FUTURE ACOUSTIC CHARACTERISTICS
OF
AIRCRAFT IN CIVIL AVIATION

FINAL REPORT
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PREFACE

Onderzoek Nederlandse Luchtvaart (ONL) is a program, managed by the Dutch Civil Aviation Authority that is involved with the development of strategic policy concerning future aviation in the Netherlands. Its tasks are, among others, the development of regulation, permits and spatial planning. In order to perform these tasks, scenarios are being developed for the period 2000-2030. The scenario development is led by the Dutch Aviation Authority (Rijksluchtvaartdienst (RLD) with the help of the ministries of Economic Affairs (EZ) and Housing, Spatial Planning and Environment (VROM), as well as with the help of the Central Planning Agency (CPB), KLM and Schiphol (scenario development team).

In certain areas, the scenario development team needs the assistance of external experts. One of these fields is the historic and future development of acoustic characteristics of aircraft. Aircraft have become less noisy over time, both as a result of technological developments within the aircraft industry as well as of international, national and local policy measures stimulating the use of more quiet aircraft or banning less compliant aircraft. It is important to be able to predict how this trend will continue.

RAND Europe was asked to provide an analysis of historic, current and future acoustic characteristics of civil aviation aircraft.

The objective of this study is to describe and explain the historical development of aircraft and aircraft engine acoustic noise characteristics and to project the next 30 years of expected development. The projections will be used to define bandwidths for future developments that can be used in the ONL scenarios.

This report describes the results of the study, which was performed by RAND Europe and AvioPlan (Berlin, Germany). The study was carried out in 2000. For further information about the research and/or RAND Europe, please contact the president of RAND Europe:

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SUMMARY

The Dutch Civil Aviation Authority requested that RAND Europe analyse the historic, current and future acoustic characteristics of civil aviation aircraft. The projections of future characteristics can be used in Dutch civil aviation scenarios currently being developed. Aircraft emissions are also analysed, principally as they relate to acoustic characteristics.

RAND Europe carried out the study in co-operation with AvioPlan (Germany).

The study looked 30 years into the past and projected 30 years into the future. In the past 30 years, the air transport industry has experienced rapid expansion as the world economy has grown and the technology of air transport has evolved. This has resulted in a steady decline in aircraft operating cost (production cost as well as maintenance cost) and, as a result of that plus deregulation, a decline in fares. World aviation has grown at an average rate of 5 percent per year.

In this period, there has been a significant decrease in aircraft noise. This decrease is in part due to technological developments and in part to changes in air traffic behaviour as a consequence of noise abatement regulations. Although the technological developments have largely been in engine and airframe redesign and focused around improvements in aerodynamics, weight reduction and fuel consumption in order to carry more weight for less fuel, there have also been changes to reduce the volume of noise produced.

Over the past 30 years, the fuel consumption efficiency gain was around 50 percent (measured as fuel consumption per mile). Noise reduction, measured in average decibels produced per aircraft type, led to a gain of 20 dBA from 100 to 80 dBA on average. Efficiency performance resulted in improved environmental performance in terms of emissions due to the fuel savings, but noise reduction and efficiency gains were typically the result of separate efforts. For noise reduction, regulation of air traffic behaviour was at least as important as technology. In 1969 the first international noise regulation came into force. Since then, different noise regulations (international, national and local) have been promulgated. The regulations not only specify maximum noise characteristics of aircraft (by age and size), but also can include time of day operational restrictions (night flying), flight patterns, and other arrival and departure procedures. More recently, regulation in terms of performance requirements has been supplemented by airport charges based on time of day and acoustic characteristics of aircraft. The sum of these changes has been an overall reduction in aircraft noise since 1960 of about 25 dB at the average measuring site. However, recent reductions (1980-2000) are significantly less than earlier ones (1960-1970).

Future aircraft noise development depends on a number of different factors. Although the potential gains in noise reduction are driven by technological developments, the economic and political climate will in large determine how much of that potential is realised.

We examined known plans for technological development and their effect on noise production. Generally, the technological forecast is for much less reduction in aircraft noise than in the past, as shown by the goals of the US NASA noise reduction program to achieve a noise reduction of 20 dB cumulative (that is, summed over three measuring sites, or about 6.7 dB at an average measuring site) in the period 2000-2030. This goal can be reached by a combination of engine noise reduction, aerodynamic noise reduction and noise avoidance behaviours. The reduction of the first 5 dB cumulative (or 1.7 dB average) is relatively easy and can be achieved without severe new regulations in the decade 2000-2010. With severe regulation, a second 5 dB cumulative (1.7 dB average) reduction can be achieved in the next 10 years. The last 10 dB cumulative (3.3 dB average) of reduced noise is much more difficult to achieve in the short-term and will be realised in the latter part of the future projection (2010-2030).

Any reductions beyond the first 5 dB cumulative are highly dependent on economic and political factors and barriers to change. New technology is expensive for airlines. As a result of increasing development cost for new technology aircraft prices will go up and increase the capital cost stronger than the reduction in variable cost (fuel, maintenance). This could result in higher fares for passengers and cargo and the
further growth of air traffic could be hampered. Moreover, for manufacturers who have aircraft and engine types that have not reached a mature stage in the product life cycle, new products can threaten profitability.

In addition to these economic trade-offs there can be possible conflicts between noise reduction and for example emissions reductions. Further enhancement of aircraft noise technology might interfere with other objectives of technology development such as aircraft economy and/or reduction of gaseous emissions. Aircraft emissions contribute to the greenhouse effect, cause acidification and air pollution, and may cause ozone depletion. The most important driving factor for emission reduction remains fuel efficiency. In the 1980’s ICAO introduced regulatory emission limits for new engines. These regulations have become more stringent in time. The estimation for the near future is that, combining a reduction per aircraft with a growth of flight, that emissions due to the aviation sector will grow at a rate of three percent per year.

Over and above economic or environmental trade-offs, political issues can be barriers in noise reduction. An example of a political barrier is the battle between the US and Europe on "hushkits", or noise-reducing modifications to current engines that reduce noise at a cost of some emissions and other characteristics. This battle has escalated to threats for bans on certain aircraft, and has hampered implementation of noise reducing measures as a result of economic considerations.

In conclusion, technological potential for further noise reduction is more limited than in the past. IETS ZEGGEN OVER TIME FRAMES. Further enhancement of aircraft noise technology can interfere with other objectives: efficiency increase, reduction of gaseous emissions and aircraft costs. Nevertheless NASA has called for and projects a further potential reduction for jet aircraft of 20 dB cumulative in the next 25-30 years.

Reductions of the magnitude of 5 dB cumulative could relatively easily be realised in the next 10 years. These reductions require no further strengthening the existing regulations. To implement more ambitious goals in the near-term future, to the extent of 10 dB cumulative, will require more stringent regulation.

The full realisation of the NASA objective of a 20 dB cumulative decrease is even more dependent on regulation, because the economic viability of airlines is endangered by introducing too much new aircraft technology and other environmental goals, especially emissions reduction, conflict with noise reduction. Improvements in efficiency and aircraft noise reductions, never fully joined, will become increasingly in conflict with each other as noise abatement technology requires additional weight. Regulation in this instance can take two forms. On the one hand, regulations in the form of non-addition rules and subsequent operating bans (such as the ICAO Chapter 2 and 3 regulations) make operations dependent on compliance. On the other hand, regulations in the form of noise-based fees and/or operating measures bring a financial incentive to airlines to operate the most noise friendly aircraft. We must not forget that the reduction of 20 dB is cumulative. This means that the reduction per measure point will be much smaller.

Technology can help in reducing aircraft noise. But although noise per engine can decline, the total amount of aircraft noise will almost certainly increase in the near future, because of traffic growth.

With regard to emissions, aircraft engines have become cleaner in time. Technology can make them even yet cleaner, but the developments depend once again upon policy tradeoffs. The total amount of aircraft emissions will, just as the total amount of noise, increase in the near future because of traffic growth. This, too, should be incorporated in scenario design.
1. INTRODUCTION

Onderzoek Nederlandse Luchtvaart (ONL) is a program, managed by the Dutch Civil Aviation Authority that is involved with the development of strategic policy concerning future aviation in the Netherlands. Its tasks are, among others, the development of regulation, permits and spatial planning. In order to perform these tasks, scenarios are being developed for the period 2000-2030. The scenario development is led by the Dutch Aviation Authority (Rijksluchtvaartdienst (RLD)) with the help of the ministries of Economic Affairs (EZ) and Housing, Spatial Planning and Environment (VROM), as well as with the help of the Central Planning Agency (CPB), KLM and Schiphol (scenario development team).

In certain areas, the scenario development team needs the assistance of external experts. One of these fields is the historic and future development of acoustic characteristics of aircraft. Aircraft have become less noisy over time, both as a result of technological developments within the aircraft industry as well as of international, national and local policy measures stimulating the use of more quiet aircraft or banning less compliant aircraft. It is important to be able to predict how this trend will continue.

RAND Europe is asked to provide an analysis of historic, current and future acoustic characteristics of civil aviation aircraft.

The objective of this study is to describe and explain the historical development of aircraft and aircraft engine acoustic noise characteristics (and to a lesser degree gaseous emissions) and to project the next 30 years of expected development. The projections will be used to define bandwidths for future developments that can be used in the ONL scenarios.

Explicitly excluded from the analysis are air transport growth scenarios and accessory fleet developments. These are needed to measure the total impact of technology on noise and emission production.

The study addresses aircraft and aircraft engine developments in a 60-year period 1970-2030. The first 30 years are based on analysis of historic developments. The future 30 years are based on an assessment of critical factors both in the field of technology as in the field of policy making. The technical possibilities are compared with what is used in practice.

In the study aircraft emissions are also addressed. Relations between the production of noise and the production of emissions are briefly described and a very general overview of the history and future of aircraft emissions are given.

The report contains 7 chapters:
- Chapter 2 provides essential background information concerning the technology of aircraft and engines and the causes of noise as well as definitions of noise measurement;
- Chapter 3 contains the historic developments and the explanations for these developments;
- Chapter 4 looks into the technological future of aircraft noise;
- Chapter 5 provides bandwidths for aircraft noise focusing on technological, economical and political barriers to improvement and the economic context for developments;
- Chapter 6 describes the development of aircraft emissions;
- The report ends with a summary of the major findings of the study.
2. BACKGROUND, DEFINITIONS AND METHODOLOGY

2.1 Aircraft noise

Aircraft noise is the result of technology, i.e. the aircraft engine and the aerodynamics of an aircraft. It becomes a problem because human beings are exposed to this noise, thus it is becomes necessary to measure, either the experienced noise levels or the nuisance.

Nuisance

Noise is the main source of nuisance caused by transport, whether road, rail or air. For civil aviation, it is currently one of the main bottlenecks for further growth. The impact of aircraft noise is primarily a local nuisance issue in the residential area around airports, because it can interrupt communication, disturb sleep and relaxation, induce fatigue and thus reduces quality of life of population around airports. Hence, to date, noise issues have received more regulatory and technological attention than any other aviation environmental problem (e.g. air pollution and third party risk) [ATAG, 1999].

Sources of aircraft noise

Two main sources of aircraft noise can be identified:

- Engine noise;
- Aerodynamic noise from the airframe (wings, landing gear, flaps, slats, etc.).

The contribution of these two sources to the total aircraft noise for a turbofan-powered aircraft (generally used) is shown in Figure 1. The contribution of engine noise, in particular the fan and exhaust noises, is separately indicated. Note that the noise level of an approaching aircraft is much higher than that of a departing airplane.

\[ \text{Figure 1, A breakdown of the noise components of a typical commercial aircraft with 1992-level technology during approach and landing} \]

Note: because decibels are logarithmic values, the graph’s total bar is not the sum of the individual bars [NASA, 1997b].

