Final Report for Publication

AEROCERT

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FFA
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LU

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Foreword and acknowledgements

This contract report is the result of collaboration between a number of authors within the AEROCERT partnership from the contributing partners: DERA, DLR, FFA, Loughborough University and NLR.

The AEROCERT Research Project has been performed under CEC Contract No. AI-97-SC.242, with financial support by the Commission of the European Communities. Additional support has been provided by the partners and by national agencies.

This project heavily draws on the willingness of several airlines to supply flight data and engine monitoring data, as well as certification data provided by the authorities and manufacturers. In addition, the AEROCERT team has appreciated being given the opportunity to take measurements of acoustic liners, subjected to deterioration.

This report also draws on interviews and discussions with stakeholders in the certification process from several countries.

The project has been presented at an AEROCERT dedicated workshop to which a representative set of stakeholders was invited. Their feedback, comments and suggestions on the AEROCERT project are included in this final report. Preliminary versions of the report of the individual tasks have been reviewed by the AEROCERT consortium partners. The overview section has been revised according to comments from the CEC, the task co-ordinators, and several project participants. The project administrator was H.B.G. ten Have, supported by J. Middel, both from NLR, the Netherlands.

On behalf of all project participants, the co-ordinator expresses his gratitude and thanks to all who supported the project financially, provided information and data, contributed to the results, and helped to prepare this final report.

On behalf of the co-ordinator,

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The reporting period covers 1-7-1997 until 1-4-2001.

Glossary, terminology, acronyms and abbreviations

ACMS	Aircraft Condition Monitoring System
AEROCERT	Aircraft Environmental Impacts and Certification Criteria
AFR	air/fuel ratio
APU	auxiliary power unit
ARAC	Aviation Rulemaking Advisory Committee
CAA	Civil Aviation Authority
CAEP	Committee on Aviation Environmental Protection
CFMI	CFM International
CFR	Code of Federal Regulations
CO	Carbon monoxide
CO_2	Carbon dioxide
dB	decibel, logarithmic expression of a ratio
DER	Designated Engineering Representative
DERA	Defence Evaluation & Research Agency, UK
DG	Directorate General
DLR	German Aerospace Centre
D_p	mass emission of gaseous pollutant over the LTO cycle
EC	European Commission
ECAC	European Civil Aviation Conference
EC/DG TREN	Directorate General VII of the European Commission
ECM	engine condition monitoring
EI	emission index, expressed as grams of pollutant per kilogram of fuel burnt
EPNL	Effective Perceived Noise Level expressed in EPNdB
FAA	Federal Aviation Administration, of USA
FAR	Federal Aviation Regulations, of US FAA
FDR	flight data recordings
FFA	Flygtekniska Försöksanstalten
F_{oo}	the rated output: (for emissions purposes) the maximum power/thrust available for take-off under normal operating conditions at ISA sea level static conditions, in kilonewtons.
GE	General Electric Aircraft Engines
GPS	Global Positioning System

H_2O	Water (vapour)
HC	unburnt hydrocarbons
IAE	International Aero Engines
ICAO	International Civil Aviation Organisation
INM	Integrated Noise Model
ISA	International Standard Atmosphere
JAA	Joint Aviation Authorities
JAR	Joint Airworthiness Requirements
kN	kilonewtons
LTO	Landing/Take-off cycle
LU	Loughborough University, UK
MTOW	maximum take-off weight
NLR	National Aerospace Laboratory of the Netherlands
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	oxides of nitrogen (sum of NO + NO_2)
NPD	noise/power/distance
NV	National Variant
PANS/OPS	Procedures for Air Navigation Services - Aircraft Operations
PNLT	Tone-corrected perceived noise level, expressed in PNdB
PW	Pratt & Whitney
RR	Rolls-Royce
SAE	Society of Automotive Engineers
SN	SAE Smoke Number
STNA	Service Technique de la Navigation Aerienne
WD	Working Document
WP	Work Package
WP#	Numbered Work Package
π_{oo}	Reference pressure ratio: ratio of the mean total pressure at the last compressor discharge plane of the compressor to the mean total pressure at the compressor entry plane at engine take-off thrust rating in ISA sea level static conditions.

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1 Introduction to AERROCERT

1.1 Purpose

The principal aims of the AEROCERT project are to improve understanding of the effect of flight-operational procedures and in-service deterioration on certificated noise and emissions levels and to identify options, if required, for possible change to certification procedures and metrics. AEROCERT has been analysing airline flight and operational data, together with associated noise and emissions performance for a range of aircraft types relative to the International Civil Aviation Organisation (ICAO) certification procedures and values. The diversity of operational procedures, the suitability of current metrics and the extent of, and reason for, deteriorated noise and emissions performance has been examined as part of the project.

This document is the project final report, which encompasses three main parts:

- General introduction, executive summary and overview
- Summaries of the work package reports
- Conclusions and dissemination aspects

AEROCERT has been carried out on behalf of DG-TREN of the European Commission between 1997-2001.

1.2 Intended audience

This document is in the public domain and it is intended to inform policy makers about the results and recommendation of the AEROCERT project. As such, this document is written to be self-explaining and comprehensive. Those readers that are looking for more in-depth information are referred to the associated documentation as available in the public domain.

1.3 Organisation of this document

This document is the AEROCERT Final Report for Publication. This document provides the reader with an assessment of the problem, the main findings, results and recommendations.

This document is structured analogous to the AEROCERT project structure. The introduction and overview of the project is followed by the summaries of the work packages WP1 – 4. This final report also reports about the conclusions including the stakeholders' views, as gathered during the WP5 workshop. The various work package reports consider the following areas of interest:

- WP1 – Generation of reference data and study of the current noise and emissions certification procedures;
- WP2 – Research into operational procedures, by studying the FDR data recordings;
- WP3 – Development of potential impact descriptors, both for noise and emissions;
- WP4 – Characterisation of through-life deterioration effects;
- WP5 – Analysis, evaluation and options for improved certification procedures, including the comments and responses from the stakeholders.

1.4 Associated documentation

The following documents are in the public domain and provide additional, more in-depth information. These documents provide a more detailed look on the matter and provide more-technical details.

- Work Package 1 Report: “Certification Test Procedures and Experience and Generation of Reference data”, AEROCERT/DR/WR/1/01
- Work Package 2 (emissions) Report: “Research into Operational Procedures”, AEROCERT/FF/WR/2/01
- Work Package 2 (noise) Report: “Review of current aircraft operating procedures and their consequences for noise in the community relative to certification procedures”, AEROCERT/LU/WR/2/01
- Work Package 3 (emissions) Report: “Potential descriptors for impacts of gaseous aircraft emissions”, AEROCERT/NL/WR/3/01
- Work Package 3 (noise) Report: “Noise impact around civil airports – potential descriptors and ICAO noise certification”, AEROCERT/DL/WR/3/01
- Work Package 4 Report: “Characterisation of Through-life Deterioration Effects”, AEROCERT/DR/WR/4/01

Summaries of these reports are included in this document. The views of the stakeholders are reported in full-length.

2 AEROCERT Executive summary

The principal aims of the EC AEROCERT (Aircraft Environmental Impacts and Certification Criteria) Research Project, Contract No. AI-97-SC.242, are to improve the understanding of the effects of flight-operational procedures and in-service deterioration on the (certificated) noise and emissions levels. This better understanding may lead to identify options, if required, for possible changes to certification procedures and metrics to better reflect the real impacts on the environment.

2.1 Setting the scene

Since the entry into service of the jet transport aircraft at the end of the 50's, the increased number of flights and the increased density of the urbanisation have given rise to much greater intrusion of aircraft noise on community life and hence to noise exposure.

Gaseous emissions from aircraft have also been an ongoing problem for airports, More recently, the environmental community has focussed on the global aspects of pollution such as global warming. This has lead to the IPCC report on aviation that is devoted to the effects of aviation gaseous emissions on the climate.

Simultaneously, the aviation community has recognised that the existing noise and emissions certifications, are not designed for, and hence might not cover all the necessary aspects to assess the aviation impacts on the environment.

This has lead the EC to decide to commission research on actual aircraft performance and impacts and the options for improved certification to better reflect these impacts, investigated. The AEROCERT project has been initiated in response to this need.

2.2 Approach

The principal aims of the AEROCERT project are to improve understanding of the effect of flight operational procedures and in-service deterioration on certificated noise and emission levels and to identify options, if required, for possible change to certification procedures and metrics. To accomplish these aims, AEROCERT has analysed airline flight and operational data (FDR and ECM), together with associated noise and emissions performance for a range of aircraft types relative to the International Civil Aviation Organisation (ICAO) certification procedures and values. The analysis includes studying the diversity of operational procedures and the suitability of current metrics. By monitoring aircraft engines through part of the life cycle, the extent of, and the reason for engine deterioration and the consequences for the noise and emission performance are determined.

2.3 Results

The AEROCERT team has processed many FDR and ECM data records, and a wealth of data has allowed comparison of the well-defined ICAO certification procedures with a diversity of aircraft operations as apparent from the recordings. The ICAO certification standards are set on the basis of technological feasibility, economic reasonableness and environmental acceptability. The data from certification testing is compared with actual noise or emissions operational values.

From the comparisons, many observations have been made. They have led to recommendations regarding better impact assessments of noise and emissions. These recommendations and conclusions are written down in the work package reports. Condensed versions of the reports are included in this final report.

In broad, general terms (the AEROCERT team recommends to read the work package conclusions and recommendations) the following conclusions and recommendations are found:

- Assessing noise impact based on certification data relies upon a few basic methods, with a large numbers of derivative methods. Significant improvements regarding accuracy of impact assessment are possible if additional noise data could be made available to the public domain.
- The investigation of flight profiles has found a large variation in thrust settings at take-off, especially for large twin aircraft that offer many opportunities for using flexed thrust in take-off, intersection take-offs and earlier turns. It has been found that weight is an highly influential factor in noise production as well, both for landing and take-off. Therefore, significant differences between the individual flight profiles in the recorded flights are apparent. Naturally, this also implies significant differences between the profiles of certification and recorded flights.
- The flight profiles and the resulting noise that are deemed characteristic for the day to day traffic have been compared to the certification flight profiles as well as the certification noise test data. From this comparison, it has shown that for wide-body short haul operations, noise at the lower flyover point may be significantly lower than the certification values, but at the same time, no direct relation between flyover noise and contour areas is apparent. Narrow body aircraft and twin-engine, long haul operations generate more noise at take-off than certification values indicate. Four-engined, long-haul operations appear to be quieter than certification values. Based on these observations, a better impact assessment can be made if the flight profiles used for impact assessment reflect the day to day operations better.
- The above observations do not imply a recommendation to change the noise certification procedures, rather to secure certification noise map data that can be used for noise assessment purposes.
- Regarding emissions at and around airports, a better impact assessment can be made by having information available on more species, and obtaining certification data for additional thrust levels applied in actual operations. The current Landing and Take-off (LTO) cycle is regarded as a worst case situation for the aircraft emissions at airports and is still a viable means of certification. Times in mode for the LTO cycle are generally found to be less than specified in the certification test regime.
- Regarding gaseous emissions impact on the global atmosphere and at higher altitudes, the current state of the art technology is not yet capable of providing well-proven and well-accepted methods for impact assessments. Although there are models to calculate emissions at (higher) altitudes at reasonable accuracy, the transition from emissions to immissions is still not fully understood. Further research, especially into impact assessments is highly recommended. ICAO/CAEP considers the issue currently a priority work item.
- The flight data recordings and engine condition monitoring data show appreciable reduction in engine component efficiency and commensurate fuel burn increase over the on-wing maintenance cycle. From acoustic liner measurements, and the monitoring of engine health over many flights, it is observed that the evident in-service deterioration of engine components does not significantly change the noise performance. No justification exists to represent deterioration effects in the noise certification procedures.

- Regarding emissions, the deterioration effects of engine deterioration are indeed noticeable. At maximum levels of deterioration, both fuel use and NO_x emissions increase significantly at all conditions. It is recommended that the consequences of deterioration of fuel and emissions need to be translated into impacts both at the local airport level and at the global level. Only after such an assessment, it will be possible to rule out including deterioration effects into emissions certification.

2.4 Conclusion and future work

The AEROCERT consortium has analysed the noise and emissions of a significant number of recorded flights for a number of representative aircraft. Comparison of these flights with each other and with for equivalent certification flights has shown marked variation in aircraft operations for a certain type or mission and, at the same time, has shown significant differences relative to certification flight test conditions.

From these observations, a number of recommendations have been drawn up to serve as a starting point for focussing further research on tools, models and data required for impact assessment and certification. Finally, it is noted that the need for additional data for impact assessment does not necessary imply the need for a change to the certification rules.

2.5 Contact details

AEROCERT / DG TREN – Transport

Time scale:	01.07.1998 – 30.04.2001
Keywords:	aircraft, aviation, environment, impacts, flight data recording, FDR, engine condition monitoring, ECM, certification, emissions, noise.
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3 Project overview

3.1 Setting the scene

The progressive growth of air transport and of populations near airports poses a major challenge to civil aviation, especially in terms of the noise pollution it produces. This increased number of flights also has lead to an increase of gaseous emissions in the atmosphere. For the upper atmosphere these emissions, with possibly long resident times, lead to an accumulation of gases that are strongly suspected of contribution to climate change processes. Close to ground level, especially near airports, the emissions contribute to a deteriorated local air quality.

Up to now, emissions and noise produced by civil jet aircraft have been, to some extent, been ruled by the certification standards, set in the late 60's, early 70's. These international noise and emission standards have been established by the International Civil Aviation Organisation (ICAO) and are set out in Annex 16 Volumes I (noise) and Volume II (emissions). The procedures require aircraft and engines to undergo a type test certification before entry into service but there are no requirements for further checks on environmental performance during the life of the equipment.

It is recognised that the current certification procedures were designed to ensure the incorporation of the latest available technology in aircraft designs. There are concerns that these certification procedures were not specifically designed to reflect the impacts of noise and emissions as a result of the day to day operations.

The current noise and emissions standards are developed to set limits to the emissions and noise relatively close to the airport surroundings. For certification, no limits exists further away from the airport, e.g. in the cruise or 'continued climb' phases, in which most of the flying time is spent. The current certification process does not consider performance deterioration of engines and airframes, or the effects of day to day operating procedures that may vary significantly and may be differ greatly from the well-defined certification operating procedures.

Airworthiness requirements 'only' ensure that operators maintain their equipment to a high standard through frequent in-service maintenance checks and periodic major overhauls. These checks and overhauls retain / restore performance close to the as-new standard. It simply has been assumed that environmental performance does not deteriorate significantly.

Community noise is today cited as a major problem to be solved by the aircraft transport industry (including government or governmental services) if its current growth is to be sustained. There is also world-wide debate about the climate effects of emissions, including those from civil aviation, that has resulted, amongst other things, in the Kyoto protocol. ICAO has a remit from the United Nations to address the aviation contribution to these problems.

At the same time, the air traffic is predicted to grow substantially. It is feared that this growth in air traffic and its environmental impact cannot be offset fully by the introduction of new environmental friendly technology in the aircraft fleet.

There are other, non-technical considerations that spurs further research in the field of emissions and noise. There is evidence, for example, that over the last decade or two there has been a growing sense of public awareness and anxiety about environmental issues. Simultaneously, there is an increasing knowledge of the subject and an associated rising demand for detailed facts and figures relating to new or changing environmental issues. But for example, whereas several different impact measures or descriptors for noise emissions have been developed by EU member states, they do not use the same data sources or approach, thus making comparisons difficult or confusing.

These observations have led the EC DG TREN to identify a need for research into certain certification issues that bear upon the impact of air traffic on the environment. The EC has expressed the need for the definition and development of noise and emissions certification procedures for the next generation of requirements that will take fully into account:

- Present and future growth in global air transportation;
- The true environmental impact of such growth both at altitude and at airports;
- The technological advances (and their economic impact) which have taken place in aircraft and engines since the present regulations were introduced;
- The associated operational and maintenance issues.

In the Research Task 4.2.4/39 in DG TREN's research, technological development and demonstration programme [Ref. 3-1] states:

"Define and develop aircraft noise and emissions levels, reflecting actual impact on airport surroundings and the en-route atmosphere, without undue manufacturing or operational cost and to define operational and maintenance procedures to maintain original noise and emission levels through the service life."

This task definition recognises fully the need for a more informed position in future discussions with other organisations such as EC DG RES, JAA, ECAC and ICAO, responsible for the regulation of aircraft in order to control their environmental impact. The principal objective is to ensure that regulatory standards and certification procedures keep pace with the environmental impact of a rising volume of air transportation. The "deliverables" quoted in the request for proposals specifically call for options, if appropriate, relating to new noise and emissions certification procedures that would effectively achieve such aims.

These and other considerations add weight to the prime objectives and to the approach outlined in the objectives of the AEROCERT project.

3.2 Objectives

As a starting point of this research, it is recognised that the current ICAO noise regulations [Ref. 3-2], revised in 1977 when the so-called Chapter 3 levels were published) are becoming increasingly out-dated in terms of their influence on present conditions at airports (data: [Ref. 3-3]). Similarly, the 1981 volume II of the ICAO annex 16, where standards for CO, HC, NO_x, smoke and fuel venting are published, does not take account of the many recent and likely future changes in aircraft engine emissions technology [Ref. 3-4], [Ref. 3-5]. Thus, a number of questions arise concerning the present ICAO certification standards and procedures and their relevance to the environmental impact of aircraft, being:

- The certification data do not reflect possible influences such as flight procedures on the impact on the environment.
- The landing/take-off cycle limits for emissions of exhaust gases do not reflect the en-route impact at altitude on the environment.

- Exhaust gas emission standards are coupled to engines rather than aircraft types, they are not related to the overall aircraft mission efficiency.
- Deterioration of aircraft and engines is expected to have an influence on the emission of noise and exhaust gases during the aircraft or engine lifetime. Certification does not account for these influences.

Starting in 1997, AEROCERT is a research project partially funded by the European Commission addressing a number of the above issues related to the adequacy of the existing ICAO noise and emissions certification regimes. The project aims to provide the EC with information on the current relevance of the existing noise and emissions certification regimes to current operational impact of air transportation. In particular, the AEROCERT main mission is to establish whether the current emission and noise standards are sufficient to limit the environmental impact and whether there is scope for improvement through modifications to existing information derived from certification, maintenance and operational procedures.

To reach these aims, AEROCERT has been analysing airline flight and operational data, together with associated noise and emissions performance for a range of aircraft types relative to the International Civil Aviation Organisation (ICAO) certification procedures and values. The diversity of operational procedures, the suitability of current metrics and the extent of, and reason for, deteriorated noise and emissions performance has been examined and compared with certification. As certification, for both noise and emissions, is undertaken under controlled conditions that do not represent actual day-to-day operational variability, there is a need to understand the significance of the differences. AEROCERT focuses on three important issues namely:

- the difference between certificated values and actual performance in operational practice;
- the range and suitability of metrics in use; and
- the effects of performance deterioration of in-service aircraft and engines on noise and emissions.

Analysis of these issues will assist regulators determine the need for revision to and/or extension of the certification regimes. One purpose of AEROCERT is to define options, if appropriate, for improvement of noise and emissions certification procedures. Two key objectives which correspond directly to the ‘deliverables’ are identified below:

I To identify necessary revisions and/or extensions of the emission (e.g. noise and exhaust emissions) certification procedures:

   a. To identify the known and possible impacts of aircraft emissions on the environment and to identify the data needed to quantify these impacts.
   b. To define possible indices showing the actual impact of aircraft emissions on the environment or usable to quantify the actual impact on the environment.
   c. To identify whether the existing certification procedures reflect the impact on the environment considering different influences such as flight procedures.
   d. To define options for possible improvements by changing procedures or by extending them considering the technical feasibility, effectiveness and economic impact of the proposed improvements.

II To identify the effect of operational and maintenance procedures on the certified emission levels:

e. To identify the influence of the deterioration in the emission levels of engine and aircraft and to characterise the deterioration in noise and emission levels.

f. To make recommendations on operational and maintenance procedures to keep near to the certification levels.

3.3 Approach

The approach to the AEROCERT investigation has been based on the comparison of data from certification test conditions and the analysis of day to day operations as recorded using flight data recorders (FDR) and engine condition monitoring (ECM) data. In the early stages of the project development, it was recognised that the nature of the work to be undertaken is multidisciplinary and allows identifying several tasks. Accordingly, the project has been split into 5 work packages, with the addition of management and data acquisition packages. The work packages comprise:

- WP1 – **Generation of reference data**. This WP reviews existing certification procedures, together with current developments, and provides a full, concise description of the data that are available through these procedures. This WP also provides a set of reference data to be used in comparative assessments of noise and emissions levels resulting from operational practices. These data are obtained for representative aircraft and engine combinations.
- WP2 – **Research into operational procedures**. The environmental impacts of aircraft are influenced considerably by operational conditions and procedures as well as by the intrinsic static and dynamic characteristics of the airframe-engine combinations. The actual operations may differ substantially from those specified as part of the certification procedures. This WP aims to identify the character of existing operations, estimate the emissions and noise produced by existing operations, compare the actual emissions and noise performance with that derived from the certification data and procedures.
- WP3 – **Development of potential impact descriptors**. WP3 establishes an inventory of the impacts of aircraft noise and exhaust gas emissions on the environment and what data are needed to describe these impacts. It also identifies what data are needed from the certification processes for aircraft environmental impact assessment, and studies the relevance of the data obtained from the actual certification processes.
- WP4 – **Characterisation of through-life deterioration effects**. The WP4 objectives are to identify the magnitude of any deterioration from the ‘certified’ levels of noise and exhaust emissions levels throughout the service life of aircraft and engines. Current overhaul and maintenance procedures focus on the safety and performance aspects, without taking account of noise and emission levels.
- WP5 – **Analysis, evaluation and options for improved certification procedures**. Based on the ‘fact finding’ and analysis of the WP 1 through 4, WP5 identifies options, together with appropriate recommendations, for improved certification and operational procedures. Feedback from the various stakeholders is included through a workshop. This work package aims to set out issues to be addressed in further development of the current certification procedures.
- **Data acquisition** – A fundamental activity supporting the substantive tasks within the project is the acquisition of aircraft-engine FDR flight records of a number of representative aircraft-engine combinations. The resulting database of FDR data provides a solid base to derive actual flight procedures. In addition, engine condition monitoring (ECM) data has been gathered. This data acquisition process has been an ongoing effort

throughout the project to build data histories for specific engines (and aircraft) to facilitate a study on engine deterioration effects.

- **Management** – This activity has been an ongoing effort throughout the project, and covers co-ordination across all partners and activities.

3.4 Results

The results of each work packages are reported in one or two WP reports. In the latter case one report is focuses on noise aspects and a second report focuses on emissions aspects. These reports are in the public domain as described in the introduction and are part of the AEROCERT project reporting.

The remainder of this document contains condensed versions of these reports. The views of the stakeholders are exclusively reported in this report, i.e. part II, chapter 5. This final report is to be regarded as comprehensive and complete.

3.5 Conclusion and future work

It should be noted that the determining factor in the range and quantity of data available to the project is the cost of acquiring it from the airlines. During the course of the project, airline restructuring into business units with internal charging between these units has altered the cost basis upon which AEROCERT has been acquiring data from that originally expected. A lesser quantity of data has been available than originally anticipated but with careful selection, this has not adversely affected the ability of the consortium to fulfil the main the project objectives. The statistical samples are still judged to be robust.

Each work package document can be regarded as independent of other work package reports, though there are linkages between a number of the issues addressed. The findings, conclusions and recommendations are drawn up and documented for each work package. This final report has a similar structure. Conclusions, findings and recommendations are drawn up per work package summary, and brought together in the discussion and conclusions part (chapter 10).

3.6 Confidentiality aspects

This project would not have been possible without the support and willing co-operation of several airlines that have provided Flight Data Records (FDR) and Engine Conditioning Monitoring (ECM) data. These data have been provided to the AEROCERT team under strict confidentiality and anonymity clauses. For these reasons, the public reports, including this one, have no references to any airline, aircraft or engine type. Instead the representative airframe-engine combinations are coded throughout the AEROCERT documents, the code common to all documents. The Table below gives a list of aircraft-engine combinations used.

Table 3.1: list of aircraft/engine combinations used in Aerocert

Aircraft	*Engine*	*Design duty*
A	1	short range
B	4	short range
C	2	short range
C	5	short range

D	7	short range
E	12	short range
F	12	short range
G	6	short range
H	10	medium range
H	11	medium range
I	9	long range
I	5	long range
I	13	long range
I	15	long range
J	16	long range
K	3	long range
L	8	long range
M	9	long range
M	14	long range
N	17	long range
N	18	long range
N	19	long range

3.7 Dissemination aspects

As part of the Work Package 5, the AEROCERT team has organised a workshop. For this workshop, various stakeholders (aircraft manufacturers, airlines, governmental policy makers, authorities, airports, engine manufacturers) have been invited. Before gathering the views and interests of these stakeholders, the stakeholders have been introduced to the project through presentations of the approach and findings of the various work packages.

During the course of the AEROCERT project, aspects of the work have already been identified as relevant to ongoing analysis within the noise work programme of ICAO/CAEP and its working group 1 (noise technical). Specifically comparisons between certificated and actual noise performance, and of interest to the JET-10 group which is looking at noise certification requirements. Participants of both JET-10 and ICAO-CAEP have expressed their interest to bring forward the results and conclusions from the AEROCERT project. During the workshop, it was evident that AEROCERT reporting could benefit developments on ICAO Annex 16, FAR 34 and the JAR 34. It has been strongly recommended to bring the AEROCERT findings forward drawing, as far as possible, on the available supporting data.

