure planning is key to controlling the impact of emissions on the surrounding community. Examples of infrastructure design are the longitude and path of taxiways, which is critical to determine the effects on local air quality of emissions from aircraft engines idling at low thrust settings, or high-speed runway turnoffs, a measure to reduce runway occupancy time and reduce taxi-in time (and therefore emissions) by expediting aircraft vacating runways.

Other technical innovations that work jointly with the reduction of noise contemplate modifications such as appropriately equipping stands with GPU to deter the use of APU. From a survey conducted in 2018 at 51 European airports, 82% of respondents provide GPU options to aircraft on-stand and 58% of respondents provided pre-conditioned air to aircraft at the airport gate. In order to reduce polluting emissions, modifications have been made at many airports, such as changing the distribution of taxiways as mentioned before. This takes part in a larger effort to enhance flow management to increase airport capacity as well as to optimize the time aircraft spend taxiing or manoeuvring to reduce emissions. Parallel take-off and landing runways, for instance, facilitate efficient operations and greater control of the flow of airport movements, and lead as a side-effect to less congestion during demand peaks and therefore towards less time spent lingering or idling. This form optimization is convenient not just for airport managers to increase capacity and redistribute demand, but also for aircraft operators to improve the economic cost of operations by diminishing fuel burn. Continuous descent operations and RNP, which have positive effects on noise annoyance, are also useful solutions to ameliorate the concentration of emissions locally by avoiding the overflight of populated areas or optimizing fuel burn during approach(44, 95).

In the same way, Eurocontrol is the regulatory authority in the EU for the establishment of programmes and procedures devised to the reduction of polluting emissions. The Single European Sky ATM Research project, or SESAR, aims to unify criteria at a European level for more fluid and standardized air traffic, developing different practices with very promising results. One of them is the AMAN programme (Arrival Management, extended to en-route airspace) that allows for smoother traffic management by earlier sequencing of arrival traffic at a point further away from the airport, leading to less fuel burn from reduced vectoring at lower levels, reduced holding, and maintaining more fuel efficient flight levels for longer.

Other solutions part of SESAR that contribute to reduce the fuel burn and emissions are the automated assistance to controller for surface movement planning and routing. This allows controllers to graphically edit routes and automatically compute estimated taxi times, contributing to more predictable surface operations and therefore decrease the fuel burn and polluting emissions(112).

Other notorious technical improvements include the development of cleaner aircraft engines under the pressure to renovate aircraft fleet, as well as the use of alternative fuels with a lower pollutant release ratio. Newer engines become cleaner thanks to techniques such as novel cycles that increase bypass ratios, incorporation of lean burn technology, and rich quick quench lean technology, all of which rely on adequate modelling of thermodynamic and aerodynamic engine behaviour under the use of new materials and designs. On the other hand, sustainable alternative fuels seek to reduce the carbon footprint of aircraft engines as well as to ameliorate the release of certain pollutants such as NO_X without changing aircraft or infrastructure. Due to severe constraints for aviation fuel (such as a high energy content and a very low freezing point), ICAO has adjusted policy to contemplate alternative fuels since 2009 in what is denominated as drop-in jet biofuels, which reduce carbon impact while being completely interchangeable with conventional fuels retaining technical and safety characteristics. The EU has the potential to increase its bio-based aviation fuel production capacity, but the uptake by airlines remains minimal due to various factors, including the cost relative to conventional aviation fuel and low priority in most national bioenergy policies. Alternative fuels have also been proposed for GSE and many European airports contemplate projects to promote GSE fleet renewal in the hands of private operators within the airport area, moving towards the adoption of vehicles based on the combustion of natural gas, compressed natural gas, liquefied natural gas and petroleum gas, or based on electrical and hybrid drives. The installation of emission reduction devices and fuel fume capturing systems, such as PM filter traps, may also be mandated by the airport authority. In a survey conducted by ACI in 2018 on the 51 airports of the EU28+EFTA, 86% of the respondents reported that their vehicle fleet included electric vehicles, 47% have hybrid models and 35% have vehicles that run on sustainable alternative fuel. In addition, 18% of airports indicated that they provide incentives for taxis to also use these types of ‘green’ vehicles(110, 113).

There is also considerable effort in the transition towards cleaner plant energy generation, adopting measures to augment how much of the energy demand is covered by renewable energy sources on site. Other measures for infrastructure and stationary sources consist in low emissions energy plants and incinerators (including the installation of filters), energy conservation measures both in existing buildings and in maintenance and construction projects, or changes in stack heights and location to reduce geographic impact. From the same

2018 survey, 61% of survey respondents indicated that renewable energy is produced on site, of which 87% was declared to be solar, 3% wind, 32% geothermal, 16% biomass, and 16% other miscellaneous sources, covering 20% or more of their energy needs for 11% of those airports. Finally, enhanced public transit and intermodal connections, as well as road structure layout, are measures that depend on infrastructure planning, deployment, enhancement, and renewal based on technical advancement. While 98% of airports indicated that public transport was available, a majority of airports also reported that less than 20% of their employees actually use it to travel to work. In a separate analysis, on average, 36% of passengers travelled to airports by public transport in 2018, compared to 43% in 2016(44).

Economic

Economic measures follow a similar pattern to those explained in noise correction, and are frequently associated to increased operational charges for carriers. Similarly, in regards to economic measures to decrease the emissions and improve local air quality, ICAO has established in its Policies on Charges for Airports and Air Navigation Services a series of principles for states interested in levying charges to recover the value of the externality cost from the users that generate it(106):

i) Local air quality charges should apply to airports with a defined local air quality problem, and designed to recover no more than the costs of measures applied to its mitigation or prevention.
ii) The cost basis for charges should be transparent, and the share directly attributable to aircraft should be properly assessed.
iii) Consultations with stakeholders should take place before any such charges are imposed on users.
iv) Local air quality charges should be designed to address the local air quality with cost-effectiveness in mind.
v) Local air quality charges should aim to resolve the problem at airports in a fair and equitable manner, should be non-discriminatory between users, and not be established at such levels as to be prohibitively high for the operation of certain aircraft.
vi) Special consideration should be given to the need to reduce the potential impact on the developing world when levying such charges.
vii) Local air quality charges emissions-related charges should be associated with landing charges, possibly by means of surcharges or rebates, or as separate charges but subject to the proper identification of costs.

viii) Aircraft emissions charges should be based on data that most accurately reflect the actual operations of aircraft, following ICAO standardized LTO cycle times-in-mode as seen in Annex 16 Volume II.

ix) Air quality charges on aircraft that are in international operation should be annually reported to ICAO. The charging authority should maintain records regarding the fees collected and the use of funds to be made available to all users.

As may be seen, these principles are more specific and contain more clauses than those pertaining to noise related charges, due to the nature of aircraft emissions not being as tightly tied to local air quality, but also being relevant during cruise. The ultimate goal of these charges should be to function as a Pigouvian mechanism to recover the value of externality and allocate tax revenue to its correction or compensation, as well as to incentivising airlines towards a phasing out of more pollutant aircraft to relieve tax pressure.

As dictated by Directive 2009/12/EC on Airport Charges, emission charges are often found in conjunction with noise charges as a form of unified environmental tax, although standalone presence is not rare. Approximately 60% of the busiest EU28+EFTA airports have implemented environmental charges as of 2019 according to the EU Aviation Environmental Report of that year. In line with ICAO guidance, these charges are focused on local noise and/or air quality (mainly NO_X) impacts rather than global climate change impacts (CO_2), and are dependent on numerous factors including the aircraft and engine type, the certified noise and emission levels and time of the day. The overall proportion of environmental charges relative to total airport charges is increasing, but remains small as of 2016 (approximately 4% for long haul and 1% for short haul flights). As airport charges represent 15-20% of low-cost carrier costs and 4-8% of network carrier costs, the evaluation report concluded that it is questionable whether those charging schemes influence the fleet operating at the airports(44, 114).

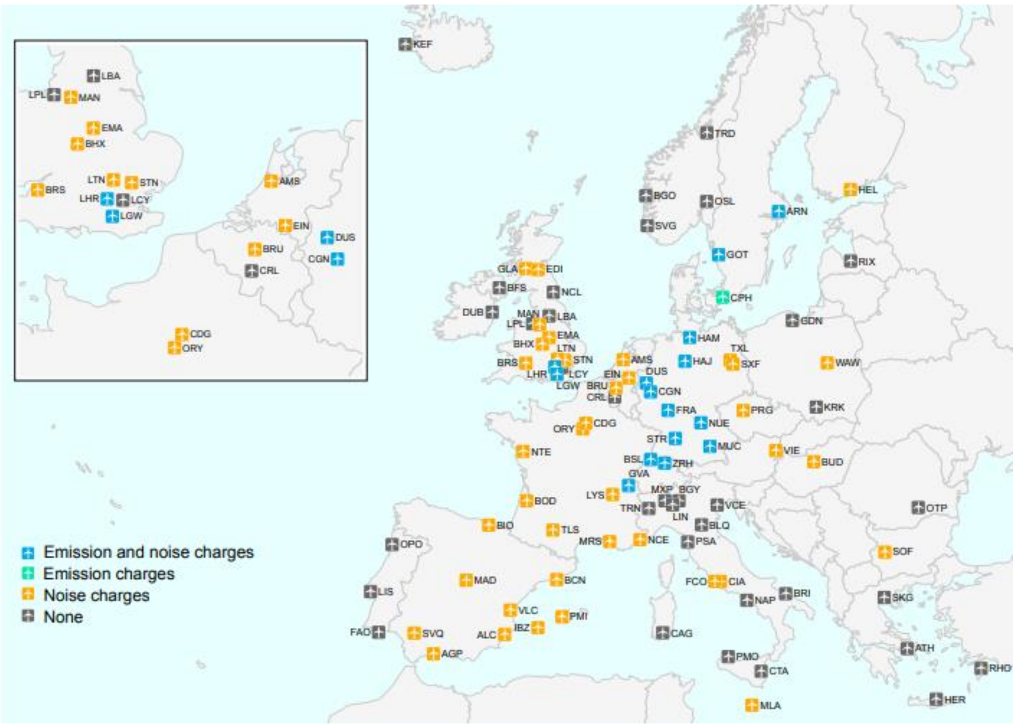


Image 20: EU28+EFTA airports and whether they apply joint emission and noise charges, either of those solely, or neither as of 2019 [Source: (44)]

The EU Emissions Trading System is a market-based measure based on a cap and trade system aiming to ambitiously reduce emissions over time. The EU ETS seeks to incentivise CO_2 mitigation within the sector or, alternatively, to offer trading these emissions by further CO_2 reduction in other sectors of the economy that may pose lower abatement costs or options are more readily available. Starting in 2008, aviation was included as part of EU ETS, and so greenhouse gas emissions from this sector are to meet Paris Agreement objectives and reduction targets of 20% and 40% for 2020 and 2030 respectively. Only flights between airports located in the European Economic Area are included in the EU ETS at present, up until 2023 when ICAO's CORSIA may lead to reconsideration and inclusion into a global emissions roadmap. Eurocontrol, working with the European Commission as well as individual states and aircraft operations, is responsible for the implementation of the aviation element of EU ETS, in particular to harmonise data and reduce compliance costs. The initial cap for aviation in the EU ETS was based on average historic aviation emissions between 2004 and 2006, while the current cap for aviation activities for the current phase of the ETS (2013-2020) was set to 95% of these historical aviation emissions. Aircraft operators may use aviation allowances and EU Allowances, which need to be purchased at variable EU ETS carbon prices (varied between 4 and 6 EUR per tonne of CO_2 during the 2013-2017 period) when exceeding the allocated cap, or may purchase international credits contemplated in CORSIA up to a maximum of 1.5% of their verified emissions(44).

CORSIA, the Carbon Offsetting and Reduction Scheme for International Aviation, was adopted by the General Assembly of ICAO member states in 2016 to offset international aviation's CO_2 emissions above 2020 levels through international credits as part of the objectives set by the Paris Agreement. The Implementation Elements are part of the Standards and Recommended Practices (SARPs) gathered by international experts part of the CORSIA project, including rules on eligible fuels and emission units to comply with offsetting requirements that are to be implemented by participating states through national law. CORSIA is comprised of three implementation phases: the pilot phase (2021-2023), a first phase (2024-2026) and a second phase (2027-2035). During the pilot phase and first phase, offsetting requirements will only be applicable to flights between States that have volunteered to participate. The approach used by CORSIA is route-based and applies to international flights; any flight covering a route between two ICAO states must comply with CORSIA offsetting obligations under the provision that both are participating states. As of 2019, 76 states have officially notified ICAO that they intend to voluntarily participate in the pilot and first phase of CORSIA, representing approximately 76% of international aviation activity in terms of Revenue Tonne Kilometres. As part of this scheme, aircraft operators must submit an Emissions Monitoring Plan to ICAO to monitor, verify and report their fuel use, and their annual emissions offsetting requirements are calculated by the state responsible. Operators must then meet their offsetting requirements on a 3-year compliance period basis by purchasing and cancelling CORSIA eligible emissions units, in a process similar to EU ETS(44, 115).