Noise unit

Figure 1 uses the standard unit for noise measurement, the decibel (dB), which is a unit on a logarithmic
scale that indicates the noise level in comparison to the least audible sound. Due to the logarithmic scale of dB measures, it is not possible to indicate relative changes in noise reductions as a difference in dB. An increase of 10 dB means that the noise is 10 times as loud. In this report only absolute number of decibels will be used to indicate reductions in noise levels. For reference the following comparative noise levels are available:

<table>
<thead>
<tr>
<th>dB</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Total silence</td>
</tr>
<tr>
<td>10</td>
<td>Falling leave</td>
</tr>
<tr>
<td>30</td>
<td>Library</td>
</tr>
<tr>
<td>60</td>
<td>Telephone conversation</td>
</tr>
<tr>
<td>90</td>
<td>Orchestra</td>
</tr>
<tr>
<td>140</td>
<td>Pain limit</td>
</tr>
</tbody>
</table>

The human response to single-event jet aircraft noise is typically represented in terms of Effective Perceived Noise Level in decibels (EPNdB). This unit of perceived noise takes into account the actual sound energy received by a listener, the ear’s response to that sound energy, the added annoyance of any pure tones or “screeches” in the noise and the duration of the noise [FAA, 1995].

For certification purposes, noise limits are measured at three points around an airport:

- Under the approach route (on the extended line of the runway, 2 km from the threshold);
- Under the take-off flight path (at a distance of 6.5 km from the start of roll);
- At the side of the runway during take-off (parallel to and 650 m from the runway centre line).

Noise and changes in noise are measured in the aviation sector in three different ways:

- Single: this is the improvement on a single measuring point. If one measuring point is used, it is typically the approach point; sometimes multiple points are reported;
- Average: this is the average over the three measuring points, expressed as dB(A), where the A stands for average;
- Cumulative: this measure is used only for changes (improvements) in noise and is the sum of changes over all three measuring points. Although this calculation is widely used in the aviation sector, it should be approached with caution, as the cumulative reduction is about three times the actual total noise reduction at any single measuring site. Given the complex relationship of changes in decibels to subjectively perceived noise, the cumulative reduction can be misleading.

The examples below illustrate these three definitions.

**Single:**
An Airbus Aircraft of the type A310-300 with a PW4152 engine has been tested for all three measuring points with the following result:

<table>
<thead>
<tr>
<th>A310-300, PW1452</th>
<th>Lateral EPNdB</th>
<th>Flyover EPNdB</th>
<th>Approach EPNdB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Level</td>
<td>96.9</td>
<td>91.3</td>
<td>100.5</td>
</tr>
</tbody>
</table>

**Average**
When the average noise level is discussed in the text, this relates to the average over all three points of measurement. In this example that would be 96.2 EPNdB(A).

**Cumulative**
Further when looking at improvements in noise level, the improvements are sometimes added up to indicate the total improvement over all points of measurements. This is especially relevant when looking at the margin EPNdB that an aircraft has relative to the ICAO-limits. These margins are added up to create...
a total margin in EPNdB.

<table>
<thead>
<tr>
<th>Table 2: EPNdB per measuring point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral - EPNdB</td>
</tr>
<tr>
<td>Level</td>
</tr>
<tr>
<td>96.9</td>
</tr>
</tbody>
</table>

Adding up the total noise level at the individual measurement points would lead to an unrealistic value of 288.7 EPNdB; cumulative noise measures are never used in this way. However, the cumulative margin, here 9.7 EPNdB is often reported. Note that this is approximately a 3.2 EPNdB average reduction at each measuring point, a subjective value considerably less than the 9.7, especially in the ranges of noise being considered.

The reason why the single measuring point method is used is because it expresses the specific location where noise reduction can be achieved. E.g. landing gear modification can reduce noise at the approach measuring point, while a higher bypass ratio produces a noise reduction at the lateral point.

The total margin in EPNdB or ∆EPNdB is used by the RLD for the classification of aircraft into noise categories.

The noise class limits used by the scenario development team are the current ICAO limits. For jet-powered aircraft there are two levels of stringency in the International Civil Aviation Organisation (ICAO) noise standards. Chapter 2 of ICAO Annex 16 contains the standards applicable to subsonic jet airplanes for which the application for the certification of airworthiness for the prototype was accepted before October 1977. Chapter 3 contains more stringent standards applicable to those subsonic jet airplanes designed after that date. These internationally accepted noise limits vary with the weight of the aircraft and to some extent with the number of engines on the aircraft. So the heavier the aircraft, the more noise it is permitted to make, up to a specified maximum limit (see appendix D, figure 1 and 2).

For the scenario analysis, developments are described within the framework of aircraft size and aircraft technology classes. Capacity classes are defined based on the Maximum Take Off Weight (MTOW) of aircraft.

<table>
<thead>
<tr>
<th>Table 3: Size class definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size class</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
</tbody>
</table>

Technology classes are defined on the cumulative difference with the ICAO chapter 3-noise limits. This ∆EPNL is the sum of the ICAO Annex 16 Chapter 3 limits minus the sum of the certified noise levels (flyover, lateral and approach).
Table 4: Technology classes

<table>
<thead>
<tr>
<th>Technology class</th>
<th>∆EPNL*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>∆EPNL &gt; 0</td>
</tr>
<tr>
<td>2</td>
<td>0 ≥ ∆EPNL &gt; -9</td>
</tr>
<tr>
<td>3</td>
<td>-9 ≥ ∆EPNL &gt; -18</td>
</tr>
<tr>
<td>4</td>
<td>-18 ≥ ∆EPNL &gt; -27</td>
</tr>
</tbody>
</table>

* Engine Produced Noise Limits

These classes will be used to describe the historic and future developments more in detail. As aircraft noise and regulation are applied to jet aircraft, no analysis is provided for those size classes containing turboprops (size class 1 and 2). In general, turboprop aircraft generate less noise than jet aircraft and are often not even included in noise measurement methodology. For example, in the Schiphol noise contours, turboprops are not included because the noise levels are below the minimum level that is required for the calculation.

Cost of technology and implementation

New technology ideas always exist in the brains of engineers. To get these ideas from the brain into a design and an aircraft is dependent on factors outside the design room. Development and implementation of new aircraft technology requires time and thus investment. Investment in engineering hours for aircraft manufacturers, investment in aircraft for airlines. The investment then has to pay itself back, for aircraft manufacturers in the form of more sales, for airlines by realizing lower variable cost, such as fuel and maintenance. This investment payback principle is important for the implementation of new technology. In case uncertainty increases, parties are less likely to take risk and accept a long payback period. Airlines in deregulated markets are faced with this increased uncertainty and less willing to invest in technology with long payback periods. Another success factor for implementation of new aircraft technology is the growth potential of the market. If new technology aircraft can be used for expanding the fleet, it is a less complicated issue for airlines than if an aircraft needs to replace an older type. Again, the decision is on the trade-off between variable cost (high on the old aircraft, low on the new) versus fixed cost (low on the old, high on the new). These financial economic trade-offs play a crucial role in the degree of implementation of the new technology.
3. HISTORY

3.1 Introduction

Ever since its birth in the first part of the 20th century, the air transport industry has experienced rapid expansion as the world economy has grown and the technology of air transport has developed. This has resulted in a steady decline in airline operating costs and, as a result of that, a decline in fares. The decline in fares and the economic growth have stimulated traffic growth.

### Table 5: Long term trends in aircraft technology and the effect on cost and performance

<table>
<thead>
<tr>
<th>ERA</th>
<th>Aircraft</th>
<th>Speed</th>
<th>Range</th>
<th>Seats</th>
<th>Altitude</th>
<th>Average cost per mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1926-1936</td>
<td>Ford Tri motor</td>
<td>100 mph</td>
<td>400 mile</td>
<td>12</td>
<td>8000 ft</td>
<td>$ 1.00</td>
</tr>
<tr>
<td>1937-1946</td>
<td>DC-3</td>
<td>175 mph</td>
<td>700 mile</td>
<td>21</td>
<td>12000 ft</td>
<td>$ 0.60</td>
</tr>
<tr>
<td>1948-1958</td>
<td>DC-6B</td>
<td>300 mph</td>
<td>1800 mile</td>
<td>60</td>
<td>22000 ft</td>
<td>$ 0.30</td>
</tr>
<tr>
<td>1959-1969</td>
<td>707</td>
<td>550 mph</td>
<td>3600 mile</td>
<td>110</td>
<td>35000 ft</td>
<td>$ 0.20</td>
</tr>
<tr>
<td>1970-1990</td>
<td>747</td>
<td>550 mph</td>
<td>6000 mile</td>
<td>450</td>
<td>35000 ft</td>
<td>$ 0.15</td>
</tr>
<tr>
<td>1990-2000</td>
<td>777</td>
<td>550 mph</td>
<td>7000 mile</td>
<td>350</td>
<td>35000 ft</td>
<td>$ 0.10</td>
</tr>
</tbody>
</table>

Mile: Statute Mile (1609 meter)
Mph: speed in miles per hour
Ft: Feet

Table 5 shows that the aircraft and airline industry have improved both on performance (product) and costs (price). Both developments are the direct consequence of technological developments, which in turn are the result of the economic and political developments at the time. However, since 1970 technology parameters such as size, speed, altitude and range have not changed much. The basic development is in the cost per mile. This study divides the timeframe into decades. In order to understand technology change, it is necessary to describe shortly the economic, political circumstances of the past 3 decades and the link with technology incentives.

**1970-1980**

Early in this decade the Boeing 747 made its entry into the world of civil aviation, the symbol for many representing the transition from luxury to mass consumption good. The B747 was partly based on design and development work of Boeing for a military version. As such it was one of the last major new aircraft technologies that was developed with the help of military budgets.

The oil crisis of the early seventies set a new development in motion in aircraft technology. An improvement in fuel efficiency was required in order to offset higher fuel prices. These efforts were strengthened shortly after the results of the environmental debate caused by the publication of the report of the Club of Rome. So in the decade 1970-1980 the engineering departments of the aircraft manufacturers were starting their efforts to come up with solutions for more fuel-efficient aircraft, replacing the aircraft types of the 1960’s such as DC 9 and Boeing 737-200.

The technology drive was further enhanced by the fact that Europe decided to launch a European civil aircraft industry (Airbus), based on the latest technology. Furthermore many smaller civil aircraft manufacturers, as well as some new entrants, decided to launch new products.

The period 1970-1980 was not a period of great economic prosperity. However as a result of the oil crisis and the further unification of Europe the incentives were there to start new technological research in the aircraft industry.

**1980-1990**

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13
The period 1980-1990 saw the delivery of the new technology aircraft such as the MD80, Fokker 100, Boeing 757 and 767. In the eighties, the aircraft manufactures were supported by economic prosperity, a strongly growing air transport market, and an increasing exchange rate freedom, able to sell and deliver large numbers of aircraft to airlines, providing better aircraft at reasonable prices. However, as the emphasis for aircraft manufacturers was on production and delivery of aircraft in order to earn back the investment of the previous decade, not many new technological efforts were launched. This is also due to the fact that aircraft in general have an economic life of around 25 years with no major technological breakthrough. All these factors have slowed down the technological incentives for civil aircraft manufacturers, including emission improvements. This decade saw the implementation of air transport deregulation and liberalization, creating a new less technology focus with airline managers.

1990-2000
The period 1990-2000 was, despite the short crisis due to the Gulf War in the early years of the decade, another period of world-wide economic growth. There were no clear aircraft technology incentives during this decade. In fact the break down of the Soviet Union caused careful reconsideration of military budgets. In the past the military sector was often the breeding ground for new aircraft technology, but because of the budget reductions these opportunities for transfer of technology, financed outside the market sector, have decreased in the last 10 years. For airlines this was the decade of further deregulation, but primarily consolidation through mergers, take overs and alliance building. This has led to a situation where the buying power in the aircraft market is concentrated with 5 alliance blocks, which in turn are heavily dominated by US carriers. This means that major decisions on aircraft specification are driven from the US market.