At the time of publication of this report, presentations have been made in relation to the project and its findings at the:

- AEROCERT workshop as an introduction to the stakeholders;
- AERONET-II kick-off meeting in Mallorca, March 2001;

- X-noise conference in Dublin, December 1999.

This document, and the individual work package reports are available at the Internet:

http://www.nlr.nl/hosted-sites/AEROCERT.html

4 WP1: Generation of reference data

4.1 Introduction

Certification of aircraft and engines for noise and emissions compliance is carried out according to well-defined established procedures. Though these procedures are technically robust in measuring noise and emissions from new aircraft and engines in specified certification conditions, doubts have been raised about whether these procedures adequately reflect the environmental impact of civil aviation.

Work Package 1 therefore provides reference information and data from certification testing, against which the effect of flight and operational procedures on noise and emissions determined in the other Work Packages will be compared.

The Work Package 1 report provides:

- a description of the noise certification procedures,
- a description of the emissions certification procedures,
- a description of the flight profile requirements and individual flight profiles for selected types,
- a list of the aircraft/engine combinations selected,
- reference noise and emissions certification data for these types,
- views on the certification process and on the costs involved, from the perspective of different parties involved in the process.

The AEROCERT partners have reviewed the existing noise and emissions certification procedures to provide a summary description of the procedures applied to generate the reference data used in support of the project. For a range of aircraft and engine combinations, chosen to be representative of European and world-wide operations using modern aircraft types, data have been collected to generate reference sets of noise and emissions certification values. This information will serve as the benchmark for subsequent analysis within the project, particularly for comparison against operational data. The descriptive and discussion elements will be referenced in analysis of the validity of the current regimes and possible changes thereto.

The five elements of the Work Package 1 report are briefly described in turn below.

1. Noise and Emissions certification procedures

A review has been made of the current certification requirements and procedures for noise and emissions. This has been made by drawing principally on ICAO Annex 16 (Volumes I and II) and regional and national requirements. The sections describe the purpose of the regimes and their applicability, review the test procedures themselves and set out the criteria which have to be met in order to obtain certification.

2. Noise certification profile requirements

A review has been made of the flight profile requirements included in the noise certification regime. Noise certification flight profiles for selected aircraft/engine combinations have been produced. It was not possible to obtain profiles from manufacturers or certification authorities for proprietary reasons, hence the profiles were reconstructed from certification noise values using the US Integrated Noise Model and other sources. The reconstructed profiles are presented in Appendix A of the WP1 report. The noise certification profiling is described in a little more detail in Section 4.2.

3. Reference Aircraft/Engine combinations

A description is given of the selection process and criteria for determining the aircraft/engine types used in the AEROCERT project. This includes, for example, the types of operations and fleets relevant to the research objectives and how the selection was made based on the need to obtain a comprehensive, representative sample, encompassing a wide range of engine/aircraft/operation types flown by European operators.

4. Reference noise and emissions certification data for these types

Noise and emissions certification data have been collated for the selected aircraft/engine combinations, for the weights operated by the airlines supporting AEROCERT. The data have been appropriately formatted and are presented in Appendix B of the WP1 report.

5. Certification process and costs

The certification process for both noise and emissions is described from the perspective of the applicant manufacturers and the certification authorities. Opinions are given on the current perceived strengths and weaknesses of the regimes and experience of their use, and includes discussion on the main certification cost drivers. This section includes the outcome of discussions/interviews with manufacturers and certification authorities and considers more generally issues surrounding certification which have given rise to uncertainty about the validity of the current regimes and thus sparked interest in this research.

The remainder of this summary of Work Package 1 concentrates on points 2, 3, 4 and 5 above.

4.2 Noise Certification Profile Requirements

In order to gain noise certification, subsonic jet aircraft must be flown in accordance with the test procedures required by Annex 16 Volume I. Reference take-off and landing procedures are specified in Annex 16.

AEROCERT tasks need to be able to represent the noise certification flight profiles, principally for the comparison of operational practice with certification test conditions in terms of relative noise effect. Applicants for certification tests hold the profile information and it will be released to the certification authorities but this is regarded as proprietary information by the applicant manufacturers and has not been released to the AEROCERT partnership.

In the circumstances it has been necessary to identify ways to estimate the certification flight profiles for types included in this research. This has been undertaken based upon modelled simulation of profiles using data included in the FAA Integrated Noise Model (INM) which itself is based largely upon certification data. Loughborough University undertook this work as part of the AEROCERT project.

The results of this simulation and analysis show close agreement in the flyover noise values from the predicted and the actual measurement sources. It is therefore assumed that the calculated profiles which underpin the predicted values are a reasonable approximation of the profiles actually flown for certification testing.

4.3 Reference noise and emissions certification data

Reference data have been compiled for each of the aircraft/engine combinations selected for use in AEROCERT.

4.3.1 Emissions data

The emissions data are drawn from the ICAO Engine Exhaust Emissions Databank [Ref. 4-1]. This databank contains information on exhaust emissions of production engines, composed mainly of information from newly manufactured engines submitted for certification compliance purposes. Some updated data is provided from engines during further production runs and also data from a limited number of in-service engines measured before or after overhaul. These data include the certification values for the regulated species plus the characteristic values for each engine. Additional information such as pressure ratio, certificated thrust and bypass ratio is also given in the databank, together with mass emissions per aircraft for the LTO cycle.

4.3.2 Noise Data

The noise data are drawn from the noise certification databases of JAA authorities, principally the UK CAA. The measurement values obtained at the certification test points are given. All aircraft considered in the AEROCERT research project comply with the requirements of Annex 16 Volume I, Chapter 3. In the first instance the noise data are given for the certificated weights operated by airlines supporting the AEROCERT project. Additionally data are given for other certificated weights for the same aircraft/engine combinations to permit some analysis of the effects of weight upon environmental performance.

4.4 Comments on certification processes

This section is a distillation of the comments and views of a number of experts with a direct interest in certification, on their experience of the regimes and on the perceived strengths and weaknesses of the regimes. These views are not findings of the research, but a number of these issues regarding the current certification procedures, need to be taken into account within AEROCERT when considering the findings of the other work packages. Some of these issues are closer to the objectives of the project than others.

4.5 Comments on current noise certification procedures

4.5.1 Technical level

The current test procedures are based on the technical level of two or three decades ago. Although the applicants are permitted to use the latest technology (e.g. digital test equipment, differential GPS tracking systems) the requirements do not oblige them to do so. The equipment specifications of the Annex are still deemed to be acceptably accurate though more modern equipment may present the opportunity for greater accuracy. It may therefore be reasonable to consider whether there is merit in tightening acceptable tolerances.

4.5.2 Accuracy

One of the key accuracy points is that of repeatability of the test results. This is reflected in the 90% confidence limits which must be within ±1.5 EPNdB for each certification measurement point. The noise certification figures presented include these confidence limits. However it should be realised that the confidence interval is not a measure of accuracy but of statistical repeatability.

Whilst it may not be reasonable to expect any greater level of accuracy in the tests (see *Technical level*, above) for the purposes of noise exposure calculations it would be desirable to gain access to more of the underlying data obtained in support of the certification testing. Additional accuracy would be desirable for the purposes of contouring, given the extreme sensitivity of contour area to noise level. In addition, a better understanding of the noise propagation processes, which are affected by the ground cover, atmospheric attenuation, wind, temperature and humidity, would be desirable for application of correction factors to predict noise levels at long distances. Since noise certification figures are based on noise levels measured at only a few hundred metres from the aircraft, when these data are used to derive noise exposure levels at longer range (e.g. a few kilometres) then the effect of inaccuracies in the measured data and the correction factors becomes more apparent: comparison of results from noise measurements with computed noise levels can show differences of several dB.

4.5.3 Databases

Many of the aircraft that need to be certified are derivatives. The certification data of these aircraft are for a large part based on certification data gathered during the certification of the parent aircraft. For the parent aircraft a very extensive set of NPD data are collected, often for power ranges that exceed the required range for the certification of the parent aircraft itself. These stored data are intended for future use. When consideration is given to changing the certification procedures care must be taken to ensure that these databases, which have been costly to construct and with which all concerned are familiar, do not lose their validity.

4.5.4 Microphone height

For the majority of noise certification procedures, microphones are currently placed 1.2m above the ground at each of the measurement locations which increases ground interference effects. Using microphones positioned at ground level reduces these effects and increases the value of the test results by making them less susceptible to ground reflection effects.

Ground level microphones should ideally be mounted with the diaphragm in the same plane as the ground level, with the ground level being a flat infinite plate. As a practical solution to this requirement, it is possible to sit an inverted microphone on a specially designed metal ground plate with a head 7mm above the plate surface. The design of this plate is such as to ensure that the size and shape minimises ground reflection effects received at the microphone from surrounding area. Such plates are currently defined in Annex 16, Chapter 10 for use in the certification of light propeller aircraft and helicopters.

One reason why this microphone positioning has not been implemented for jet and turbofan aircraft is the apprehension that to do so would probably render the current certification databases useless for the purpose of future certifications: the data measured by the manufacturers during certification tests of a parent aircraft for use in certifying derivatives would be in danger of being made redundant, as it would be difficult to make comparisons of the relative noise levels between the two certification procedures. If such a change were to be made it is likely that the noise ranking order of jet aircraft certificated using a new methodology would be similar.

However, it is arguable that the manufacturers hold sufficient data from previous noise certification tests that would ensure their existing databases are not made redundant before the benefit of their investments have been recovered. This is due to the fact that the certification tests are usually carried out using ground level microphones in addition to those at 1.2m; in order to obtain data for research purposes. This data could be used as the basis for a new database utilising the new procedure, or used to provide data to enable reverse engineering of the results from the microphones situated at 1.2m, producing equivalent results for the noise level received at ground level.

Introduction of measurements made at the ground plane inverted microphones could possibly increase the measured noise level by 6 dB or more compared to the current measurements, because of the pressure doubling effects at the measurement position. The question then arises as to whether a perceived increase in certification limits to take into account these higher noise levels, would be acceptable to the general public.

4.5.5 Sideline measurement

The test measurement procedure that is most sensitive to circumstances is the sideline test. The results of this test may be influenced by the noise attenuation properties of the ground cover. These will include the presence of any vegetation, condition of the soil, the level of the groundwater, or the existence of snow or dew etc. These attenuation effects are marked in the sideline case because of the relatively shallow measurement angle.

In the US the open spaces which give the required lateral distance from the flight path are far more common, whereas airports in Europe seldom have this much distance to the sides of the runways and the test is therefore far less representative for European operations. This objection to the positioning of the sideline measurement point has led to a case being made for an additional flyover test, but this introduces a number of problems, namely how to set the regulatory level, at what distance and at what height the measurements are to be taken, and that different aircraft types would need to be flown in different ways to achieve the measurement, and there is also a concern about the relationship between noise and weight.

The sideline test is possibly the most expensive to carry out and analyse and it has been suggested that the costs of certification could be reduced without affecting the objectives by including another full power flyover test instead. The lateral test has been supported by certain authorities to date as it is arguably the condition which best serves to represent a measure of source noise technology. However, one source of contention is that the power setting for this test may be different to that used for the take-off measurement, and the argument centres on whether the same profile should be used for both tests.

4.5.6 Thrust cutback

Annex 16 permits thrust cutback in the flyover measurement tests and this is, perhaps, the closest that the certification procedures come to representing operational procedures. The justification for this is that the applicant can take advantage of the different noise characteristics of this procedure to reduce the overall noise. It could be argued that this is inconsistent with the stated objectives of the certification process.

4.5.7 Deviation from normal operating procedures

The noise certification values are based on reference aircraft procedures and configurations (e.g. the maximum take-off weight, the noisiest aircraft configuration in approach) that may not be typical of operational flight procedures. The current rules and standards do not give credit to changes in flying procedures which are designed to decrease noise levels during normal operations. This has led to concerns whether it is reasonable to use such data as a basis for operational restrictions or noise related charges. Understanding the effect of flight procedures in the relationship between certificated and operational values is a key issue for AEROCERT.

4.6 Comments on current emissions certification procedures

4.6.1 Technical level

Generally, the current instruments used for emissions measurement are sufficiently accurate and cause no concern, except for the smoke measurement (see below).

4.6.2 Smoke measurement

The SAE smoke measurement is the least satisfactory of the emissions measurements. This test is the determining factor in the time that is required for the engine emissions test because of the time which is required for each smoke measurement. For the smoke testing, each point needs to be tested three times, and this can take up to eight minutes per measurement point in order to provide the degree of certainty which is required by ICAO.

The SAE smoke test was instigated in the 1960s and applied to aircraft engine exhaust smoke, when the level of technology was not to today's standard and smoke levels from aircraft engines were much higher (say 40-50 SN) than those generated by today's types. The smoke levels seen by these modern types are so low that the reproducibility of the smoke measurement (i.e. plus or minus 3 smoke numbers) can be the same as the absolute current levels. Therefore, it has been contested that this test is no longer suitable for the measurement of such low smoke numbers. Newer, (arguably) more reproducible methods are available, such as optical smoke meters.

With the low smoke numbers produced by modern engines, the visibility of the plumes from the engines is no longer a concern. With the difficulties of measuring such low visibilities and small numbers of large smoke particles, even with optical methods, another suggestion is that particle size and size distribution might be measured.

4.6.3 Characteristic levels

Coefficients are applied to the emissions measurements to ensure that the mean of the engine population meets the regulatory levels, with 90% confidence. These factors were developed in the 1970s, and given that today's manufacturing techniques reduce the variability in the production characteristics from each engine compared to the variability between the engines at that time, it is arguable that this would result in a lower variability of emissions and hence the characteristic coefficients over-compensate.

4.6.4 LTO cycle

Current larger engines idle at lower than 7% thrust setting. Concerns were expressed that the ICAO regulations requirement of 7% thrust for ground idle in the LTO cycle may perhaps not reflect the operational characteristics of these engines and thus the CO and HC emissions which are generated over the regulatory cycle may be optimistic. Manufacturers already measure the emissions lower than the 7% power level in the course of their emissions test procedure, but this data is not public. Questions have also been raised about the validity of the current LTO times in mode and the effect of these notional timings against actual practice in terms of mass of pollutants emitted.

4.6.5 Altitude emissions

The current certification requirements concentrate entirely on the LTO cycle. However this does not take into account the total pollutant emissions over the larger part of the flight cycle, which are a climatological concern. CAEP has recognised the need for the certification regime to reflect aircraft (as opposed to only engine) emissions performance at cruise and climb. This topic, pursued separately from NO_x stringency discussions which relate to the LTO based regime, is now a priority work item for CAEP with proposals on the form of a new rule embracing all phases of flight (including a review of the LTO requirements) expected by CAEP/6 (2003?).

At cruise altitudes, NO_x is the priority species for regulation, but the emissions of CO_2 and H_2O (the emissions of which are directly related to the quantity of fuel burnt) are also an issue for consideration in a new regime because of their link with productivity and their important role as green-house gases. CO and HC might approach zero at cruise conditions with modern engines and are not considered to be significant in terms of atmospheric impact.

The relationship between current LTO NO_x emissions and altitude NO_x can vary for different technologies or engines; however, a reduction in LTO NO_x will generate lower levels of NO_x at altitude. Demonstrating altitude emissions performance to the accuracy required by certification authorities is a major hurdle. On grounds of practicality and cost, it would be much more efficient for correlations to be developed which enable SLS results to be used to predict altitude NO_x rather than stipulating testing in altitude test facilities, which would be extremely expensive.

4.6.6 Trace species

It is felt that measurement of other emissions species which are present in trace amounts in the exhausts (such as specific nitrogen, hydrocarbon and sulphur compounds, as well as aerosols and particulates) would not currently be a practical addition to the emissions measurement requirements, because of limited measurement capabilities and the increased complexity and costs which would be incurred. The amounts of the trace species present in the exhaust are very small in line with the low levels of unburnt fuel emissions produced by modern engines.

5 WP2 - noise: Operational procedures

5.1 Introduction and background

The current certification standards for aircraft engines, set by the International Civil Aviation Organisation (ICAO), were developed in the 1970's. Since those days, air-traffic has grown enormously and the airport structures have changed remarkably. In addition, actual flight procedures have changed since the certification standards were adopted. For these reasons, it is believed that the certification standards are becoming out-dated, since they do not take into account the developments in the state of the art aircraft operations in relation to aircraft performance and engine emissions technology.

In parallel to these developments, the importance of noise certification has grown enormously. Since the noise certification procedure was first defined, it has become necessary for airports to use the certification data to manage the impact of flights on the community. Typically, the airports need to know the single event noise under and near the flight path throughout the departure and arrival process, even to 20 or more nautical miles away from the airport for sensitive times of the day or night, as well as the total population affected by noise from a flight. In addition, data is needed to allow the calculation of integrated noise impact metrics such as Leq.

The maximum noise generated at just three points in the community, regardless of the spatial distribution of the population and the way the aircraft are operated in real life, has become a less than adequate guide to the acceptability of the noise made by any particular set of operations, so that airports have invested in increasingly sophisticated and expensive noise monitoring systems that allow them to tailor operational rules to their own specific circumstances. It has therefore been deemed necessary to compare the everyday operations with certification procedures for the noise at several points under the flight path, including the certification points, and also to compare the area within a nominal noise contour, e.g. the 85 EPNL contour.

Consequently, the relevance of present certification standards to the environmental impact of aircraft is questioned. In this context, the main objectives of WP2, "Research into operational procedures" are:

- to identify the character of existing operations;
- to estimate the noise (and emissions) produced by these existing operations;
- to compare the actual noise (and emissions) with those implied by the certification standards.

This chapter concentrates on flight procedures in the context of noise. For information on emission certification see chapter 6 and report AEROCERT/FFA/WR2/01 [Ref. 5-1].

5.2 The Fight Data Records data

The AEROCERT project relies heavily on Flight Data Records (FDR) that have been supplied by a number of European airlines. The AEROCERT FDR database comprises more than 1800 take-off and another 1800 landing operations of flights to and from European airports using representative aircraft-engine combinations of representative airlines. These FDRs form the basis to describe the characteristics of aircraft operational procedures near European airfields. The data requested by the AEROCERT team has been specified so as to allow conclusions to be drawn on:

- The shape and consistency of the take-off and landing profiles;
- The noise generated by the flown profiles;
- The relationship between the noise generated by the actual, measured profiles and that which would have been generated by profiles equivalent to those performed during noise certification;

Detailed specifications for the information required from the FDR have been issued by the AEROCERT team some four years ago. Careful consideration has been given to the balance between cost, the need for some statistical analysis of the consistency of the profiles and the need to compare operations over a range of airlines, aircraft, airports, runway thresholds and sector lengths. The specifications include:

- The start and end time of the traces relative to take-off and landing, since the ground movements are an important part of emissions production;
- Latitude and longitude, so that the profiles could be positioned in space and so allow noise at the certification measuring points to be calculated;
- Engine setting, for the calculation of noise at source;
- Fuel flow, for the calculation of emissions;
- Altitude, air speed and ground speed, to define the character of the flight profiles;
- Gross weight;
- Timing of touchdown and configuration changes (flaps, slats, landing gear extension), to relate these to the character of the profiles.

Data for the analysis of emissions have been provided by four airlines and for six aircraft types, data on one of the types being available from two airlines. A range of sector lengths is covered. Most flights have weight data, and the actual runways used can be identified, so allowing any differences in profiles due to the SIDS, STARS or type of approach aid to be identified. However, considerations of confidentiality do not allow all rich data source to be reported, only the deltas and conclusions drawn from it.

5.3 The data analysis, an overview

The objectives of analysing the profiles are to gain an understanding of the way aircraft are flown on arrival and departure, and to generate representative profiles to input into the Integrated Noise Model (INM). It has been suggested that the statistical average of each of the profile parameters should be derived. However, this would have diluted the rich information of differences, or variation, between airlines, airports and runways. Also, it is possible that the averages of the profile parameters, taken one at a time, might prove inconsistent when put together to represent a single nominal average flight for each aircraft type. It has therefore been decided to compare a few of the groups of flights visually, in order to attempt to understand the range of variability among and between groups.

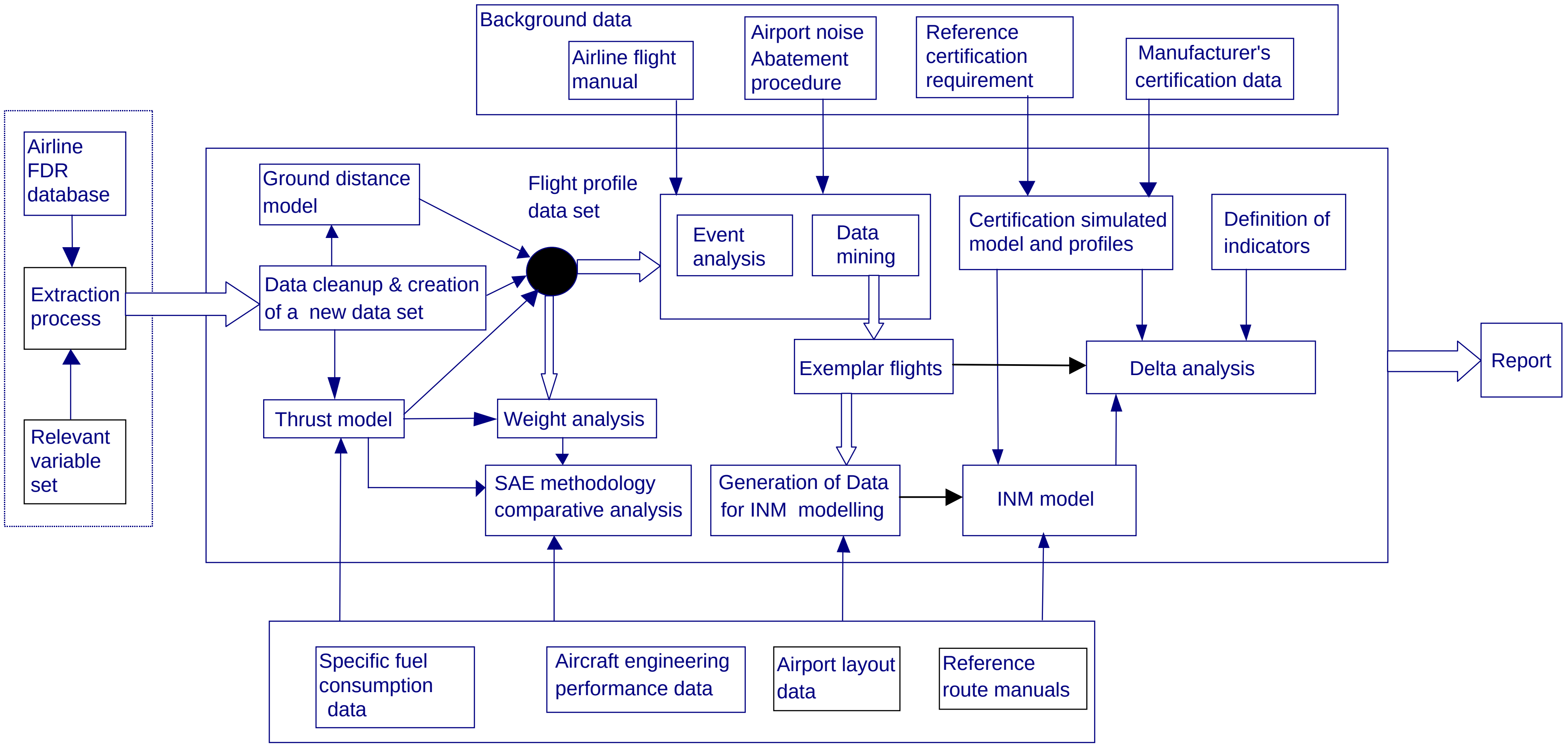
The processing of the FDR data is shown in Fig. 5.1 (next page).

The processing starts with the actual FDR data files and finally results in graphs and figures for reporting. During this processing, additional background data is fed into the analysis. The main processes that can be identified are:

- Cleaning up of raw FDR data to cope with data gaps;

- Visual inspection of the recorded profiles to make a first assessment of the variability of the aircraft operations;
- Event analysis to identify characteristic events such as landing gear retraction, thrust changes, flap setting changes etc;
- Weight analysis;
- Extraction of exemplar flights using Cluster Analysis;
- Generation of data for profile simulation in INM;
- Comparison of exemplar flights with certification flights based on selected indicators using INM.

Figure 5.1: Profile Analysis and Noise Modelling Methodology



The clean-up of the FDR data is required to derive profiles from the start of take-off role and from crossing the runway threshold for input to the INM. The type of clean-up differs between the different data sets. Many of the sets do not include ground speed or distance, and they could not be created from latitude/longitude information due to lack of precision, so they have been created from air speed, heading and wind speed. Also, some of the parameters for some of the aircraft types are not available until the aircraft were moving at some 50% of their take-off speed.

Using the insights gained from the visual analysis to guide the choice of parameters to be considered, the full data set for each pairing of airline and aircraft type has been fed into an automated analysis that grouped each set into clusters that displayed similar characteristics. The most representative flight has been chosen from each cluster as an ‘exemplar’ for the cluster. The exemplars are then fed into the INM and the noise created at the certification measuring points and other points under the flight path are calculated. Finally, these values are compared to those corresponding to certification by also representing the certification flights on the INM using the method described in the Annex to the Task 1 report.