The difference, however, is that while EU ETS is a cap-and-trade system limiting the number of allowances issued (constraining the total amount of emissions per sector) which is revised downward progressively, CORSIA is an offsetting scheme aiming for a cost-effective compensation across sectors, resulting in carbon neutral growth in aggregate terms through the purchase of offset credits by aircraft operators. EASA and EUROCONTROL are supporting the European Commission on the implementation of CORSIA both within Europe and internationally. Additionally, the Airport Carbon Accreditation programme was launched by the Airports Council International Europe in 2009 as a voluntary industry led initiative seeking to provide a common framework for carbon management. 237 airports worldwide work jointly as part of this programme to encourage and enable best practices in the industry through a certification rating organised in four levels: mapping, reduction, optimisation, and neutrality. Scope and obligations for carbon emissions management increase from the first level to the fourth. As of 2018, there were 133 European airports participating in the programme, corresponding to 1.3 billion passengers (65% of passengers in Europe)(44, 116).

Local authorities may also enforce other measures with the goal of shifting incentives towards the reduction of the carbon footprint or the total mass of pollutants released during airport operations. Emission-based charges could be applied upon licensing fees for airport GSE, or for facilities and infrastructure used by third party GSE. A similar surcharge could be applied on parking pricing, or in the way third parties manage airport parking lots through public concession. Other measures of economic nature that may be promoted include reducing the number of private cars parking at the airport by applying incentives to those who take public transportation to reach the airport, and to improve the public transport network to connect the airport with the surrounding urban centres. The promotion of carpooling is a cultural measure of economic nature that could also result in reduced ground road traffic emissions(95).

Measures for the correction of externalities can be concluded to present many similarities between noise and emissions, although with notable exceptions of regulatory and economic nature. Policy should, ideally, adhere to the principles and recommended practices indicated by ICAO and responsible EU bodies, though in practice, many differences arise in the application and justification of these measures, even if pursuing goals in line with the provisions of the supra-national institutions. As will be seen in the case study, the case of economic measures, less stringent and easier to negotiate among stakeholders than regulatory measures, is to be remarked due to the particularities of their implementation, which should respond to a Pigouvian model. Under this framework, it can be concluded that correct externality valuation is vital, as environmental charges do not otherwise satisfactorily resolve the social burden of externality.

VII. Case study: noise externality in Amsterdam Airport Schiphol

The case of Amsterdam Airport Schiphol is noteworthy for a variety of reasons. Firstly, the Netherlands was a forerunner in the implementation of noise reduction policies as early as 1967, in a period when ICAO had begun to shift its attention towards environmental impact and European airports were not yet concerned with national-level policy. Secondly, the measures envisioned in the first decade of 2000 are reaching its expiration date, causing considerable turmoil among all relevant stakeholders and particularly the surrounding community, under concern that growth may supersede quality of life. The analysis of this case study will start by laying out the events that led to current policy, and then take a detailed look at relevant literature that influenced the decisions. As the effect of this decisions is manifested through the correction of the externality, measures will be examined to then move towards concluding recommendations on their effectiveness from a technical point of view.

Current situation

Amsterdam Airport Schiphol (referred to by its IATA station code, AMS) is the main international airport of the Netherlands and the busiest airport in Europe by total aircraft movements, registering 514 625 take-offs and landings in 2017(117). The airport is located 9 kilometres southwest of the city of Amsterdam in the municipality of Haarlemmermeer, and it is composed by a single terminal serviced by six runways of which five are dedicated to general traffic. Serving as its base, Schiphol is the main hub of the Dutch flag carrier KLM, an important stakeholder in its operations as the leading airline in the airport. According to 2017 figures, Haarlemmermeer is home to 146 003 inhabitants, of a total of inhabitants for the region of North Holland of 2 809 483(118).

As is the case with many other international airports in the European continent, Schiphol quickly outgrew the region that accommodated its initially very limited infrastructure. The inception of jet engines and gradual increase of activity lead to the first concerns being voiced by the surrounding community in 1969, acknowledged in the Annual Report presented by Schiphol Group while debating the inauguration of a fifth runway. In the second half of this decade the Kosten Committee set out to investigate solutions to noise annoyance in the Netherlands, orientating noise abatement from solving it to reducing it. The introduction of noise contours allowed to fix legally controlled caps: for a given geographically indicated contour, the annual average noise level should not exceed a figure considered acceptable; the chosen unit would be the Kosten unit (*Kosten-eenheid* or Ke). Rules such as the prohibition of new housing development within a 35 Ke contour (which would be later extended to 20 Ke) or a policy to financially compensate inhabitants through noise insulation for houses located within 40 Ke were promoted. This latter project, denominated Noise Insulation Schiphol started in 1984 and charged upon airlines, leading to the insulation of 3700 house at a cost of 126.8 million EUR. Other important measures pioneered by the Kosten Committee included the Schiphol Noise Annoyance Committee, and the initiation of operational measures through the air traffic service to reduce noise annoyance, such as the use of preferential runways and of specific runways for departures(119, 120).

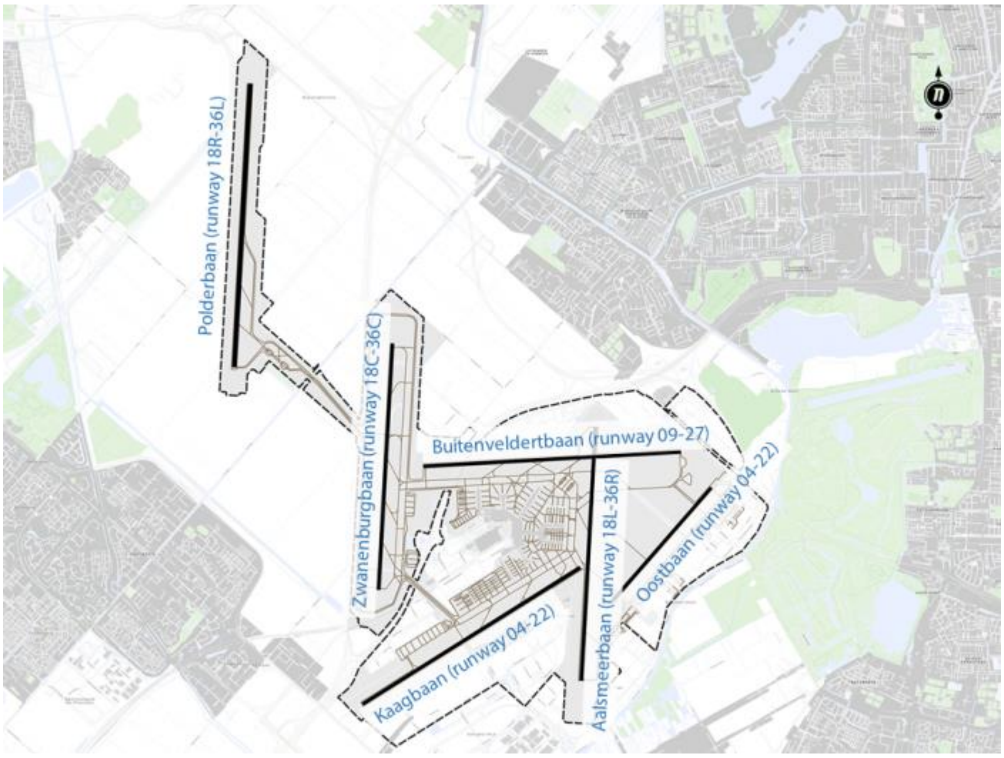


Image 21: Layout of Amsterdam Airport Schiphol. The northernmost and most recent runway, the Polderbaan, is seen along with its other 5 runways [Source: (120)]

In the decade of 1980, the rising importance of the airport for the national economy and its increased multimodality led it to embrace the role it plays today as an international distribution centre, further aided by deregulation in the European ambit the following decade. Conflicting ambitions between the competitivity of the airport and the surrounding area meant that legal reform was needed, with a chapter being dedicated to Schiphol in the new Aviation Act of 1992 (Wet Luchtvaart) that set the new environmental framework. Additionally, a new contour cap was negotiated between stakeholders in the Key Planning Decision for Schiphol Airport and Surroundings of 1995, allowing for the construction of a new runway but devising that a maximum of 15 100 houses should be located within the 35 Ke contour, though with later amendments(119). The opening of the fifth runway, the so called Polderbaan, in 2003 propagated noise impact into areas that had not experienced it before in a magnitude unforeseen by environmental planning. The Polderbaan demanded taxiing times of 10 to 15 minutes, increasing noise levels considerably in the execution of this procedure, and strayed from the forecasts on the noise enforcement points established in the surrounding area. This matter signified an important introspection into the balance between airport capacity and externality impact: denying the possibility of simultaneous take-offs due to the environmental regulations prohibiting diverting departures, and requiring a new Environmental Impact Assessment. The years between 2004 and 2006 saw a large number of studies of very diverse nature being published to address the complexity of the noise question, after public effort was coordinated in response to public outcry(121, 122).

Much of the scientific and technical research on Schiphol Airport's environmental impact comes from this first decade of 2000 as to support institutional decisions on how to control and monitor it, particularly noise. This allowed for a reformulation of the airport's environmental policy in practical terms, seeking to involve the community to much higher levels than ever before, but was also aimed at polishing technical details that made the former system complicated to explain to stakeholders, such as the usage of Kosten units instead of the EU standardized L_{den} and calculating noise contours instead of measuring them. Revised or new operational procedures, namely Continuous Descent Approach (CDA) and Noise Preferential Routes (NPR) were also implemented; the former establishes a "gliding" descent instead of a step-down descent to reduce engine usage, and the latter defines flight paths (corridors) for departures and arrivals by setting preferential runways.

Most notably, it involved the community in the elaboration of a package of measures to balance Schiphol's growth in harmony with its surroundings in what is known as the Alders Table, a series of consultation rounds taking place from 2006 to 2008. The process included representatives from the Dutch government, Schiphol Group, Air Traffic Control, the airline KLM, the province of North Holland and affected municipalities, and representatives of the Schiphol Area via consultative platforms. The measures that emerged from the Alders Agreement were(123):

- A maximum capacity of 480 000 air transport movements in 2010, and 510 000 air transport movements until 2020

- Higher selectivity regarding hub operations
- Development of regional airports to relocate non-hub operations
- Suppression of the enforcement point system and the Ke to replace it with a measurement system understandable for politicians and laymen
- Implementation of nuisance-reducing measures such as CDA
- Funding of projects to improve the quality of life in the direct surroundings

As of 2020, policies in place include the Alders Agreement, the Aviation Policy Document of 2009, the Schiphol Action Agenda of 2016, and the commitment with the European Clear Skies programme(124).

The operation cap set by the Alders Agreement is the most controversial, as this ceiling was exceeded in 2018 without a clear replacement and governmental goals shifted towards incremental growth while maintaining noise levels(125). Given the complexity of the issue, this case study will focus on the research done at its stem during the 2003-2008 period, focusing on two studies quantifying the impact of noise through the HP method and one using the CV method, and comparing their findings with the measures implemented.

Research analysis

There is not a large body of work in terms of aircraft noise valuation internationally, and in the case of the Netherlands for the last two decades, these can be narrowed down to three important publications. The first two, more recent, quantify externality through an HP methodology, and they support each other's findings in terms of content; the last one, following a CV approach, utilizes older data (pre-Polderbaan) but the conclusions are comparable as it presents marginal (i.e. per decibel) cost figures.

Schreurs et al. (2011)(126)

The first comprehensive study for the valuation of the externality caused by noise in the Schiphol Airport area after the opening of the Polderbaan was conducted by E. Schreurs, E. Verheijen, and J. Jabben under the patronage of the National Institute for Public Health and the Environment, dependent on the Ministry of Health, Welfare and Sport of the Netherlands. This study set the technical groundwork for the upcoming legislative work that would be applied later, and their conclusions are of critical interest.