On the basis of this short analysis of economic and political factors we can conclude that economic prosperity has not led to major new efforts in aircraft technology. The economic crisis of the 1970s and the political decision to launch Airbus were the two major incentives to develop new aircraft technology. As the air transport market has been deregulated in the last 20 years, it is understandable that the technology drivers were mainly concerned with cost, thus explaining the cost reductions in table 5. Furthermore the customers in the aircraft market, the airlines, are managed by business oriented people, who are basically cash flow and stock performance driven. With the long lead times for new aircraft technology it is understandable that there is little incentive from the airline side to take large financial risks in new technology steps. Whereas airlines have lost interest in new aircraft technology, this interest could be increasing with companies specialised in aircraft leasing and focussed on residual values.

From the historical descriptions it is possible to identify the following categories of critical factors, that have played a role in the past.

**External:** Economic shocks affecting the need to adjust cost levels

**Aircraft Industry:** Military participation in design and development cost
Political support for aircraft industry (Airbus)

**Airline Industry:** Deregulation, leading to uncertainty less technological focus
Concentration and consolidation

**Regulators:** Noise lobby local
Club of Rome/Kyoto
3.2 Noise trends 1970-2000

Based on data from the ICAO, International Air Transport Association (IATA), Boeing and Airbus, a database with detailed data on the developments in aircraft noise (take-off, landing, overall) was created. Each of the 9 aircraft size classes was combined with engine technology for the periods 1970-1979, 1980-1989, and 1990-1999. The database includes the following information:

- Aircraft types/version/engines;
- RLD Size class;
- Year designed/built;
- Noise: overall/take off/landing;
- RLD Technology class.

The database shows that the aircraft noise emissions on average or per single measure point have been reduced by about 25 dB since 1960. The reduction of aircraft noise due to optimised engine technology from the early 1960’s to the beginning of the 1990’s is shown in table 6.

The table shows that there are time gaps between introduction of new aircraft types. There is a hausse in 1967, then two new types in 1972, then a gap of 10 years after which a gradual introduction of new types is taking place, however most types such as A300-300 or B737-500 are derivatives of earlier versions. The history thus shows that the time to develop and introduce a total new aircraft technology is increasing and that on the other hand aircraft manufacturers take a more gradual approach introducing derivative upgrades of already existing aircraft types.

Table 6: Reduction of aircraft noise

<table>
<thead>
<tr>
<th>Type</th>
<th>Manufacturer</th>
<th>Year</th>
<th>MTOW [t]</th>
<th>Take-Off EPNdB</th>
<th>Approach EPNdB</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC 8-61</td>
<td>Douglas</td>
<td>1967</td>
<td>161</td>
<td>105,5</td>
<td>107,9</td>
</tr>
<tr>
<td>DC 9-30</td>
<td>Douglas</td>
<td>1967</td>
<td>48,0-55,0</td>
<td>90,3-97,8</td>
<td>99,4-101,9</td>
</tr>
<tr>
<td>B 737-200</td>
<td>Boeing</td>
<td>1967</td>
<td>47,9-58,1</td>
<td>84,4-93,2</td>
<td>100,8-104,8</td>
</tr>
<tr>
<td>DC10-30</td>
<td>Douglas</td>
<td>1967</td>
<td>249</td>
<td>103,7-104,8</td>
<td>103,0-108,4</td>
</tr>
<tr>
<td>B 747-200</td>
<td>Boeing</td>
<td>1969</td>
<td>351-363</td>
<td>100,2-110,0</td>
<td>103,0-108,0</td>
</tr>
<tr>
<td>L-1011</td>
<td>Lockheed</td>
<td>1971</td>
<td>195-231</td>
<td>*95,0-99,4</td>
<td>*102,0-103,5</td>
</tr>
<tr>
<td>A 300 B4</td>
<td>Airbus</td>
<td>1972</td>
<td>150,0-170,5</td>
<td>89,0-93,9</td>
<td>99,1-103,2</td>
</tr>
<tr>
<td>B 757-200</td>
<td>Boeing</td>
<td>1982</td>
<td>103,8-113,4</td>
<td>*85,3-88,9</td>
<td>*95,0-100,3</td>
</tr>
<tr>
<td>A 310-200</td>
<td>Airbus</td>
<td>1983</td>
<td>125,0-142,0</td>
<td>*86,7-91,3</td>
<td>*102,3-102,7</td>
</tr>
<tr>
<td>B 737-300</td>
<td>Boeing</td>
<td>1984</td>
<td>56,4-62,8</td>
<td>*84,4-87,2</td>
<td>*99,9</td>
</tr>
<tr>
<td>B 737-500</td>
<td>Boeing</td>
<td>1990</td>
<td>52,9-59,0</td>
<td>*83,6-85,5</td>
<td>*99,8</td>
</tr>
</tbody>
</table>

Figure 2 shows development in noise reduction, expressed in dB(A).
Also this figure shows that the reductions have become smaller in later decades and that the intervals between introduction of new aircraft have become larger.

With the help of the aircraft noise database it is possible to describe the developments in aircraft noise in each size class as defined by the RLD. Of the three noise levels, the measurement under approach is used for the comparison.

Table 7: Developments per RLD size class, relevant aircraft type (aircraft noise dB(A))

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Saab340(92.0)</td>
<td>F28(100)</td>
<td>ATR72(94.0)</td>
<td>Saab2000(88.0)</td>
<td>-12.0</td>
</tr>
<tr>
<td>2</td>
<td>DC9(99.0)</td>
<td>B727-200(101.0)</td>
<td>Fokker100(94.0)</td>
<td>RJ100(88.0)</td>
<td>-11.0</td>
</tr>
<tr>
<td>3</td>
<td>B707(100.0)</td>
<td>MD80(93.3)</td>
<td>A310(98.6)</td>
<td>MD90(92.0)</td>
<td>-9.0</td>
</tr>
<tr>
<td>4</td>
<td>B747-200(104.2)</td>
<td>B747-200(104.2)</td>
<td>B747-100(97.0)</td>
<td>B747-400(104.0)</td>
<td>-1.0</td>
</tr>
<tr>
<td>5</td>
<td>DC10(105.0)</td>
<td>MD11(103.0)</td>
<td>A300(101.1)</td>
<td>B777(99.0)</td>
<td>-6.0</td>
</tr>
<tr>
<td>Technology</td>
<td>Class</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Table 7 shows that the RLD technology classes 1,2,3 can be linked with the reference aircraft of each of the past three decades. There have been sharp reductions in aircraft noise in the last 30 years. In some classes, the reduction in aircraft noise was not realised, but the size of the aircraft increased within its class, while noise levels remained constant. As larger aircraft mean larger engines it could be expected that also noise levels would increase, but that did not happen due to new technology.

### 3.3 General aircraft technology trends

Most technological improvements made in civil aviation have not been driven by noise problems, but were developed because there was a military or commercial need for them. The decrease in the amount of aircraft noise because of these improvements has mostly only been a positive by-product.
Three main technological trends have been responsible for the increase of productivity and decrease of aircraft unit cost:

- Aerodynamics;
- Weight reductions;
- Reduction in specific fuel consumption.

**Aerodynamics**

Further optimisation of the high lift devices increases the lift/drag ratio of an airplane. This reduces the thrust required for take off, climb, approach and landing. The reduced thrust leads to lower noise emissions. Significant for the optimisation of flaps and slats is that the devices are relatively quick to install, although have high costs [Flight, 1998b]. Advanced operating procedures, including automatic optimised flap and throttle settings, offer additional acoustic benefits.

**Figure 3: Developments in aerodynamic efficiency**

L/D at M(L/D) max is a measure for aerodynamics of aircraft wings. L/D stands for Lift over Drag and indicates how large the aircraft wing needs to be, causing Drag in order to Lift the aircraft from the ground. From Figure 7 the relative improvement in aerodynamics can be directly calculated.

**Weight reductions**

Modern aircraft design relies heavily on the use of advanced composite materials for combining weight reduction and thus fuel savings with the same strength and durability as conventional materials. The use of composites will almost certainly continue to increase, but presumably at a measured pace. Airlines have started to complain about the often heavy maintenance cost of new materials outweighing the savings in operating cost, so the speed of future new applications will depend on the balance between prospective savings and new costs. If these new materials also make a difference in the amount of noise produced, the ‘savings’ could be increased.

Weight savings mean that less thrust is needed and therefore less noise.

---

1 **Lift** is the component of aerodynamic force perpendicular to the relative wind. **Drag** is the component of aerodynamic force parallel to the relative wind.
Reduction in specific fuel consumption

The cruise thrust specific fuel consumption is a standardised (at equal speed performance) measure for fuel consumption per engine. From Figure 5 the relative savings can directly be calculated. The trend of the cruise thrust specific fuel consumption is going down, but the steep of the line is flattening and the assumption is that this will stay this way in the future.

These three areas of aircraft technology development have led in the past 30 years to a relative efficiency gain of 50%. This efficiency gain is either translated into lower unit costs or in better aircraft performance (speed, range, capacity). As such the developments in the last 30 years fit into the long-term trend in aircraft development.

The technology trends will serve as input for the calculation of bandwidths in chapter 5. It is clear that, until now, aircraft noise reduction went hand in hand with increases in aircraft efficiency. However, as
table 5 shows these increases in aircraft efficiency have become smaller in the last two decades.

3.4 Aircraft noise technology trends

Jet exhaust noise reduction
In early turbojet engines, the major noise source was the mixing of the high velocity jet exhaust with the surrounding air. Low-bypass-ratio turbofan engines, introduced in the 1960s, provided greater propulsive efficiency and lower noise. These engines were a significant 10 dB quieter than their immediate predecessors. With the help of internal mixers, high bypass turbofans combine the high-speed exhaust from the engine core with the slower fan exhaust, resulting in less shear with the outside air and leading to significant reductions in aircraft engine noise. A 10% reduction in the velocity of the overall exhaust flow cut the resulting noise by more than half.

An even greater reduction in noise came in the early 1970s with the introduction of second-generation turbofan engines with yet higher bypass ratios [ATW, 1995; AA, 1999].

The earlier high bypass ratio engines were designed with coaxial but separate fan and core nozzles. The early 1980s saw the introduction of the Rolls-Royce mixed exhaust engine with a common final nozzle (so called “forced” mixer, see appendix D, figure 3).

The next figure shows diagrammatically the beneficial rearrangement of the noise radiation pattern for a high bypass engine.

Figure 6: Difference in noise between low and high bypass engine

[Jamieson, 1990]
To use the advances of high bypass ratios, some aircraft types were re-engined during the last decades. With little or no degradation in airplane performance, the re-fan technologies could provide noise reductions of 5 to 10 dB. For many Boeing B727 aircraft, the older JT8D-7/9s engines were replaced by higher bypass, more efficient JT8D-217/219s [Flight, 1999c]. Re-engining reduces not only the noise emissions but also improves performance and fuel economy, since the new engines are more advanced than the ones they replace. However, it is expensive for the aircraft operators [ATW, 1990].

**Hushkits**

In addition to purchasing newer jets or installing new jet engines on existing planes, older aircraft can be modified and brought into compliance with recently implemented international noise standards (from Chapter 2 to Chapter 3) by installing hushkits (a set of high-technology engine noise reduction components). See appendix D, figure 4 for explanation of hushkit installation. Depending on which technical treatments are necessary and whether the airplane carries two or three engines, the costs of hushkitting amounts to about $1.4 million - $3 million per aircraft. In comparison, it would cost a minimum of $3 million per engine if the option of re-engining (re-equipping an old aircraft with new engines) were chosen. [ATW, 1990]

However, hushkits have some disadvantages including increased fuel burn and air pollutant emissions. [ATW, 1995].