5.4 Visual examination of flight profiles

The data for this visual examination have been brought to common touchdown and lift-off points for purposes of comparison. The identification in time of these points is only approximate due to some difficulty in correlating the data on ground/air contact with the altitude information. When ground distance is not available directly from the FDRs, it is derived from ground speed, heading and wind vectors. Appendix A of the Work Package 2 report [Ref. 5-2]) shows several samples of profiles for the airline/aircraft combination coded as G6, and Appendix B of the [Ref. 5-2] deals with a sample of flights coded as D7.

The raw, visualised material does allow some conclusions to be drawn about the differences between aircraft as they are operating today compared with the way they are required to operate for noise certification:

- It is clear that the introduction of the high bypass ratio fan engines, particularly on twin engine aircraft, has improved the take-off performance and so allowed operators to use much less than maximum take-off power on most runways. This, in turn, has resulted in longer take-off runs and lower initial climb paths that, to some extent, offsets the benefits from the lower levels of source noise by taking the aircraft much closer to the noise meters. This would also be influenced by the use of intersection take-offs, but the positional data in the FDRs are not good enough to identify the location of the start of roll in order to ascertain which runway entry was used. Indeed, the data for some of the aircraft did not have information on the runway or even the airport being used.

- The use of regulated thrust varies from little or no reduction to quite extreme reductions for the two twin engine aircraft considered here. The direct consequence of the use of large take-off thrust reductions is that there is little or no further cut back to climb power.

- The weights for the short haul flights examined vary between 75 and 90% of the maximum take-off weight used for certification.

- The variations in track at the 3.5 nm measuring point are approximately contained within 10% of the distance from start of roll. The height variations at that point are within 5% above or below the average height. Further out on the climb, the variations are much greater as they become influenced by air traffic control (ATC).

- The approach tracks are strongly influenced by ATC, as are the number and height of the steps in the approach. Some interceptions of the glideslope are at or below 2000 feet, but it is not possible to say whether this is due to ATC or pilot technique. These procedures may have a substantial impact on the noise contours, but not, in general, on the noise at the approach measuring point. The dispersion in track and height as the certification point is overflown, is usually below 10%, and the aircraft are stabilised in velocity.
- The thrust varies around the various 'steady-state' conditions much more than is commonly realised, as the engine is used to accelerate or decelerate the aircraft to fly precise speeds and to respond quickly to the need to change the descent rate.
- As with the take-offs, the information about the position in space is not, in fact, good enough to assess the height over the approach certification point. The necessary assumption made here, of no variability in touchdown location, is clearly not valid.

5.5 Statistical analysis

Following the visual examination of the flight profiles, a statistical analysis of the sets of combinations of airlines and aircraft for which appropriate FDR data are available has been made. The complete set of data that has been examined is tabulated in Table 5.1. This table shows the variety of aircraft, engines, and the number of flights, whether short or medium/long haul. For confidentiality reasons, the aircraft-engine types are coded.

Not all the FDR datasets could be used, because of corruption, data discontinuities, and incompatibility with the INM database and the time available for the analysis.

Table 5.1: The FDR data sets used for statistical analysis

Aircraft/airline Combinations	No. of engines	No. of flights short haul	No. of flights medium and long haul
G6	2	81	0
F12	2	20	0
D7	2	150	0
I13	2	20	36
I15	2	204	80
J16	3	0	80
M14	4	0	236
K3	4	0	150

5.5.1 Selection of representative flights

For identification of the characteristics of flights, it was necessary to develop a consistent way of selecting flights from the totality of each set of data for input to the INM. Given the diversity of the profiles shown during the visual analysis, and hence the need to pick several flights to represent each data set, a technique called Cluster Analysis was adopted to detect automatically those flights sharing common characteristics and, therefore, also identifying groups with differing characteristics. The Cluster Analysis approach condenses a set of FDR data of several flights to a limited number of exemplar flights, while preserving the diversity of the character of the operations. A brief resume of Cluster Analysis is given in Appendix D of the Work Package 2 report [Ref. 5-2].

Eight parameters are selected to describe (the character of) the flights for the Clustering. Depending on whether the flight is a take-off or a landing, they were:

- Take-off or landing weight;
- Ground roll distance;
- Lift off time from start of roll or time from 5000 feet to glideslope intercept;
- Speed at lift off or at 1000 feet on approach;
- Take-off thrust or thrust at 1000 feet on approach;
- Cut back or glideslope intercept height;
- Initial flap retraction or gear down height;
- Final flap retraction or initial flap down height.

These and several other parameters were extracted automatically from the FDR data using dedicated, tailor made computer software.

Once the clusters of similar flights were identified, the flight within a given cluster that had the maximum similarity to the other flights was taken as the exemplar flight for that cluster. Exemplars for those clusters representing only a small number of flights were ignored, so that some 90% of all flights have been represented in the derivation of noise on the ground. The remaining 10% of the flights were considered not sufficiently representative of everyday operations to be processed.

To show the flight character preserving features of Cluster Analysis, an example of a set of take-off exemplars for the medium haul twin engine aircraft/airline combination I15 is given in Figure 5-1, 5-2 and 5-3. Some very different take-off profiles in this particular case of a set of flights are shown. Taking any one parameter at a time, several of the exemplars appear to be quite similar, but there is always a significant difference in at least one of the parameters.

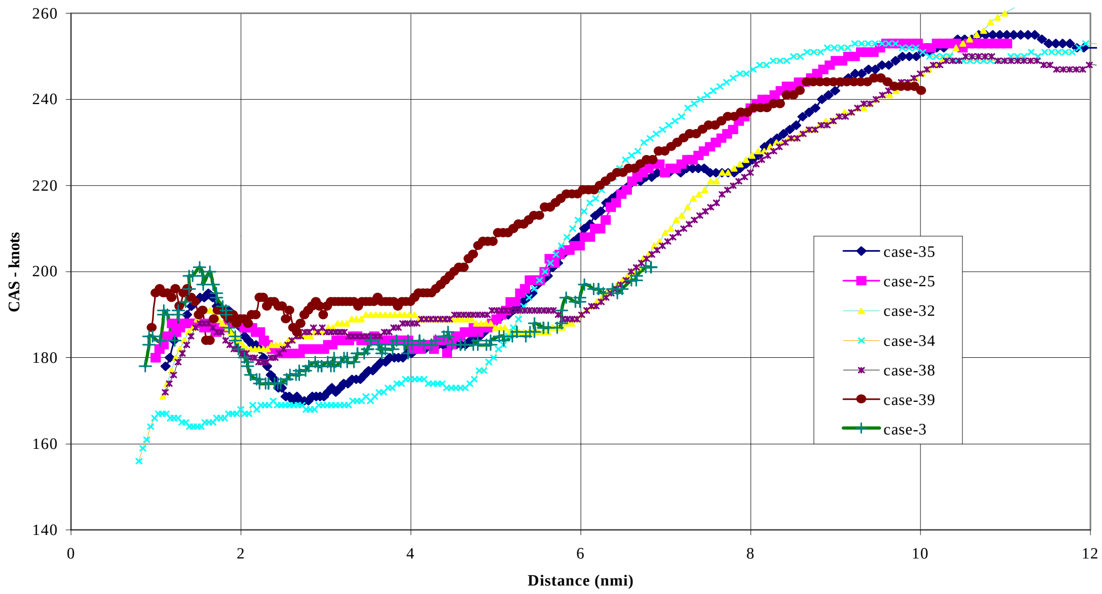


Figure 5-1.: Wide body twin examplars, speed profiles

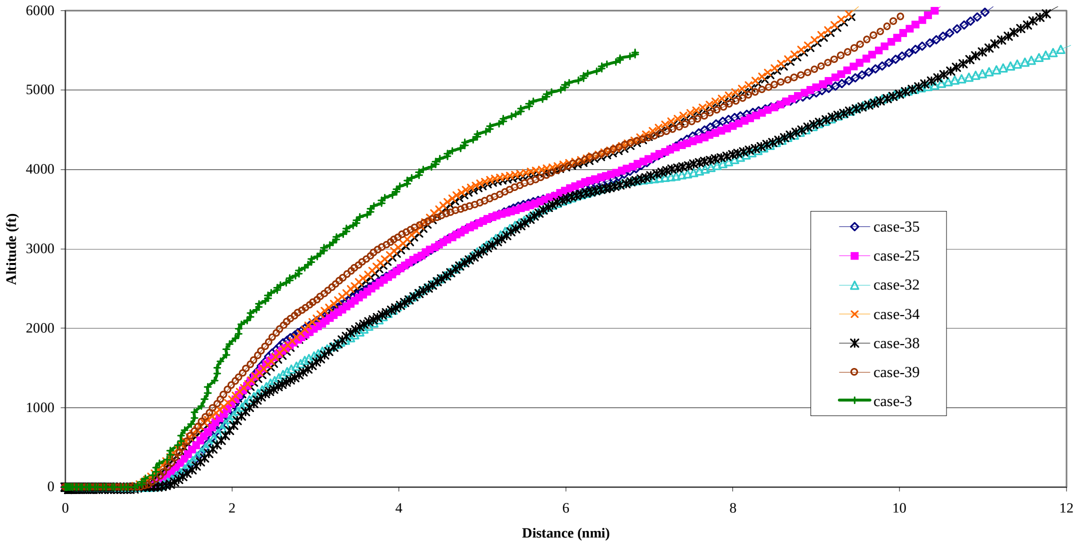


Figure 5-2: Wide body twin examplars, altidude profiles

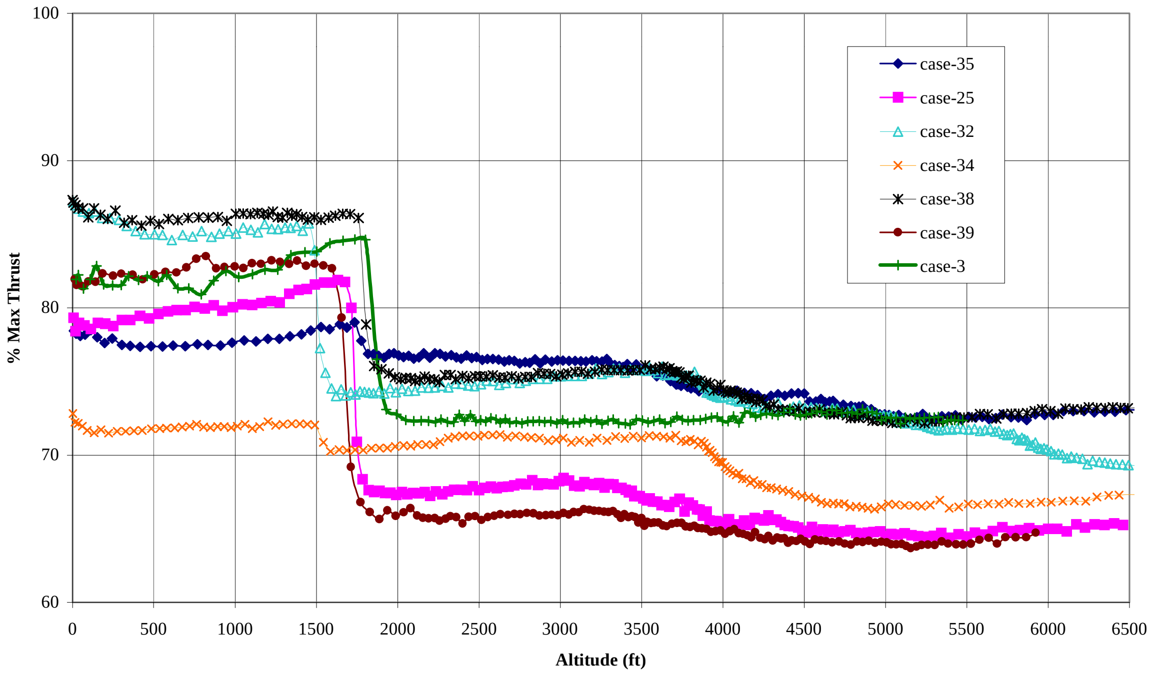


Figure 5-3: Wide body twin examplars,thrust profiles

5.5.2 The character of operations

Once the FDR are clustered, and the exemplar, most representative flights, are identified, specific events are identified for these flights. The most important events are:

- Take-off or landing weight
- Ground roll distance
- Lift off time, speed and thrust
- Instant of flap change (time, height, speed, thrust)
- Instant of power cutback (time, height, speed, thrust)
- Heading change
- Climb rate
- Instant of gear up/down (time, height, speed, thrust)
- Instant of slope intercept (time, height, speed, thrust)
- Instant of touchdown (time, speed, thrust)
- Reverse thrust (thrust, time)

The full set of events captured is described in Appendix F of the Work Package 2 report [Ref. 5-2] for the analysis performed on the data made available early in the study.

5.6 The use of regulated thrust

The visual analysis already suggests, as may be expected, that the lighter flights in a fleet tend to climb faster than the heavier flights. From the data analysis, the take-off thrust settings for the lighter flights are usually lower than for the heavier flights. Apparently, the take-off thrust settings are not sufficiently lower to reduce the vertical profile to that which would have been obtained at maximum weight with maximum thrust, as commonly indicated in operations manuals.

Since the degree of thrust regulation is likely to make a significant difference to the noise at the flyover point, before the full statistical analysis a separate investigation on the use of regulated thrust has been undertaken. The observations are varying and strongly dependent on the different kind of operations and (number of engines on the) aircraft. E.g. for the short haul flights, there is almost no relationship between thrust and weight, whereas there is a quite strong relationship between weight and the maximum climb angle (Work Package 2 report [Ref. 5-2] Appendix C Figures C 1.1 – 2.2, 3.1, 3.2). For I13 long haul twin engine operations, no relationship between thrust and weight is apparent to (Appendix C, Figure C 2.3), but there is also no relationship between weight and climb angle (figure C 2.4), though the weight range is limited. On the other hand, with a much greater range of weights, aircraft type I15 shows a strong and consistent use of regulated thrust for very similar operations (figure C 4.1). The plots of M16 four engine operations show results on two series of multi-sector routes (figures C 5.1, 5.2). These indicate again a strong relationship of thrust with weight, particularly across sectors but also when weight varies considerably within a sector.

These observations are confirmed if looking at non-dimensionalised thrust at lift-off and also climb angle at 1000 feet altitude against percent of maximum weight. The plots are shown in Appendix C of the Work Package 2 report [Ref. 5-2].

There is always likely to be considerable scatter in the thrust/weight relationship, as the decision on thrust to be used depends on the available runway length, the meteorological conditions, runway and airspace congestion, as well as the policy of many airlines to use maximum thrust from time to time to verify the engine’s capability. Yet, the relatively strong relationship for the four engine aircraft suggests that the lack of a strong relationship in the other cases is equally valid and that the vertical profiles are therefore far from consistent. It therefore becomes necessary to identify several different profiles in order to represent the actual operations.

5.7 Noise generated by everyday operations

The available data on everyday operations in the year 2000 have been reduced to exemplar flights that capture at least 90% of the total data for each set of airline/aircraft combinations, both for landings and take-off. These flights have been loaded onto the 6.0b version of the INM in the same way as the certification flights described in the Annex to the Task 1 report, and the noise generated by the exemplar flights has been calculated for the three certification points. These certification points are located relatively close to the runway.

The noise generated at these certification points have become the basic data to manage the impact of flights on the community. Typically, these data are used to judge the single event noise under and near the flight path throughout the departure and arrival process, even to 20 or more nautical miles away from the airport for sensitive times of the day or night, as well as the total population affected by noise from a flight.

The maximum noise generated at just three points in the community, regardless of the spatial distribution of the population and the way the aircraft are operated in real life, has become a less than adequate guide to the acceptability of the noise made by any particular set of operations, so that airports have invested in increasingly sophisticated and expensive noise monitoring systems that allow them to tailor operational rules to their own specific circumstances. In addition, data is needed to allow the calculation of integrated noise impact metrics such as Leq.

It has therefore been deemed necessary to compare the everyday operations with certification procedures for the noise at several points under the flight path, including the certification points, and also to compare the area within a nominal noise contour, chosen as the 85 EPNL contour.

5.8 Comparison with certification flights

This work package aims to produce ‘deltas’ that indicate the difference in noise impact between day-to-day operations now and those implied by flights reproducing certification conditions for the aircraft concerned. This has been achieved by using INM version 6.0b by comparing the certification procedures (see the Annex to the WP 1 report) and the chosen exemplar flights (see section 5.5)

The exemplar flights have been entered in the INM with the same straight-in and out flight tracks as applied to the certification flights. It was felt that the FDR data used in this study was not sufficiently representative of arrival and departure procedures throughout Europe for it to be useful to include turns in the cluster analysis: Turns are therefore ignored in the analysis. In fact, the visual analysis has revealed that in some cases, particularly with short haul flights, aircraft are allowed or asked to turn well before the flyover noise certification point. Though a turning aircraft will have either more thrust or a lower climb rate than one in straight flight and will therefore generate more noise under its flight path at a given distance from start of roll, the increased slant distance may cause it to generate less noise at the certification point.

The deltas derived by this analysis may therefore be smaller than those that really occur at the flyover point for any flights that incorporate early turns, though, depending on effects of airframe directivity, greater than that under the real flight path at the same distance from start of roll. Equally, actual wind speeds and directions experienced will alter the comparison with certification flights made under the certification conditions. Even though the surface winds in the sample flights were never much more than 8 kts on the nose, natural windshear sometimes increased this to 30 or even 40 kts at 2000 feet. This will have the effect of lifting the aircraft above the certification flight path, so reducing noise at the flyover point relative to that predicted by the INM, all other things being equal.

With the above caveats, the exemplar flights may be used to derive deltas for the noise at the certification points, for other points under the flight path, and also for the area within the 85 EPNL contour for take-offs. These deltas are presented in Tables 5.2, 5.3 and 5.4 respectively and some examples of the results are graphed in Figure 7 of the main Work Package report [Ref. 5-2]. The sideline deltas have been derived by calculating the maximum noise for each exemplar 450 m off the extended runway centreline, rather than the noise at the same point as the maximum for certification.

It is to be expected that sideline noise in simulated normal operations will not be more than certification flights, since the thrust used is always equal to, or less than, the maximum take-off thrust used for certification. This is confirmed by the results for the airline/aircraft combination I15.

The differences between the certification and the recorded flights are due to a combination of the aircraft weight on the day, the amount of flexible thrust used and the point at which the thrust is cut back. The exemplar flights that are substantially quieter during the later portion of the departure have often been held down by air traffic control, thus needing less thrust. Noisier flights, although these use less take-off thrust, tend to leave the ground later and climb more slowly, so the reduced slant range becomes the dominant factor.

The noise contour area deltas for the same exemplars vary between 90% to 127% of certification, the difference being mainly due to the noise quite close in to the airport. Contours of different noise levels would give different results, but the certification flight simulation after the measuring point is, in any case, not very realistic.

For the same long haul twin operations, but in the reverse direction on the same route as the I13 set considered above, i.e. departures from Europe, several of the flights are quieter at 2 nm, by up to 1 dB. Others are up to 3 dB noisier, as they are at 3.5 nm. They are mostly still up to 2 dB noisier at 5 nm, though 15% of them are slightly quieter. Almost all the European departures have larger contours than the certification flight, by up to 40%.

This is also true for short haul narrow body operations in the G6 set of flights. The flyover noise of the exemplars is up to 1 dB noisier, and the noise at 3.5 and 5 nm is up to 3 dB more than the certification flight.

The landing case, as illustrated by 10 individual G6 flights, show deltas at the approach certification point to be rather more variable than the take-off cases, 30% of the flights being quieter than certification, the others being up to 2.3 dB noisier. The results depend mostly on the thrust used and the speed of overflight, this affecting the duration of the noise exposure.

Table 5.2: take-off noise deltas

	flyover			flyover			flyover		
AC	2 NM			3.5 NM			5 NM		
	min	max	(avg)	min	max	(avg)	min	max	(avg)
I15	-5.1	2.8	(-1.07)	-4.6	1.0	(-1.71)	-4.2	0.3	(-1.89)
G6	0.4	0.9	(0.66)	1.8	3.0	(2.52)	1.4	2.8	(2.12)
I13	2.3	6.5	(5.36)	1.3	5.9	(2.81)	-6.0	2.6	(0.55)

N.B: Delta = exemplar noise output minus certification value

Table 5.3: Approach noise deltas

AC	min	max	avg
G6	-1.0	2.3	0.7

N.B: Delta = exemplar noise output minus certification value

Table 5.4: Contour area ratio

AC	min	max	avg
I15	72	135	100
G6	191	215	205
I13	91	127	112

Ratio (%) is the ratio between 85 EPNL level divided by certification times 100

5.9 Conclusions

The data from the take-off and landing phases of some sets of flights by airline/aircraft combinations have been examined in order to understand their characteristics, relative to operations flown in accordance with noise certification procedures. Some of the data were examined visually. This allowed some of the more pertinent factors that drive the profiles to be identified. For take-off, these were the aircraft weight, the amount of regulated thrust used and the height at which thrust was cut back. These were, in turn, affected by the high bypass ratio of modern jets, allowing considerable use of flexible thrust. This, together with the necessary high installed thrust in twin-engined aircraft, allows earlier turns and the use of intersection take-offs. For landings, the weight was again a significant factor, together with the height at which the glideslope was intercepted and the extent to which constant altitude sectors were used on the approach.

Large differences were detected in the way individual flights within a set were flown, particularly with short haul twin engine operations. This leads to differences in the vertical and lateral flight profiles, more so before intercepting the glideslope and after lift-off. Similar differences were also detected between sets of operations with the same aircraft flown by different airlines, and between different short haul aircraft flown by the same operator. The heavier four-engined aircraft were flown more consistently, particularly with respect to the relation between the use of regulated thrust and the aircraft’s weight. Where the data was sufficiently comprehensive to allow them to be examined, further differences were identified with respect to the airports and runways used.

Having identified the significant events, the full data set was subjected to an automated data mining procedure to capture the character of those events and to compare flights within each data set. A Cluster Analysis procedure allowed the flights within a set to be separated into groups with similar characteristics and a most representative flight of each group to be selected. These representative flights were called ‘exemplars’.

The exemplars were entered into Version 6.0b of the Integrated Noise Model (INM) in the same way that the certification flight profiles had been entered into Version 5.2 of the INM as described in Appendix 1 of the Task 1 report. The noise ‘deltas’ for the exemplars relative to the INM simulation of the certification flights were then calculated in terms of the certification points, together with other points under the flight path and the area within an 85 EPNL contour. The INM simulation of certification flights did not, in general, give exactly the same values as those certificated, but were deemed to be the appropriate basis for calculating consistent deltas.

The results show that the samples of wide body twin engine aircraft used in medium haul operations are quieter than the certification values at the take-off flyover point and at the sideline, in some cases by 5 or 7 dB. These results are due to the use of less than maximum weight and to a complex combination of operating conditions and decisions as to how to fly at the lower weight. Thus, the height at flyover might be the same as for certification or twice that height. The deltas at other points under the flight path do not necessarily follow those at the certification points, given these complex variations in behaviour.

Equally, there is not a direct relation between the flyover noise and the contour areas, though the general noise ranking of the exemplars is similar for the contour area and the average noise under the flight path. Some of the exemplars generate contours 30% larger than those produced by certification flights, others 30% less. The three quietest exemplars represent only 20 per cent of the 41 flights in the set, while the two noisiest exemplars represent 32 per cent. The populations affected are likely to vary by more than these areas, since more people will tend to live further from the runway. In this respect, some normal operations may be considered to be noisier than certification flights, though the normal operations may have been flown deliberately to reduce close-in noise at the expense of noise further out. The conclusion will depend also on the noise level chosen for the contour area calculations.

The results for the samples of narrow body aircraft and for wide body twin engine aircraft used in long haul operations both generate more noise at the flyover than the certification flights, by 3 or 4 dB in several cases. The noise at the approach certification point is also generally higher than certification for the narrow body aircraft, by up to 2 dB. The four engine aircraft operations appear, in contrast, to have been quieter than the certification values, though difficulties with the analysis make it difficult to have much confidence in the results.

6 WP2 – emissions: Operational procedures

6.1 Introduction and Background

The current certification standards for aircraft engines, set by the International Civil Aviation Organisation (ICAO), were developed in the 1970's. Since those days, air-traffic has grown enormously and the airports structure have changed remarkably. It is alleged that the certification procedures are becoming out-dated, since they do not take into account the developments in the state of the art aircraft performance and engine emissions technology. In addition, actual flight procedures have changed since the certification procedures were adopted. Consequently, the relevance of present certification procedures, and thus of the standards applied to them, to the environmental impact of aircraft is questioned. In this context, the main objectives of WP2, 'Research into Operational Procedures' are:

- to identify the character of existing operations;
- to estimate the emissions (and noise) produced by existing operations;
- to compare the actual emissions (and noise) with those implied by the certification standard.

The flight procedures to be studied in WP2 are the taxi, take-off, climb-out, en-route, approach and landing phase. This document concentrates solely on exhaust emissions and flight procedures. For information on noise certification see [Ref. 5-2] AEROCERT /LU/WR2/01.

6.2 Material and Methods

With access to Flight Data Recordings (FDR) the character of the existing operations can be deduced and the flight modes distinguished. To estimate the emissions from each flight, basic information on different engine emission levels can be found in the ICAO Engine Exhaust Emission Data Bank [6-10]. This data bank contains rates of pollutant emissions at sea level static conditions for different thrust settings. The databank quotes values measured during the emission certification process for all engines that are in production. An emission model can be created which uses the flight data recordings and data from the emission data bank in order that the emissions can be estimated for each flight.

The flight data recordings (FDR) that have been used were made accessible by a number of airline operators in Europe and span a couple of hundred flights.