The focus of the study is to perform a cost-benefit analysis noise and noise measures in the Netherlands by studying the noise depreciation of real estate and land values through the hedonic pricing method. As explained, the goal is to assess the decrease of this value due to increasing noise levels using the Noise Depreciation Index as key parameter. The scope is set on the national level, but Schiphol is of considerable importance due to its concentrating role in air traffic operations in the Netherlands.

For the purpose of generating a hedonic pricing model, data from both noise levels and property prices are required. The study uses noise maps generated from data gathered in 2007 by the Dutch National Aerospace Laboratory determining noise levels in L_{den}, resulting for the case of Schiphol in a region of interest of 55x71 km^2. Secondly, it employs real estate appraisal values from 2005 collected from the tax assessment database of Dutch municipalities and averaged for each postal code.

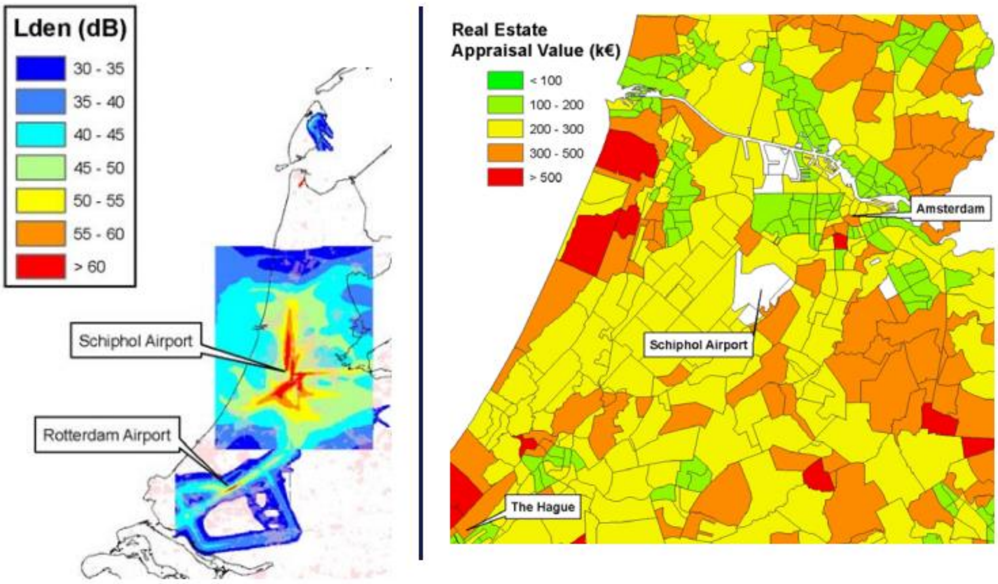


Image 22: To the left, noise map obtained from data of the National Aerospace Laboratory in 2007. To the right, real estate appraisal values around Schiphol in 2005, associated to postal code [Source: (126)]

The model used by Schreurs et al. is based on the HP method described earlier in this study, with the important inclusion of a threshold level L_{TH}. The economic loss of real estate is relevant for values exceeding this threshold(126):

$$\mathrm{loss} = \mathrm{NDI}\sum_{i}(L_i - L_{TH})P_i$$

Where P_i is the price of the dwelling, L_i is the noise load at each individual dwelling (in L_{den}), and *NDI* is the Noise Depreciation Index. The NDI, expressed as a percentage, should give the rate of depreciation of the market value for each increase in noise levels above the threshold; for each 1 dB increased, a house would decrease its value in a percentage indicated by the NDI. As acknowledged by the authors, the NDI suffers from uncertainties in its calculation. The studies of Nelson (2004), yielding a value of 0.6%, and Schipper (1998), with values ranging 0.9-1.3%, are cited to exemplify this uncertainty; a value of 0.8%, closer to the study by Dekker and van der Straaten that will be reviewed below, is taken for the purposes of this study, close to the study's own estimation of 0.77%. As for the threshold value, literature mentions values in the range of 45-55 dB, though lower values seem to increase uncertainty and lead to an overestimation of social losses; under this justification, the authors chose a threshold of 50 dB(126).

The formula explained above yielded in the study a total loss of 670 million euros for the Schiphol Airport area, 65% of the total loss evaluated in the study. The study follows with an estimation for the depreciation of land prices, considering the prohibition on new developments in the 20 Ke (or 58 L_{den}) noise contour explained previously (denominated LIB-4). Schreurs et al. use estimates derived by De Regt (2003) to establish possible noise damage of the prohibition of new dwellings in natural, agricultural, residential (unprepared and prepared) and business plots. A 50% decrease in value for residential land within LIB-4 is assumed, as well as a percentage of 20% to define to which extent it is prepared. Depreciation is set at 6.5 EUR/m^2 and 50 EUR/m^2 respectively for prepared and unprepared residential land. As an example, a residential area of 10 000 m^2 would consist of 8 000 m^2 prepared and 2 000 m^2 unprepared; therefore, the loss for the prepared surface would be 100 000 EUR at a price of 50 EUR/m^2 and for the unprepared surface 52 000 EUR at a price of 6.5 EUR/m^2, for a total loss due to airport noise of 152 000 EUR in this example. For the LIB4 area, with a surface of 190 km^2 after subtracting 17 km^2 corresponding to the airport itself, 24 km^2 are dedicated for residential use, resulting in a total loss of 360 million euros from residential surface(126).

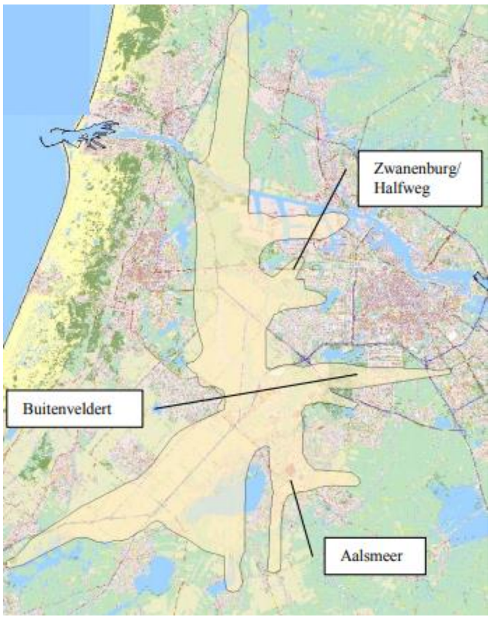


Image 23: LIB4 area delimitation around Schiphol [Source: (126)]

Dekkers and van deer Straaten (2008)(127)

The second study, published by Dekkers and van der Straaten in 2008, follows a similar HP approach, stemming from similar literature about this method. The model chosen in this case responds to a basic regression model to obtain a price function based on explanatory variables(127):

$$P = \alpha + \beta S + \gamma L + \tau G + \varepsilon$$

Where *P* is a vector of house prices, *S* is a matrix containing transaction-related characteristics (transfer tax, year of sale...), *L* is a matrix of structural characteristics (number of rooms, quality of maintenance...), and *G* is a matrix of spatial characteristics (neighbourhood, accessibility...). α, β, γ and τ are regression coefficients and ε is a vector of random error terms. A log-linear model is used as is common in these studies.

For this study, the threshold value taken is cited as being determined by the Environmental Assessment Agency of the Netherlands at 45 dB, 5 dB lower than seen at Schreurs et al. to account for a subjectively larger disturbance; similarly as in the latter study, this is the lower significant bound for an effect on housing prices, but it also contemplates larger uncertainties. Spatial data, consisting in price, date of sale and structural house characteristics such as floor area or number of rooms, is provided by the Dutch Association of Real Estate Agents for the 1999-2003 period. After linking these characteristics to each postal code, neighbourhood characteristics are included: population density, number of shopping outlets, and distance to nearest railway and highway accesses. Aircraft noise data is provided by the Netherlands Institute for Health and the Environment via the National Aerospace Laboratory for an area of 70x55 km^2 as seen in Schreurs et al. Other noise sources, railways and main roads, are also contemplated. Temporal devaluation effects are also considered, as well as other differences on municipal level [See Annex 6].

The regression analysis is applied over 66 000 house transactions, following a log-linear model (whereupon the dependent variable equals the natural logarithm of the transaction price). The results show that house price increased in the 1999-2003 period likely due to interest rate development and demand pressure on the housing market; understandably, there is a positive dependency on surface area, number of rooms, maintenance quality, presence of a garden, and, with the highest influence, the level of urban facilities. The NDI obtained for aircraft noise is the largest among all noise sources, at 0.77, well within the wide range found in literature (0.10-3.57) (127).

To analyse the effect of different noise levels on house prices, the authors generate six separate noise level classes, of which four are significant for the range studied (over the threshold of 45 dB). As noted in the study, the coefficients of the regression analysis are very sensitive to this threshold, and become insignificant (i.e. below standard error) at threshold values above 50 dB.

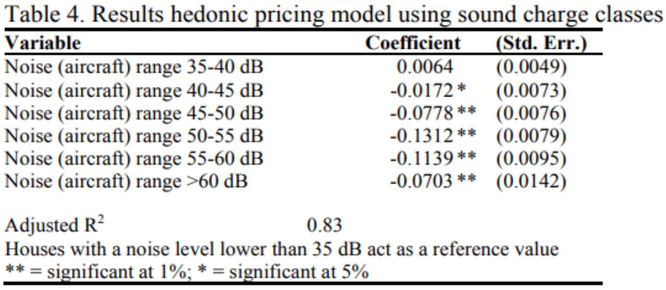


Table 4. Results hedonic pricing model using sound charge classes

Variable	Coefficient	(Std. Err.)
Noise (aircraft) range 35-40 dB	0.0064	(0.0049)
Noise (aircraft) range 40-45 dB	-0.0172 *	(0.0073)
Noise (aircraft) range 45-50 dB	-0.0778 **	(0.0076)
Noise (aircraft) range 50-55 dB	-0.1312 **	(0.0079)
Noise (aircraft) range 55-60 dB	-0.1139 **	(0.0095)
Noise (aircraft) range >60 dB	-0.0703 **	(0.0142)

Adjusted R^2 0.83

Houses with a noise level lower than 35 dB act as a reference value

** = significant at 1%; * = significant at 5%

Image 24: The six noise classes generated, along with their corresponding regression coefficients. An R^2 of 0.83 is to be noted [Source: (127)]

The study proceeds with the calculation of marginal and total benefits of noise reduction. As explained, following a linear model allows for the estimation of the impact of a 1 dB increase or decrease regardless of the current noise level of the house above the threshold (e.g. a house under a noise level of 50 dB would experience the same increase or decrease in its price as a different house under a noise level of 60 dB). The theoretical basis for this procedure is inferred from deriving the abbreviated regression function with all the other variables being constant(127):

$$\ln(\mathrm{P}) = \mathrm{C} + \beta$$

$$\mathrm{M}_{\mathrm{B}} = \beta\mathrm{P}$$

Where *P* is the average house price from the dataset, *C* is the aggregate of all constants in the model, β is the coefficient of the aircraft noise variable, and M_B is the marginal benefit. As the average house in the dataset is priced at 234 883 EUR, a reduction of 1 dB in noise level would result in a marginal benefit of 1 872 EUR for any house above the threshold level. Adjusted to interest rate (7% for the 1999-2003 period), this yields a marginal benefit of 102 EUR per dB per house per year(127).

As seen in Schreurs et al., total benefits of noise level reductions follow from the multiplication of the marginal benefits of an average house by the total tax-value of all the houses in the dataset exceeding noise levels of 45 dB. A hypothetical reduction in residential areas of 1 dB in 2008 (interest rates disregarded) would result in a total benefit of 574 million euros. At an interest rate of 7%, this converts to 40 million euros per year assuming the number of houses remained equal in the area studied. In a parallel fashion, an increase would also set some houses at a level above 45 dB, therefore being relevant for the cost calculation. Values obtained by the authors are modelled to reproduce the social cost/benefit model. The diminishing marginal benefits per dB noise reduction are noteworthy, as well as the increasing marginal costs per dB noise increase.