**Fan noise**

Research in noise reduction due to fan optimisation was started by engine manufacturers in the 1970s. One approach to solve the problem in the past was the reduction of the “obstacles” such as inlet guide vanes and struts that can distort the flow of air. Another approach was the harmonisation of the number of “obstacles” with the number of fan blades to minimise the efficiency of the irregular interaction. With this fan blade passage frequency (BPF) “cut-off” design, the BPF tone does not propagate outside the engine nacelle. Blade number and spacing, to tailor noise frequencies and avoid siren effects, were carefully chosen to minimise noise and optimise performance [AA, 1994]. The number and placement of fan blades can be arranged so that the loudest tones generated by one row are blocked by succeeding rows.

**Nacelle**

In the early 1970s NASA started a noise reduction program. This program focused on quiet nacelle design technology to retrofit existing engines to reduce aircraft noise of aircraft such as the Douglas DC-8 and Boeing 707. Sound absorbing liners were added to the intake, fan duct, jet pipe and nacelle. The “Quiet Nacelle Program” demonstrated a noise reduction potential during approach by as much as 15 dB. Later on the “Quiet Engine Program” was started as a step toward the concept of integrated acoustic design in new production engines. To reduce the internal engine noise, the intake was kept free of struts and other obstructions that could distort the flow of air. The shape, number and placement of blades were arranged so that the loudest tones generated by one row were blocked by succeeding rows [NASA, 1997a]. Other engine modifications to reduce the engine noise, such as lengthening the intake duct, reducing the rotational speed, increasing rotor/stator separation and improving the fan blade aerodynamic design, are still under investigation [ATW, 1995; NASA, 1997b].

**Operational Measures**

In addition to technological improvements in noise reduction, noise abatement arrival and departure procedures have been developed to reduce the impact of aircraft noise on people living close to airports. The current ICAO noise abatement departure procedures were approved in 1982 and are contained in the “Procedures for Air Navigation Services - Aircraft Operations Vol. 1 - Flight Procedures” (PANS-OPS, Doc. 8168).
3.5 Trends in Noise regulation

Of all of the environmental problems associated with civil aviation, aircraft noise has been considered to be the most important for many years. Since the introduction of jet-powered civil transport aircraft into passenger service in the early 1960’s, the topic of noise reduction became a more and more important issue.

Regulations, noise budgeting or/and aircraft access and operational restriction at airports have been established to reduce aircraft noise at airports. To meet the new standards, the effort to diminish aircraft noise over the past 25 years has been aimed mainly at reducing noise at source by building and operating quieter engines [ATW, 1995].

In 1969, the first national noise limits for certifying commercial aircraft were implemented in the United States by the Federal Aviation Authority (FAA) as Federal Aviation Regulation (FAR) Part 36. A similar rule was adopted as the international standard, published in Volume 1, Part 2 of Annex 16, by ICAO in 1971. In addition, noise regulations and certification standards have been legislated by national governments (i.e. law against aviation noise in Germany etc.) and by specific airports.

Table 8 gives an overview of international noise regulations that have been promulgated and reactions to the regulations.

Table 8: Overview of Noise regulations in the World

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969</td>
<td>FAA introduces Federal Aviation regulation Part 36 World’s first aviation noise limits</td>
</tr>
<tr>
<td>1971</td>
<td>Adoption of similar standards by ICAO</td>
</tr>
<tr>
<td>1977</td>
<td>Chapter 3 standards drawn up by ICAO</td>
</tr>
<tr>
<td>1990</td>
<td>ICAO adopts Chapter 3 noise standard, due to be phase in by 2002</td>
</tr>
<tr>
<td>January 1986</td>
<td>Enforcement of ICAO annex 16 chapter 2 in Europe bans all Chapter 1 aircraft</td>
</tr>
<tr>
<td>December 1989</td>
<td>EC adopts a new no addition to register direction, which prohibits the addition of aircraft not capable of meeting Annex 16 Chapter 3 noise limits to EU member states registers after November 1990, with a few exceptions, including hushkits.</td>
</tr>
<tr>
<td>November 1990</td>
<td>No more Chapter 2 aircraft are allowed for import to operate within the 48 contiguous US states</td>
</tr>
<tr>
<td>June 1998</td>
<td>EU transport ministers agree on the EC’s proposal to ban aircraft hushkitted to Chapter III after 2002 if they are not grandfathered by April 1999</td>
</tr>
<tr>
<td>May 1999</td>
<td>EU agrees to delay the cut–of date for grandfathered aircraft by a year to May 2000</td>
</tr>
<tr>
<td>January 2000</td>
<td>US airlines claim to be fully Chapter III compliant</td>
</tr>
</tbody>
</table>

Noise certificates have proved to be adequate in containing the cumulative noise problem at many airports and they have also been used as the basis for extensive general limitations and operating restrictions on aircraft. After adopting the new noise certification standards several States have legislated a non-addition rule of Chapter 2 aircraft, which prohibits the addition of aircraft types meeting only Chapter 2 standard. Some States such as Australia, Canada, the United States and many countries in Europe are also phasing out operations by Chapter 2 aircraft. This started in 1995 and the goal is to have all of them withdrawn in 2002 [IATA, 1995]. The EU has passed an ordinance that hinders registration of hushkitted aircraft2 after April 1, 1999, and prohibits hushkitted traffic after April 1, 2002. The USA view this as a trade barrier and demands that it be revoked, since the hushkitting industry is found only in the USA [SAS, 2000].

In 1995 the EU pushed hard within Committee on Aviation Environmental Protection (CAEP) for a so-called Chapter 3.5, but was beaten back by the US, and in 1997 the EU commission issued a directive using a standard for bypass ratios, not performance, to measure noise. Hushkitted/re-engined airplanes

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2 hushkit: a set of high-technology engine noise reduction components
fell below the standard. In 1998 the EU tried again to push ICAO, suggesting that year’s Assembly permit
regional variations in noise limits. Unfortunately for the EU this proposal had little support. The poss-
bility of the set of a new Chapter 4 will be discussed in the fourth chapter of this report, in the para-
graph on future.

Apart from ICAO and national regulations, individual airports have also been imposing measures in order
to reduce aircraft noise emissions. In the US these local measures were implemented in the 1980-1990
period. The FAA opposed local, often non-standardised rules, and as a result such measures need to be
approved by congress. This in effect, makes local rules impossible.

In Europe local airports and the relevant authorities have much more freedom to install local measures.
These new measures have come in place in the period 1990-2000. These measures are focused on influ-
encing the composition of airline fleets and not so much in stimulating new technology. For example the
phase out of chapter 2 aircraft on Amsterdam airport has increased due to local noise regulations. The
following table provides a comprehensive overview of local noise measures at main European airports.

Table 9: Local noise measures at main European airports

<table>
<thead>
<tr>
<th>Airport</th>
<th>Curfew/Cap Chapter 2</th>
<th>Differential charging</th>
</tr>
</thead>
<tbody>
<tr>
<td>London LHR</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Frankfurt</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Paris CDG</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Amsterdam</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>London LGW</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Paris ORY</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Rome</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Madrid</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Zurich</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Munich</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Copenhagen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manchester</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Dusseldorf</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Stockholm</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Barcelona</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milan LIN</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Vienna</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Berlin TXL</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Source: Air Transport World 4/2000

The most striking local noise policies are those of Zürich airport. Zürich airport has adopted a landing fee
policy, depending on the noise class of aircraft. These fees range from 0 Swiss Francs for an aircraft with
noise category 5, to 800 CHF (1 CHF = 0.64 Euro) for an aircraft in category 1. While in 1993 only 50%
of the aircraft were category 5 aircraft, this percentage has grown to over 70% in 1997. Chapter 2 air-
planes are not allowed to land or start between 19:00 hours and 09:00 hours. The airport is closed during
the night (for landings: 01:00-05:00; starts: 00:30-06:00). The closing time for charter and private flights
is even longer. While it is impossible to introduce a night ban at all European airports, a fee structure is
suitable anywhere.
4. FUTURE TECHNOLOGICAL AND REGULATORY TARGETS

4.1 Potential technological breakthroughs

Aircraft technology developments are influenced by the economic and political climate worldwide, specifically in the US and Europe. These factors, as well as their positive or negative impact on aircraft noise will be discussed in chapter 5. In this chapter the targets for noise reduction will be examined, both from a technological point of view (technological targets) as from a regulatory point of view (regulatory targets).

It is important to realise that of the five technology parameters for aircraft (speed, size, flight altitude, range and cost) practically all, except for cost, are limited in their further development by market requirements, operational standards or environmental limitations. With a range of 7000 miles aircraft are able to fly most commercially viable routes non-stop. Flying altitude and speed are limited by the air traffic management standards. A new generation of supersonic aircraft could be developed, however after the latest accident and the operational limitations for supersonic aircraft over land, the future for this kind of technology is bleak. Clearly, the A380/A3XX will be a large step both in terms of aircraft size and aircraft economics, if the market for such large aircraft is sufficiently large.

Several airlines have already expressed interest in aircraft with 600 to 800 seats, because they hope to be able to realise continued growth despite airport congestion. The super jumbo is a huge commercial risk for individual manufacturers because of the development costs, estimated at around 10 billion dollars, and the limited expected market. A joint project between the biggest two aircraft manufacturers, Boeing and Airbus, has come to nothing.

Boeing has the advantage of being able to cover part of the market by stretching the B-747. Such a derivative would not offer the same technical and economical benefits of a new design, but it would be available sooner and cost less, compensating the relative lack of sophistication. For Airbus the super jumbo is of strategic importance. To sustain the competition with Boeing, the company must be able to offer customers a B747-class aircraft of its own because the airlines increasingly want fleet commonality in order to reduce cost. The projected A3XX Airbus aims for a direct operating costs (DOC) reduction of 15-20% against the B747-400. This is a welcome advantage considering the continuously declining yields in civil aviation.

The super jumbo presents considerable technical problems. Preferably the aircraft must fit into the 80x80 meter squares used as standard for airport infrastructure, for if not it would create a capacity problem rather than solving one. The plane will presumably have two passenger decks, and therefore presents new requirements concerning the capacity and location of entrance doors, emergency exits, and terminal gates. Its landing gear will have to distribute a much higher weight sufficiently to allow the aircraft to use existing runways, but increasing the number of bogeys and wheels also increases drag, i.e. engine power and noise, at landing. The engines will have to meet stringent air pollution and noise requirements. Finally, a super jumbo will produce a strong wake vortex. Airbus is optimistic that the A3XX will comply with the most stringent proposal for future noise certification limits envisaged in the latest ICAO meeting. The target is to make the A3XX both larger and quieter than its predecessors. Even though seating 30-50% more passengers, it will be quieter than the 747-400 at each of the three standard noise measurement points (fly-over, sideline and approach) [Airbus, 2000].

To avoid accidents, lighter planes flying behind it will have to keep more distance, reducing airport capacity. Thus the A3XX will require both extensive use of new materials and engineering, and changes to airport infrastructure and air traffic control procedures.

Airbus has already signed memoranda of understanding with Rolls-Royce and the Engine Alliance, who will offer respectively the engines: Trent 900 and the GP 7200 [Airbus, 2000].

Outside the scope of traditional turboprop or jet aircraft are two new concepts: Vertical Take Off and
Landing (VTOL) aircraft and zeppelins.

VTOLs combine the flexibility of helicopters with the speed of conventional turboprop aircraft. They do not have to use runways, and may therefore help to ease airport congestion. The Bell-Boeing V-22 Osprey is a fully-fledged VTOL, capable of carrying up to 22 passengers. It has been designed for military use. The civilian versions have so far remained on the drawing board. The projected operating costs are lower than for a helicopter, but much higher than for a turboprop, limiting commercial use to replacing helicopter services and catering to other market segments, which can bear heavy surcharges. Western Europe has until now offered hardly any scope for such premium services.

For economic reasons it is not very likely that this type of airplane will develop a substantial market share. But since noise during take-off and landing is relatively low for VTOLs, we discuss this technology. The exact effect on noise depends on substitution effects.