Two fuel flow methods, from DLR and Boeing [6-1, 6-2] were used to calculate the emissions produced by the flights in the recordings.

6.3 Character of Existing Operations

The operational conditions and procedures are of great importance to the environmental impact of aircraft. For example, the pollutants emitted during landing and take-off phases of a flight depend, among other things, on the length of the taxi segment and how fast the aircraft climbs up to 3000 ft. From the flight data recordings, the actual flight profiles and resultant emissions were examined to try to determine whether they differ from those presumed when the current emission certification rules were applied.

6.3.1 Flight Parameter Profiles

In the figures below the parameters altitude, speed (Mach) and fuel flow, used in the emission calculations, are plotted for a typical flight with an short range aircraft:

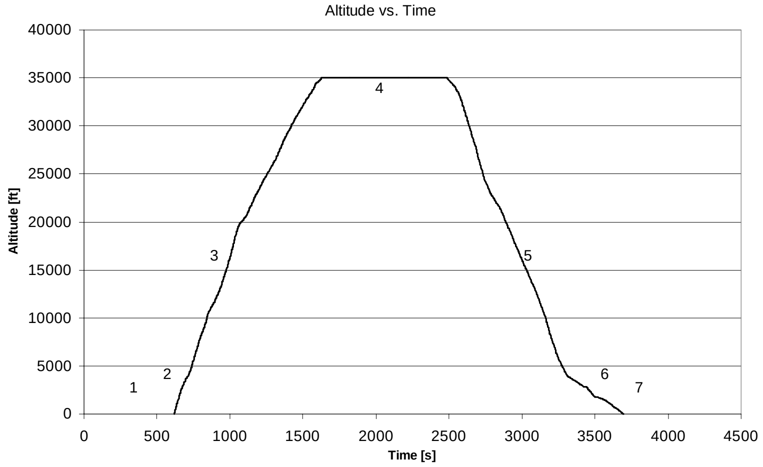


Figure 6-1: Altitude profile for a flight of aircraft E12.

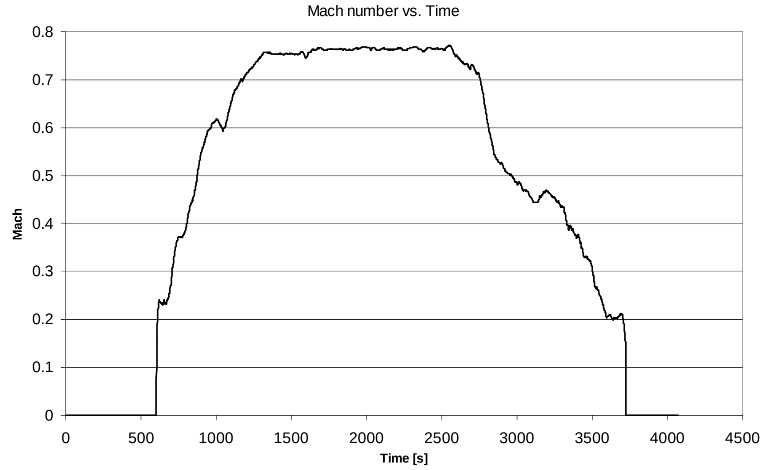


Figure 6-2: Mach number for a flight of aircraft E12.

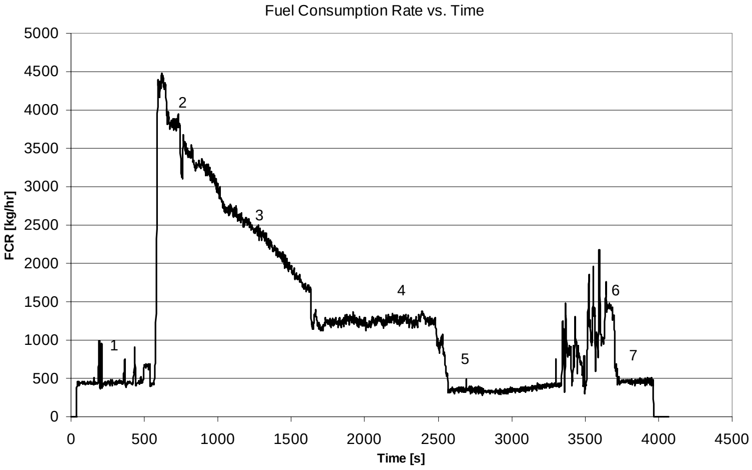


Figure 6-3: Fuel flow for a flight of aircraft E12.

The flight data recordings were divided into seven parts corresponding to different characteristic segments of a flight. In Figure 6.1 and Figure 6.3 these segments are indicated. Below is a list of the different segments and a brief description of what characterises them.

1. Taxi-Out - The engines are running at the power setting referred to as ”idle” in the ICAO reference LTO cycle. There are often a couple of peaks in the fuel consumption rate corresponding to the extra thrust applied to get the aircraft moving after a stop.
2. Take-Off and Climb to 3000 ft - The engines are typically throttled up to about 85% - 100% of ICAO’s take-off reference thrust setting. Often a cutback in thrust is performed from take-off to initial climb thrust, but if the take-off weight is small and the runway length is sufficient, a reduced thrust setting can be used initially for the take-off. The climb rate is normally about 1200 - 1800 ft/min depending on how heavily loaded the aircraft is. This segment lasts until the geometric altitude reaches 3000 ft.
3. Climb to Cruise - The Mach number increases from 0.2 - 0.4 to somewhere around 0.70 - 0.80. The last part of the climb is performed at constant Mach number. Altitude increases from 3000 ft to cruise altitude at a typical climb rate of 1500 - 2100 ft/min. The fuel flow is steadily decreasing throughout the climb. In many areas a speed restriction is applied below 10 000 feet. The maximum indicated speed is limited to 250 knots below this altitude.
4. Cruise – The fuel flow is decreased to 20% - 30% of the maximum value. Cruise altitude normally varies between 29 000 ft and 37 000 ft. On longer flights the flight levels are often changed during the cruise segment due to weather, traffic or to achieve better efficiency.
5. Descent to 3000 ft - This segment begins when the engines are throttled back to idle and altitude starts to drop at a rate of 1200 - 1800 ft/min. During this phase the Mach number decreases to 0.25 - 0.30.
6. Approach and Landing - When the aircraft gets below 3000 ft geometric altitude the descent rate is decreased to approximately 700 ft/min. This segment is also characterised by frequent throttle corrections with resulting fluctuations in fuel consumption rate, and by increased fuel consumption as the aircraft extends landing gears and high lift devices prior to landing.
7. Taxi-In - This segment was defined to commence when the aircraft was on the ground and the fuel flow and velocity decreased to values within the range of normal taxi conditions.

6.3.2 Flight Segment Times in LTO

In the Figure 6.4– 6.6 below eight short haul and eight long haul aircraft are presented. With each aircraft type, one or more routes are associated. The short haul aircraft, the columns on the left hand side in Figure 6.4 – 6.6, are flown at short haul routes within Europe and the long haul aircraft are flown at long haul routes, except for al13 which is a route in Europe. The quoted times are averaged recorded values for each route and aircraft type.

Figure 6.4 shows taxi time, out and in, for different aircraft route combinations. The total taxi time can be seen to be well below the 26.0 minutes (1560 seconds) specified by ICAO [6-9] for all flights except for eaI13. The taxi time can also be seen to vary extensively from airport to airport. It is therefore difficult to derive an average taxi time due to the large differences between airports.

The take-off and climb modes have been compiled into one phase as earlier described in Chapter 6.1. The time for the combined take-off and climb segment is well below 0.7 + 2.2 minutes (174 seconds). (Figure 6.5).

The reference emissions landing and take-off cycle prescribes an approach time of 4.0 minutes (240 seconds). Comparison of the averaged recorded approach times with the ICAO quoted one, shows that the ICAO reference time is on the low side, see Figure 6.6.

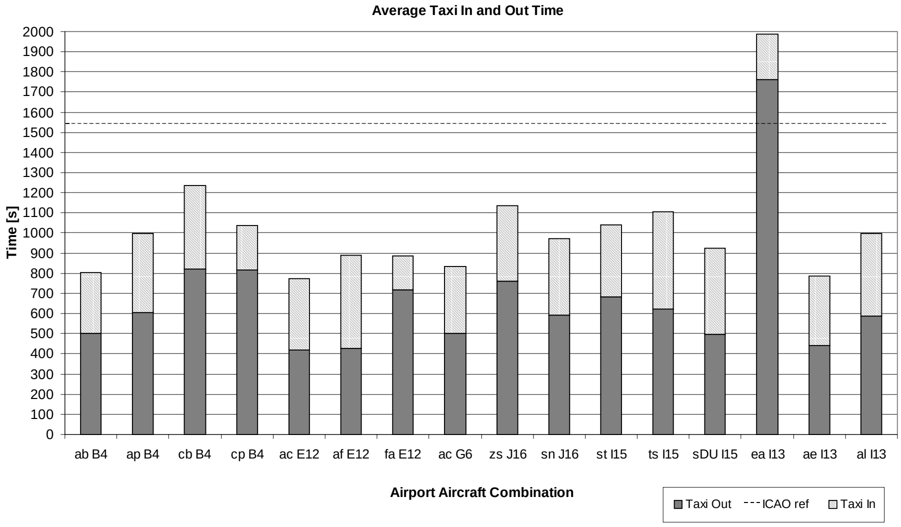


Figure 6.4: Average taxi out and in time and ICAO reference value.

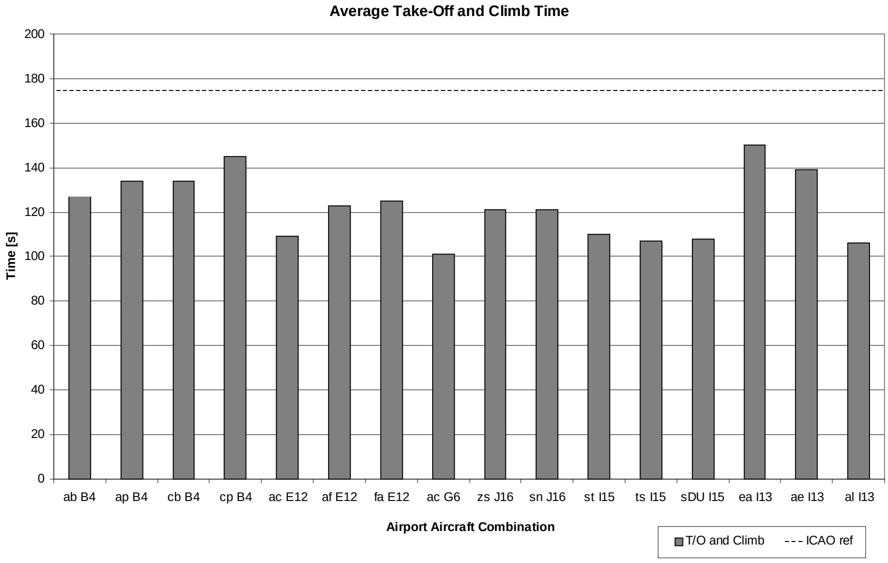


Figure 6.5: Average take-off and climb (to 3000 feet) time and ICAO reference value.

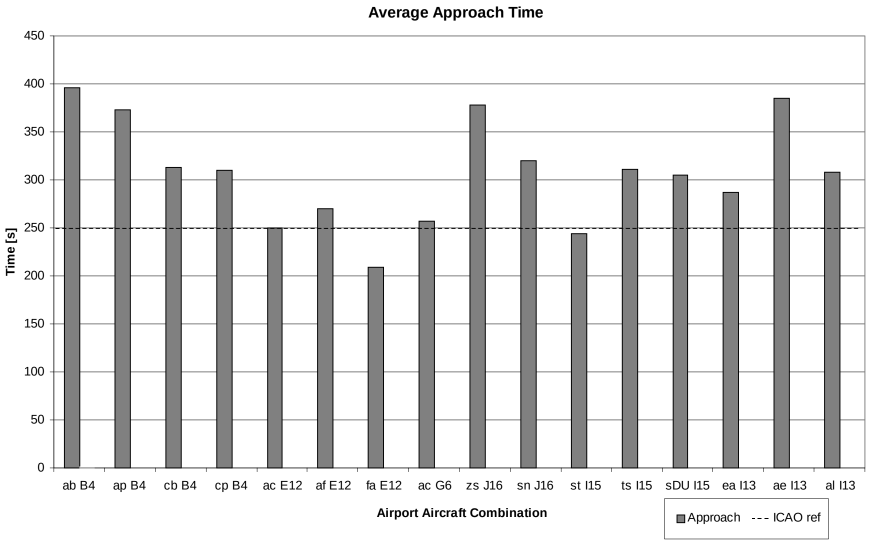


Figure 6.6: Average approach time (below 3000 feet) and ICAO reference value.

6.3.3 Thrust Setting and Flight Segment Times in LTO

In order to examine the LTO cycle more in detail, a study of thrust settings and times in mode in the different flight segments was made for a few flights. The thrust settings and times in mode were also compared to the ICAO reference LTO cycle.

The flight data recordings do not directly state the thrust setting for the engines. However, the thrust setting can be approximated with knowledge of fuel flow to the engines. In Figure 6.7 thrust setting versus fuel flow for an aircraft engine is presented. The data, four pair of values, are collected from the ICAO Engine Exhaust Emissions Data Bank [6-10]. A polynomial of third order is adjusted to fit the four measured values. With the thrust setting equation and fuel flow values from the flight data recordings, corresponding thrust settings can be calculated.

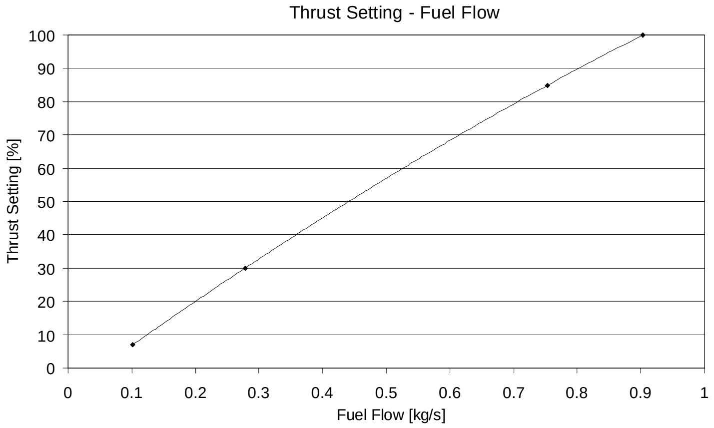


Figure 6.7: Thrust setting versus fuel flow for an aircraft engine

Regarding the thrust settings, the LTO phase can be divided or viewed in two different ways. The first method divides the aircraft procedures from a pilot's view. When pilots are calculating performance for an actual flight, the take-off length is the length from the location were take-off power is set up to the location were the aircraft reaches a height of 35 feet. The segments of the LTO phase in this method are defined as T/O_{01}, C/O_{12}, C/O_{23}, approach and taxi, see Table 6.1.

Table 6.1: Definition of flight segments

Segment	Acronym	Description
Take-off 1	T/O_{01}	From thrust is set at take-off to the aircraft has reached 35 feet
Take-off 2	T/O_{02}	ICAO definition: from take-off thrust is set until climb thrust is set
Climb segment 1	C/O_{12}	Climb from 35 feet to around 1500 feet (take-off thrust) setting)
Climb segment 2	C/O_{23}	Climb from around 1500 feet to 3000 feet (climb thrust) setting)
Descent	-	Descent from 3000 feet until landing
Taxi	-	Taxi in and out

The second method divides the flight procedure below 3000 feet according to the LTO cycle definition by ICAO [6-10]. The ICAO Environmental protection, Annex 16, volume II [6-9] defines take-off as *"The operating phase defined by the time during which the engine is operated at the rated output"*.

Starting at full thrust, the climb thrust is generally set at around 1500 feet, i.e. take-off ends at 1500 feet according to ICAO's LTO definition. The segments in the second method are T/O_{02}, C/O_{23}, approach and taxi which is identical to the ICAO definition, see Table 3.1.

In both methods the thrust setting is calculated for every recorded value of the fuel flow. As the fuel flow is not constant with time and segment, a characteristic thrust setting value needs to be determined. The thrust settings chosen to represent the take-off, climb and taxi segments were the median record values. For the approach phase, the average value was chosen. The next paragraphs elaborate on the observations and results.

6.3.4 Take-off and Climb

In Figure 6.8, times in mode and thrust settings for take-off and climb for aircraft-engine combination B4 is presented. The times in mode and thrust setting for aircraft B4, E12, I13 and G6 are shown in Table 3.2. The values for thrust setting and times in mode are average data for ten flights on the same routes with each aircraft type.

The average recorded time from application of take-off power to when the aircraft have reached 35 feet complies well with the ICAO certification values. (see Table 3.2). If one considers the ICAO certification view for take-off (42 seconds), the duration (37+39 seconds) is twice as long as the definition implies.

The thrust setting for aircraft G6 is interesting because climb thrust setting is higher than take-off thrust setting, see Table 3.2. The reason is that climb thrust is a fixed thrust setting in relation to temperature and pressure and the take-off thrust setting is adjustable with respect to temperature. With knowledge of runway condition, wind and take-off mass the pilot can chose to use derated thrust setting during take-off if it is applicable. This is done for aircraft G6 by adjusting the temperature in the flight computer, which gives the correct thrust setting for take-off. In cases like this, the climb thrust can be larger than the take-off thrust.

Starting at full thrust, the climb thrust setting is generally applied around 1500 feet which follows the rules and regulations set by ICAO regarding procedures for noise abatement. ICAO has specified aeroplane operating procedures for take-off in ICAO RAR Doc. 8168 [6-11]. Two different procedures are described where procedure A (climb power is set at 1500 feet) results in noise relief in the latter part of the take-off procedure. Procedure B results in noise relief close to the airport.

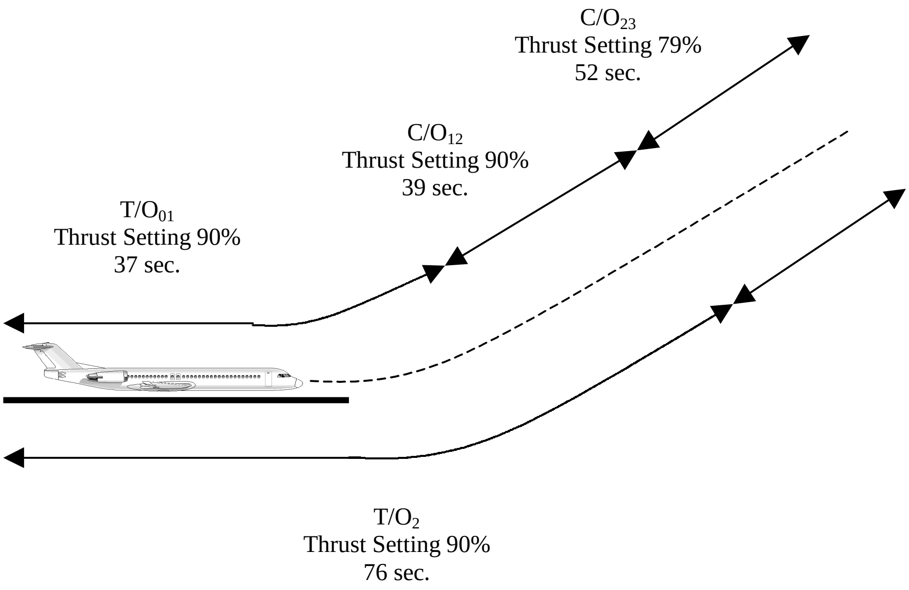


Figure 6.8: Take-off and climb procedures from the pilots view for aircraft B4.

6.3.5 Approach

During the approach segment ICAO's LTO cycle specifies a thrust setting of 30 percent during 240 seconds, see figure 6.9. This is seldom the case for actual flight procedures. The actual thrust setting fluctuates as the aircraft joins the glide slope and when the aircraft is changing its configuration before landing. In Table 6.2 the average thrust setting values for four aircraft types are presented. The average thrust setting, for the four studied aircraft, during approach are 21 – 24 percent of rated output. The approach segment time in mode depends on the air traffic situation and is often longer than the time stated by ICAO.

6.3.6 Taxi

The ground movement of aircraft and the time each aircraft needs to taxi to/from the gate depends on the airport layout and runway used, weather situation, traffic density etc. For example fog and slippery taxiways makes the taxi time longer. However, the taxi times are far-away from the 1560 seconds specified by ICAO . Values for the taxi times are all between 50 – 100 percent of the ICAO LTO certification value. To keep the taxi time to a minimum it is important to have a well organised airport that is capable of processing the traffic efficiently. Important factors are the layout of taxiways that improve the traffic flow to and from the terminals [6-6].

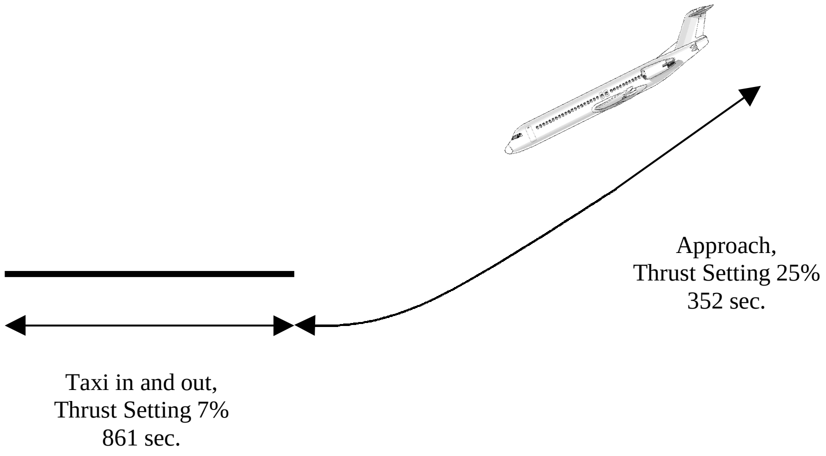


Figure 6.9: Approach and taxi from the pilots view for aircraft B4.

To compare the time the aircraft actually operate below 3000 ft, i.e. within the LTO cycle with the LTO time suggested, Table 6.2 and Table 6.3 have been produced for the above described flights. The time the aircraft actually spend within the LTO cycle is 50-90 percent of the ICAO certification time. The ratio is considerably influenced by the fact that the ground movements and taxi time is much shorter than the certification rules specified time of 1560 seconds.

Table 6.2: Segments time and thrust setting (T) in LTO for different aircraft.

Aircraft Type	T/O_{01}		C/O_{12}	C/O_{23}		Approach		Taxi	
	T	Time	Time	T	Time	T	Time	T	Time
B4	90	37	39	79	52	24	352	7	861
I13	97	45	28	86	62	21	325	6	1259
E12	99	44	29	88	38	24	270	6	815
G6	91	41	31	99	27	23	272	4	740

Table 6.3:Total LTO time – Ratio actual time to ICAO time.

Aircraft Type	Ratio Actual LTO time to ICAO LTO Time
B4	0.68
I13	0.87
E12	0.61
G6	0.56

6.4 Results From Emission Calculations

For all flights, around 600 flights, recorded on the FDR data the emissions of CO_2 , NO_x, CO and HC were calculated separately for each of the flight segments defined in Chapter 3.1. The Boeing-2 fuel flow method was used for NO_x, CO and HC calculations and the DLR fuel flow method was used as an alternative NO_x emissions calculation. The fuel flow methods are based on measured emission indices, from the ICAO Engine Exhaust Emissions Data Bank [6-10], which are corrected to take account for altitude and speed effects.

6.4.1 Influence of Operating Conditions on Emissions

For operating points at idle or part-throttle conditions the temperature in the combustor is relative low, which results in incomplete combustion of the fuel and increased production of CO and HC emissions. Another factor that decreases combustion efficiency is poor atomisation caused by small flow rates of fuel through the fuel injection nozzles. The flight modes with the highest emission indices of CO and HC are consequently the taxi and descent segments with their typically low throttle settings.

The production of NO_x is due to the reaction of nitrogen from the ambient air with oxygen in the high-temperature zones of the combustor. In general, emissions of NO_x are highest at operating modes with high thrust settings, e.g. take-off and initial climb. In these modes, the burner residence time at high temperature is longer which increases the NO_x emissions.

Below are some examples of how the calculated emission flow rates varies (for one of the engines) during a flight between a and c with aircraft E12 (same flight as is shown in Section 6.3).

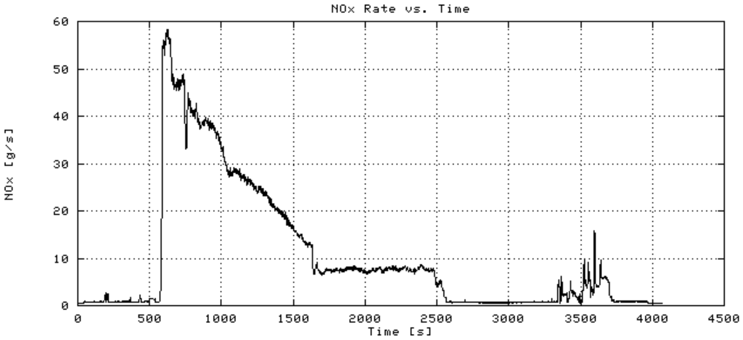


Figure 6-4: **NO_x rate for a flight of aircraft E12.**

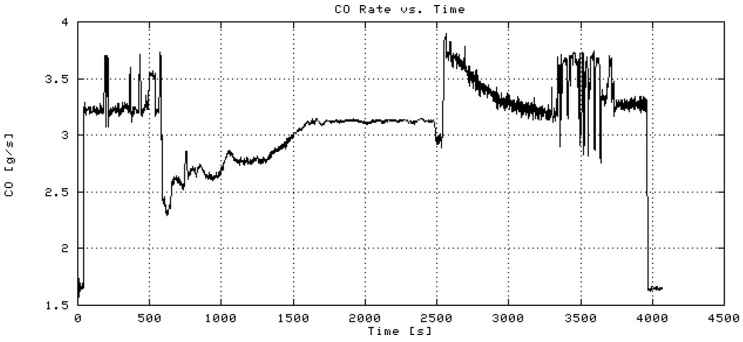


Figure 6-5: CO rate for a flight of aircraft E12.