Noise variation (dB)	Marginal benefits/costs per annum (M EUR)	Total benefits/costs (M EUR)
-5	12	1732
-4	15	1560
-3	23	1339
-2	31	1015
-1	40	574
1	49	697
2	57	1505
3	67	2469
4	77	3558
5	87	4798

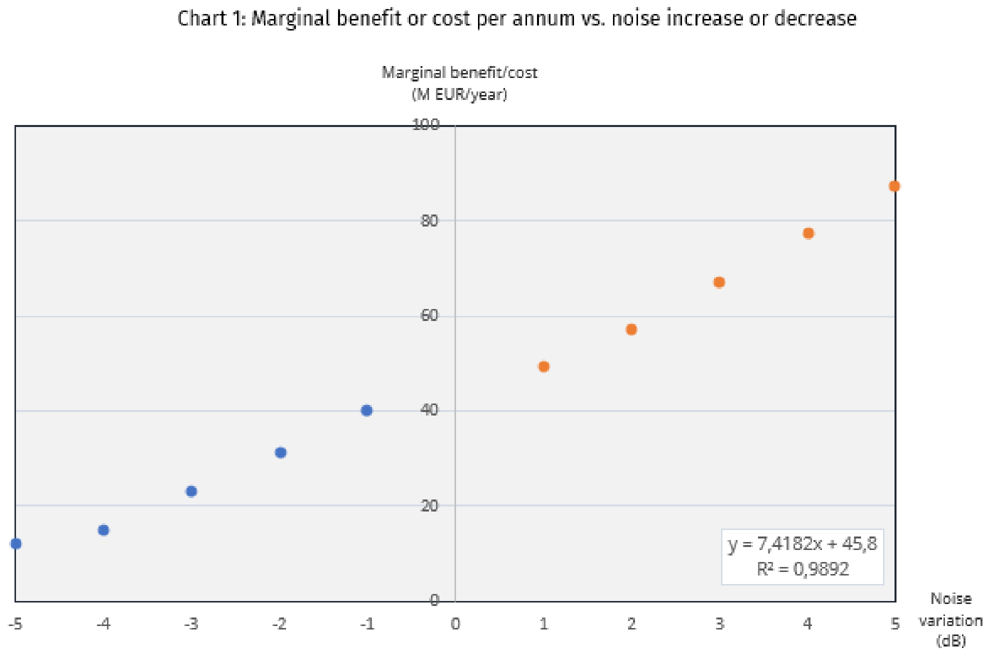


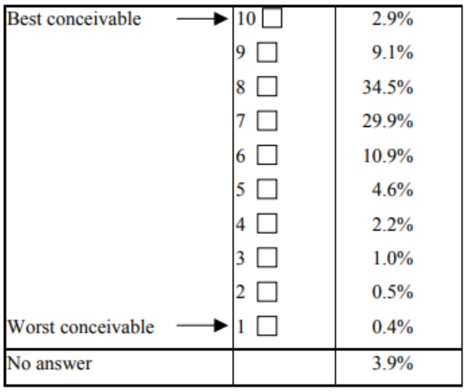
Chart 1: Marginal benefit or cost per annum vs. noise increase or decrease

Image 25: Development of the data found in the study. The linear trend is clear (at R^2=0.99) for the unitary increases of L_{den}. Data points in blue represent a cost, but are shown positive for illustrative purposes [Source: elaborated with data from (127)]

van Praag and Baarsma (2004)(128)

Lastly, the research of van Praag and Baarsma (2004) will be covered. Using a stated preference approach consisting in a CV method, denominated by the authors as happiness survey, the goal is the same as in the HP studies seen above. Based both on market information and subjective questions, where respondents are asked to rate their quality of life on a 1-10 scale, variables such as income and exposure to aircraft noise should permit modelling of the WTP of the individuals towards repairing the effects of the externality.

The methodology consisted in a mail questionnaire consisting in 51 questions not focused on aircraft noise as to avoid bias in the respondents, but rather on quality of life in more vague terms (“Health, well-being and living situations in the Netherlands”). As a second objective, the questionnaire should collect the relative importance of aircraft noise from a list of nuisance factors. The questionnaire was sent by mail to random households in a 50x50 km^2 area around Schiphol, and an additional later reminder to increase engagement among respondents; the response late was of 17%, for a net sample of 1 400 respondents. The relevant items in the questionnaire were the main question addressing the well-being of the individual (*Cantril ladder-of-life*) and question 25, which asked the participants to rate the nuisance perceived from different noise sources. As is typical in CV studies, other demographic parameters such as household incomes, age, family composition, education, or type of dwelling were also collected, as well as postal code. This latter data variable should allow for linkage with postal code-based noise levels as formerly seen in HP studies, drawing from the same source (National Aerospace Laboratory of the Netherlands) [See Annex 7 for Question 25].



Best conceivable →	10 ☐	2.9%
	9 ☐	9.1%
	8 ☐	34.5%
	7 ☐	29.9%
	6 ☐	10.9%
	5 ☐	4.6%
	4 ☐	2.2%
	3 ☐	1.0%
	2 ☐	0.5%
Worst conceivable →	1 ☐	0.4%
No answer		3.9%

Image 26: Cantril ladder-of-life. The top of the ladder (10) represents the highest achievable level of happiness for the respondent, whereas the bottom (0) represents the worst possible life. The relative frequency of the 1400 respondents is shown on the right [Source: (128)]

The study follows general CV assumptions, defining a welfare function *W(y,p,z)*, where *y* stands for income, *p* for price, and *z* for the value of the externality. This discussion can be further simplified as *W(y, p(z), z)* or *W(y, z)* considering that price depends on noise as an external factor. The discussion then proceeds to defining the market in the Schiphol area as either in equilibrium or in dis-equilibrium. The equilibrium situation, as followed by HP methods, would state that differences in the welfare function would depend exclusively on the externality, all other variables being equal (thus $W(y,z) = W(y,0)$). However, in this case price differentials do not perfectly compensate for differences in noise exposure, which as the authors note is applicable to the Schiphol area. The Dutch housing market is strictly regulated and geared to guaranteeing dwelling opportunities over self-regulating market mechanism, constrained by planned size and prices, a split between the stocks of the free sector and social housing (the latter amounting to 70% of the market and being available only under certain income conditions), price control for rent increases linked to inflation, and permanent rent contracts. Under these assumptions, the authors theorize that the correct expression would be(128):

$$C_z = \left(P_h(0) - P_h(z)\right) + \Delta y$$

Where C_z is the shadow cost of the noise externality z, $P_h(0)$-$P_h(z)$ is the price differential as identified in the HP method (price bearing the cost of externality subtracted to the ideal price bearing no cost), and Δy is income compensation, or in other terms, the difference needed to adequately balance out the decrease in welfare due to the price differential. This expression emerges from the welfare function $W(y,z)$ expressed previously, which finds its basis in the empirical analysis of the Cantril ladder-of-life question shown before.

The variables selected for the estimation of W are net monthly household income ($ln(y)$), family size ($ln(fs)$, $ln^2(fs)$), interaction term of income and family size ($ln(y)*ln(fs)$), age of the respondent ($ln(age)$, $ln^2(age)$), noise (*noise*), and an interaction term between noise and a dummy for noise insulation (*Ins*noise*). The subjective noise perception variable (*noise)* is made to depend on monthly housing expenses, the presence at home, the presence of a balcony, and the presence of a garden, as well as family size and objective noise level in Ke. The resulting welfare function is as follows(128):

$$\begin{aligned} W = {} & \beta_0 + \beta_1 \ln(y) + \beta_2 \ln(fs) + \beta_3 \ln^2(fs) + \beta_4 \ln(y) * \ln(fs) + \beta_5 \ln(age) + \beta_6 \ln^2(age) \\ & + \beta_7 noise + \beta_8 Ins * noise \end{aligned}$$

Under the assumptions made before, welfare W can be expressed as depending on a noise increase and a compensating factor for income y. *noise* is the perceived noise nuisance (depending on objective noise level in Ku and other intervening variables already mentioned, abbreviated as x) and n as a vector for other variables:

$$W(y + \Delta y, noise(Ke + \Delta Ke, x), n) = W(y, noise(Ke, x), n)$$

Substituting the first expression in the welfare equation results in the following:

$$\begin{aligned}(\beta_1 + \beta_4 \ln(fs)) * (\ln(y) + \Delta \ln(y)) + (\beta_7 + \beta_8 \mathrm{Ins}) * \big(\mathrm{noise}(Ke + \Delta Ke)\big) \\ = (\beta_1 + \beta_4 \ln(fs)) * \ln(y) + (\beta_7 + \beta_8 \mathrm{Ins}) * \mathrm{noise}(Ke)\end{aligned}$$

$$\Rightarrow\ (\beta_1 + \beta_4 \ln(fs)) * \Delta \ln(y) = -(\beta_7 + \beta_8 \mathrm{Ins}) * \alpha \Delta \ln(Ke)$$

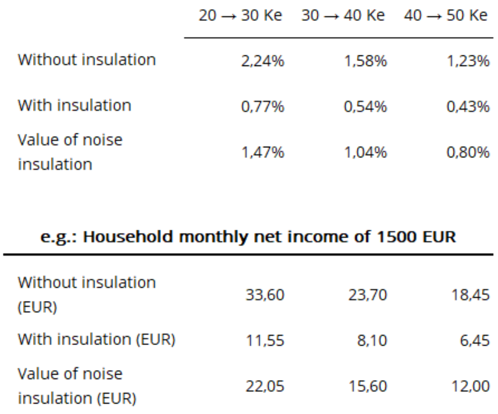
$$\Rightarrow \frac{\partial \ln(y)}{\partial \ln(Ke)} = -\alpha * \frac{\beta_7 + \beta_8 \mathrm{Ins}}{\beta_1 + \beta_4 \ln(fs)}$$

Which is the expression that gives rise to the estimated residual shadow cost. In other words, this offers an elasticity function between noise levels Ke and income y, so for any increase of Ke a corresponding increase in income would be necessary to maintain welfare as a constant. A wealthier individual then would be less affected by an income loss of 100 EUR than a poorer individual, but would also have to be compensated by a larger amount. Substituting the parameter values given by the study results in two different expressions depending on the presence or absence of noise insulation$^{(128)}$:

$$\xRightarrow{\text{with noise insulation}} \frac{\partial \ln(y)}{\partial \ln(Ke)} = -0.3445 * \frac{0.1126 + 0.0736}{0.5039 + 0.3061 * 0.6743} = 0.0189$$

$$\xRightarrow{\text{no noise insulation}} \frac{\partial \ln(y)}{\partial \ln(Ke)} = -0.3445 * \frac{0.1126}{0.5039 + 0.3061 * 0.6743} = 0.0546$$

The compensation being much larger if the house is not insulated. It is worth noting that this reproduces the log-linear relationship seen in HP methods, due to subjective perception generally working logarithmically.



	20 → 30 Ke	30 → 40 Ke	40 → 50 Ke
Without insulation	2,24%	1,58%	1,23%
With insulation	0,77%	0,54%	0,43%
Value of noise insulation	1,47%	1,04%	0,80%
e.g.: Household monthly net income of 1500 EUR			
Without insulation (EUR)	33,60	23,70	18,45
With insulation (EUR)	11,55	8,10	6,45
Value of noise insulation (EUR)	22,05	15,60	12,00

Image 27: Values as shown in the study, reproduced and extrapolated for an exemplary household with a monthly net income of 1500 EUR. Annotation: 20 Ke equal approximately to 53 dBA L_{den}, 30 Ke equal approximately to 55 dBA L_{den}, and 40 Ke equal approximately to 58 dBA L_{den} . [Source: elaborated with data from (128)]

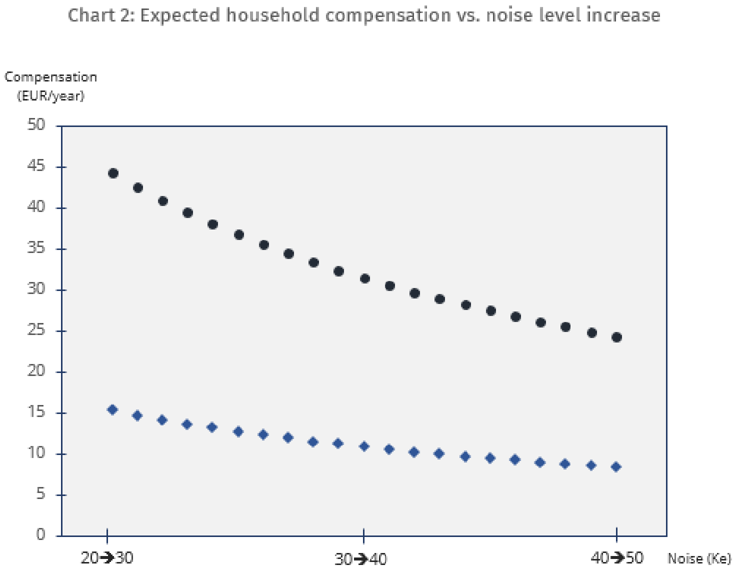


Image 28: Chart reflecting the extrapolated data based on the values given by the study. The log-linear relationship is clear. Increments are of 10 Ke for each data point [Source: elaborated with data from (128)]

According to Dutch legislation discussed above, the obligation to insulate dwellings applies for those properties at 45 Ke or more. The total cost of aircraft noise under this perspective could be understood as the total amount of compensation for the population living in the area of study, computing the residual cost compensation per household respective to the income and noise level for each household and aggregating all the resulting values. The figures obtained demonstrate that for a threshold of 20 Ku (approximately 53 dB L_{den}), the compensation required is 100.62 million euros, at an average of 56.63 EUR per household. Over 397 000 commercial flights carrying a total of 36.8 million passengers in Schiphol in 1999, that gives a figure of 253.45 EUR per flight or 2.73 EUR per passenger, for a noise threshold of 20 Ku. The authors do not, however, justify the application of this tax, which disregards aircraft type, or the setting of 20 Ku as a noise threshold.