Zeppelins offer a very quiet way of air travel. Recently, interest in the old zeppelin has revived, with a design team based in the Netherlands in Lelystad. According to the initiators, airships provide an ideal platform for advertising, monitoring, and security operations. In civil aviation, zeppelins would offer environmental advantages over conventional aircraft. However, zeppelins are currently not designed for regular traffic because they have a maximum speed of 200 kilometres an hour, which is even less than the high speed trains. We foresee little impact of this technology in the next 30 years mainly because of lack of market potential.

Thus, due to lack of viability for total new concepts and the limitations for major breakthroughs on jet aircraft, the future noise reductions can only be anticipated on current aircraft and engine concepts.

4.2 Potential improvements to existing aircraft and engine concepts

Although there are declining noise reduction gains to be wrung out of the current technology [ATW, 1995], there remain several opportunities to reduce noise emissions on existing aircraft and engine concepts. The still existing potential in aircraft noise reduction is illustrated e.g. in the objective for the Advanced Subsonic Technology program (AST) that was started in 1997 by NASA. NASA’s goal is to reach a noise reduction of 20dB by the year 2022 (compared to the 1997 standard). Although most of this improvement would come from decrease in engine source noise and advances in nacelle acoustic treatments, noise generated by the airframe itself needs attention as well. Researchers realised that improving the way airplanes operate at airports could also reduce community noise (see the following figure) [NASA, 1997b].
CFM International has also outlined a broad-based technology development initiative called TECH56, investigating different noise reduction measures for the CFM56 engine family. The initiative is aimed at reducing cumulative noise levels by up to 20 dB for the higher thrust engines and by up to 27 dB for the smaller engines [Flight, 1999a].

Pratt & Whitney have proposed a new engine, the PW8000. Pratt & Whitney is claiming that it can save 30dB over the original Chapter 3 baseline, depending on the airframe. This will be about 7dB lower than the current Boeing 777 that has a GE90 engine of which GE says it was designed to meet the ‘highest expected noise standards’.

Comparing the objectives of these research programs, a considerable potential for aircraft noise reduction can be expected for the future. The most promising approaches under investigation are:

- Fan noise reduction;
- Jet exhaust noise reduction;
- Further increase of bypass ratio;
- Fan nozzle design;
- Active noise control (ANC);
- Sound absorbing materials;
- Improvement in engine performance;
- Airframe noise.

For a detailed description of each of these, see appendix C.

In comparison, Boeing considers cumulative reductions in the future of 8, 11 and 14 dB.

Tradeoffs
Further enhancement of aircraft noise technology might also interfere with other objectives of technology development such as aircraft economy and/or reduction of gaseous emissions.

The advantageous effect of an increase in high bypass ratio is a slower fan exhaust, resulting in less shear with the outside air and therefore noise reduction. However, this includes the extension of the fan diameter and the lengthening of the engine nacelle that would cause an increase of the engine’s total weight and an increase in drag. Higher weight and drag results in an increase in fuel consumption and also in air pollutant emissions. Another penalty of extending the fan diameter is the increasing noise from the fan and turbine systems, even more if a multi stage fan is used or, as with a propeller, noise is not controllable by conventional means.

To minimise the increase in weight, new fan cowl concepts have to be designed. Short, thin and light have to be the characteristics of such cowls, which can be achieved by new materials such as composite. But these features are not conductive to noise control (e.g. noise absorbing material, which thicken the cowl). In addition, new material turns often out to be very difficult and costly to maintain.

Another critical factor in noise reduction is the variety of aircraft noise sources. Since efficient and quiet high bypass ratio engines propel new commercial aircraft, airframe noise has become a dominant noise source during landing approach. In future airplanes, the airframe noise will be equal to engine noise not only during landing but also during takeoff.

Noise reduction can cause other environmental problems. For a noise abatement departure procedure that reduces noise relief near the airport due to fast climb, it is necessary to fly with take off thrust for a longer time than during standard departure procedure. This results in higher fuel consumption and a higher level of air pollutant emission, especially in NOx-emissions, during take off. Additional to this, an increase in fuel consumption also results in higher operating costs for airlines.

Some of the developed noise reduction technologies have failed because of a raise in operating costs, less acceptance by passengers and technical problems such as more frequent engine failure or less efficient thrust reversal. A wide study of MTU and Pratt & Whitney compared the most encouraging concepts with the conventional high bypass turbofan concept: the single-stage advanced ducted prop (ADP), the counter rotating ducted propfan, the Counter Rotating Integrated Shrouded Propfan (CRISP) and the unducted fan (UDF). Although the propulsive efficiency of such designs is very high, they are often less desirable than the engines with more moderate bypass ratios. This is due to the difficulties of installing these very large diameter engines, especially on low-wing configurations, and on the weight and drag penalties associated with the large duct [MTU, 1994].

Table 10: advantages and disadvantages of new engines compared with the current turbofan

<table>
<thead>
<tr>
<th></th>
<th>Turbofan</th>
<th>ADP</th>
<th>CRISP</th>
<th>UDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel consumption</td>
<td>O</td>
<td>+</td>
<td>++</td>
<td>+++</td>
</tr>
<tr>
<td>Emissions</td>
<td>O</td>
<td>+</td>
<td>++</td>
<td>+++</td>
</tr>
<tr>
<td>Noise</td>
<td>O</td>
<td>+</td>
<td>O</td>
<td>-</td>
</tr>
<tr>
<td>Speed</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>-</td>
</tr>
<tr>
<td>Engine failure</td>
<td>O</td>
<td>-</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Thrust reversal</td>
<td>O</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Installation</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>-</td>
</tr>
<tr>
<td>Weight</td>
<td>O</td>
<td>-</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Production costs</td>
<td>O</td>
<td>-</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>O</td>
<td>-</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

[MTU, 1994]

The above overview shows the positive and negative developments of new engine technologies compared with the current turbofan. It shows the tradeoff between economics and environment in most cases, and
sometimes the tradeoff between emissions and noise.

**Pipeline effects**

A key element in the technical development of aviation has been the steep reduction in fuel consumption. Further cuts are to be expected, for instance by the use of bigger fan blades at the price of producing more noise. Since the late 1980s there has been a viable alternative in the shape of propfans with counter rotating propellers, which offer impressive fuel savings. However, at present fuel price levels, the cost of these engines far outweighs the potential savings. Other problem areas for propfan powered aircraft are in the field of customer/pasenger acceptance as well as Air Traffic Control compatibility. The introduction of the propfan depends on a drastic fuel price rise and/or a technical breakthrough cutting engine cost.

Figure 3 to 5 provide, apart from a historic development of aircraft technology factors, also future trends. These can be summarised as follows:

Table 11: Relative gains in aircraft technology over the next 30 years

<table>
<thead>
<tr>
<th>Technology</th>
<th>Efficiency gain 2000-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerodynamics</td>
<td>13%</td>
</tr>
<tr>
<td>Weight</td>
<td>20%</td>
</tr>
<tr>
<td>Engine (Specific Fuel Consumption)</td>
<td>12%</td>
</tr>
</tbody>
</table>

These efficiency gains will be more or less evenly spread over the relevant period and applicable to all jet aircraft. The effect on aircraft noise is not directly through new technology, but achieved by applying smaller engines on larger aircraft. This will, according to NASA, reduce noise levels with a cumulative 3 dB. The effect will take place after 2010.

4.4 Regulatory targets

The EU has been fighting a battle for the introduction of a more stringent ‘Chapter 4’ (certification standards for jet airplanes that are more stringent than the present Chapter 3 standards) for a long time (see also Chapter 2 on History in this report). Now, ICAO’s CAEP has a group of experts examining the issue of a new ‘Chapter 4’ category. However, there is still discussion how the Chapter 4 limits would be defined.

Table 12: Crucial dates with respect to noise regulations

<table>
<thead>
<tr>
<th>January 2001</th>
<th>ICAO’s CAEP working group due to meet to discuss new noise standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autumn 2001</td>
<td>ICAO’s 33rd assembly – new noise standard agreement would be ratified here – if agreed</td>
</tr>
<tr>
<td>2002</td>
<td>Final chapter 2 phase out. EU’s proposed hushkit ban due to take effect</td>
</tr>
</tbody>
</table>

Source: Airline Business, 2000

The US argues that once a Chapter 4 standard exists, demands to meet it rather sooner than later will increase even if it applies only to new designs and certainly before airlines are ready. The pressure will be greater still if better engine technology is available [ATW, 2000].

US airports are far more exposed to hushkitted aircraft then the Europeans, and in an article in Air & Space Lawyer, the ACI-NA General Counsel says that the US airports want a ‘reasonable’ retirement schedule for models not meeting Chapter 4. If the 2001 Assembly fails to produce a new standard, European airports want the EU to establish uniform airport noise restrictions [ATW, 2000].

Many questions remain, even when a ‘Chapter 4’ definition is adopted:
- Should Chapter 4 be applied to in-production or new-technology aircraft;
- Which dates for implementation, completion and transition;
- What are the technical possibilities of reducing other emissions along with noise and the economics
of all permutations.

However, these questions are more related to fleet development and phase-out scenarios.

4.6 Expected noise reduction based on technological and regulatory targets

According to the US National Science and Technology Council (NSTC), by next year, technology under development by the FAA, National Aeronautics and Space Administration (NASA) and the aviation industry will enable a 5 dB reduction in aircraft noise relative to 1997 technology. In the long term, the agencies are aiming for a 20 dB reduction that would contain 55 dB noise contours within airport boundaries despite projected increase in operations. The Environmental Protection Agency considers 55 dB average day-night level necessary to protect public health and welfare [NRR, 2000]. The target of all participants from research and industry is to reduce aircraft noise by more than 20 dB. In the opinion of experts this seems to be achievable for new aircraft programs launched after 2005.

Autonomous technology developments could produce further noise reductions in the amount of 20 dB cumulative. The major reduction is foreseen in the first decade (2000-2010) with 10 dB cumulative. In the periods 2010-2020 and 2020-2030 reductions in the order of 5 dB cumulative can be expected. The reductions can be applied on all aircraft classes and are thus size independent. The technology can be applied on all existing and newly developed jet aircraft.

Technological and regulatory targets seem to be well coordinated, however the regulatory targets are mainly set by the economic phase-out of airline fleets than by the availability of new technology.
5. CRITICAL FACTORS AND BANDWIDTHS

5.1 Introduction

In this section the critical factors (bottlenecks) which prevent a further reduction of aircraft noise in the future are analysed. These critical factors include the effect of the political environment on technology, but also airline and aircraft manufacturers and costs/profitability aspects. The bandwidths of possible noise reduction are also described in this chapter.

Barriers that could hamper a further reduction of aircraft engine noise are identified and discussed below. These can be of technical nature (including the relationship with fuel consumption, safety, etc.), but also of economic nature.

This boils down to assessing new technology for its practical and economical viability. The analysis of economical viability centres on the profit potential for airlines and aircraft manufacturers. Since ticket prices show a declining trend, new technology will have to offer the same or better yields to be viable. The combination of operational expenses and price of a new technology aircraft will thus have to result in operational costs per seat kilometre equal to or lower than available aircraft with the same capacity.

5.2 Critical factors

Economic parameters

Cost of fuel, crisis

Political bottlenecks

Asian manufacturer

The so-called Hushkit-war is the most recent example of the influence that politics can have on aircraft noise and noise regulations. The EU says that its motive is to fight for the environment, not protectionism. But in the USA, the EU’s strategy is not regarded as environmentally friendly.

The USA has been eliminating Chapter 2 aircraft ahead of the ban, with all such aircraft barred from the 48 contiguous states, as of 31 December 2000. The USA, however, has no qualms about allowing aircraft hushkitted to Chapter 3 standards to continue operating after the ICAO deadline. The chief battleground between the EU and the USA is Annex 16 of ICAO’s founding document, the Chicago convention. The EU says that the Annex 16 Chapter 3, which are used as the basis for certification, were never meant to include re-certificated aircraft, defined as: “civil subsonic jet aircraft initially certificated to Chapter 2 or equivalent standards, or originally not noise certificated, which have been modified to meet Chapter 3 standards, either directly through technical measures or indirectly through operating restrictions” [Flight, 2000b]. Here, the political issues are bigger than the technical ones.