The NO_x production rate curve looks similar to the fuel flow curve, (Figure 6.3), and consequently most of the NO_x is emitted during the take-off and climb segments.

As mentioned above the highest emissions of CO and HC are produced where the aircraft is operated at idle or low thrust settings.

There are no available emission measurement data for the engines operating at these low fuel flows. The lowest thrust setting for which emission data is available is the ICAO-specified 7% thrust setting. Therefore, for sub-7% thrust settings the emission index curves have been extrapolated to obtain the corresponding indices. At thrust settings below 7 percent CO and HC are changing significantly and to be able to calculate the emissions at low fuel flows more accurately, emission data for these low thrust conditions are needed.

Another condition that is believed to contribute with large emissions is the start-up of the engines. This procedure has not been accounted for in these calculations as data for this phase were not available.

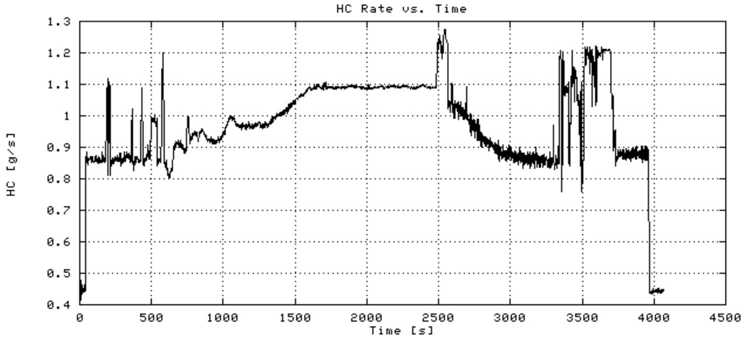


Figure 6-6: HC rate for a flight of aircraft E12.

6.4.2 LTO Cycle Emissions

The emissions that are subject to certification regulations are smoke and the gaseous emissions HC, CO and NO_x. Existing certification procedures only relate to these emissions during the reference LTO cycle. The regulatory levels of the above mentioned gaseous emissions emitted during the reference LTO cycle are defined by ICAO by the following formulas:

Hydrocarbons (HC): $D_p /F_{oo} = 19.6$

Carbon monoxide (CO): $D_p /F_{oo} = 118$

Oxides of nitrogen (NO_x):

a) $D_p /F_{oo} = 40 + 2\,\pi_{oo}$

b) $D_p /F_{oo} = 32 + 1.6\,\pi_{oo}$

Where:

a) applies for engines of which the date of manufacture of the first individual production model was on or before 31 December 1995 and for which the date of manufacture of the individual engine was on or before 31 December 1999.

b) applies for engines of which the date of manufacture of the first individual production model was after 31 December 1995 and for which the date of manufacture of the individual engine was after 31 December 1999.

D_p is the mass of any pollutant emitted during the reference emissions landing and take-off cycle. F_{00} is the rated output π_{oo} is the engine reference pressure ratio. The last two parameters, F_{00} and π_{oo} , which are specified for all certified aircraft engines can be found in the ICAO engine exhaust emissions data bank [6-10], where also the D_p /F_{oo} values from the certification measurements are listed.

In Table 6.2 the calculated ‘delta’ emission values per engine from the actual flights are presented (actual emissions in the LTO cycle divided by the emission values from the ICAO data bank). In this Table the times of the segments below 3000 ft have been used, i.e. these are the values corresponding to the total emissions in the LTO cycle. The acronyms in the first column correspond to the airports - aircraft combination and also declare which type of engine is used with the aircraft in question. The first letter stands for departure airport. The second letter is for arrival airport. The third letter is for aircraft type and the number is for engine type.

Table 6.2: ‘Delta’ values for emissions during LTO. Values calculated from actual flight data recordings (FDR) versus measured engine certification data (ICAO).

Airports - Aircraft - Engine Combination	HC_{actual}/HC_{ICAO}	CO_{actual}/CO_{ICAO}	$NO_{x\ actual} / NO_{x\ ICAO}$
a – c, G6	0.59	0.72	0.56
c – a, E12	0.59	0.61	0.59
c – a, F12	0.49	0.50	0.53
a – f, E12	0.65	0.67	0.72
a – e, I13	0.71	0.67	0.93
e – a, I13	**1.49**	**1.45**	0.90
c – b, B4	0.92	0.84	0.75
p – a, B4	0.78	0.74	0.70
n – s, J16	0.30	0.56	0.79
z – s, J16	0.18	0.46	0.97
j – s, M14	0.12	0.32	0.63
s – j, M14	0.16	0.40	**1.15**
s - j_1, M14	0.12	0.31	0.62
k – s, I5	0.15	0.40	0.78
s- t, I5	0.17	0.44	0.75

In general, the actual emission production rates are significantly below those derived from the LTO assumptions. One flight that exceeds the emitted amounts measured during the engine certification for the reference LTO cycle is the I13 flights between e and a (values in bold). This would be the consequence of the long taxi times at airport e since the emissions of exceedence are CO and HC which are emitted at a higher rate when the engine is at idle. Some of the flights with M14 have rather high NO_x values. From the corresponding FDR files it can be seen that the fuel flow to the engines at maximum take-off thrust are higher than the certification values suggest. Fuel flow values almost 20 percent higher than in the certification have been recorded with a resultant increase in combustion temperature and NO_x production.

6.4.3 En-route Operations

Emissions performance for en-route operations is not currently subject to regulatory requirements. The major environmental concern for the en-route segment is NO_x emissions. NO_x emissions are of concern for their potential impact on ozone and climate change [6-13]. Airlines attempt to fly aircraft at optimum altitude for fuel efficiency and by the shortest route distance with respect to aircraft weight and design to minimise operating costs. In dense, congested airspace, it is difficult to achieve an optimum flight profile and route. Other factors that influence the en-route altitude and route are meteorological conditions like (head) wind, turbulence etc. The atmospheric effect of NO_x emissions will vary according to altitude.

To assess the effects of different altitudes and routes on fuel burn and emissions, real flight data have been used to compare to simulated flights at different altitudes. One short haul (B4) aircraft was chosen for the analysis. The methodology was to extract data from a real recorded flight and to simulate the same flight in a performance and emission calculation program, PIANO [6-12]. Information from the real flights used was en-route altitude, Mach number, fuel burn, take-off mass, flight route and calculated emissions (NO_x from Boeing 2 Method). Inputs for the simulation process with the software PIANO were aircraft/engine combination, distance, en-route altitude, Mach number, take-off mass and payload. As the FDR file does not specify the actual payload onboard the aircraft, the payload had to be estimated in an iterative cycle in PIANO. The simulation was then performed in PIANO for the real flight and for flights at different altitudes (flight levels). For every simulation run, the payload was held constant for the purpose of studying transportation of the same load at varying flight levels resulting in different emission volumes and fuel consumptions. To show the effects of payload (variations) these simulations have been repeated at full payload.

In Figure 6.7 – 6.8 below, the resulting flight-totals of the fuel consumption and NO_x production are presented as a function of en-route altitude (flight level) for the short haul aircraft. The reference flight is the simulation of the chosen real flight mentioned above. The deltas (ratios), for NO_x and fuel consumption as a function of altitude, are all associated with the reference flight.

In these figures, the fuel consumption and NO_x production number quoted include the take-off, climb and en-route phases of the flight. Descend and approach flight segments are excluded: The NO_x production during these segments is small and the performance and emission program has difficulties modelling these segments (i.e. a lack of flap settings model). The cruise segment is shorter for aircraft flying at higher altitudes. However, the difference by excluding the descend phase for the total, changes the NO_x emissions only by one percent and the fuel consumption by three percent.

The short haul aircraft appears to be more efficient for high flight levels seeing that the fuel consumption decreases for flight levels as high as 41000 feet in the fuel consumption versus flight level graph in Figure 6.7.

As the en-route altitude decreases, the fuel consumption and NO_x emissions increase. Interesting is the rapid increase in NO_x as the altitude decreases (Figure 6.8). This increase in NO_x, when altitude is decreased, is caused by the increase in thrust that is needed to fly at the same Mach number at the different altitudes.

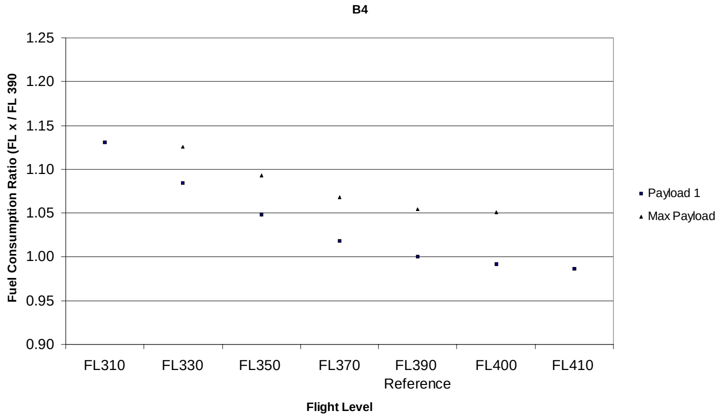


Figure 6-7: Fuel consumption as a function of flight level – short haul aircraft. (Note: Fuel numbers include take-off, climb and en-route).

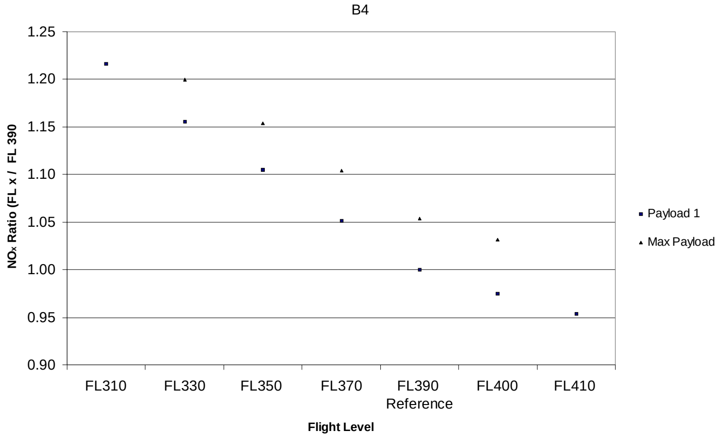


Figure 6-8: NO$_x$ emissions as a function of flight level – short haul aircraft. . (Note: Emissions numbers include take-off, climb and en-route).

6.5 Conclusions and Discussion

The existing engine certification procedure is based on four modes at different thrust settings and times in mode. These thrust settings and times are supposed to represent different operating modes in the landing and take-off cycle. The analysis of the flight recorder data showed that the ICAO reference times did not match the actual times very well. In general, the taxi segments were much shorter than the reference taxi time. However the length of the taxi mode varies significantly and is depending on several factors such as the taxi distance, the number of movements at the airport, the weather and the weight of the aircraft. The fuel flow values for the actual flights were generally lower than the ICAO's assumed value for taxi. This implicates that the engines often are operating at thrust settings for which there are no measured emission values.

Because of the difficulty in consistently separating the take-off and climb modes below 3000 ft, these segments were kept together. This joint segment was in almost all cases much shorter than the take-off and climb of the ICAO LTO cycle. For a couple of flights a more detailed study was performed where take-off was decoupled from climb. This study revealed that the take-off time is close to 0.7 minutes (if the take-off is defined to end at an altitude of 35 feet). The thrust setting during take-off on the other hand is varying because airlines often use derated take-off thrust settings. The time for approach and landing mode varies among the different flights.

A limited number of aircraft types and city pair combinations were available in the flight recorder data. From these FDR data it seems obvious that it is impossible to represent all types of flights in one general reference LTO cycle. The existing engine operating conditions for certification measurements could probably be modified to better correspond to the actual flight conditions, e.g. by lowering the thrust setting for taxi and by adjusting the segment times for take-off, climb and taxi.

7 WP3- noise: Potential Impact descriptors

7.1 Introduction and overview

ICAO noise certification is, by its basic definition, a tool to force the application of the latest knowledge in noise reduction technology to aircraft design. It is realised by precise noise measurements under highly-controlled reference conditions. This offers different, useful fields of application of the certification results.

AEROCERT's workpackage 3 deals with potential improvements to the noise certification procedure, including the discussion of suitable noise descriptors as well as the discussion of the technical aspects of certification. Especially the following problems and questions related to the process of aircraft noise certification are investigated:

- The impact of aircraft noise is strongly related to many different physiological and psychological parameters, whereas the noise certification provides only a limited set of physical data. Do they reflect the effects of aircraft noise on man in an appropriate way and if not, are there additional or more suitable impact descriptors?
- The certification procedure has to be defined well. It must be based upon standardised conditions as well as upon standardised operational procedures. However these conditions usually differ from those occurring during day-to-day operations. What are the effects of the differences and are there better descriptors, approaches or possible solutions for the problems?
- Noise certification data are used for several purposes apart from verifying compliance with noise certification standards, such as noise ranking or definition of aircraft noise databases. Sometimes they are also misused also, in that the objectives of certification as well as the very specific measurement conditions are not taken into account. What are the limitations for the use of data acquired during certification? What modifications of the certification process are appropriate or necessary to provide data which are suitable for applications besides the original objective of certification?

7.2 Aircraft noise descriptors – analysis and field of application

7.2.1 Single event noise descriptors

Any single noise event (e.g. an aircraft flyover) can be described by its level-time-history $L(\tau)$. The level L usually includes a frequency weighting and sometimes corrections for tonal or impulsive noise components. Two typical parameters are used for the description of such a single noise event: the maximum sound level L_{max} and a typical noise duration t (e.g. the "10dB-down-time" t_{10}) or a time-integrated noise level L_e which combines maximum level and duration:

$$L_e = L_{max} + k \cdot lg\left(\frac{t}{t_1}\right) \qquad \text{(eqn. 7-1)}$$

The specific form of a single-event noise level depends on the trade-off-factor k, the noise duration t, the reference time t_1, as well as on the frequency weighting used for the description of the sound level. For aircraft noise, two types of frequency weighting are commonly used. The first one is the A-weighted sound level L_A [Ref. 7-2], the second is the Perceived Noise Level PNL [Ref. 7-3]. It is broad practice to use additive adjustments for tonal or impulsive noises. Such a “tone correction” is usually applied to the Perceived Noise Level *PNL*, thus resulting in the tone-corrected Perceived Noise Level *PNLT*. The additive tone correction is calculated by a relatively complicated procedure [Ref. 7-3] from 1/3-octave band spectra.

The most commonly used single event noise levels based on A-weighting and *PNLT* are the “Single Event Exposure Level”

$$L_{AX} = L_{A,max} + 10 \cdot lg\left(\frac{t_e}{1[s]}\right) = L_{A,max} + 10 \cdot lg\left(\frac{t_{10}}{2[s]}\right) \qquad \text{(eqn. 7-2)}$$

(sometimes denoted “Sound Exposure Level” *SEL*) and the “Effective Perceived Noise Level”

$$EPNL = PNLT + 10 \cdot lg\left(\frac{t_e}{10[s]}\right) = PNLT + 10 \cdot lg\left(\frac{t_{10}}{20[s]}\right). \qquad \text{(eqn. 7-3)}$$

The Effective Perceived Noise Level *EPNL* is the basic noise metric used for aircraft noise certification according to Annex 16 to the Convention on International Civil Aviation [Ref. 7-1], published by the International Civil Aviation Organization ICAO.

7.2.2 Cumulative noise descriptors

Based on the descriptors maximum sound level and single-event noise level, a lot of so-called cumulative “aircraft noise descriptors” can be estimated. They are used for the description of aircraft noise over longer time periods and/or for special purposes such as the effect of aircraft noise on sleep. Aircraft noise descriptors are a very helpful tool for land-use planning and aircraft noise regulation. They can include weighting factors for different periods of the day (e.g. night penalties) or seasonal weightings. Usually they are based on the single event noise levels mentioned above, but there are definitions which are based only on maximum sound levels and number of operations.

Aircraft noise descriptors should be defined in a way that they provide a good correlation between annoyance and the physical measurable quantities upon which they are based. They can be classified roughly into three categories:

- Equivalent sound levels L_{EQ},
- descriptors based on maximum sound levels and
- “number-above-threshold” criteria.

7.2.2.1 Equivalent sound levels

Most of the world-wide used aircraft noise descriptors are based on time-integrated (i.e. single-event noise) levels and have the form of an equivalent sound level L_{EQ} as defined by:

$$L_{EQ} = k \cdot lg\left(\frac{1}{T}\sum_{i=1}^{N} g_i \cdot 10^{L_{e,i}/k}\right) + C \qquad \text{(eqn. 7-4)}$$

In eqn. 7-4, $L_{e,i}$ is single event noise level of the *i*-th noise event. The weighting factor g_i accounts for the increased sensitivity to noise during different periods of the day. The trade-off-factor *k* usually has a magnitude of 10. The summation in (eqn. 7-4) is performed over all *N* noise events occurring during the reference time period *T* for which the L_{EQ} is calculated. *C* is a normalising constant and equals zero in most cases.

The various equivalent sound levels defined by (eqn. 7-4) are highly correlated with the mean annoyance (mean percentage of highly annoyed people). This means that any form of equivalent sound levels is suitable to describe aircraft noise by a single numeric value. Therefore the choice of a certain descriptor can be made only partly from scientific arguments, other criteria should be used also (e.g. aspects of the international harmonisation of noise descriptors).

Equivalent sound levels based on A-weighting are established as a standard for aircraft noise description as well as for other noise sources (such as road and railway traffic or industrial noise). The most recent recommendation on the use of A-weighted L_{EQ} was published in January 1999 as a position paper by the Working Group on Noise Indicators, established in 1998 by the Commission of the European Communities [Ref. 7-4].

7.2.2.2 Descriptors based on maximum sound levels

Different descriptors based on maximum sound levels only (and not on time-integrated levels) are in use in some countries. Examples are the averaged A-weighted maximum sound level used in Germany, the Kosten-Index used in the Netherlands or the Noise and Number Index *NNI* currently used in Ireland. However, descriptors based on maximum levels are mostly only of national importance.

7.2.2.3 “Number-Above-Threshold”-Criteria

This third category of aircraft noise descriptors, often abbreviated to “NAT”-criteria, is defined by the number of excesses of a certain threshold level within a defined time period. NAT-criteria are, by their definition, not single-value noise descriptors, rather a combination of a level value and an average number of aircraft movements. They are useful especially for the description of wake up reactions. Although the physiological background of such criteria is proved [Ref. 7-5] they are not adopted widely. The Netherlands use an A-weighted L_{EQ} for the description of night noise disturbances [Ref. 7-6]. The position paper on EU noise indicators recommends the same descriptor [Ref. 7-4]. However, it seems to be ambiguous whether or not a time-integrated metric, the magnitude of which can be significantly determined by a high number of noise events with low maximum levels, is suitable for the assessment of wake up reactions.

7.3 Calculation of aircraft noise

7.3.1 Classification of aircraft noise calculation models

Measuring and monitoring are suitable ways to determine aircraft noise levels around airports. But noise legislation and land-use planning are usually based on the noise to be expected for future scenarios. For these purposes, measurements are not very helpful. The future noise load can only be calculated and predicted. Such calculations are performed by models that combine information on air traffic, with data on aircraft-specific noise production and performance as well as with calculation algorithms based on the laws of acoustics.

Aircraft noise calculation models can roughly be divided into two categories. The structure of these categories determines the structure of the database needed for a noise calculation:

- *”Conventional” models:* These are based on a segmentation of the flight path (usually into straight segments and circular arcs). Noise at the ground is calculated for the distance of closest approach including corrections for flight path geometry. Such models (for different aircraft types or categories) require only information about the relationship between noise level and sound propagation distance for different engine power settings (“NPD-curves”).

- *Simulation models:* These models describe the flight path by a series of points in space which are passed by the aircraft at constant intervals (usually in time). At each point, the location, spatial orientation and flight performance are known completely. Additionally, information on sound spectrum and directional characteristic is available. Such models offer the capability of computing a noise-time-history at a point on the ground. They offer the greatest flexibility, but they can only be used if high-quality noise and operational databases are available.

Most of the prediction models currently in use (such as FAA’s INM [Ref. 7-8]) are of conventional structure and comparable with respect to the basic calculation algorithms.

7.3.2 Operational databases

An operational data set for an aircraft noise calculation procedure consists of a flight-altitude profile with corresponding information on aircraft speed and power setting. Many calculation procedures use such datasets for pre-defined flight procedures and weights of operation. Another approach is the use of a database consisting of a set of aerodynamic and flight performance coefficients. The use of such data provides the possibility to calculate the flight path and the corresponding performance data for any prescribed operational procedure. So, the situation is that flight operational data are available in good quality, but the problem is that numerical aircraft noise prediction is related mainly to the poor availability of noise data.

7.3.3 Noise databases

The structure of a noise database depends strongly on the structure of the calculation model. Any noise database should at least include NPD-Data, preferably for maximum levels (L_A and/or *PNL/PNLT*) as well as for single-event noise levels (*SEL* and/or *EPNL*). Such simple NPD-based databases can only be used by conventional models. No restrictions must be made on the form of the calculation model if full spectral and directivity information is available for a sufficient range of engine powers (an ideal noise database). If the requirements for a simulation model are fulfilled, all the data needed by conventional models can be derived also from such a database.

Currently a lot of different NPD-based databases exist world-wide within national and international noise prediction models, although there are significant differences between particular databases. Unfortunately the availability of information on spectra and directivity is rather poor since controlled measurements are related to high costs. Nevertheless the aircraft manufacturers (mainly Boeing and Airbus Industries) have these data at their disposal, resulting from noise certification tests as well as additional measurements.

7.4 Aircraft noise certification and noise impact

7.4.1 Purpose and objectives of noise certification

In the early 1970s, the International Civil Aviation Organization ICAO established recommended procedures and standards for the noise certification of subsonic jets. These standards were incorporated as Chapter 2 into Annex 16 on the Convention on Civil Aviation. Since then several new editions of this annex have been issued. The most important change was the definition of a more stringent standard (“Chapter 3”) which accounted for the development of high-bypass technologies. The current version of Annex 16 was issued in 1993 [Ref. 7-1].

The prime purpose of noise certification is to ensure that the latest available noise reduction technology is incorporated into aircraft design.

During the certification process noise data of high quality for an accurate definition of an aeroplane's noise characteristic are measured under reference conditions. These data, i.e. the certification noise levels, are compared to defined noise limits. In practice, certification data are also used as a basis for the definition of databases for aircraft noise calculation procedures and as a basis for noise ranking.

7.4.2 The test procedures of ICAO Annex 16, Chapter 3

The Annex 16 noise certification procedure is described in a very comprehensive form within Chapter 4 and AEROCERT's workpackage 1 report [Ref. 7-7], including all aspects such as technical procedures, data processing or costs. In the following, only a short description will be given on the certification test procedure. Since AEROCERT deals with civil jet aircraft, the description will be restricted to subsonic jet aeroplanes falling under Chapter 3 of Annex 16.

Chapter 3 noise measurements are performed at three reference monitoring points:

The flyover (take-off) measurement:

The flyover measurement point is located on the extended centre line of the runway at 6500 m from the start of roll. The reference flight procedure is defined as:

- Initial climb with average take-off power, take-off flap and a speed of between V_2+10 kt and V_2+20 kt.
- Thrust reduction, at height to be selected by the applicant (not below 689 ft for aircraft with 4 engines, 853 ft with 3 engines and 984 ft with 2 engines), to not less than that required to maintain a climb gradient of 4% or for a level flight with one engine inoperative.

The lateral (sideline) full power measurement:

The reference point for this measurement is located on a line parallel to and 450 m from the runway centre line where the *EPNL* is a maximum during take-off. The reference flight procedure is the same as for take-off.

The approach measurement:

This monitoring point for the approach measurement is located on the extended centre line of the runway at 2 km distance from the landing threshold. The following reference flight procedure is prescribed for this measurement:

- The aeroplane should be stabilised and following a 3° glide path.
- The approach should be performed at a stabilised airspeed of not less than the minimum value of V_{REF}+10 kt with thrust or power stabilised during approach and over the measuring point and continued to a normal touchdown.

7.4.3 Current certification-related activities of ICAO

Certification standards as well as certification procedures should not be static. It is the aim of the Working Group 1 (Noise) of ICAO's committee on Aviation Environmental Protection (CAEP) to keep them up to date and to ensure that the certification procedures are as simple and inexpensive as practical.

During the CAEP/4 meeting in 1998 a comprehensive work programme was defined for WG1. In relation to AEROCERT, the most important task of this work programme is JET-10 that covers the following items:

- Determination of the future purpose of noise certification.
- Review of the present demonstration procedures for noise certification according to Chapter 3 of Annex 16 with respect to a better adaptation to modern aircraft and modern operational procedures.
- Examine the feasibility of extending noise certification to include the provision of NPD-data for use in assessing operational noise.

The work of JET-10 is still going on, dealing partly with the same questions as AEROCERT. However within AEROCERT, certification-related problems can be discussed in a more fundamental way. Although part of the recommendations may be not carried out in practice, it is to be hoped that the work of AEROCERT gives additional impulses to the activities of CAEP.