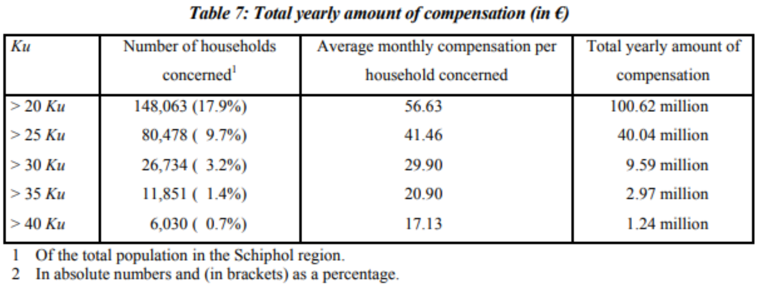


Table 7: Total yearly amount of compensation (in €)

Ku	Number of households concerned[1]	Average monthly compensation per household concerned	Total yearly amount of compensation
> 20 *Ku*	148,063 (17.9%)	56.63	100.62 million
> 25 *Ku*	80,478 (9.7%)	41.46	40.04 million
> 30 *Ku*	26,734 (3.2%)	29.90	9.59 million
> 35 *Ku*	11,851 (1.4%)	20.90	2.97 million
> 40 *Ku*	6,030 (0.7%)	17.13	1.24 million

1 Of the total population in the Schiphol region.
2 In absolute numbers and (in brackets) as a percentage.

Image 29: average monthly compensation and number of households affected per noise level [Source: (128)]

Externality correction policies

Despite the diverging conclusions for the studies, Schiphol strengthened its noise policies as a result of the Alders Agreement and the environmental legislation that followed. The decisions taken, while radically finding their origin on a technical perspective, were very much political in nature, and resulted from institutional commitment to community perception of the annoyance, which is inherently biased as confirmed by the neutral approach found in the CV method applied by van Praag and Baarsma. The Polderbaan was chiefly responsible for growing hostility toward Schiphol Airport's activity, and while the switch towards a more stringent policy was not unjustified and grounded on very real concerns in quality of life, there is also the confounding phenomenon of an increasing sensitivity to noise, scepticism about public control, and requests for further operational measures.

These changes in corrective measures were manifested first of all in more restrictive noise levels and standardization of the methodology, moving away from the Kosten standard of the late 60s. A total of 33 calculation points would reveal noise levels around an imaginary aggregated runway handling all traffic during the year; noise levels, in turn, would be an average of L_{den} and L_{night} (as explained, L_{night} adds a penalty of 5 dBA for the 19-23h frame and 10 dBA for the 23-07h frame) and not expressed in the more complex Ke. Similarly, 35 enforcement points for L_{den} levels and 25 for L_{night} levels designated by the government would determine compliance with cumulative yearly limits, also known as a noise budget. In principle, excess in a single enforcement point would result in government measures, which makes balance in the presence of uncertainty of meteorological conditions very complex. This task is handled by the Air Traffic Service (LVNL) through preferential runway lists depending on the period of the day(129).

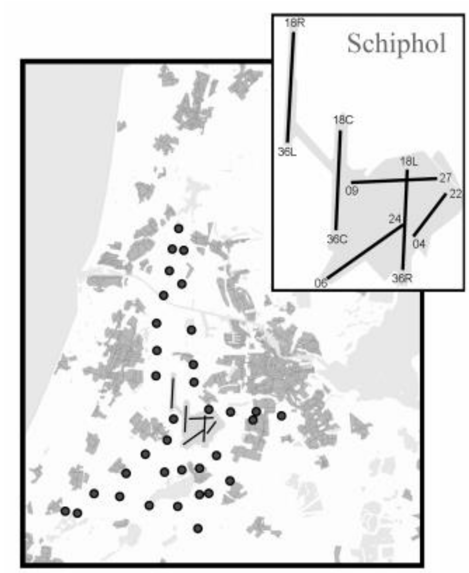
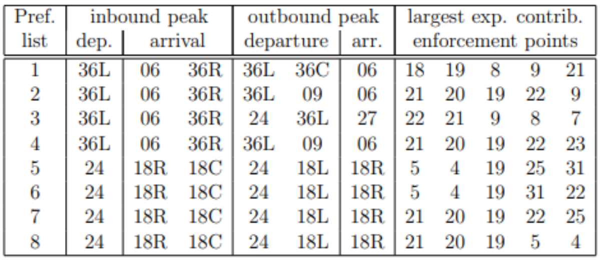


Image 30: Enforcement points for L_{den} in Schiphol [Source: (129)]

In a parallel fashion to airline seasonal planning, noise planning is made for Schiphol airport for an operational year running from November 1 through October 31, when noise exposure metrics are reset. This operational plan must clearly demonstrate that the environmental impact of the planned operations does not exceed the noise budget allocated for the year;

the remaining capacity once environmental limits are applied is distributed through slot assignment to airlines. The efficiency of this method relies on the distribution of traffic over the available runways in such a way that annual budget is met for every enforcement point, though discrepancies between planned and actual operations occur and enforcement points are closely monitored during the operational year. Data is collected automatically by the Schiphol Noise Monitoring System, or NOMOS(130).

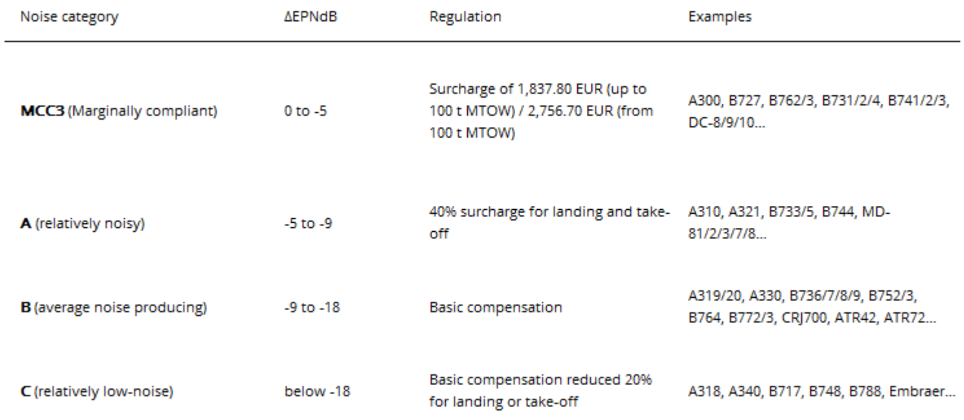
The multiple runway configuration present in Schiphol was initially conceived due to the strong wind dominance in the Dutch weather, mostly from Southwest to Northwest, and is the main reason for the large area affected by noise externality. Since Schiphol serves as a hub airport, traffic is characterized by arrival and departure waves, resulting in inbound and outbound peaks that determine runway combinations. This, along with the aforementioned uncertainties, helps determine which priority lists are used to properly manage noise load. A study by Meerburg et al. (2007) suggested the application of a mathematical framework to optimize runway combinations similar to the one currently in place, based on an optimization tool in conjunction with a traffic forecast model, though other methods have been proposed by authors like Kuiper et al. (2011)(129, 130).



Pref.	inbound peak			outbound peak			largest exp. contrib.				
list	dep.	arrival		departure		arr.	enforcement points				
1	36L	06	36R	36L	36C	06	18	19	8	9	21
2	36L	06	36R	36L	09	06	21	20	19	22	9
3	36L	06	36R	24	36L	27	22	21	9	8	7
4	36L	06	36R	36L	09	06	21	20	19	22	23
5	24	18R	18C	24	18L	18R	5	4	19	25	31
6	24	18R	18C	24	18L	18R	5	4	19	31	22
7	24	18R	18C	24	18L	18R	21	20	19	22	25
8	24	18R	18C	24	18L	18R	21	20	19	5	4

Image 31:Priority list for runways (departure and arrival) and how many enforcement points are expected to be affected by noise load [Source: (130)]

As for economic regulations, the latest updated information available is the document for Airport Charges in 2018. The charge applicable in accordance to the noise generated depends on the extent to which each individual aircraft occupies the available capacity within Schiphol's noise budget for the noise contour area. The airport authority adheres to ICAO standards for engine certification in terms of noise (in EPNdB), by subtracting the sum of the three limit values (take-off, side-line, and approach) by the sum of the three certification values. Four noise categories emerge from this calculated value (ΔEPNdB). The first of these categories, MCC3, is banned from operating in Schiphol; a surcharge regulation charge is applied such a landing occur in case of emergency, dependent on MTOW. Additionally, noise-dependent surcharge is applied for night take-offs and landings (23-06h): 50% for take-offs and 27% for landings, with an additional 100% surcharge for MCC3 aircraft, and an additional 50% for category A aircraft(131).



Noise category	ΔEPNdB	Regulation	Examples
MCC3 (Marginally compliant)	0 to -5	Surcharge of 1,837.80 EUR (up to 100 t MTOW) / 2,756.70 EUR (from 100 t MTOW)	A300, B727, B762/3, B731/2/4, B741/2/3, DC-8/9/10...
A (relatively noisy)	-5 to -9	40% surcharge for landing and take-off	A310, A321, B733/5, B744, MD-81/2/3/7/8...
B (average noise producing)	-9 to -18	Basic compensation	A319/20, A330, B736/7/8/9, B752/3, B764, B772/3, CRJ700, ATR42, ATR72...
C (relatively low-noise)	below -18	Basic compensation reduced 20% for landing or take-off	A318, A340, B717, B748, B788, Embraer...

Image 32: Summary for the charges found for 2018, dependent on aircraft noise category [Sources: (131)]

This form of taxation is clearly Pigouvian (i.e. aims to internalize the externality cost by charging the unitary price of the activity that gives rise to it), and pursues a balance of incentives that invites airlines to modernize their aircraft fleet. This is clearly seen in the positive charge, or reduction, in landing and take-off charge for category C aircraft, among which newer versions stand out. Schreurs et al. point out that air fleet renewal represents the most significant factor for a trend in noise reduction. Considering that the approximate life expectancy off an aircraft is at least 25 years, as older aircraft are phased out progressively the effect of noise levels will be increasingly notorious, leading to overall much quieter traffic. The authors note that for Schiphol airport, a reduction in noise emission of 1 dB can be expected due to renewal of the air fleet by 2020, resulting in up to a 17% increase in surface available for real estate development(126).

Image 33: Scheurs et al. note the downward trend in aircraft noise owed to quieter engines. Extensive research exists on the topic [Source: (129)]

Regarding operational restrictions, airport authority Schiphol takes particular care to avoid noise impact particularly in night hours. This approach is both to avoid exceeding enforcement point noise budgets and to diminish community annoyance, due to the particularly augmented sensitivity to noise events during the night in the presence of overall lower background noise levels. Thus, while the number of operations is not directly limited, accumulated L_{den} and L_{night} values serve a similar purpose. Operational restrictions during the 11-06h time frame include exclusivity for slot-regulated operations, which are already limited by Eurocontrol regulations; APU use is forbidden in the ramp, making GPU compulsory; and reverse thrust is forbidden. Aircraft equipped with engines certified with a bypass ratio above 3 for this time frame are forbidden from landing and take-off, and for a bypass ratio equal to or below 3 the restriction for landing or take-off is extended to the 18-08h time frame. Low noise landing procedures (CDA) are also obligatory during this time frame, as well as special instrumental approaches, and the deviation from airways is limited. A ban is also in place for engine tests and exercise and training flights. The largest operational impact however is due to night-time runway combinations, closing runways 36C, 09/27, 04/22 and 18L/36R for departures, and 18C, 09/27, 24, 04/22 and 18L/36R for arrivals(99).