Another US objection is the EU rule that will ban aircraft with engines having a bypass ratio of less than 2 from using European airports from April 2002. “The EU should not be in the business telling manufacturers, engine makers and entrepreneurs what bypass ratio an engine must have. They should be telling us what noise footprint we should have to live with, and then let us figure out how we can do it”, says James Raisbeck of Raisbeck Commercial Air Group [Flight 2000b].

It might be that ICAO regulations in other fields than aircraft noise or the EU-USA situation give rise to certain problems concerning the reduction of aircraft noise.
**Aircraft industry**

For manufacturers who have aircraft and engine types that have not reached a mature stage in the product life cycle, new products can threaten profitability. For example, it is known that the current Boeing 737 aircraft will have difficulty with accommodation of newer larger engines that reduce engine noise by 3 dB. As Boeing anticipates the high cost of developing a new aircraft type, there is quite some resistance to allow these new technology engines to be further developed.

Most important however is the development of aircraft prices. These prices are partly determined by production cost, but more importantly by the engineering/aircraft development cost. In constant, prices per aircraft seat these have increased considerably. For example, the Boeing 777 has an estimated development cost of $17.5 mln. per seat (1993 prices), while the Boeing 747 is estimated to be $8.0 mln. per aircraft seat (1993 prices). Thus in a period of 20-25 years these costs have doubled. This is mainly due to higher technological complexity and the increased safety standards that aircraft have to comply with. These higher fixed costs should be compensated for the airlines by either a larger market or by lower variable costs. In chapter 2 we mentioned that the unit costs have levelled out in the recent years, which leaves the compensation for higher aircraft development costs totally to larger production batches. And here also the possibilities are limited. Aircraft prices have risen in recent years, while airline revenues have come under pressure due to increased competition as a result of deregulation and liberalisation. All these developments have created an aircraft market in which it is very difficult to justify the cost of new aircraft technology, if this new technology does not lead to new efficiencies in aircraft economics. Thus the cost of new technology will become a critical factor for airlines to implement it. To estimate the cost of all potential technological developments leading to aircraft noise reductions mentioned in the NASA report is beyond the scope of this study.

**Airline industry**

Costs for airframe and engine maintenance and depreciation have a share of 45% of an airline’s operating costs. The resulting development costs for new technologies could increase maintenance costs and depreciation and therefore may exceed the financial budgets of manufacturers and operators (airlines), which could effect higher fares for passenger and cargo transportation. In price sensitive areas of air transport (i.e. last minute, low budget flights, etc.) the efficiency of air traffic could be reduced and the expansion of air traffic could be hampered.

If further noise regulations are coming after Chapter 3, hushkitted airplanes will not be able to cope in. Alternatively, older aircraft could be re-engined with high bypass engines, which ensures compliance with future stringent noise regulations. As mentioned before, re-engining is very costly compared with hushkitting and could therefore cause significant economic implications for the airlines concerned, particularly those from developing countries [ICAO, 1993].

### 5.3 Bandwidths

From the technological analysis, it is clear that a further reduction of 20 dB cumulative could be realised (NASA). This reduction is widely applicable to all jet aircraft. Therefore, a detailed analysis of developments per size class is not relevant. More emphasis should be placed on the timing aspect. From NASA’s analysis a cumulative 10 dB reduction seems feasible in the first decade (2000-2010), while the remainder could be implemented in the next 15-20 years.

As this describes the technological potential for the next 30 years, the question becomes how much can be implemented. It is clear regulatory incentives will play an important role.

Based on expert opinions, the first 5 dB cumulative could be relatively easy obtained. This reduction will be realised in the first decade without any further strengthening of regulatory limits. To implement the other cumulative 5 dB reduction regulatory action will be required.
For the next two decades an autonomous further reduction of 5 dB cumulative can be foreseen, bringing the total autonomous reduction in aircraft noise to −10 dB cumulative. The other 10 dB cumulative reduction must be obtained by more stringent regulations.

This provides the following trends per aircraft size class:

Table 13: Development dB(A) one measuring point (approach)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>99</td>
<td>94</td>
<td>88</td>
<td>84-86</td>
<td>82-85</td>
<td>80-84</td>
</tr>
<tr>
<td>4</td>
<td>101</td>
<td>93</td>
<td>92</td>
<td>88-90</td>
<td>86-89</td>
<td>84-88</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>99</td>
<td>95</td>
<td>91-93</td>
<td>89-92</td>
<td>87-91</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>102</td>
<td>97</td>
<td>93-95</td>
<td>91-94</td>
<td>89-93</td>
</tr>
<tr>
<td>7</td>
<td>105</td>
<td>103</td>
<td>99</td>
<td>95-97</td>
<td>92-96</td>
<td>90-95</td>
</tr>
<tr>
<td>8</td>
<td>106</td>
<td>104</td>
<td>104</td>
<td>100-102</td>
<td>98-101</td>
<td>96-100</td>
</tr>
</tbody>
</table>

The table above gives the potential noise reduction at one measure point: under the approach route. The first figure indicates the potential reduction, obtained with the help of regulations, the other figure is the reduction that can be achieved without regulation. The trend is a declining one. Based upon the assumption that the cumulative reduction can be 20 dB cumulative with regulation and 10 without, the following table can be made. The assumption is that the noise reduction at the flyover and lateral measure points are identical.

KLM >>>>>>>>>>

Table 14: Potential reduction at the three measure points

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2010</th>
<th>&gt;2020</th>
<th>Total dB(A) reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach with regulation</td>
<td>-4</td>
<td>-2</td>
<td>-2</td>
<td>-8</td>
</tr>
<tr>
<td>Flyover with regulation</td>
<td>-3</td>
<td>-2</td>
<td>-1</td>
<td>-6</td>
</tr>
<tr>
<td>Lateral with regulation</td>
<td>-3</td>
<td>-2</td>
<td>-1</td>
<td>-6</td>
</tr>
<tr>
<td>Approach no regulation</td>
<td>-2</td>
<td>-1</td>
<td>-1</td>
<td>-4</td>
</tr>
<tr>
<td>Flyover no regulation</td>
<td>-1.5</td>
<td>-1</td>
<td>-0.5</td>
<td>-3</td>
</tr>
<tr>
<td>Lateral no regulation</td>
<td>-1</td>
<td>-0.5</td>
<td>0</td>
<td>-1.5</td>
</tr>
</tbody>
</table>

Note that the 20 dB NASA is talking about is cumulative. Table 15 shows potential noise reduction at single measure points.

TIMING>>>>>>>

---

3 Under take off flight path
4 At the sight of the runway during take off
6. EMISSIONS

6.1 Introduction

Emissions
The combustion of aviation fuels gives rise to emissions of:
- Carbon dioxide (CO$_2$);
- Water vapour (H$_2$O);
- Sulphur dioxide (SO$_2$).

If the combustion is not complete, the following additional emissions develop:
- Carbon monoxide (CO);
- Volatile organic compounds (VOC);
- Particulate emissions.

- In addition, aircraft also emit nitrogen oxides (NO$_x$) which are not directly related to fuel consumption, but to high temperatures in the combustion chamber. These high temperatures generate the oxides of nitrogen monoxides (NO) and nitrogen dioxides (NO$_2$), together termed as NO$_x$ from the nitrogen and oxygen out of the air [CE, 1998].

Impacts of aircraft emissions

Ozone depletion
The atmospheric environmental impacts associated with aviation emissions are probably ozone depletion (which might be the case in supersonic flying), greenhouse effects, acidification and local air pollution. Important emissions from aircraft at an altitude above 900 meters are: NO$_x$, particulate emissions, CO$_2$, sulphur compounds, and H$_2$O. Important emissions from aircraft at an altitude less than 900 meters are: CO, NO$_x$ and VOC.

The aircraft pollutant that probably plays the most important role in depleting the ozone layer is NO$_x$, (and to a lesser extent methane (CH$_4$)). Subsonic aircraft fly in the upper troposphere and lower stratosphere (at altitudes of about 9 to 13 km). Ozone is expected to increase in these layers in response to NO$_x$ increases. At higher altitudes, where supersonic aircraft fly (17-20 km), increases in NO$_x$ lead to decrease of ozone. It is possible that supersonic flying contributes to ozone depletion.

Greenhouse effect
Scientific understanding of the indirect effects of SO$_2$, soot and H$_2$O emissions by aviation is still incomplete, and the possibility of these effects proving important cannot be excluded. Aircraft emissions contribute to the greenhouse effect. The climate effects of aircraft CO$_2$ emissions are not different from other CO$_2$ emissions, and are relatively clear.

Air quality problems
A further environmental issue related to aviation emissions is the contribution to local and regional air quality problems in the residential areas around airports. For some airports this contribution is low, while for others it is high and may cause severe problems. The emission products of potential importance are therefore NO$_x$, VOC, CO, SO$_2$, particles and odours [CE, 1998]. In future, more stringency in air pollutant emission regulations could limit further expansion of airports.

Acidification
Emissions of NO$_x$ cause acidification of ground and water.
Of all these gases, the emissions of CO$_2$ and NO$_x$ are seen as the most important ones with regard to aviation. According to the U.S. Environmental Protection Agency, data the contribution of aircraft to world-wide air pollution is between 2 and 3%, which is rather small. But the total amount of aircraft emissions is growing as well as the percentage of aircraft emissions with regard to the total amount of world-wide emissions. This is due to the growth of aviation traffic. The relative growth is due to fact that other polluting factors have become cleaner [ICAO, 2000]. Figure 8 gives an indication of the relative contribution of aviation to the total amount of emissions.

![Figure 8: Relative contribution of aircraft emissions to total emissions](image)

Sources: U.S. Environmental Protection Agency (aircraft emissions), IATA breakdown of other sources

**www.boeing.com, 2000**

### 6.2 History of aviation emissions

#### Fuel efficiency

Changes in aircraft emissions are related to fuel efficiency. The increase in fuel efficiency of jet aircraft over time has been one of almost continuous improvement as can be seen in figure 9 below. Therefore, the growth rate of fuel consumption by aviation has been lower than the growth in air traffic demand. [Albritton et al., 1997].

![Figure 9: Trend in transport aircraft fuel efficiency](image)

[IPCC, 1999]
In the above figure the relative improvements in fuel consumption per engine and per aircraft seat are illustrated with the Comet 4 aircraft as reference point. The improvement per seat is much larger (-70%) than per engine (-40%) for the latest technology (B777-200) because the size of the aircraft has increased. Thus, not only fuel consumption per engine has been reduced, but also the same engine is capable of lifting more seats.

Improvement in fuel efficiency mainly resulted from engine efficiency improvements (about 70%), with a minor contribution from airframe efficiency (about 30%). The increasing use of modern high-bypass engine technology that relies on higher compressor pressure ratios and higher combustion exit temperature has resulted in drastic decreases in emissions of carbon monoxide (CO) and unburned hydrocarbons (HC) by about 60 to 80% over the past 20 years. However, with rising temperature and pressure in the combustion chamber, NOx emissions are as a rule increasing. As a result, reductions in specific NOx emissions have nearly stagnated over the last 40 years as can be seen in figure 10 [IPCC, 1999, Airbus, 1991].

Figure 10: Benefits of technology on emissions

![Figure 10: Benefits of technology on emissions](image)

The above figure shows the emissions of various gases measured in grams per kilogram of engine thrust. This latest unit measures the power of the engine needed to lift one kilogram.

6.3 Regulation of aircraft emissions

ICAO Annex 16 Vol. II Section 2.3.2 (ICAO 1993) gives the regulatory limit for the emissions of NOx from engines of an output greater than 26.7 kiloNewtons (= the regulatory minimum thrust for transport category aircraft). The ICAO standards are designed for purposes of certification. The certification limits have been revised as engine and airframe technology have advanced and as concern over the effect of aircraft emissions has grown.