7.4.4 Certification results and the assessment of noise around airports

The definition of the purpose of noise certification is related closely to physical aspects of noise reduction at the source. Certification shall guarantee that all available technical measures are applied to ensure that the sound energy emitted from an aircraft in operation is minimised as much as possible. On the other hand, the effects of noise on men are primarily psychological and physiological. The term "annoyance due to noise" is more appropriate than "noise impact". Nevertheless physical parameters, such as maximum levels ($L_{A,max}$, *PNL)* or time-integrated sound energy *(SEL, EPNL)*, are closely related to noise effects: Averaged time-integrated levels show a good correlation with annoyance over longer time periods (e.g. six months or one year) whereas maximum levels are useful for the assessment of noise during night-time (wake up reactions).

Generally the results of the certification process are only of limited applicability with respect to the assessment of aircraft noise impact and with respect to annoyance due to aircraft noise around airports:

- The total physical noise load around airfields usually is determined by a complex traffic situation, including airport- and airline-specific influences such as differing operational procedures.
- Certification data are measured close to the start of roll or landing thresholds, whereas noise problems in the vicinity of airport are more and reported more to occur in areas located up to 20 km from the runway system.
- The criterion for successful certification of an aircraft is based only on a time-integrated metric, the Effective Perceived Noise Level *EPNL*. Maximum levels, although they are

measured and partly published in outside of the ICAO domain [Ref. 7-9], are not included in the certification process. This is not sufficient for adequate noise assessment purposes.

Nevertheless, noise certification is a powerful measure to guarantee that optimal noise reduction measures are applied before an aircraft goes into service, thus influencing positively the noise situation around airports. However the certification process can provide more extensive information that may, in a direct or indirect way, be very useful to optimise the reduction of noise around airports.

7.4.5 Trade-off regulation and noise impact

The Annex 16 certification procedure allows that the maximum noise levels can be exceeded at one or two of the measurement points as long as (1) the sum of the excesses is not greater than 3 EPNdB, (2) any excess at any single point is not greater than 2 EPNdB and (3) any excess is offset by corresponding reductions at the other point(s).

This makes sense as long as only comparable operational procedures are taken into account, i.e. when the measured noise levels for the two take-off conditions (lateral and flyover) are compared. The inclusion of the approach measurement into this trade-off regulation is not suitable with respect to noise impact aspects: Calculations of noise contours (L_{eq}, *LDN)* for 3 major airports showed, that departures contribute to 70–80% to the total contour areas whereas approaches contribute only to 20–30% [Ref. 7-11].

These results indicate clearly that, with respect to noise impact, it makes no sense to weight the departure and approach measurements from certification equally as it is done by the trade-off regulation. A well-known example for this is the current discussion on the future operation of hush-kitted aircraft. These fulfil the requirements of Chapter 3 only due to the trade-off-regulation and the relatively low noise levels measured under approach conditions.

Nevertheless a trade-off regulation for the noise levels measured at the flyover and at the lateral monitoring location is very useful; these measurements represent two different operational conditions which both contribute to the total noise load produced from aircraft departures.

7.5 Operational procedures

7.5.1 The influence of operational procedures on noise metrics

Aircraft noise descriptors are based either on maximum sound levels or on time-integrated levels. Due to the effect of aircraft velocity, these two metrics show different behaviour as a function of sound propagation distance. The maximum sound level decreases with increasing distance whereas the noise duration increases with increasing distance and decreasing aircraft speed. So time-integrated metrics as *SEL* or *EPNL* show a decrease with increasing distance as well, but with a smaller decay than maximum sound levels.

This behaviour has to be taken into account when noise abatement flight procedures have to be defined. To demonstrate this, noise calculations were carried out for a two-engined aircraft with a TOW of roughly 63 t for two different take-off-procedures:

ATA-procedure: After lift-off climb with maximum T/O-thrust and V_2+10 knots to 1000 ft altitude. Then reduce power to maximum climb thrust and accelerate to 250 knots while retracting flaps. Afterwards climb out to cruise altitude without acceleration.

IATA-procedure: After lift-off climb with maximum T/O-thrust and V2+10 to 1500 ft altitude. Then reduce power to maximum climb thrust and climbing without acceleration to an altitude of 3000 ft. Then accelerate to 250 knots indicated airspeed and finally climb out to cruise altitude without acceleration.

Noise contour calculations were carried out for both scenarios. Footprints of the Sound Exposure Level *SEL* as well as contours of the A-weighted maximum sound level $L_{A,max}$ were estimated. The results are shown in Figures 7a and 7b.

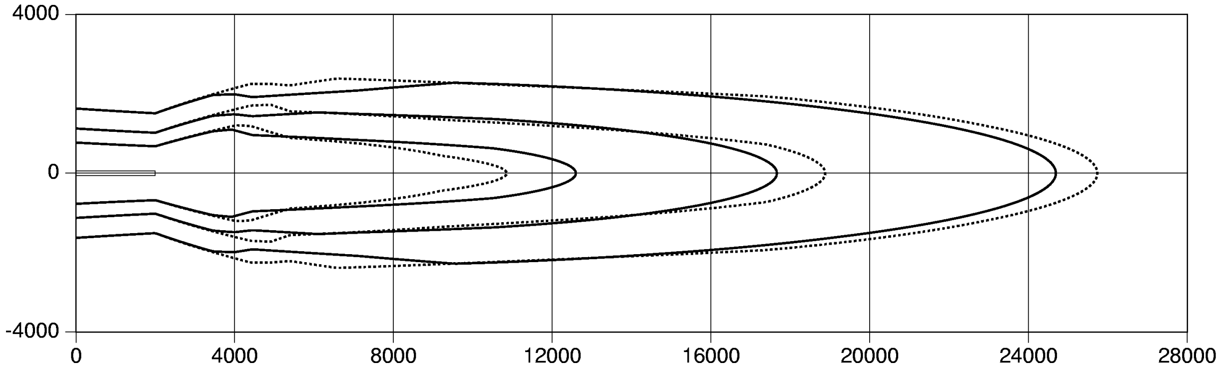


Figure 7.1a: Contours SEL = 80, 85 and 90 dB for take-off using ATA-procedure (solid) and IATA-procedure (dotted). Co-ordinates are in metre.

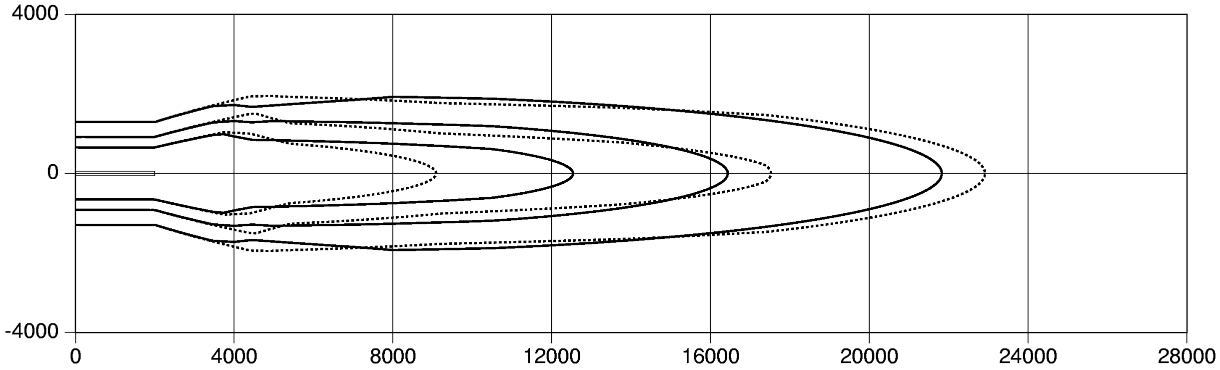


Figure 7.1b: Contours $L_{A,max}$ = 70, 75 and 80 dB for take-off of using ATA-procedure (solid) and IATA-procedure (dotted). Co-ordinates are in metre.

For more quantitative information, the areas enclosed by the estimated contours were calculated. They are shown in Table 7.1. In addition to the areas of the individual contours, the table shows the percentage in- or decrease of the areas estimated for the IATA-procedure with respect to those calculated for the ATA-procedure.

Table 7.1: Areas enclosed by noise footprints calculated for take-off using IATA- and ATA-procedure. Δ IATA is the deviation from IATA to ATA contour area.

Procedure	Areas enclosed by contour [km^2]:					
	SEL = 80 dB	SEL = 85 dB	SEL = 90 dB	$L_{A,max}$ = 70 dB	$L_{A,max}$ = 75dB	$L_{A,max}$ = 80dB
IATA	98.15	46.62	17.03	71.85	34.73	13.23
ATA	91.71	44.44	20.09	68.86	36.16	18.36
Δ IATA	+7.0%	+4.9%	–15.2%	+4.3%	–4.0%	–27.9%

7.5.2 Certification flight procedures and operations in day-to-day practice

The certification process provides noise data measured for single aircraft with specific airframe-engine-combinations, for a defined take-off- or landing-mass and for certification-specific operational procedures.

As demonstrated by the results in the preceding section, the noise resulting from an aircraft operation is determined not only not by aircraft mass, but also by the operational procedure used. It is well known that the flight procedures and aircraft masses in day-to-day practice differ usually from the conditions in which certification tests were carried out. A comprehensive investigation to that effect was carried out within AEROCERT work package 2 [Ref. 7-10].

One important result of this work was, that for normal operations of short-haul, twin-engined aircraft, the levels at the flyover point deviated by –1 dB to +5 dB and at the sideline monitoring location by –2 to –7 dB from the levels estimated for the certification procedures. Corresponding calculations of 85 dB EPNL-contours yielded area differences in the range ±30 percent. The results indicate again that, especially for 2-engined aircraft equipped with modern high bypass-ratio engines, derated thrust take-offs are standard operational practice.

7.5.3 Noise ranking based on certification data

The difference between day-to-day operational procedures and certification procedures becomes important when noise certification data are used for noise ranking purposes, e.g. as a basis for setting noise-related fees. From a fundamental point of view, a noise ranking should be based on the principle “the polluter pays”. In other words, the noise fee should be based on the real impact produced by the airline operator. This can be an argument against noise ranking based on certification data, if the flight procedures used during real operations differ from certification procedures (e.g. use of derated take-off-thrust) and/or if typical operational weights differ from certification weights (from relatively low weights for line services up to maximum weight for charter services).

Experience has shown that a ranking based on certification data is generally comparable to a ranking based on measured noise data [Ref. 7-12]. However, in individual cases differences can be observed. If such airport-specific differences between certification data and noise data under real operations are occurring, a ranking based on data from real operations should be preferred.

7.6 Derivation of noise databases from certification procedures

7.6.1 General requirements on noise data

Aircraft noise certification is a measurement process under highly controlled conditions, operational, geometrical and weather data being well known throughout the procedure. Thus certification data are the most suitable source of noise data used in noise calculation and prediction procedures. Currently, there is an urgent need for world-wide for high-quality acoustic databases, whereas flight operational data are available in any degree of accuracy. (see [Ref. 7-11] for more detail).

The amount of data needed for aircraft noise prediction purposes depends strongly on the type of the prediction model. As described within section 7.4.1, aircraft noise prediction models can roughly be divided into two categories, conventional models and simulation models. Both types of model need different amounts of acoustic data.

7.6.2 Data requirements for conventional models

The minimum requirements are NPD-curves that cover a suitable range of propagation distances and engine powers. These curves should be defined for time-integrated metrics as well as for maximum levels to provide the capability to calculate the most important noise descriptors. Additional data, which are useful for conventional models, are:

- Octave or 1/3-octave spectra for the engine power settings for which the NPD-curves are estimated. This makes it possible to derive maximum sound levels data for non-reference atmospheric conditions.
- Approximate equations for the noise duration as a function of aircraft velocity and propagation distance allow, together with spectral information, to estimate time-integrated levels as well as maximum sound levels for any propagation condition.
- Directional characteristics can be used to model the noise behind the take-off-roll and to derive corrections for flight-path segments of finite length.

7.6.3 Data requirements for simulation models

Simulation models require at least NPD-curves for maximum sound levels and corresponding additive directivity corrections to estimate a level-time-history at any immission point on the ground. The quality of simulation results can be increased when additional information is available.

- As for conventional models, octave or 1/3-octave spectra for reference conditions make it possible to derive noise data for non-reference atmospheric conditions.
- Directivity information for different flight speeds can be used together with information from static tests to derive semi-empirical velocity corrections for the directional characteristics.

An ideal noise data set would consist of complete spectral directional characteristics. However, these cannot be estimated from certification measurements. Their derivation requires an extended test set-up.

7.6.4 Choice of noise monitoring locations

If noise databases have to be derived from certification measurements, some basic requirements have to be fulfilled:

- The measurements should cover a sufficient range of engine powers to provide the possibility of generating a complete set of noise-power-distance data.
- Monitoring locations should be chosen in a way that ensures that overground excess attenuation does not affect the measurements.
- The distance between monitoring site and aircraft should be large enough to guarantee that the aircraft can be assumed to be a point source. The minimum propagation distance should be about 300 metres. However the distance between microphone and flight path should be small enough to minimise influences of atmospheric turbulence, temperature and wind on sound propagation.

These requirements suggest a very careful definition of the monitoring locations. A proposal for a suitable configuration could be that two monitoring points are be used for the approach as well as for the take-off procedure.

- The first approach measurement point should be located about 4-5 km from the landing threshold.

Comment: This definition forces the definition of noise limits other than those currently used.

- The second approach measurement point should be located about 10-12 km from the threshold.

Comment: The introduction of this monitoring location raises the problem of an exact definition of the aircraft configuration (speed and flap setting) and could lead to the risk that transient noise levels are measured. This could be avoided if the certification level is averaged from two separate measurements (e.g. at 10 and 12 km from threshold). However this would result in a need for extended technical equipment and hence greater cost.

- The first take-off measurement (take-off-power) should be performed similar to the current sideline measurement but closer to the flight path than 450 m, to avoid any effects of lateral attenuation.

Comment: This requirement would also result in a revised definition of the certification noise limits.

The second monitoring point (climb-power) should be located at a distance from the start of roll where it is guaranteed that the levels within the 10dB-down time of the measured level-time-history originate completely from the installed climb-power.

Comment: The location of this monitoring point depends strongly on the flight procedure used, i.e. on the power setting as well as on the cutback height. The current certification procedure using deep cutback seems to be unrealistic, maximum climb power being a better alternative.

One should be aware of the fact that these recommendations represent a more or less ideal set-up for a certification measurement. However, from a fundamental point of view it is at least a minimum requirement, if the total noise load produced by the aircraft under the test conditions has to be described in an adequate way. From the standpoint of the ICAO authorities, some of these recommendations should not be transferred into practice for several reasons.

Nevertheless, they can be used as an additional input to the current certification-related CAEP activities.

7.7 Use of noise footprints – an alternative approach

The single-event noise descriptors measured during certification tests are the basic quantities for any cumulative noise descriptor. Certification results are reduced to a set of 3 single *EPNL*-values which cannot provide a suitable description of the total noise load produced by any possible operation of the tested aircraft.

An alternative approach is the estimation of noise footprints (i.e. contours of constant time integrated or maximum level). Such a footprint can be described (1) by the area it encloses, (2) by its extension along or perpendicular to the flight track or (3) by a quotient of the area and one of these two dimensions. The last item seems to be the most useful one, since not only area or extension, but also the shape of the footprint is of importance.

The estimation of a noise footprint from certification measurements can be performed by the following steps:

1. Derive spectral information and directional characteristics from the certification measurements.
2. Derive NPD-curves for time-integrated levels as well as for maximum sound levels.
3. Define the appropriate flight operation data (e.g. from the manufacturers operational manual).
4. Calculate the footprint using a standardised calculation procedure.

Footprints for a time-integrated metric as well as for a maximum sound level should be estimated because time-integrated metrics provide the best basis for the estimation of long-term, averaged noise load and maximum levels are useful for the description of the noise impact related to operations during the night (i.e. wake up reactions).

Since A-weighted metrics are becoming more and more the standard for aircraft noise prediction purposes, a calculation of *SEL* as well as of $L_{A,max}$ is recommended. Additionally, information on *EPNL* and *PNLT* can be derived.

7.8 Conclusions / Recommendations

The following conclusions and recommendations are made from a fundamental and scientific point of view. No attempt has been made to account for any practical and technical aspects of transfer to the real certification process, this should be done better by CAEP's certification experts. The current report has the intention mainly to give impulses for future certification-related activities of ICAO.

1: Results of certification process should be expressed at least in terms of one time-integrated metric and one maximum level metric. In addition to Perceived Noisiness, the A-weighted metrics should be reported.

Reason: Each aircraft noise descriptor can be derived from the maximum sound level and the noise duration (or the time-integrated level). Both should be estimated during certification tests. A-weighting is necessary since it becomes more and more the standard frequency weighting for aircraft noise (e.g. for a harmonised European noise descriptor [Ref. 7-4]).

2: Data from certification tests can generally be used for noise ranking purposes. However there can be individual situations where a ranking should be based better on noise measurements under day-to-day operational conditions [Ref. 7-12].

Reason: The noise data measured during certification cannot be representative for the noise produced by an aircraft operated under day-to-day conditions in any case – reasons may be the use of derated take-off thrust, or strongly differing aircraft weights (results from AEROCERT Work Package 2 [Ref. 7-10]).

3: An additional noise measurement point located further from the landing threshold should be added for the approach tests.

Reason: The current approach measurement performed very close to the runway whereas around civil airports problems related to approach noise are observed up to distances of 10 to 20 km from the landing threshold.

4: The location of the noise measurement points should be revised to guarantee that at least the most representative operational conditions during take-off (take-off power, typical climb power) and approach (final approach power with full flaps and gear down, landing power with gear up) are monitored.

Reason: A representative description of the noise produced from take-offs and approaches respectively cannot be based on only one measured noise value. The total noise produced by an aircraft operation is determined by all operational conditions. Additionally, an extended measurement setup could guarantee that certification data can be used to derive high-quality noise databases for prediction purposes.

5: The take-off flight procedure should be revised, especially with respect to cutback power setting.

Reason: The deep cutback currently prescribed for certification is not characteristic for real operations. A maximum climb power setting seems to be more appropriate. (see also AEROCERT Work Package 2 report [Ref.7-10])

6: The trade-off-regulations should be applied to take-off and approach measurements separately.

Reason: Around civil airports the noise produced by departures covers a much greater area than the noise produced by approaches [Ref. 7-11]. So it is not appropriate to weight approach and take-off noise equally. However a modified trade-off regulation is necessary, since the total noise produced during a departure or an approach is not determined only by a single thrust setting.

7: Since the certification measurements are performed under well defined and controlled conditions they can be used to derive spectral information as well as information on directional characteristics. These should be published in more detail.

Reason: Currently there is an urgent need for world-wide for high-quality acoustic databases for aircraft noise calculation procedures.

A proposal for an extended certification scheme could be certification based upon the use of separate noise footprints for take-off and approach. This requires a standardised noise calculation procedure as well as a set of acoustic and operational data. Noise data can be derived from the certification measurements, whereas operational data are available from the manufacturers. The noise produced by a take-off or landing can be quantified in terms of footprint area and/or footprint extension. The use of calculated footprints makes it possible to investigate the influence of different operational procedures on noise without performing expensive measurements. It also offers the capability of quantifying an average or typical noise signature of an aircraft as well as a worst case noise signature.

8 WP3- emissions: Potential impact descriptors

8.1 Introduction

This chapter reports about Work Package 3 “Development of potential impact descriptors“ for gaseous emissions. This documents elaborates on the possible indices showing the actual impact of aircraft emissions on the environment and the relation to the current Landing and Take-Off (LTO) cycle certification. The investigation is executed by:

- Identifying the impacts of aircraft exhaust gas emissions on the environment and what data are needed to describe these impacts.
- Specifying the data needed from the certification processes for aircraft environmental impact assessment.
- Studying the relevance of the data obtained form the actual certification processes.

At the start of this work package, it has been realised that there are many omissions in the current state of knowledge to accurately describe the impacts of gaseous emissions to the extend that these can be used for certification purposes. In order to identify these omissions, a deliberate attempt has been made to quantify the impacts of the gaseous emissions. The purpose of this attempt is to reveal what descriptors can be used, what information can be used and what information is still lacking.

8.2 Inventory of impacts of gaseous emissions

8.2.1 Introduction

Aircraft emit gases and particles that modify the chemical composition of the atmosphere and trigger processes in the atmosphere such as contrail formation and increased cloudiness. In this section, the impacts of the modifications of the atmosphere on the earth and on life on earth are listed.

The relationship between the amount of gases emitted by aircraft and the resulting impacts on the environment is complex and dependent on many parameters. Atmospheric chemistry, transport of gases, the altitude, the season, the weather conditions, engine related factors (temperature of the exhaust gases, combustion conditions, etc.) and many other factors play an important but, to a large extent still poorly understood role in the relationship. This section gives an inventory of the impacts, where the description of the mechanisms behind the relations will be referenced shortly for as far as these are known.

The relevant aircraft emissions are carbon dioxide (CO_2), water (H_2O), nitrogen oxide and nitrogen dioxide (NO_x), sulphur oxides (SO_x), carbon monoxide (CO), unburned hydrocarbons (HC), sulphate particles, and soot. Although the magnitude of these emissions are small relative to corresponding industrial emissions from surface sources [Ref. 8-7], they are emitted for a considerable part directly into the upper troposphere and lower stratosphere and are the only directly injected source of anthropogenic emissions at these altitudes. At these high altitudes, their removal time is much longer than close to the earth’s surface. As a consequence, the emissions may disproportionately modify this part of the atmosphere.

Impacts of the gaseous emissions can be divided in local impacts around airports, regional impacts and in global impacts. In this section, the global impacts are further categorised in impacts on UV radiation and on climate. The categories identified are therefore:

- Local effects: pollution of the airport environment
- Regional effects: tropospheric ozone formation and acidification
- Global effects: UV radiation change and climate change

The impacts are described in the next sections.

8.2.2 Local effects: pollution of the airport environment

Gaseous and particle emissions by aviation are concentrated around airports due to the high density of low altitude and ground level activities of aircraft at and around airports. The result is that life around airports is subjected to a higher concentration of aircraft engine exhaust gases than other parts at the earth's surface. Therefore, regulation for aircraft emissions was established in the 1970's [Ref. 8-1, Ref. 8-2]. This regulation has been limited to the amounts of emissions close to the airport, i.e. during final approach, landing, taxiing, take-off and initial climb. Impacts are not directly considered.

The impacts of gaseous aircraft emissions on the local airport environment are:

- Health issues with respect to humans, animals and vegetation and
- Smell.

The primary health concern is that several gases emitted by aircraft are toxic if concentrations are too high, such as CO, ozone, NO_y, SO_x and HC. Respiratory diseases or injury to plant life can be the result of too high concentrations [Ref. 8-3]. However, a direct correlation with pollution from aircraft has never been found.

The major source for smell around airport is HC production. SO_x emissions also contribute to smell if concentrations are too high, but aircraft rarely cause concentrations that high. In contrast, HC emission is considerable around airports, as aircraft engines do not efficiently burn their fuel during landing and taxiing.

8.2.3 Regional Effects

8.2.3.1 Acidification

Acidification of soil and water due to aircraft emissions is small compared with contributions of non-aviation sources. Both NO_x and SO_2 contribute to the formation of acid. The NO_x and SO_2 depositions of worldwide air transport in 1990 were 0.7 % of the total NO_x and SO_2 deposition calculated in acid equivalent units [Ref. 8-4]. On the total worldwide NO_x and SO_2 emissions of 5845 acid equivalents 5 were due to SO_2 emissions of aircraft and 39 due to NO_x emissions of aircraft. For worldwide acidification also the emissions of NH_3 are relevant [Ref. 8-5]. This effectively reduces the acidification impact of aviation. Acidification is primarily a local effect but may be regarded a regional effect also if lower concentrations are considered relevant, [Ref. 8-7]. In this respect, damage to vegetation and to wild life is the main concern of the acidification. Acids also have an unfavourable impact on building materials and human health.

8.2.3.2 Photochemistry

Ozone is an oxidator and as such is responsible for pulmonary effects on the human health. The formation of ozone at high altitudes is a natural process, whereas the formation of ozone in the troposphere (lower part of the atmosphere) is for some conditions severely enhanced by human activities and associated emissions. Especially in summertime, the combination of NO_x, HC and light leads to high ozone levels at ground level.

The chemistry responsible for the formation of ozone is rather complex, non-linear and dependent on light intensity. Aircraft emissions alone will not lead to any significant effects. The interaction of aircraft emissions and the background atmosphere is not yet understood. Many assumptions about background atmospheres from other antropogenic sources are not obvious. There is a lack of sound knowledge about the relevant chemistry processes.

8.2.4 Global effects

8.2.4.1 UV radiation change

The ozone layer in the stratosphere provides a shield against solar ultraviolet (UV) radiation, thus protecting the earth's surface from most of the UV radiation harmful for life on earth. UV radiation with wavelengths shorter than 280 nm is almost completely blocked by the ozone layer. The UV radiation in the UV-B band (wavelengths from 280 to 315 nm) is largely absorbed. The reduction of radiation in the UV-A band (315 to 400 nm) by ozone is much smaller, but still significant. The latter type of UV (-A) radiation leads to skin tanning. Long-lasting exposures to UV-A radiation and any exposure to shorter wavelength UV radiation leads to skin burning and higher risks of skin cancer. Vegetation is also damaged by too much or shorter-wavelength UV radiation. This leads to both environmental and economic impacts as it leads to reduced crop yields.