On a strategic level, investment in infrastructure and re-allocation of intramodal and intermodal traffic are part of government initiative to improve noise conditions in the vicinity of Schiphol. As to diminish ground noise (long wavelength vibrations transmitted at the ground level), the Dutch government funded the construction of Buitenschot park, designed to alleviate the perception of these mechanical waves for the population located in the vicinity of runway 18R-36L. Redistribution measures for airport traffic in Schiphol see the reassignment of 70 000 operations of leisure character (mainly low-cost flights) to regional airports such as Rotterdam, under an agreement with the main carrier KLM, airport authority and the Ministry of Transportation. This should allow Schiphol to increase its capacity from 370 000 to 470 000 operations, adapting to the market of transit flights and increasing European competitivity. Other strategic measures contemplate the replacement of short-range flights by the alternative of railway transportation(132).

Lastly, institutionally backed outlets have flourished as part of government effort to collect and address community complaints, founding the Local Community Contact Centre Schiphol (BAS) and publishing quarterly and yearly complaint reports. Runway usage, complaint records linked to flight path and runway use, as well as complaints linked to postal code, are compiled and published for both regulators and the community to keep track of the progress in noise levels and perceived annoyance. Other institutions and tools are the Schiphol Living Environment Foundation, backed by the government and the province of North Holland, offering a safety net function for the public and support to compensation options under current laws and regulations. Schiphol Noise Predictor, a phone application designed to predicting aircraft noise around Schiphol is also noteworthy, allowing for feedback evaluating its accuracy based on user perception of the forecasted information(132–134) [See Annex 8 for LIB4 contour and flight path noise load in L_{den} and Annex 9 for LIB4 contour and flight path noise load in L_{night}, as described in the 2019 BAS Yearly Report – Source: (133)].

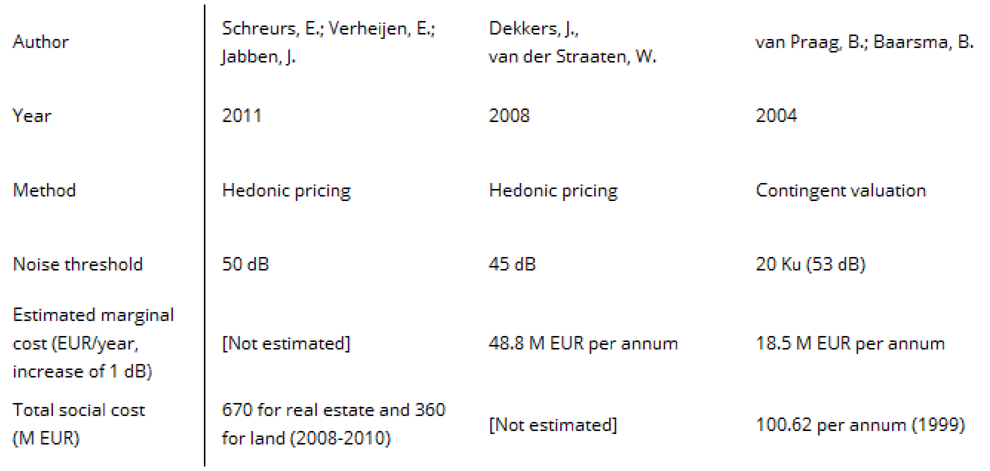
Commentary and recommendations

Some interesting observations can be made after careful examination of each study and their methodology. On one hand, while it could be argued that both approaches (revealed and stated preference, here represented by hedonic pricing and contingent valuation respectively) are compatible, and that the disadvantages are supplemented by the advantages of the other, it must be questioned to what degree the valuation can be taken as a baseline. On the other hand, the role quantification plays in internalization is, as seen, very moderate; the policies outlined contemplate a wide spectrum of applications, and while there is a common strategy pursuing specific goals, internalization under the terms of quantification is not fully satisfied through the current policy.

On the first of these two items, the results from each study explain the situation of a snapshot (in the range 1999-2008, due to the diverging dates of the studies) that is in every case extrapolated with the help of the model. Whilst the projections might be roughly accurate, at least in terms of predicting the overall trend of noise impact, or the shrinking of the contour lines and therefore the total number of people affected, the values obtained do not seem sufficient to establish specific yearly guidelines.

This problem stems, first of all, from the fact that conducting these studies is complex, and in some cases expensive; it is not surprising that quantification methods of airport externality, while abundant internationally, are carried out only occasionally for individual airports, and generally with the help of government backing. This latter factor demonstrates an interest from the institutions towards stating the overall cost of the externality, but it is also due to the leading role of those same institutions in collecting and monitoring demographic and noise data. The situation in 1999, however, was different than that of 2008: the Polderbaan had not been built yet, a new generation of quieter engines was only timidly entering the market, and the population's sensitivity to noise was much lower than it would be later, as seen in previous chapters.

Secondly, studies disagree as a product of their separation in time, but also due to methodological practice. Inherently, CV studies will offer values lower to those of HP studies, though the capability of individuals fully asserting the impact of noise can be brought to question, as seen before, due to the insidious nature of some of the negative health effects associated with it. HP studies, on the other hand, find more obstacles towards correctly identifying the cost of noise impact, which might be conflated with other factors, and must assume a market in equilibrium that does not correspond with the housing market in Amsterdam. These broad quantitative discrepancies are plainly seen in the figures of Schreurs et al. and Dekkers and van der Straaten compared to those of van Praag and Baarsma. The estimated marginal cost per annum of increasing one decibel is rated by Dekkers and van der Straaten following an HP method as 48.8 million euros each year, two and a half times the appreciation of van Praag and Baarsma under a CV approach. While the area of study is different (70x55 km^2 due to the inclusion of the Polderbaan, versus 50x50 km^2), this is a large difference and makes taking a single value difficult. A similar problem arises when comparing the total social cost, albeit comparison is complicated by differing time periods and a wider scope including the land market. Other notable divergencies that may generate uncertainties in the results are the selection of an NDI value (although there is apparent consensus on a 0.7-0.8 figure for Schiphol), and particularly a threshold value for noise, which should be strictly revised and linked to noise perception surveys in the vicinity. This last parameter should not be decided arbitrarily, and research would benefit from thorough justification of its estimation in terms of health effects rather than subjective perception.



Author	Schreurs, E.; Verheijen, E.; Jabben, J.	Dekkers, J., van der Straaten, W.	van Praag, B.; Baarsma, B.
Year	2011	2008	2004
Method	Hedonic pricing	Hedonic pricing	Contingent valuation
Noise threshold	50 dB	45 dB	20 Ku (53 dB)
Estimated marginal cost (EUR/year, increase of 1 dB)	[Not estimated]	48.8 M EUR per annum	18.5 M EUR per annum
Total social cost (M EUR)	670 for real estate and 360 for land (2008-2010)	[Not estimated]	100.62 per annum (1999)

Image 34: Summary of the literature analysis conducted

The influence of these studies on government policy is debatable. The publications analysed all respond to the necessity of measuring aircraft noise before, during, and after new legislation, centrally the Alders Agreements, was approved and executed. They all count either on direct government backup or are referenced by the others for their importance setting benchmarks in the monetary valuation of noise externality. Additionally, there is no doubt to the adhesion of government policy to the conclusions of the studies: the trends identified, the measurement of the positive impact of insulation (and the degree to which it is worthwhile financially), and the quantification of compensation and benefit or loss to the variation in overall noise levels attest to the alignment of government policy and the extrapolation of the results. To illustrate how pursuing noise insulation projects, subjective noise perception monitoring, and active reduction of noise levels in the vicinity to reduce social cost has reflected in effective improvements, the Schiphol Action Programme of 2015 offers an interesting outlook(135):

> *A reduction in the number of seriously affected residents, from approximately 170,000 in 2000 to nearly 120,000 in 2015 (a decrease of some 30%) and a reduction in the number of serious sleep disruptions among residents from more than 25,000 in 2000 to 17,000 in 2015 (a decrease of some 32%).*

It must be noted that the concerned period fits well the literature examination conducted above. The correct identification of problems and establishing adequate goals to solve them seems, as seen in the review of corrective measures, very effective. However, to which degree monetary valuation determines this policy beyond guidance, and how deeply it influences monetary aspects, is debatable.

One of the debilities of the studies is that no recommended environmental tax is offered, although the correlation between aircraft engine efficiency and noise levels is noted as an effect of fleet renewal. Landing and take-off taxes, as seen, depend both on time frame (whether the operation is comprised within the 23-06h) and engine categorisation, so their purpose as a tool for the control of environmental externality is evident. A Pigouvian tax of this kind, dependent on the activity of the market (symbolised, in this case, by the MTOW of the aircraft upon which it is applied, and the noise category to which the aircraft type belongs) is directed at externality correction, and its adjustment is a complex matter. As seen in cost-benefit analysis, the only possible way to address a balance between the benefit and the cost of a public good is to account for the environmental cost inflicted on society; and as concluded, the only way to determine environmental cost is through externality quantification, whatever the method may be. In this case, there is no direct link between the estimated costs and the taxes applied, or if there is, it has not been inferred from externality quantification, but from empirical gauging. Evidence of this fact can be seen in the 20% discount on landing and take-off charges upon Boeing B787 aircraft, which for the year reviewed (2018) had not yet produced large experimental data to extrapolate a precise value through externality quantification. Finally, while the EU 2019 Aviation Environmental Report acknowledges the effectiveness of Amsterdam in responsive environmental policy, centrally on the areas of noise monitoring, mediation with stakeholders, building restrictions, passive protection, flight procedures, noise caps, and noise charges, it also pronounces the following consideration(44):

> *Noise and emissions charges are used extensively, but the low level of charges (less than 1% of airline operating costs) is unlikely to affect the fleet operating at airports.*

Finally, the model presented by the Alders Table, reliant on yearly aircraft movements, seems to be wavering under the pressure of capacity updating. While strategically governmental effort is committed to find the means to divert much of the demand through alternative airports or modes of transportation, the key role of Schiphol as a passenger and logistic hub is only strengthened over time, and the demand curve may only stay positive. This is chiefly a good argument in the defence of aircraft noise quantification: an aggregate of aircraft operations obscures the impact of noise upon the people in its vicinity, more so when the limit is the product of a 15-year forecast as is the case with the Alders Agreements. A single noise event in 2005 did not produce, on average, the same disturbance it does today, nor is the public identically sensitive to this potential disturbance. Therefore, a revision of the model, rather than an update on the yearly aircraft movement cap, is needed, possibly shifting towards a monetary model where activity in Schiphol is more heavily taxed and dependent on the perception of noise and the social cost caused. This new model, when combined with the already existing enforcement points and yearly revised noise budgets, could both guarantee peace and quiet for the surrounding population while allowing for capacity to grow naturally under adequate tax pressure, punishing the real contributors towards noise disturbance.

Naturally, other challenges would emerge from following a closer monetary approach to the situation in Schiphol. Compensating more those households with larger income rather than those with a smaller income (due to the direct relationship between income and welfare), or enforcing more ambitious insulation programmes (which, while conclusively more efficient than direct monetary compensation, imply higher government intrusiveness), are difficult decisions that can only be navigated politically and within the cultural framework present in

Schiphol. Inviting the community to partake and be heard in the debate has proven important and vital to a sustainable, if ridden with dispute, growth model for the last two decades. Schiphol, as acknowledged in EU Aviation Environmental Report, is an exemplary model for the application of Collaborative Environmental Management in the design of noise correcting measures, greatly successful at involving all relevant stakeholders, and it must rely on this as a strength towards building new policy.

In summary, the recommendations that result from the examination of the case study are the following:

- through a Balanced Approach procedure, to reinforce management policies (economic measures) at the expense of the more stringent operating restrictions (regulatory measures);
- phasing out the 500 000 aircraft movement limit for Schiphol, already exceeded in 2018, and transitioning towards a monetary-based tax model under no yearly operations cap;
- to determine such taxes through the real and not extrapolated impact of aircraft and other sources upon society, as measured by quantitative methods;
- quantitative methods should receive further support and be methodically executed and applied;
- to consider the positive effect of fleet renewal and the negative effect of subjective noise annoyance through those methods;
- to include and listen to the community, which is the ultimate target of internalization.