ICAO regulations have been set to ensure all newly developed engines incorporate technologies that are able to meet the more stringent emissions levels attainable by existing best technology. In 1985 the ICAO Council first adopted standards and recommended practices for aircraft engine emissions by establishing regulatory emission maxima for engines manufactured after 1985. The objective of this regulation was to improve the air quality in the immediate vicinity of airports. The regulatory conformance criteria for covered emissions were based on characteristic engine performance during the landing and take-off phases of a flight (the Landing and Take-off (LTO) cycle). The emissions that come free in this cycle are only a small part of the amount of emissions that come free during the whole flight. The LTO cycle operating requirements are characterised by very low and near maximum engine performance and are not representative of aircraft performance at cruise conditions. The introduction of the ICAO NOx regulation has
had great impact on engine performance.

In the second half of the eighties, the concerns on the effects of emissions on the atmosphere began to grow. On the recommendation of the ICAO Committee for Aviation Environmental Protection (CAEP), the ICAO Council amended the emissions standards for NO$_x$, reducing the permitted levels by 20%. This standard has been adopted by ICAO Member States and is the universally recognised international standard for aviation. The certification regime follows the LTO cycle basis established under the original stringency standard.

CAEP recommended in 1995 a further reduction in the ICAO NO$_x$ limits. The cost-benefit analysis at that time found that the anticipated costs of implementing the proposed stringency increase far exceeded the benefits of adopting the measure. To protect the asset value of the existing fleet, the new standard (16% reduction) was applied only to new or derivative engines certified after 31 December 2003.

6.4 Future

Despite the growing pollution caused by aviation, aviation itself has become cleaner. Aviation is predicted to grow by 5% per year, while aviation emissions are predicted to grow by 3% per year until the year 2015. (IPCC, 1999). It is expected that emissions per kg of engine thrust will keep declining, but it is extremely difficult to predict future engine technology development. The incorporation of new technologies will demonstrate diminishing gains. This means that as a given technology level becomes more mature further gains in emissions reductions become smaller relative to earlier gains and, in general, come at a higher cost.

Emissions of CO$_2$ will keep declining because developments in fuel efficiency will go on. But in the case of emission species, for which there is little economic incentive to spur reduction, like for NO$_x$, anticipation of continued attention to emissions stringency has provided incentive to meet and exceed current requirements where applicable. Regulatory pressure becomes for a part competitive pressure.

Tradeoffs

Some engines can be seen as most environmental friendly from the emissions standpoint: unducted engines and UDF (Unducted fans) engines. Unfortunately these engines fail to comply with current noise regulations. Solutions can be found by incorporating the emission reduction techniques in other engine designs, but the costs increase dramatically in that case. In general, for situations where “n” objectives involve tradeoffs, at best only n-1 objectives are able to attain a solution to reach their maximum. At the moment, the economic incentives are not sufficient enough for aircraft manufacturers to develop a reduction in fuel consumption further. A perspective of on reduction of direct operating costs (DOC) of 10% is required.
All new designs that have reduced fuel consumption, except for the U-fan, have lower cruise speeds. This can have an impact on the demand for flying (especially over long distances). The U-fan, which does not have that problem, might have higher NO\textsubscript{x} emissions.

**Incentives**

Incentives for a better environmental performance of aircraft can be divided into three aspects:

- More stringent ICAO regulation;
- Operational measures: better use of CNS and ATM technologies;
- Market based options: environmental levies and emissions trading.

**More stringent ICAO regulation**

ICAO emission regulation has already resulted in better engine performance. This trend can continue in future. Although it becomes more difficult to gain more results.

**Better use of CNS and ATM technologies**

Aircraft can reduce their emissions, when the existing communication, navigation and surveillance (CNS) and air traffic management (ATM) technologies are optimally used and/or approved. Then flight and taxi times can be reduced, cruise speed can change, etc. The reduction of NO\textsubscript{x} emissions can be large: up to a 50% reduction of the increase in 2040, according to the working paper from CAEP Working Group 3 [ICAO/CAEP, 2000].

**Market based options**

Market based options are: environmental charges and taxes and emissions trading.

Possible environmental levies:

- Fuel levy;
- Ticket levy;
- Route levy;
- Airport levy.

- The airports of Switzerland have introduced an emission charge, which is also an option.

The development of an internationally agreed environmental charge or tax that all States would be expected to impose is not practicable at this time, given the different views of States and the significant organisational and practical implementation problems that would be likely to arise. Levies can be introduced on individual basis.

The trading of industry emissions is of great importance in the United States, and is also being introduced in some European countries. This concept could also be introduced in aviation.

The technology platform Efficient and Environmentally Friendly Aero Engine (EEFAE) (a co-operation between NAS and the EC) is developing 2 engines that are cleaner than the current ones:

- A standard turbofan engine that will incorporate a higher pressure and bypass ratio and high efficiency aerodynamics to provide a substantial reduction in fuel burn. A new low emissions combustor will be incorporated that will be capable of achieving a NO\textsubscript{x} level of 60% below that of the current regulatory level. The reduction of CO\textsubscript{2} will be 12%;
- An inter-cooled recuperative aero engine, that will incorporate high efficiency advanced aerodynamics and a new low emissions combustor capable of achieving a NO\textsubscript{x} level 80% below that of the current regulatory level. The reduction of CO\textsubscript{2} will be 20%.
The amount of aircraft emissions in the future
It is very difficult to predict the amount of aircraft emissions in the future. Although the emissions per aircraft will decline, it is unlikely that the total amount of aircraft emissions will decline in the near future. The estimation is that aircraft emissions will grow with 3% per year.

NASA has four emission objectives:
- Reduction of emissions of LTO NO\textsubscript{x} of future aircraft by a factor of three within 10 years;
- Reduction of emissions of LTO NO\textsubscript{x} of future aircraft by a factor of five within 25 years;
- Reduce CO\textsubscript{2} emissions by 25% of future aircraft in 10 years;
- Reduce CO\textsubscript{2} emissions by 50% of future aircraft in 25 years.

NASA sees in their demand scenario possibilities for a total reduction of NO\textsubscript{x} by 2030. Total reduction of CO\textsubscript{2} emissions is more difficult to project. Based upon technological possibilities, the market-based options could also reduce the demand for aviation, which can reduce aircraft emissions.
In the past 30 years, aircraft technology developments have focused on improving performance and cost characteristics of aircraft. Simultaneous with these developments, although sometimes independently of them, aircraft noise has been reduced. This latter phenomenon is in response to growing public dissatisfaction with aircraft noise, especially in areas surrounding major airports. Noise regulation, essentially first started in 1969, has been promulgated by international bodies (e.g., ICAO), national bodies (e.g., the United States) and local bodies (e.g., Zürich); compliance with this regulation has been achieved by a combination of technological development and change in aviation procedures and behaviours around airports.

The technological potential for further noise reduction is more limited than in the past. Further enhancement of aircraft noise technology can interfere with other objectives: efficiency increase, reduction of gaseous emissions and aircraft costs. Nevertheless NASA has called for and projects a further potential reduction for jet aircraft of 20 dB cumulative in the next 25-30 years.

Reductions of the magnitude of 5 dB cumulative could relatively easily be realised in the next 10 years. These reductions require no further strengthening the existing regulations. To implement more ambitious goals in the near-term future, to the extent of 10 dB cumulative, will require more stringent regulation.

The full realisation of the NASA objective of a 20 dB cumulative decrease is even more dependent on regulation, because the economic viability of airlines is endangered by introducing too much new aircraft technology and other environmental goals, especially emissions reduction, conflict with noise reduction. Improvements in efficiency and aircraft noise reductions, never fully joined, will become increasingly in conflict with each other as noise abatement technology requires additional weight. Regulation in this instance can take two forms. On the one hand, regulations in the form of non-addition rules and subsequent operating bans (such as the ICAO Chapter 2 and 3 regulations) make operations dependent on compliance. On the other hand, regulations in the form of noise-based fees and/or operating measures bring a financial incentive to airlines to operate the most noise friendly aircraft. We must not forget that the reduction of 20 dB is cumulative. This means that the reduction per measure point will be much smaller.

Technology can help in reducing aircraft noise. But although noise per engine can decline, the total amount of aircraft noise will almost certainly increase in the near future, because of traffic growth. Volume development, economic and environmental tradeoffs, and developments in social (non-) acceptance of aircraft noise. Thus, it is not completely clear whether the full technological potentials can be realised. This important unknown characteristic of the future should be a core consideration in determining the bandwidth of aviation scenarios used in planning.

Changes in flight paths, spatial planning, window insulation, financial compensation, etc. can also cause reduction of noise and/or nuisance. These potential gains should also be included in the scenario planning.

With regard to emissions, aircraft engines have become cleaner in time. Technology can make them even yet cleaner, but the developments depend once again upon policy tradeoffs. The total amount of aircraft emissions will, just as the total amount of noise, increase in the near future because of traffic growth. This, too, should be incorporated in scenario design.
APPENDIX A: LITERATURE

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## APPENDIX B: ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>ACI-NA</td>
<td>Airport Counsel International</td>
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<tr>
<td>ADP</td>
<td>Advanced Ducted Prop</td>
</tr>
<tr>
<td>AEA</td>
<td>Association of European Airlines</td>
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<tr>
<td>ATA</td>
<td>Air Transport Association</td>
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<tr>
<td>ATAG</td>
<td>Air Transport Action Group</td>
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<tr>
<td>ATC</td>
<td>Air Traffic Control</td>
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<tr>
<td>CAEP</td>
<td>Committee on Aviation Environmental Protection</td>
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<tr>
<td>CPB</td>
<td>Centraal Planbureau (Central Planning Agency)</td>
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<tr>
<td>CRISP</td>
<td>Counter Rotating Integrated Shrouded Propfan</td>
</tr>
<tr>
<td>DOC</td>
<td>Direct Operating Costs</td>
</tr>
<tr>
<td>dB(A)</td>
<td>Decibels average</td>
</tr>
<tr>
<td>DLR</td>
<td>Deutsches Zentrum für Luft- und Raumfahrt</td>
</tr>
<tr>
<td>DNW</td>
<td>Deutsch-Niederländischer Windkanal</td>
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<tr>
<td>EC</td>
<td>European Commission</td>
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<tr>
<td>ECAC</td>
<td>European Civil Aviation Conference</td>
</tr>
<tr>
<td>EPNL</td>
<td>Engine Produced Noise Limits</td>
</tr>
<tr>
<td>EPNdB</td>
<td>Effective Perceived Noise Level in decibels</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>EZ</td>
<td>Economische Zaken (Economic Affairs)</td>
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<tr>
<td>IATA</td>
<td>International Air Transport Organisation</td>
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<tr>
<td>ICAO</td>
<td>International Civil Aviation Organisation</td>
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<tr>
<td>MTOW</td>
<td>Maximum Take Off Weight</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NSTC</td>
<td>National Science and Technology Council</td>
</tr>
<tr>
<td>ONL</td>
<td>Onderzoek Nederlandse Luchtvaart</td>
</tr>
<tr>
<td>RLD</td>
<td>Rijksluchtvaardienst (Civil Aviation Authority)</td>
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<tr>
<td>SAS</td>
<td>Scandinavian Airlines System</td>
</tr>
<tr>
<td>UDF</td>
<td>Unducted Fan</td>
</tr>
<tr>
<td>VROM</td>
<td>Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (Housing, Spatial Planning and Environment)</td>
</tr>
<tr>
<td>VTOL</td>
<td>Vertical Take Off and Landing</td>
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APPENDIX C: IMPROVEMENTS ON EXISTING AIRCRAFT AND ENGINE CONCEPTS

Fan noise reduction
In the past a lot of research has been carried out to reduce fan noise. Fortunately the fan thrust provides many options to explore and there are many components to, e.g.:

- Two stage fan;
- Slower fan speeds;
- Fan blade aerodynamic design;
- Variable pitch fan blades.