There is concern about the concentration of ozone in the (stratospheric) ozone layer, because decreases have been observed. Gaseous emissions of aircraft above an altitude of about 15 kilometres have a net ozone depletion effect (in particular due to NO_x). The contribution of these emissions to ozone depletion is small however, as very little gas is emitted above 15 kilometres. Ozone depletion is strongly enhanced by halogens in the atmosphere (e.g. CFCs, fluorides, and chlorides), but the halogen emissions of aircraft are negligible. Below 15 kilometres altitude, the net effect of aircraft emissions is a creation of ozone. The altitude limit for depletion or creation is dependent on the local atmospheric conditions changing with, amongst others, the season and latitude.

Subsonic aviation, as it is today, does not significantly contribute harmful emissions to the atmosphere where ozone is depleted, simply because the activity is at lower altitudes. However, supersonic aviation is efficient at these higher altitudes and therefore emissions from supersonic aviation will contribute to the depletion of the ozone layer. Currently, due to the small scale of operations, the effects of civil supersonic aviation are negligible, but plans to introduce supersonic aviation on a larger scale face the problem of ozone depletion.

Water emission, SO_x emission and soot emission also have their impacts on the ozone concentration and therefore on the UV radiation. Apart from that, SO_2 absorbs UV radiation considerably and all gases play an important role in cloud formation. Clouds at high altitude, primarily cirrus clouds and contrails, influence the ozone concentration. At the current rates of emissions, the SO_x, water and soot generated by aviation have a small influence on the UV radiation.

8.2.4.2 Climate change

Gases emitted by aircraft affect the radiative properties of the atmosphere, possibly leading to climate change. The gases, injected into the atmosphere, tend to increase the absorption of infrared light emitted by the earth's surface, resulting in changes in the emission of energy through the earth's radiation in space, the so-called enhanced greenhouse effect. Some gases also absorb sunlight directly. Absorption leads to temperature increases of air and a modification in the temperature distribution in the atmosphere. The result is that the temperature of the earth's surface increases.

The most important greenhouse gases (i.e. gases that contribute to the greenhouse effect) are CO_2, H_2O, CH_4 (methane), N_2O and O_3 (ozone) [Ref. 8-4]. Gases with a considerable absorption of visible or UV sunlight are NO_x and ozone. The role of NO_x is a complex one as it enhances the depletion of HC, causes ozone concentration changes, as mentioned in the previous section, and absorbs light.

Ozone plays an important role for the temperature distribution in the stratosphere. Depletion of ozone in the ozone layer may therefore lead to modified temperature distributions in the atmosphere and will therefore have an effect on climate. Modifications of the ozone distribution in the atmosphere induced by supersonic aviation may therefore not only have the adverse radiation effects mentioned in the previous paragraph, but may also have an effect on climate.

One of properties of the atmosphere that is affected by emissions is cloud formation. Cloud formation is enhanced by the emission of water, SO_x and particles. Particles act as potential condensation nuclei enhancing droplet or crystal formation. At higher altitude droplets and crystals contribute to the absorption of light and therefore to the greenhouse effect. At lower altitudes clouds have a net cooling effect. Modifications of temperature distributions in the atmosphere and global warming in general may have effects on rainfall, wind fields, sea currents and sea levels. As the atmosphere is a complex dynamic system, these effects are hard to identify and even harder to predict. Of all effects, the temperature rise is considered to be the primary impact.

8.3 Enumeration and calculation of impact descriptors of gaseous emissions

Following the elaboration on the impacts of the aircraft gaseous emissions in the preceding section, a series of potential descriptors are formulated. The nature of these descriptors range from typical impact describing parameters to parameters that describe aircraft emissions. Some of the listed descriptors are considered in detail. For the selected descriptors, algorithms to quantify the descriptors have been developed. During the development, it has appeared that some essential information is not available, or has a large degree of uncertainty. In many cases, assumptions and simplifications are introduced for the sake of quantification. However, the lack of information is such that, in many cases it is not justified to present quantitative results of descriptors. The identified omissions in the information resulting in either assumptions, simplifications or stalling of calculations are listed.

The following descriptors for gaseous emissions and their impacts are considered:

- Emitted total mass of gas constituents (CO_2, NO_x, CO, HC, particles, SO_x and H_2O.)
    - for fixed thrust settings, per second
    - for fixed thrust settings, per kilometre
    - for fixed thrust settings per kiloNewton thrust
    - for thrust settings applicable in actual operations of the aircraft, per second

  - for thrust settings applicable in actual operations of the aircraft, per kilometre
  - for the LTO cycle (already included in regulation)
  - for the whole flight
  - for the whole flight per kilometre
  - for the whole flight per passenger
  - for the whole flight per passenger kilometre
  - for the whole flight per RTK (revenue ton kilometre)
- Emission Indices
  - for fixed thrust settings
  - for thrust settings applicable in actual operations of the aircraft
  - for the LTO cycle (already included in regulation)
  - for the whole flight
- Descriptors reflecting the impact of emissions
- GrI, a descriptor reflecting the Enhanced Greenhouse Impact
- UrI, a descriptor reflecting the UV radiation change Impact at the ground
- ToI, a descriptor reflecting the Toxic Impact
- SmI, a descriptor reflecting the Smell Impact
- AcI, a descriptor reflecting the Acidification Impact

From an inventory of the quantitative information it appears that it is not possible to calculate the latter category of descriptors reflecting the impacts of gaseous emissions. Although some information about the relative contributions of gases to impacts is available, the basis for calculating the combined effects of different gases in a background atmosphere is not available.

Whether such a descriptor in the latter category, depending on many parameters, will be a useful parameter for certification is very doubtful. Simplifications of the impact descriptor by omitting dependencies will probably neither fulfil requirements for certification purposes, as this will neglect aspects. For certification purposes, it is recommended to consider the direct gaseous emissions as parameter.

A set of descriptors was selected for calculation from FDR data. The algorithm for quantification of these specific descriptors is considered in this section. The data to serve as input for the calculations are recorded flight (FDR) data and some specifications of the aircraft [Ref. 8-8]. The FDR data are supplied by several airlines covering several series of representative flights with representative aircraft, see chapter 3.6.

As an intermediate step, the FDR data are used to calculate gaseous emissions as a function of time. For this step, three well known and widely used models are considered:

- the Gas turbine Simulation Program (GSP) [Ref. 8-9]
- the combustor inlet pressure and temperature (p_3T_3) method [Ref. 8-10] and

- the Boeing 2 fuel flow method [Ref. 8-12]

In a second step intermediate data is used to calculate the descriptors.

In trying to calculate the aircraft impacts on the environment the following information is lacking:

- Validated models for the calculation of gaseous emissions in all aircraft conditions.
- More certainty about impacts, e.g. altitude dependency, dependency of background atmosphere
- Resident times of gas constituents in the atmosphere and how to handle lifetime issues in impact assessment. The impact of gases with a large lifetime is obviously more long term than gases with a short lifetime. For example the lifetime of HFC is larger than the lifetime for CO_2, which is larger than the lifetime for NO_x. There is no clarity how to parameterise this issue.
- Plume chemistry in aircraft exhaust gases for different types of aircraft is not clear. Impacts are primarily dependent on the end products of plume chemistry. Therefore impacts are uncertain.
- The assessment of impacts for which different emission gases contribute to the impact. The contributions should be added somehow. Calculating the sum of contributions is not correct, although for some impacts such an approximation is better (e.g. acidification) than for other impacts (e.g. toxicity, smell). Additional information is necessary.
- Particle contributions to the impacts are largely unknown. Furthermore, the models for calculating particle emissions are not well developed.
- The HC emissions can not be related unambiguously to toxic and smell effects. This needs further investigation.

8.4 Results

8.4.1 Recommendations for additional data gathering

In section 8.3 above it is noted that there are considerable omissions in the information of (‘true’) impacts on the environment and, to a lesser extent, of the emissions of aircraft. Considering the impacts on the environment, further investigations on the various aspects are necessary. The information on the emissions of aircraft engines can be supplemented with additional data gathering. In this section recommendations for the additional data gathering are made.

8.4.1.1 Emission for additional thrust setting

Emission data at thrust settings used in considerable parts of the flights are not included in the ICAO database [Ref. 8-11]. From the FDR data it has appeared that in the cruise phase of flights the thrust setting is between the approach (30 %) setting and the (85 %) climb-out setting. It is recommended to add measurements at one (50 %) or more intermediate thrust settings relevant for cruise.

In the taxi phase thrust settings lower than 7 % are commonly used. The HC and CO emission indices and the emissions increase considerably at these settings according to extrapolation methods applied to the calculate emissions (e.g. GSP and Boeing 2). This is in agreement with measurements at some engines, but these conditions, relevant for local air quality, are recommended to be included in the ICAO data. Emission data at 4 %, or even better, at a commonly applicable ground idle thrust is recommended. This is confirmed by Work Package 2 results.

The thrust setting at take-off is for some flights above 100 %. Like in the very low thrust setting ranges described above this induces that extrapolation of ICAO data is needed. The NO_x emissions are high and the dependence on thrust setting is high for these conditions. Therefore, it is recommended to add relevant high thrust emission data in the ICAO database.

In addition, the engine operating conditions for which the measurements at the recommended power settings are done, should reflect typical operating conditions, such as bleed air and power extraction to power aircraft systems e.g. air-conditioning and avionics.

8.4.1.2 Additional particle emission measurements

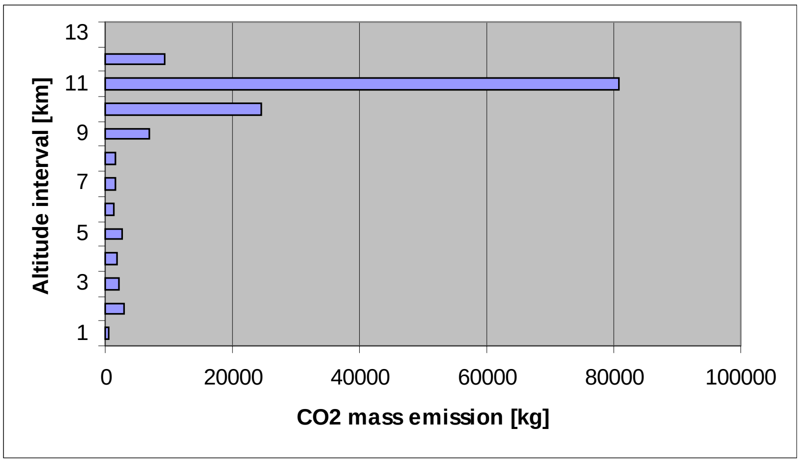
The level of attention currently paid to particle emissions is high. Both health issues for local air quality and the condensation effects at altitude give rise to concerns. The ICAO database contains information on smoke numbers only. These numbers cannot unambiguously be converted to the parameters for health issues (e.g. PM 10) or condensation (e.g. number of condensation nuclei). Therefore it is recommended to add relevant particle parameters for the environmental aspects in the ICAO database. It is acknowledged is that there is a lack of current measurement information to support a methodology for particulate data gathering let alone certification.

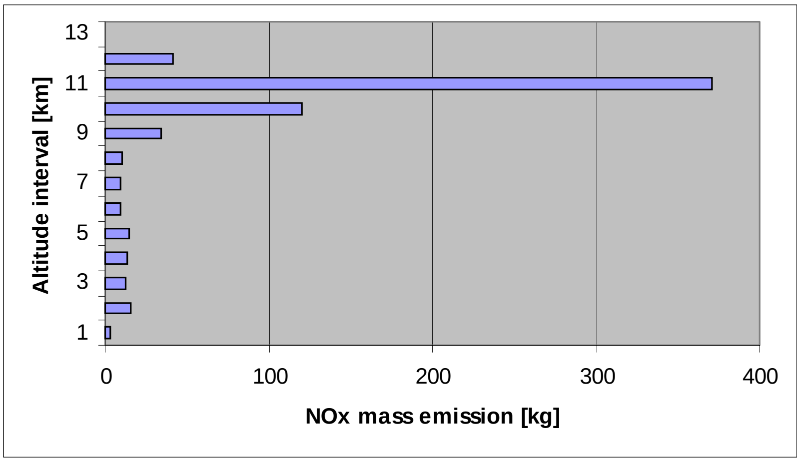
8.4.1.3 Additional hydrocarbon measurements

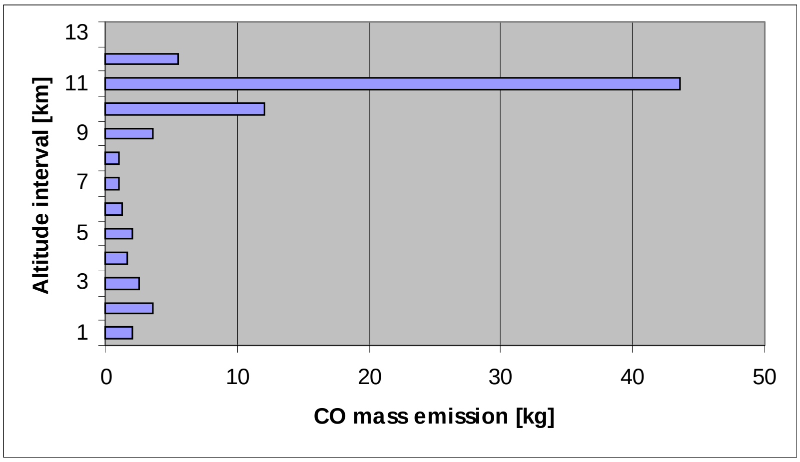
The effects of hydrocarbons for the different impacts depend very much on what is the composition of the hydrocarbons. For instance the health effects are much larger for the average aromatic hydrocarbons than for the average for non-aromatic hydrocarbons. Better knowledge of parameters reflecting the health, smell and enhanced greenhouse impacts is needed for which a differentiation in hydrocarbons in ICAO data is recommended.

8.4.2 Emissions as a function of altitude

Emissions are collected as a function of altitude to gain insight in where in the atmosphere the gases are emitted. The FDR recordings are incomplete below 1 km altitude because the FDR recordings start well after the engine start-up, and stop well before shutdown. Figure 8-1 shows the distribution of gaseous emissions over 1 km altitude intervals for 10 flights over 6500 km distance. The emissions at cruise altitude are considerable, independent of the gas specie, where the relative contributions of cruise emissions with reference to emissions at lower altitudes differ considerably. For global impacts it is obvious that cruise emissions should be taken into account.


Altitude interval [km]
13
11
9
7
5
3
1
0
20000
40000
60000
80000
100000
CO2 mass emission [kg]


Altitude interval [km]
13
11
9
7
5
3
1
0
100
200
300
400
NOx mass emission [kg]


Altitude interval [km]
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11
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3
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20
30
40
50
CO mass emission [kg]

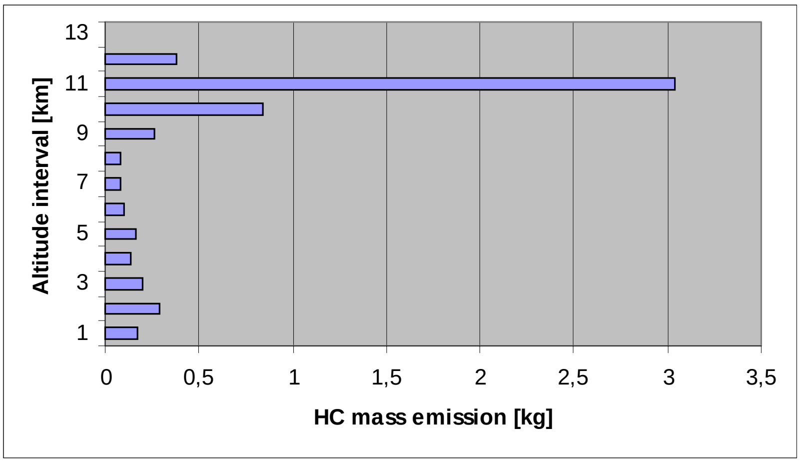

Figure 8-1: Emissions of transatlantic flights per 1 km altitude intervals. Emissions are the average total mass per flight of gaseous emission covering 10 flights over 6500 km distance.

8.4.3 Comparison of descriptors with certification parameters

Several descriptors have been calculated for several aircraft types and flight ranges using FDR data and the calculation methods presented in section 8.4. These descriptors reflect the emissions and (RTK- and fuel flow-) weighted emissions for whole flights. The descriptors have been compared with the data available from certification of engines. The relations between descriptor values and (LTO) certification parameters are not strong, which means that the ICAO LTO parameters do not describe the emissions and weighted emissions for whole flights unambiguously. The larger correlation is found for NO_x descriptors. Furthermore, the data for different flights of the aircraft show a considerable fluctuation. The fluctuations for shorter flights are larger than for longer flights. Here, the omission in FDR data, in particular the taxi phases, that varies from flight to flight plays a role.

It is noted that both the LTO emissions and the descriptors are calculated using the same ICAO emission indices. This implies that the differences found are solely due to the differences in (the nature of) the descriptors. There are no differences in the underlying engine emission characteristics. Obviously, only a weak correlation is found.

8.5 Conclusions

In this Work Package, the impacts of gaseous emissions of aircraft on the environment have been enumerated. Quantitative information in relation to these impacts has been gathered. It has been investigated whether descriptors of impacts can be designed with this information. The descriptors that potentially quantify impacts or relevant aspects of the impacts have been enumerated. Omissions in the quantitative information and uncertainties in the current knowledge of the chemical and physical processes in the atmosphere are large. Therefore it is currently not feasible to calculate justifiable descriptors reflecting the impacts.

From the comparison of the information available from the certification process and the information needed for the calculation of impacts of gaseous emissions, a number of recommendations are made for additional data gathering in the certification process. Emission data gathering at more thrust settings, both very low, very high and intermediate settings, are recommended to reduce uncertainties in extrapolation and interpolation procedures for assessing emissions relevant for impacts. Furthermore, the smoke number used for particle emissions in certification data does not allow to calculate soot emissions. It is recommended that the soot number is to be supplemented with parameters that allow an assessment of emitted mass, as well as health and enhanced greenhouse effects. Finally, the ICAO parameter for hydrocarbon emissions is recommended to be supplemented with parameters describing health, smell and enhanced greenhouse effects of (the different kinds of) hydrocarbons.

The impacts on the environment are correlated with the gas mass emissions in different parts of the atmosphere. The quantities of gas species emitted in the atmosphere were calculated applying generally accepted models. The information about the validation of these models for all engines and flight phases is currently not available, but in environmental studies these uncertainties are commonly accepted. Insight in the emissions during flights has been obtained applying the emission models on flight data gathered in the AEROCERT project.

Relations between descriptors of the gaseous emissions during the flight and available data on emissions during the LTO cycle have been investigated. For different engines and aircraft the data were plotted to reveal dependencies. No simple relation was determined between available (LTO) data and total gaseous emissions.

In the process of trying to calculate potential impact descriptors and gaseous emissions, a lack of verified and validated data becomes apparent. The missing data was listed. In addition, and partly due to these data omissions, there is a lack of well-established and validated models. Key issues here are:

- impact models as a function of emissions at certain time (of the day, of the year, etc), altitude and global position.
- validated models for the calculation of gaseous emissions in all aircraft conditions.

9 WP4: Characterisation of through-life deterioration effects

9.1 Introduction

Work package 4 of AEROCERT has determined the magnitude of the deterioration of noise and emissions performance of a representative range of aircraft and engines operated by European airlines in line with the following objective:

“ to identify the effect of operation and maintenance procedures on the certified emissions and noise levels of engine and aircraft throughout their service lives”

The main elements of work required are:

- to identify the influence of in-service deterioration on the engine and aircraft performance and to characterise the deterioration in noise and emissions levels
- to make recommendations on operational and maintenance procedures to keep near to or below the certification levels.

9.1.1 Background

Procedures for regular overhaul and maintenance of aircraft and engines are set out by airline operators to comply with airworthiness requirements and to restore deterioration in performance due to normal in-service wear and tear. The frequency of overhaul is determined by a combination of economic and technical considerations such as performance deterioration. This deterioration is likely to lead to changes in noise and emission levels. It is important to assess the extent to which the levels deteriorate both between overhaul and also over the service lives of aircraft and engines, in order to establish the severity of the problem. This may also help to identify the key factors responsible for deterioration so that options and procedures can be developed for maintaining the original certified levels, if required.

9.1.2 Commercial sensitivities

Examination of the deterioration in performance of a range of aircraft types operated by different European airlines is dependent upon the support of those airlines and the data and results of this project are commercially sensitive and must be safeguarded. Anonymity has been kept by amalgamating results and providing results as a ‘delta’, or change, in percentage terms, from original specification or reference values.

9.1.3 General approach

Engines and airframes deteriorate with time and use necessitating maintenance to retain or restore acceptable performance levels during service and at major overhauls. For engines, component performance is critical to the overall efficiency and losses result in reduced engine thrust, which is compensated by a higher throttle setting with consequent increases in fuel use, noise and some emissions. For airframes, external aerodynamic performance is critical to the overall efficiency. Losses may result from poor surface cleanliness, excessive gaps or incompletely retracted moving surfaces and will result directly in increased drag, which has to be compensated by higher engine thrust with consequent increases in fuel use, noise and some emissions.

Deterioration normally takes place over a substantial period. Data required for this task have been gathered over at least the period of time between major overhauls for engines but, given the time limitations of the research, it is harder to address the airframe deterioration issues where deterioration time scales are much longer.

Engine deterioration is evident in measurements of engine parameters such as exhaust gas temperature (EGT) and fuel consumption rates over time, which can show marked increases over the service life of an engine. Changes to engine component characteristics as a result of deterioration cannot be measured directly. However, the effects of the changes on an engine's performance can be determined from analysis of measured engine gas path parameters over time.

9.1.4 Aircraft and engine types

Work Package 4 uses data supplied by the five airline operators supporting the project but it used only a subset of the number of representative aircraft/engine combinations for which data have been provided, on account of data limitations. A list of the anonymized types used in Work Package 4, with short description of each, is shown in Table 3.1.

9.2 Analytical approach

9.2.1 Engines

The conceptual approach followed in Work Package 4 can be summarised as follows:

- Acquire relevant data from the aircraft Flight Data Recorders (FDR) and Aircraft Condition Monitoring Systems (ACMS), and check for validity;
- For each component or group of components being considered in each of the engines, calculate the performance efficiency trend with service life from the ACMS data at specific conditions e.g. take-off, cruise, etc;
- Generate computer models, using the NLR GSP tool, of each engine using actual component efficiencies and measured data from FDR/ACMS;
- Validate performance predictions from models using measured FDR/ACMS data;
- Use the models to derive values of gas path parameters and engine performance as component efficiencies deteriorate, and restore engine thrust to compensate for loss in performance through deterioration and calculate new values of gas path parameters;
- Calculate the consequential effects on noise and emissions performance and present as changes, or 'deltas', relative to a 'new' engine.
- Do this for each of the noise and emission certification requirement flight points.

In addition, field measurements were made on different types of acoustic liners in engine intake nacelles using impedance measurement devices in order to assess noise deterioration.

9.2.2 Airframes

Airframe deterioration is countered by increasing the thrust from the engines. The approach taken for the airframe deterioration assessment is to:

- Determine baseline, or 'reference', values of gas path parameters and engine performance for an engine running at a flight condition;

- Re-run the engine model at the same flight condition but at an increased thrust from the engine to simulate compensation for increased airframe drag;
- Calculate the consequential effects on emissions of running at the higher thrust, and present as changes relative to the baseline case.

9.2.3 Analytical tools

A number of different analytical tools are required to perform Work Package 4 analysis: data analysis tools; computer models and an acoustic impedance device to measure the performance of engine acoustic liners in situ. The key tool for assessment of the effects of engine and airframe deterioration is the NLR Gas Turbine Simulation Program (GSP) – an engine performance model [Ref. 9-1]. GSP enables degradations in component efficiencies to be applied to engine models in order to calculate deteriorated engine performance. GSP also incorporates an algorithm for calculating emissions indices and thus it is possible to assess changes in emissions production due to the deteriorations that have been observed. GSP performance output data is also used as inputs to the DERA Coaxial Jet Noise (CAJEN) prediction model [Ref. 9-2] to estimate noise deterioration.

9.3 Data

The prime source of data for the Work Package 4 analysis is the aircraft on-board flight data recording systems. There are two main types of recording system that have been used, the Flight Data Recorder (FDR) and the Aircraft Condition Monitoring System (ACMS), the latter being the most important data source for Work Package 4. The parameters that are recorded on the FDR and ACMS recorders vary by aircraft type and operator. The ACMS produces an ECM report, which records engine operating parameters at specific conditions and, when parameters have remained constant for some predefined period of time, a 'stable frame' snapshot is taken. These snapshots, taken for cruise, take-off and approach can reveal patterns of gradual deterioration in efficiencies and performance over many hours and cycles of operation.

Limited access to engine service histories has been possible to help AEROCERT to understand, and possibly identify reasons for, any changes in efficiency due to deterioration between overhaul periods, and the benefits seen from restorations of efficiencies following overhaul. The noise assessment work has included making an investigation into the deterioration of the performance of engine acoustic liners.

The sub-tasks within Work Package 4 have different data requirements, depending on the flight regime or phase, as shown in Table A below.

Table 9.1: Flight data requirements for noise and emissions evaluations.