VIII. Conclusions

The structure of this thesis has been proven to be correct in analysing the magnitude and complexity of externality costs as well as their appraisal and correction. As seen in the initial chapter, an equilibrium between the ample benefits that aviation concedes and the costs imposed by environmental externality can be hard to strike, as it relies first upon correct identification and association of the related negative effects, and secondly on their valuation through monetary quantification methods. Exploring noise and air quality, by far the most widely well-researched externalities associated with airport activity, permitted to observe the first differences in how they affect society: whilst most of the negative effects of noise may be gauged through the annoyance caused on the surrounding community, air quality does not result in the same manner in a conscious perturbance of the quality of life of individuals. Therefore, as made evident in the next chapter, the valuation of the externality cost of air quality must rely on the correct association of morbidity and mortality effects and pollutant exposure through dose-response indirect methods; the externality cost of noise, on the other hand, may be approached through direct valuation methods, such as stated preference and revealed preference. Stated preference methods are based on the inference of the externality cost through the effect of prices on a related market, of which hedonic pricing stands out as the most prevalent method in literature. As for revealed preference, methods seek to simulate a market where the cost of externality on welfare can be quantified, and in this case contingent valuation was examined. Figures presented in some of the relevant literature were explored and explained to better the understanding of both methods. A subsequent chapter on the correction of externality for both noise and air quality summarised the diverse measures that regulators and stakeholders may adopt to diminish the negative impacts of aviation, classifying them depending on their mechanism of application as regulatory, technical, operational, or economic.

One of the important conclusions to be drawn from the correction of externalities is that in the European Union, the chosen framework for this thesis, environmental taxes are still notably low and do no significantly affect operation by air carriers, despite their markedly Pigouvian character. The case study, centred in the noise externality of Amsterdam Airport Schiphol, allowed an in-depth compilation of the historical approach towards environmental measures and the outstanding concern of the institutions to correct the negative impact of noise in the surrounding community. A review of the research produced in the last two decades focused on two hedonic pricing studies (Schreurs et al. in 2011, Dekkers and van deer Straaten in 2008) and a contingent valuation study (van Praag and Baarsma in 2004) in their effort to quantify noise externality in the region around the airport; calculations were reproduced, and some of the findings discussed. After consulting externality correction measures as applied by Schiphol and the Dutch government, in collaboration with stakeholders, the presence of a 500 000 yearly airport movements cap for 2020 was noted, a unique approach that while initially appeasing the community, seems to be failing at present after limitations were exceeded in 2018. Similarly, noise charges on aircraft operation, while present, do not seem to be based on the aforementioned studies, or bear any relation with the estimated costs supported by each household despite their strong Pigouvian character.

Further reflection onto this case study led to the following concluding statements: first, it revealed that as indicated by the 2019 EU Aviation Environmental Report, the Balanced Approach is not strictly adhered to, and that regulatory measures, such as the movement cap, prevail in Schiphol over economic measures; second, that environmental taxes in Schiphol are not determined by noise externality, but rather by aircraft characteristics, and that this is likely due to the inaccuracy and discrepancy of externality valuation studies; third, a lack of frequent studies with larger public backing impedes more accurate monetary quantification, and thus the determination of larger, cost-dependant noise taxes; and fourth and last, that fleet renewal and community involvement are key positive trends for a successful internalisation approach for the future, phasing out the old operation cap model. Under the ICAO-EU Balanced Approach, the economic measures should lead to better self-regulation of the aviation market in Schiphol and avoid jeopardising the balance between the quality of life of resident and the economic benefits generated by the airport.

It is worth mentioning as well that further research is required in identifying and resolving the negative costs of aviation. Knowledge gaps still exist in the study of ultrafine particulate matter in health, with ICAO implementing related metrics only in 2020, and epidemiological studies should allow for a more profound understanding of the health effects of long-term noise and emissions exposure. Additionally, the industry is experiencing an evident onward trend towards cleaner, quieter operations that guarantee economic viability for carriers and consumers. In a world that is increasingly more knowledgeable about the environment and its effects in quality of life, the public is shifting towards options that envisage their concerns and offer greener alternatives, which in turn is compelling the market to shift in this direction.

Finally, the author would like to highlight that the complexity in researching and aptly composing this thesis exceeded expectations. The very nature of the topics discussed is multidisciplinary, ranging from the fields of physics and chemistry to those of health sciences, economics, and advanced knowledge about airport operations. Nevertheless, the result is satisfactory, and the initial goal of expanding and compiling current literature has been fulfilled.

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X. Annexes and supplementary media

Annex 1: WHO Community Noise Guidelines.

DWELLINGS

Day-time

- Indoors the dwelling during the day/evening – 35 dB L_{eq} (16 hour)
- Outdoor living areas - 55 dB L_{eq} (16 hour) to protect the majority of people from being 'seriously annoyed' during the day-time
- Outdoor living areas – 50 dB L_{eq} (16 hour) to protect the majority of people from being 'moderately annoyed' during the day-time

Night-time

- Outside façades of the living spaces should not exceed 45 dB L_{eq} (8 hour) and 60 dB L_{max} to protect from sleep disturbance
- Inside bedrooms - 30 dB L_{eq} (8 hour) and 45 dB L_{max} for single sound events to protect from sleep disturbance.

SCHOOLS & PRE-SCHOOL

- School playgrounds outdoors should not exceed 55 dB L_{eq} during play to protect from annoyance.
- School classrooms should not exceed 35 dB L_{eq} during class to protect from speech intelligibility and, disturbance of information extraction.
- The reverberation time in the classroom should be about 0.6 s.
- Pre-school bedrooms – 30 dB during sleeping time & 45 dB Lm_{ax} for single sound events to protect from sleep disturbance.

HOSPITALS

Day-time

- Hospital ward rooms indoor values during the day-time/evening - 30 dB L_{eq} (16 hour) to protect from sleep disturbance and interference with rest and recovery

Night-time

- Hospital ward rooms indoor values at night - 30 dB L_{eq} (8 hour), together with 40 dB L_{max} to protect from sleep disturbance and interference with rest and recovery

PARKLAND AND CONSERVATION AREAS

- Existing large quiet outdoor areas should be preserved and the signal-to-noise ratio kept low.

Annex 2: WHO DALY loss for highly annoyed people due to air traffic noise in the EU.

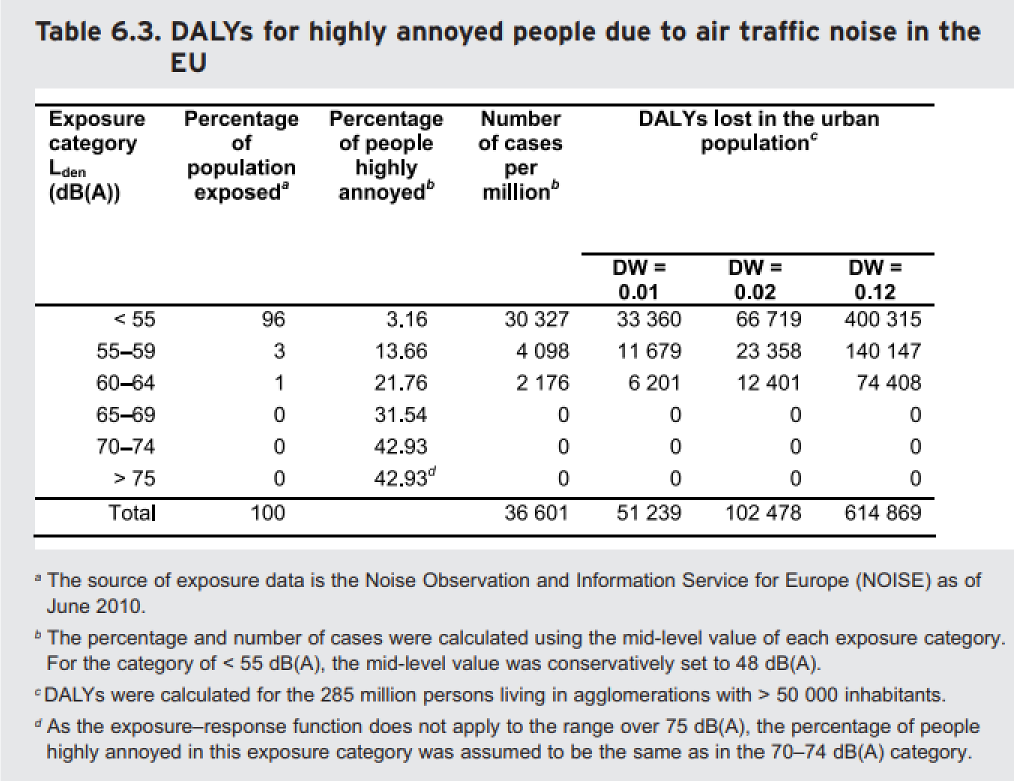


Table 6.3. DALYs for highly annoyed people due to air traffic noise in the EU

Exposure category L_{den} (dB(A))	Percentage of population exposed[a]	Percentage of people highly annoyed[b]	Number of cases per million[b]	DALYs lost in the urban population[c]		
				DW = 0.01	DW = 0.02	DW = 0.12
< 55	96	3.16	30 327	33 360	66 719	400 315
55–59	3	13.66	4 098	11 679	23 358	140 147
60–64	1	21.76	2 176	6 201	12 401	74 408
65–69	0	31.54	0	0	0	0
70–74	0	42.93	0	0	0	0
> 75	0	42.93[d]	0	0	0	0
Total	100		36 601	51 239	102 478	614 869

[a] The source of exposure data is the Noise Observation and Information Service for Europe (NOISE) as of June 2010.

[b] The percentage and number of cases were calculated using the mid-level value of each exposure category. For the category of < 55 dB(A), the mid-level value was conservatively set to 48 dB(A).

[c] DALYs were calculated for the 285 million persons living in agglomerations with > 50 000 inhabitants.

[d] As the exposure–response function does not apply to the range over 75 dB(A), the percentage of people highly annoyed in this exposure category was assumed to be the same as in the 70–74 dB(A) category.

Annex 3: Health effects from nocturnal noise exposure as described by WHO.

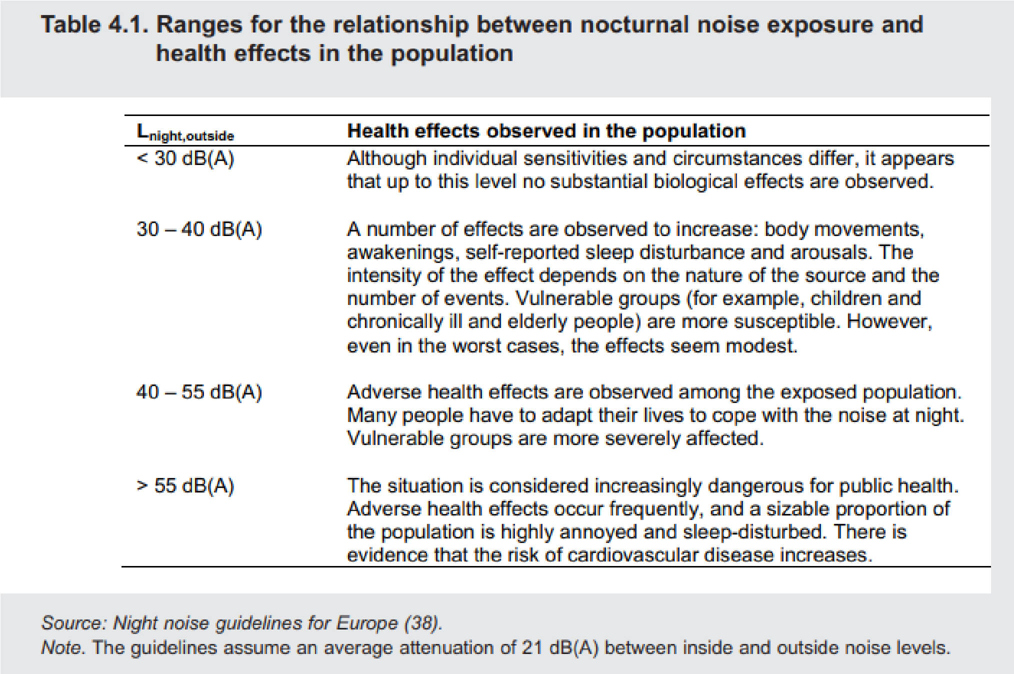
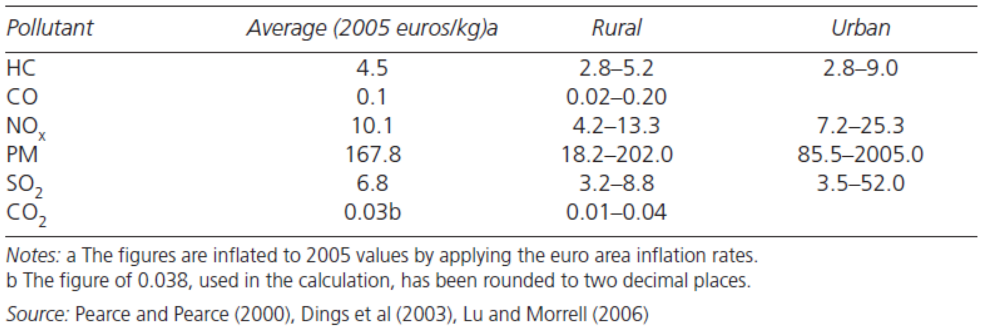


Table 4.1. Ranges for the relationship between nocturnal noise exposure and health effects in the population

$L_{night,outside}$	Health effects observed in the population
< 30 dB(A)	Although individual sensitivities and circumstances differ, it appears that up to this level no substantial biological effects are observed.
30 – 40 dB(A)	A number of effects are observed to increase: body movements, awakenings, self-reported sleep disturbance and arousals. The intensity of the effect depends on the nature of the source and the number of events. Vulnerable groups (for example, children and chronically ill and elderly people) are more susceptible. However, even in the worst cases, the effects seem modest.
40 – 55 dB(A)	Adverse health effects are observed among the exposed population. Many people have to adapt their lives to cope with the noise at night. Vulnerable groups are more severely affected.
> 55 dB(A)	The situation is considered increasingly dangerous for public health. Adverse health effects occur frequently, and a sizable proportion of the population is highly annoyed and sleep-disturbed. There is evidence that the risk of cardiovascular disease increases.