These different components can be combined within one future engine concept. [NASA, 1998]

Two Stage Fan
A new noise reduction concept investigated by NASA is the two-stage fan. The two-stage fan allows low tip speed while it is still maintaining a reasonable total pressure rise across the two stages. The two fan stages are placed far apart and driven by two separate spools of the engine, one being driven by the front of the engine and the other by the aft.

The use of two fan stages brings in the additional noise of the second stage. If the two noise sources are assumed to add in a random nature, a 3 dB noise increase will be observed. The new two stage concept would then have a 7 dB noise reduction instead of the desired 10 dB [NASA, 1998].

Slower fan speeds
The fan of a jet engine works best at slower speeds, while the rest of the spool (the compressors and turbines) run more efficient at high speeds. Therefore, Pratt & Whitney is developing a new engine with a geared fan. This PW8000 will be equipped with a fan drive gear system, which allows the fan, compressors and turbines to run at speeds closer to optimum. The fan speed is selectable via the gear ratio.

The resulting slower tip speed of the fan, which will generate around 90% of the thrust, is also expected to reduce noise levels to a cumulative 30 dB below current Stage 3 levels. Disadvantageous is therefore the additional weight of the gear system. [Flight, 1998a].

Fan blade aerodynamic design (blade-wake tailoring)
An appropriate blade shape can reduce the noise caused by steady blade forces. In model fan experiments, swept and leaned fan blades, designed with noise generation models, have produced much lower tone and broadband noise levels [AA, 1999]. This effect has already been used advantageously in modern high tip speed propfans, which usually are designed with sweep and lean [MTU, 1990].

In the frame of their TECH56 program CFM International investigates a swept fan blade design for the CFM56 engine family [Flight, 1999a]. The favourable effect of sweep has been validated by measurements. Depending on the blade tip speed, a reduction of the fundamental tone level of up to 6 dB can be achieved.

Variable pitch fan blades
A joint NASA/Pratt & Whitney/MTU Munich project has developed a new engine for large subsonic passenger jets that could cut fuel consumption 10 to 12 percent and significantly reduce engine noise. The Advanced Ducted Propulsor (ADP) should be used in 300-to-700 seat commercial transport aircraft. The ADP features a large, variable-pitch fan system, a 40,000 horsepower fan-drive gear system and a new, high-speed, low-pressure turbine. The engine has a maximum forward thrust of more than 50,000 pounds with an intended bypass ratio of up to 15:1. The ADP's variable-pitch fan system, which is nearly 10 feet (3 meters) in diameter, places its 18 fan blades in the most efficient position for take off, cruising
and reverse thrust. The researchers say that this system could end the need for thrust reversers that are normally used to slow down an aircraft after landing. Elimination of thrust reversers can provide weight, reliability and cost benefits unattainable with conventional fixed-blade turbofans [DCA, 1996].

In its further research study “A fan concept to meet the 2017 noise goals” NASA is using the ADP engine as the base engine to test new fan concept configurations [NASA, 1998].

Jet exhaust noise reduction
As mentioned before jet exhaust noise is created when the high velocity jet exhaust gases are mixing with the stationary atmosphere which produces a very broad, hay-stack-shaped sound frequency spectrum. Of particular difficulty, the jet exhaust noise is actually created after the exhaust leaves the engine. This means that jet noise cannot be reduced where it is created, but must be addressed before the exhaust leaves the engine. Reduction measures concentrate therefore on lowering the nozzle exit velocity by increasing the bypass ratio [AA, 1999]. But researches also investigate new fan nozzle concepts that could help reducing the jet exhaust noise.

Further increase of bypass ratio
When bypass ratio was increased on new engines to improve fuel efficiency, one beneficial by-product was a reduction in noise. In the past the introduction of “high by-pass ratio” engines has led to dramatic reductions in jet exhaust noise. However, to date, the physically limits for the enhancement of the bypass ratio are nearly exhausted.

For further noise reduction new ultra high bypass engine concepts, such as a ducted propfan, are under investigation. A reduction of 10 EPNdB at the side measuring point can be realised with a fan pressure ratio of 1,3. But this also includes the extension (e.g. 2,44 meter to 3,30 meter) of the fan diameter and the lengthening of the engine nacelle. This would cause an increase of the engine’s total weight of 80 percent. Another alternative to raise the fan diameter is to keep the covering of the fan lengthwise on a constant level. But, according to GEAE engineers, the possibility that the airflow can be separated in the air intake diffuser seems to be too dangerous. Besides, a shorter covering, it would reduce the noise absorption and with that probable increase the total noise level [LuR, 1992].

Fan nozzle design
A lot of investigation work is done in fan nozzle design to reduce jet exhaust noise. Computer models and enlarged acoustic databases for fan and core test model geometric, developed by NASA, have revealed much about jet mixing noise. Experiments have shown that nonaxixsymmetric fan nozzles, multi-lobed core and fan nozzles and the use of other mixing devices affect the process noise generation. Additional jet noise reduction measures occur with coaxial nozzles. Inversion of the jet profile, i.e. expelling the bypass air at the centre of the jet, and the hot core gases in the coaxial region, leads to a considerable noise reduction, compared to conventional profile jets. A fully mixed common nozzle, produced with an internal mixer, however, normally leads to the lowest jet noise level. But often mechanical mixing devices reduce low-frequency noise while increase high-frequency noise, and it is necessary to assess tradeoffs between noise reduction benefits and performance penalties [AA, 1999].

One part of CFM International’s TECH56 program is the investigation of a “chevron” nozzle. The design, which resembles the serrated edge nozzle of stealth aircraft engines, was expected due to lab tests to reduce acoustic energy by more than 50% and jet noise by up to 3,5 dB. [Flight, 1999b]. Experimental test at full scale in 1999 on a CF6-80C2 had shown a 3dB improvement in exhaust noise levels [Flight, 2000].

Active Noise Control (ANC)
A very sophisticated approach to reduce noise in general is active noise control (ANC). ANC uses the principle of destructive interference, where the noise sound wave is sensed with a microphone. This signal is amplified and fed to a loudspeaker, which emits it precisely 180 degrees out of phase with the original wave. Cancellation is created at that point [Campanella, 2000].

Applied at aircraft jet engines, the loudspeaker installed into the engine duct transmits active out-of-phase
sound fields, which will partly blot out the noise of the fan. The result is a combined sound field of reduced amplitude and thus, reduced noise \cite{NASA, 1997b}. Today this method is already in use to reduce the noise in the cabin of some turboprop aircraft \cite{DCA, 1999}.

**Active noise control**

![Active noise control diagram](image)

\cite{NASA, 1997b}

**Sound absorbing materials**

A hardwall engine duct transports all sounds with practically no losses, because every sound wave impinging on a wall is reflected totally. If the duct walls are lined with sound absorbers, however, only a part of the sound energy is reflected. In this way small cavities are formed with one hole each, called Helmholtz resonators. They work as a spring-mass system when subjected to a pressure fluctuation outside of the cavity, where the air in the cavity is the spring and the air in the region of the hole is the mass. The fluctuating airflow through the hole is connected with losses, leading to an absorption of acoustic energy. This results in a reduction of the sound amplitudes of the modes along the duct axis.

The type of absorbers commonly used in aircraft engines consists of a honeycomb structure fixed to a based plate and covered with a perforated face sheet (see Figure 16) \cite{MTU, 1990}

![Sound absorbing materials diagram](image)

\cite{MTU, 1990}

While modern fan absorbers provide noise reductions of up to 15 dB in the blade passing frequency region, the potential reductions with future shrouded propfan concepts are much smaller, mainly because the shrouds tend to be shorter, compared to the diameter \cite{MTU, 1990}. 

44
Different materials will be used for the hot air flow (steel) and the cold airflow (light metal). Sound absorbing liners can be added to the intake, fan duct, jet pipe and nacelle. Sound absorbing materials are only effective in a small bandwidth around their resonance frequency.

**Improvement in engine performance**

Engine performance describes mainly the fuel consumption per thrust unit and the thrust/weight ratio of an engine. While improvements in engine performance are mainly aimed at economical ..., they also help in the campaign against noise. As thrust/weight ratios increase, so does an aircraft's rate of climb, separating the noise source more rapidly from the communities below. [ATW, 1995]

Further noise reductions are possible due to engine cycle changes. A cycle is the term used to describe the basic overall engine operating characteristics, for example engine bypass ratio, fan pressure ratio, fan tip speed, and core temperature. Cycle change generally requires new engine development, as opposed to noise reduction concepts, which may be retrofittable to existing engine lines. [NASA, 1997a]

**Airframe noise**

While engine noise still dominates during full power take off conditions, in the landing approach phase airframe noise represents the essential contributor to overall fly-over noise signature for high bypass powered large commercial aircraft. During landing the airframe noise from the flaps, slats, and landing gear on today’s airplanes almost matches the level of engine noise. In future airplanes, the airframe noise will be equal to engine noise not only during landing but also during takeoff [Dobrzynski, 2000].

In the early 1970s, it became evident that further decreases in propulsion noise would not be enough to lower aircraft noise level significantly. Airframe noise was thought to be a lower limit, or the ultimate noise barrier. Researchers knew that landing gear, trailing-edge flaps and leading edge slats were the primary noise sources on landing approach, but the physics of the generation mechanism remained unclear. Studies revealed some basic insight into the relevant noise source mechanism and radiation characteristics. Detailed and reliable noise prediction schemes were ultimately not obtained due to a lack of understanding about the extremely complex aerodynamics surrounding landing gears or multi-slotted wing/flap systems [Dobrzynski, 1997].

A more systematic approach to understanding airframe noise began in the early 1990s. This involved computing the steady flowfield surrounding key component structures that might develop the strong unsteadiness required for noise production. The aircrafts high lift devices (flaps and slats) disrupt airflow and are one of the main airframe noise sources. Furthermore, they consist of a lot of parts, which are inducing noise in the extended flap position [AA, 1999].

**Landing Gear**

As mentioned before landing gear noise is contributed mostly from smaller components, including hydraulic lines, wiring, details around the tires and axles, brackets and tubes.
From results of full-scale experimental wind tunnel studies DLR expects that a noise reduction potential of 8 dB (corresponding to a fly-over noise reduction of 5 EPNdB) could be realised through localised applications of streamlined fairings and/or flow spoilers [Dobrzynski, 1997].

**High Lift Devices (extended leading edge slats and trailing edge flaps)**

Between the extended slats and the wing a gap is opening. At the concave backside of the slat a turbulent flow is forming, which passes high turbulent “separation bubbles” into the accelerated gap flow (see Figure 18). This is a considerable source of noise, especially during approach.

Wind tunnel studies, carried out by DLR, had shown, that a broadband slat noise reduction up to 2 dB could be realised through the application of a slat-cove-cover - which partially closes the slat-cove - without a decline in lift and drag. The slat-cove-cover captures the vortex in the concave rear slat contour and thus avoids the noise effecting turbulence spots. [Dobrzynski, 2000]
The flap side edge i.e. at the extended fowler flap, was also revealed as an important noise contributor. Significant noise reduction could be obtained with innovative flap edge devices, focusing on flap edge vortices strength reduction. Measuring trials at the German-Dutch wind tunnel had shown, that by modifications at the flap side edge the noise could be reduced possibly by up to 4 dB. Therefore the flap edge has to be equipped with a so-called “fence”. [DLR, 1999a]

Source: Aeronautics and Space Engineering Board
Figure 1: ICAO Chapter 3 Fly over Noise Limits, measured under the take-off path

Figure 2: ICAO Chapter 3 Approach and Lateral Noise Limits
figure 3: Improvements in exhaust geometry for high bypass ratio engines

Jamieson, 1990

figure 4: a with hushkit modified engine

Federal express, 1999