Source: Night noise guidelines for Europe (38).
Note. The guidelines assume an average attenuation of 21 dB(A) between inside and outside noise levels.

Annex 4: Social costs of each exhaust pollutant as of 2005

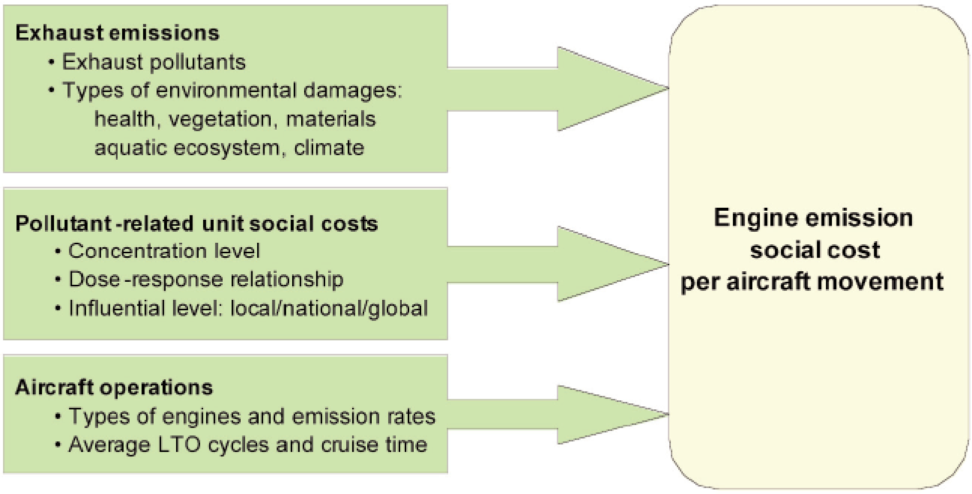


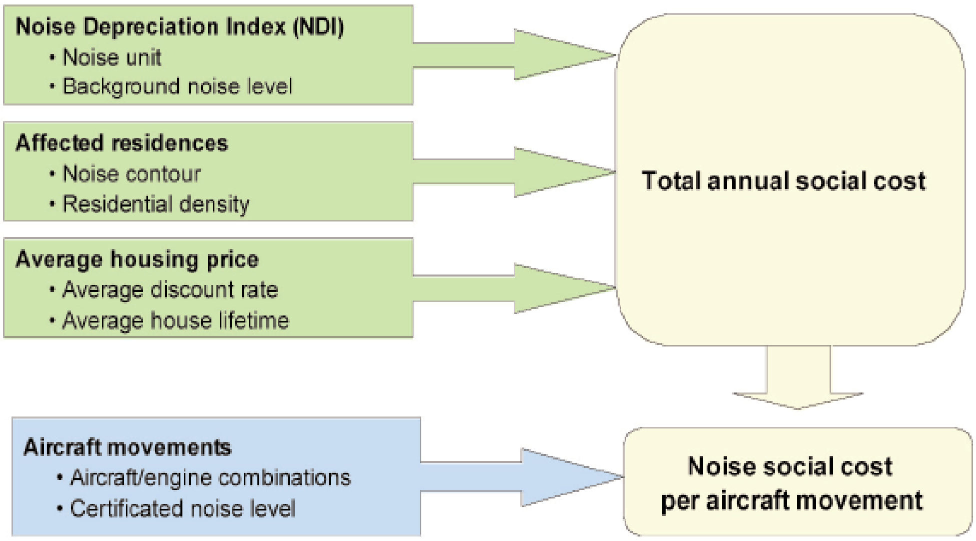
Pollutant	*Average (2005 euros/kg)*[a]	*Rural*	*Urban*
HC	4.5	2.8–5.2	2.8–9.0
CO	0.1	0.02–0.20	
NO_x	10.1	4.2–13.3	7.2–25.3
PM	167.8	18.2–202.0	85.5–2005.0
SO_2	6.8	3.2–8.8	3.5–52.0
CO_2	0.03[b]	0.01–0.04	

Notes: a The figures are inflated to 2005 values by applying the euro area inflation rates.
b The figure of 0.038, used in the calculation, has been rounded to two decimal places.

Source: Pearce and Pearce (2000), Dings et al (2003), Lu and Morrell (2006)

Annex 5: Comparison of methodologies between aircraft emissions valuation and aircraft noise valuation (following HP method)





Annex 6: L_{den} per neighbourhood in 2003.

Annex 7: Question 25 regarding noise annoyance

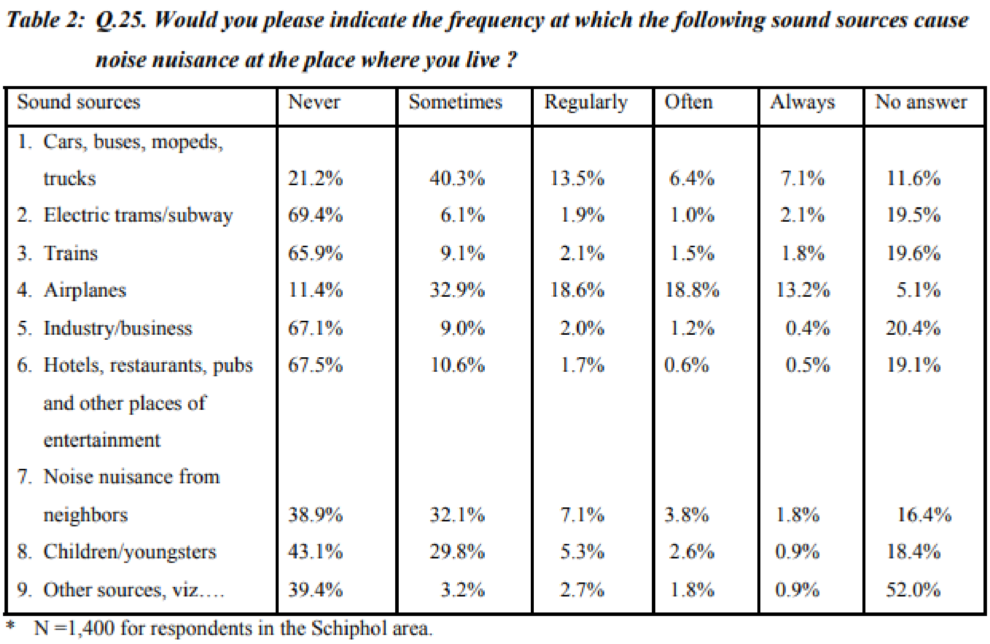
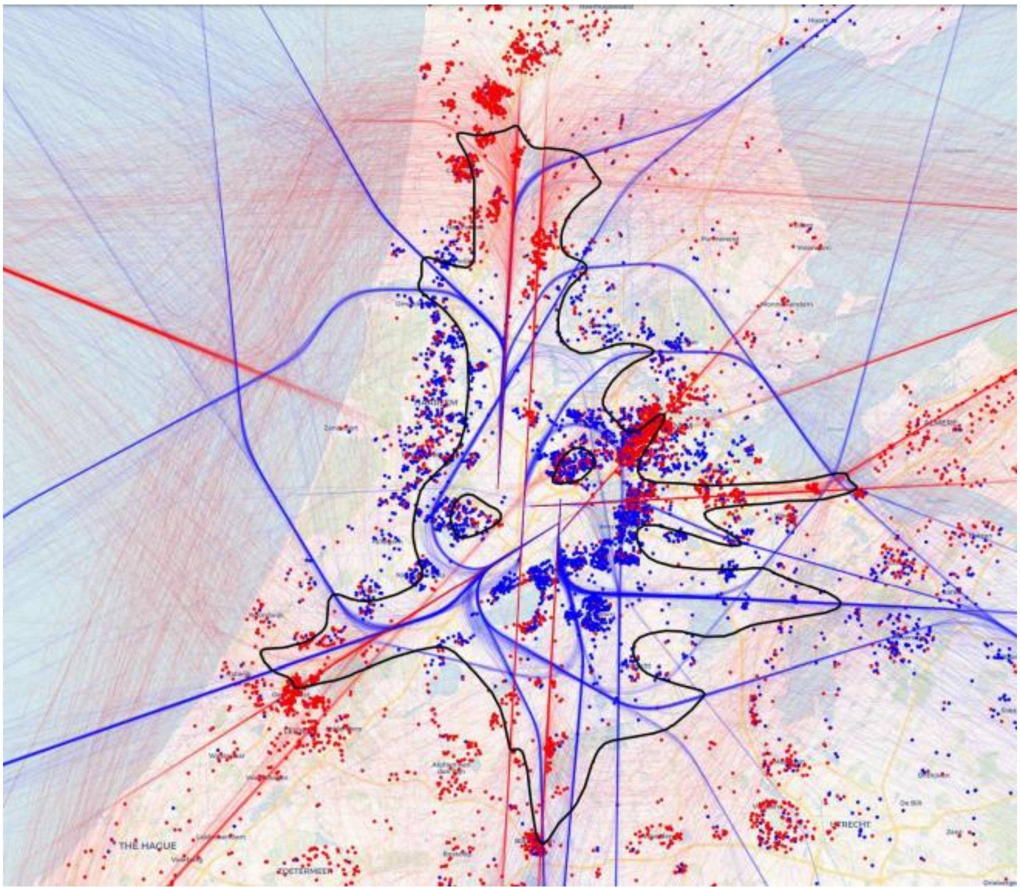


Table 2: Q.25. Would you please indicate the frequency at which the following sound sources cause noise nuisance at the place where you live ?

Sound sources	Never	Sometimes	Regularly	Often	Always	No answer
1. Cars, buses, mopeds, trucks	21.2%	40.3%	13.5%	6.4%	7.1%	11.6%
2. Electric trams/subway	69.4%	6.1%	1.9%	1.0%	2.1%	19.5%
3. Trains	65.9%	9.1%	2.1%	1.5%	1.8%	19.6%
4. Airplanes	11.4%	32.9%	18.6%	18.8%	13.2%	5.1%
5. Industry/business	67.1%	9.0%	2.0%	1.2%	0.4%	20.4%
6. Hotels, restaurants, pubs and other places of entertainment	67.5%	10.6%	1.7%	0.6%	0.5%	19.1%
7. Noise nuisance from neighbors	38.9%	32.1%	7.1%	3.8%	1.8%	16.4%
8. Children/youngsters	43.1%	29.8%	5.3%	2.6%	0.9%	18.4%
9. Other sources, viz.…	39.4%	3.2%	2.7%	1.8%	0.9%	52.0%

* N =1,400 for respondents in the Schiphol area.

Annex 8: contour for 48 dBA L_{den} and flight path noise in 2019.



Annex 9: contour for 40 dBA L_{night} and flight path noise in 2019.