Regime:	*Noise*	*Emissions*
Gate to runway		✓
Take-off and climb to 915m	✓	✓
915m to top of climb		
Stable frame cruise		✓

Descent to 915m		
915m to ground	✓	✓
Runway to gate		✓

9.3.1 Acquisition and initial review of ECM and FDR data

Data time histories were drawn from airline archives or downloaded at specified periods during the project to build up statistically sound samples, by engine type, over the maintenance cycle. Engine casing numbers and aircraft tail numbers have been tracked throughout the life of the project to enable monitoring of performance deterioration over time and the tracking of some engines, where possible, through overhauls. Data received from the airlines were in ASCII text format. In some cases an initial sift of the data was undertaken to select and reformat data, and to check the validity of the data received. The data were then used for component efficiency analysis and for verification of the engine performance models.

9.4 Engine deterioration

9.4.1 Background

Over time, a gas turbine engine’s performance will be reduced due to deterioration of its component parts. Axial flow compressor deterioration is due to reduction in aerodynamic capability of the rotor and stator aerofoils. This reduced capability decreases the total pressure rise across each stage of the compressor. The physical changes in the compressor blades that cause the performance deterioration are fouling, erosion, and rubbing wear. Turbine losses are due to profile loss, profile incidence loss, secondary flow loss, blade tip clearance loss, cooling air injection aerodynamic loss and cooling air thermodynamic loss. Changes to engine component characteristics as a result of deterioration cannot be measured directly. However, the effects of the changes on an engine’s performance can be determined from analysis of measured engine parameters over time.

9.4.2 Calculation of engine performance deterioration

Gas path temperatures and pressures are the parameters that are required for calculation of efficiency. These data were obtained from ECM reports. The number of parameters recorded on ECM reports varies depending on aircraft type, from a limited range, for example only EGT, fuel flow and shaft speeds, to a very comprehensive set of readings including gas path temperature and pressure data.

A basic assumption of this Work Package is that component efficiency is essentially independent of engine shaft speed / power within the range of speeds / power typical of take-off, climb and cruise. Individual component relative efficiency indices can be calculated where the requisite gas path data is available from the FDR or ECM reports. Isentropic efficiencies of a component can be determined using basic gas dynamics equations from temperatures and pressures measured at the component entry and exit planes. In this analysis, the most frequently available temperature and pressure data allow calculations to be made of LP and HP compressor efficiencies. Temperature and pressure measurements cannot be made easily in the hot-end components and usually there is insufficient data to calculate individual turbine efficiencies from the ECM data.

The data recorded on the ECM reports were the prime data source of the Work Package 4 analysis. However, the FDR data were still required for analysis of engine performance at conditions other than cruise, and to validate the required engine performance models. With a large enough sample data set it is possible to chart not only the average deterioration of the engine but also the standard deviations from the average deterioration level.

Engine usage is measured by Airlines in both operating hours and cycles (one ‘cycle’ equates to a full mission, which comprises taxi/idle, take-off, climb, cruise, descent, landing and taxi/idle operating modes) but all results in this study are given in cycles.

The method for determining the fleet average deteriorations of engine components is summarised below:

a) calculate each individual engine’s component efficiencies from ECM stable frame data;

b) plot efficiencies of each of the engine’s components against number of cycles for each individual engine. Establish the trend line;

c) determine efficiency at 500 cycle intervals for each engine;

d) collate data from each engine;

e) develop average engine trend for the fleet.

9.4.3 Variability and validation

Some variability was expected and found in the data, due to sensor to sensor variability, operating conditions, and atmospheric conditions. The approach was taken whereby all the data was used for analysis without correction. With a large enough data set, trends due to deterioration become apparent through the scatter. Anomalies were apparent in some datasets which indicated some disturbance in the typical operation of the component subsequently rectified, probably by some form of on-wing maintenance. Engine-to-engine variability is another possible cause for scatter. Some of these features are evident in Figure 9.1.

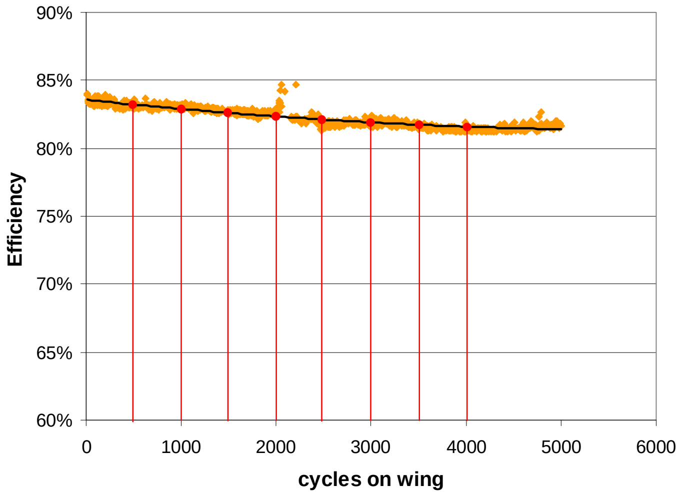

Figure 9.1: Data taken from component efficiency trend graph, for a typical engine.

Procedures were developed to validate the use of data that were received from some airlines in small batches - usually one week's worth of flight data every few months. Additionally procedures were developed to validate the basic assumption that component efficiency is independent of the range of variable parameters encountered in real operations, e.g. flight speed, altitude and engine power settings, together with differences in ambient conditions.

9.4.4 Engine performance deterioration results

A table of the efficiency changes, calculated in this study as percentage change from a reference 'as new' value, is shown in Table 9.2. It was expected that component efficiencies would decrease with time on wing, and this is clearly seen in the table. The results in Table 9.2 are presented as overall compressor (i.e. LP and HP combined) and overall turbine efficiencies because of incompleteness of data for individual components and confidentiality reasons.

Trends are reported on a linear rate of deterioration from the baseline value with number of cycles. Examination of the trends indicated that there may be a slightly more rapid rate of deterioration occurring early in an engine's life, but quantification of this would require more data than currently available for all engines.

Table 9.2: Calculated component efficiency (η) deterioration rates, at cruise

Engine type	*Δη Overall Compressor ** *%*	*Δη Overall Turbine ** *%*	*typical hours/ cycle ratio*	*typical high life cycles*
3	-0.84	-	8.0	2500
6	-0.10	-0.34	1.1	7000
7	-0.32	-0.07	1.2	5000

13	-0.01	-0.26	4.8	3500
14	-0.45	-	7.8	2000
15	-0.17	-	3.7	3500

* deterioration rates shown are per 1000 cycles

With deterioration of component efficiency, fuel flow must be increased to maintain a required level of thrust. Figure 9.2 indicates a typical increase in fuel flow with time, at the take-off condition. With the increases in fuel flow there are corresponding increases in EGT, as the combustor exit temperatures are higher. Additionally, shaft speeds increase to compensate for the lower efficiencies.

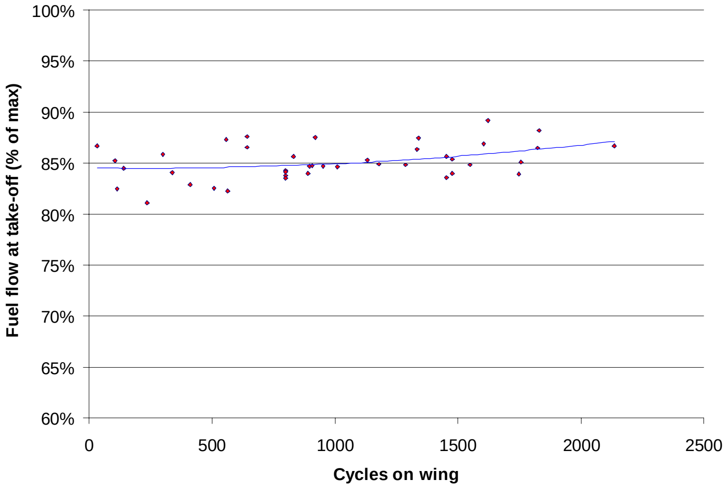

Figure 9.2: Fuel flow trend with engine cycles on wing.

Changes in EGT and shaft speed as well as for fuel flow and EGT for take-off are shown in the main Task 4 report but results from ECM trends for cruise are shown in Table 9.3.

Table 9.3: Results from ECM trends, cruise.

Engine type	*FF ** *%*	*EGT ** *K*	*N1 ** *%*	*N2 ** *%*
3	0.65	11.5	0.30	0.20
6	0.80	5.4	0.21	0.15
7	1.18	6.1	0.39	0.29
13	0.20	2.8	0.29	0.12
14	1.17	1.5	0.20	-0.06
15	0.76	2.6	0.02	0.12

* deterioration rates shown are per 1000 cycles

9.4.5 Overhaul/service histories

It has been possible in the course of this study to track some engines through overhaul periods. Figure 9.3 below shows the only example where it is clearly possible to see that a component's performance has been restored following a maintenance period.

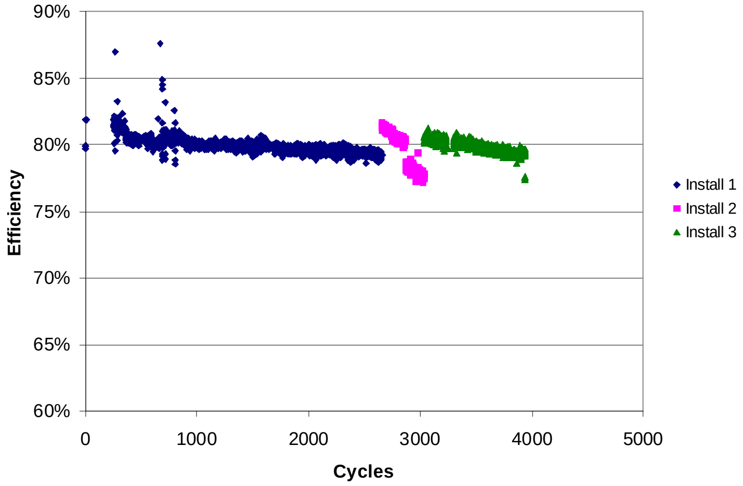

Figure 9.3: Performance restoration from overhaul.

The figure shows three installations of the engine with clear changes of the measured efficiency. It is not known what maintenance action was taken on the engine between installations or whether such changes are typical. On the basis of current data, it was not possible to make a detailed investigation into the effects of overhaul or servicing on engine performance. However, the knowledge that has been gained from airline operators on service and maintenance schedules, and the reasons for removal of an engine from the wing, is reported in Section 9.7.

9.5 Development and validation of engine performance models

9.5.1 Engine performance models

Performance models for the aircraft and engines are required to evaluate the effects, in terms of noise and emissions, of performance deterioration. Aero-thermodynamic engine cycle models of engines, representative of the types in service with the participating airlines, have been developed using NLR's Gas Turbine Simulation Program GSP (a description of GSP is given in [Ref. 9-1]). The key parameters are P3, T3 and EGT for the emissions analysis and exhaust gas velocities for noise modelling analysis. GSP enables degradations in component efficiencies to be applied to the engine models in order to simulate deteriorated engine performance. Emissions production rates can be calculated by GSP to underpin emissions deterioration analysis and performance data output from GSP is also used for noise predictions.

9.5.2 Validation of models

Validation of GSP engine models consisted of running the model at flight conditions taken from the ECM data. The model outputs (gas temperatures and pressures through the engine) were compared to the ECM data. Fairly close agreement was demonstrated. A study showed that the calculated EINOx was more susceptible to variation in T3 than in P3. Thus it is important for the engine models to achieve the maximum possible accuracy on T3. Table 9.4 provides a summary for all engine models.

Table 9.4: Comparison between GSP model prediction and ECM data, showing average deviation and range.

Engine type	T3 %	P3 %	EGT %	Thrust %
3	0 (±3.5)	1.5 (±10)	5 (±5)	7.3 (+3.1, -4.3)
6	0.7 (±1)	-1 (+2.4, -1.4)	0.6 (±1.2)	2.3 (±3.7)
7	0.7 (±1)	-1 (+2.4, -1.4)	0.6 (±1.2)	2.3 (±3.7)
13	-0.8 (±1.6)	-2.2 (±5.5)	0 (±2.5)	1.3 (+5, -8.8)
14	1.8 (±1.8)	5 (±2.8)	-4.6 (±2)	-2.8 (±2.8)
15	1.8 (±1.8)	5 (±2.8)	-4.6 (±2)	-2.8 (±2.8)

On the basis of the findings Table 9-3 indicates a high level of confidence in the engine models, though engine type 3 is not as good as the others.

9.6 Emissions

9.6.1 Emissions calculation

GSP has a built-in emissions calculation procedure using engine certification emissions data from the Aviation Emissions Databank[1] [Ref. 9-3] and a correlation method to predict emissions at any flight condition from the reference data. The GSP correlation method is similar in principle to the more well-known P3-T3 methods, reviewed elsewhere [Ref. 9-4]. The emissions calculation methods within GSP have been validated and reported by NLR [Ref. 9-5, Ref. 9-6].

The predictions have been made for a single engine at a reference performance level, for example representative of a ‘new’ or a recently overhauled engine, and compared to predictions made for an engine with deteriorated components. The pollutant emissions reported are oxides of nitrogen (NO_x), carbon monoxide (CO) and unburnt hydrocarbons (HC). Prediction methods for CO and HC are less robust than those for $NO_{x.}$ Additionally, fuel usage is reported, which can be taken as a proxy for carbon dioxide (CO_2) emissions.

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[1] The Aviation Emissions Databank is available on the internet at http://www.dera.gov.uk/aviation-emissions-databank.htm

Incompleteness of data does not allow calculation of the efficiencies of all the individual compressor and turbine components throughout each engine so overall compressor and overall turbine efficiencies have been calculated. The difficulty therefore is how to use the available efficiency data to estimate emissions and noise changes due to deterioration. The following approach has been adopted for emissions:

- define the reference operating conditions of interest,
- carry out parametric studies using the engine models to assess the consequence of independent changes in component efficiencies and their inter-dependency,
- develop 3-D plots of overall compressor efficiency, turbine efficiency and fuel or NOx emissions, using the engine models,
- estimate the expected fuel and NOx changes from the 3-D plots, using the deterioration data derived from the flight data records.

The procedure for noise is developed in Section 6.

9.6.2 Selection of reference operating conditions

Emissions have been predicted at a number of engine operating conditions which are representative of those encountered during a typical flight, i.e. cruise and during landing and take-off operations. Emissions at cruise have been determined at typical flight altitudes and flight speeds for the aircraft under consideration. A consistent approach was taken with each of the aircraft to determine aircraft weight at the cruise point, and this was to assume a lift coefficient (C_L) of 0.5.

Landing and take-off Emissions were calculated for two sets of operation:

a. Typical noise departure procedure

Based on the ICAO Departure Procedures [Ref. 9-7], the following nominal operating points (Table 9.5), were selected to cover the range of aircraft types included in AEROCERT. These flight points were modelled primarily for use for noise prediction, but emissions at these points are also reported.

Table 9.5: Nominal reference Noise operating points.

Operating mode	*Thrust setting*	*Altitude*	*Flight speed*	*Atmospheric conditions*
Take-off	100% of available	300m	0.3 Mach	ISA*
Cut-back	85% of available	500m	0.3 Mach	ISA*
Approach	30% of available	120m	140kts	ISA*

* emissions & noise results are reported at 60% & 70% relative humidity respectively

b. Emissions certification

Emissions at the engine power settings for the ICAO LTO emissions certification points (Table 9.6) were also calculated. These allow direct comparison of emissions from deteriorated engines with the certified values for new engines.

Table 9.6: Emissions certification points.

Operating mode	*Thrust setting*	*Time in operating mode (minutes)*	*Atmospheric conditions*
Take-off	100% F_{oo}	0.7	ISA *
Climb	85% F_{oo}	2.2	ISA *
Approach	30% F_{oo}	4.0	ISA *
Taxi/ground idle	7% F_{oo}	26.0	ISA *

* emissions results are reported at 60% relative humidity

9.6.3 Results from parametric studies

The following method was adopted to study the effects of deterioration. The model was firstly run with no deterioration, to establish a baseline reference for the emissions and fuel flow. A uniform deterioration level was then applied to each of the components. The model was run with these deteriorations and with the baseline fuel flow, which revealed the thrust lost due to the deterioration. To maintain the flight profile of the baseline case, the deteriorated engine must deliver the same level of thrust as the baseline engine: this was achieved by increasing the fuel flow to the deteriorated engine. The effects on emissions were calculated.

The uniform deterioration levels applied to each of the components are explained thus. For a 1% deterioration level on all components, the fan would be deteriorated by 1%, and the LP compressor would be deteriorated by 1%, and so on. Efficiencies were calculated for each of the engines being studied to show how the uniform deterioration levels equate to overall compressor system and turbine system efficiency deteriorations. These are shown in Table 9.7.

Table 9.7: Overall efficiency changes for uniform deterioration on every component.

	1% deterioration on every component		*2% deterioration on every component*	
Engine type	*$\Delta\eta$ Overall Compressor (%)*	*$\Delta\eta$ Overall Turbine (%)*	*$\Delta\eta$ Overall Compressor (%)*	*$\Delta\eta$ Overall Turbine (%)*
3	-0.42	-1.00	-0.95	-1.98
7	-0.25	-0.69	-0.71	-1.32

13	-1.19	-0.77	-2.41	-1.49
14	-0.73	-1.47	-1.53	-2.91
15	-0.73	-1.48	-1.51	-2.95

Figures 9.4 and 9.5 show the effects of deterioration on emissions at the take-off flight condition, modelled using GSP. Deterioration has been applied in two distinct ways:

a) an equal level to all components. The points resulting from this approach forming the basis for the trendlines shown (Figure 9.4);

b) a deterioration of 1% to every component, and then sequentially apply an additional 1% to each of the components in turn (Figure 9.5). The data points are highlighted to indicate the component to which the extra deterioration was applied.

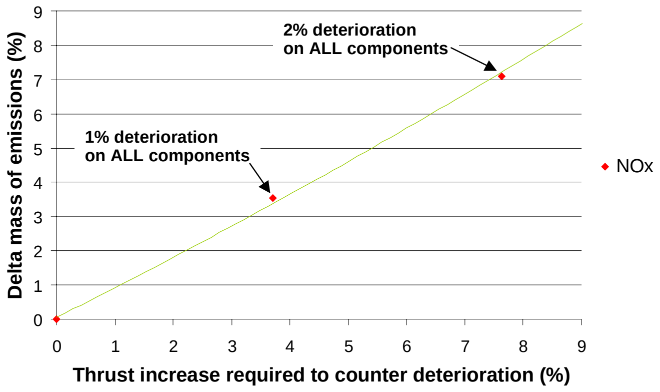

Figure 9.4: Changes in emissions at full power take-off.

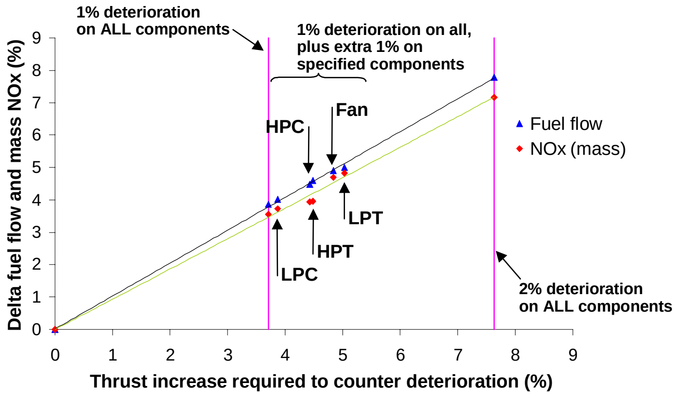

Figure 9.5: Changes in emissions at full power take-off due to varying the deterioration of a component.

The fuel flow rate and NO_x emissions increase when deterioration is applied and engine thrust restored to the baseline level. Deteriorations of up to 1% are more common and these will be taken as typical of in-service deterioration.

GSP calculates a change in air mass flows for given component efficiency changes due to the engine operating point changing, but it does not automatically compensate for flow-capacity changes due to effects such as blade deformation. However, using a correlation between components' efficiency reduction and typical change in mass flow [Ref. 9-8], the influence of possible flow changes was investigated. The results of the investigation into flow capacity changes showed only small differences between the engine operating with deteriorations applied in the form of efficiency changes only, or with efficiency changes and flow capacity changes. Since changes between the results of running deterioration calculations with and without mass flow changes are small, and with a lack of mass flow change data from the flight data, the following parametric studies of deterioration are made without any mass flow corrections.

Parametric studies were made for typical cruise points, the reference noise operating points and at the emissions certification points. Degradations of 1% on every component and 2% on every component were applied and the models run at the same power setting as the base cases. The resultant increases in fuel flow and NO_x were plotted against the percentage of thrust loss that would be associated with the applied deterioration if thrust were not restored. Additionally, in the case of the emissions certification points, changes for CO and HC were calculated. The emissions that were predicted for the full LTO cycle are shown in Tables 9.8 and 9.9 for the 1% and 2% deterioration levels respectively. It can be seen that over the cycle emissions of fuel flow and the pollutant species all increase significantly.

Table 9.8: Certification LTO emissions change with 1% deterioration on all components.

Engine type	*Fuel flow % change*	*mass NO_x % change*	*mass CO % change*	*mass HC % change*
3	9.73	7.15	10.66	8.55
7	3.88	4.00	1.59	3.44
13	3.95	5.24	1.20	1.46
14	4.47	4.68	3.85	1.51

Table 9.9: Certification LTO emissions change with 2% deterioration on all components.

Engine type	*Fuel flow % change*	*mass NO_x % change*	*mass CO % change*	*mass HC % change*
3	13.90	12.11	11.61	8.00
7	8.11	8.46	3.38	7.23

13	7.94	10.65	2.58	3.18
14	9.07	9.66	5.47	2.62

9.6.4 Emission Results

Thus far, all emissions change results have been derived using generic levels of deterioration.

For all engine types at the cruise condition, the efficiency of the components was varied systematically to form a matrix ranging between the ‘as new’ undeteriorated level and certain levels of deterioration. This matrix provided a means of determining actual changes in NOx production from the overall compressor and fuel flow deterioration results presented in Tables 9.2 and 9.3.

Emissions were determined by this method for each of the engines being considered. The results are presented in Table 9.10.

Table 9.10: Cruise emissions results, calculated from actual deterioration levels.

	at 1000 cycles			*at typical high life cycles*		
Engine Type	*$\Delta\eta$ overall compressor (%)*	*Δ FF (%)*	*Δ NO_x (%)*	*$\Delta\eta$ overall compressor (%)*	*Δ FF (%)*	*Δ NO_x (%)*
3	-0.84	0.65	1.8	-2.10	1.625	4.05
6	-0.10	0.80	0.35	-0.70	5.60	3.4
7	-0.32	1.18	0.7	-1.60	5.90	4.6
13	-0.01	0.20	0.2	-0.035	0.70	0.8
14	-0.45	1.17	1.1	-0.90	2.34	2.15
15	-0.17	0.76	0.6	-0.60	2.66	2.25

9.7 Noise

9.7.1 Noise background

It is considered that the best way to assess factors causing deterioration in engine/aircraft leading to performance community noise is to consider the impact on the noise in terms of ΔdBs at the three standard ‘Noise Certification’ monitoring positions, namely, Sideline, Flyover and Approach.

It has been assumed that with the high-bypass ratio engines considered in this study, the dominant noise sources at the three positions will be:

- Jet mixing noise for the full-power sideline point;

- A mix of Bypass fan and jet noise for the Cutback; and,
- Bypass fan noise at approach.

Any changes to the liner performance will also directly affect the fan noise levels.

9.7.2 Noise calculations

Changes in the engine noise sources due to deterioration or thrust increases have been computed from the relevant engine characteristics derived from the engine cycle studies. The in-flight coaxial jet-mixing noise has been computed using the DERA CAJEN (CoAxial JEt Noise) prediction method [Ref. 9-9] corrected for flight [Ref. 9-10] based upon its on-going research programmes. The fan noise has been computed using the Heidmann method [Ref. 9-11], which has been computerised by ESDU [Ref. 9-12]. Changes in flight trajectory will only have an impact on the Flyover noise. The variation in distance of the aircraft from the Sideline position is relatively independent of the aircraft altitude. Under Approach conditions the aircraft will normally follow the 3-degree glide slope which is rigorously defined by the Instrument Landing System (ILS) beam. Thus, it is only at Flyover that variations in the aircraft flight trajectory become important with regard to the noise due to changes in the propagation distance from aircraft to the ground.

However, this picture is complicated by the probability that on any particular aircraft only a single engine is likely to be deteriorated to the limit. This means that the engine noise source changes would be diluted by the remaining unchanged engine(s), provided they are of similar levels. In an example a 2 dB source change on a single engine resulted in only 1 dB for the total noise from two engines and about half that for four engines.

9.7.3 Acoustic liner measurements

The question of absorbent liner deterioration has been addressed by a series of impedance measurements on the acoustic main intake liners of various engine types during turnaround at airports or in the maintenance bay [Ref. 9-13]. For the purposes of the present study it is considered that these intake cowl measurements will be representative of the likely deterioration in all the cold stream linings. Non-intrusive impedance measurements were taken at several locations in the engine cowling to determine the liner performance. The liner investigation approach was different from that used by the main engine deterioration study in that a more statistical approach has been adopted. This is due to cost and the improbability of the selected engines all being available at specific times. The liners were considered as generic groups, e.g. perforate, linear, double layer etc.

9.7.4 Changes in source noise levels

The differences in source noise due to increased engine power to overcome any loss of thrust are expressed as noise deltas determined using noise prediction models of the major engine sources. Note that the other engine noise sources such as combustor, turbine and booster, whilst contributing to the overall levels will not significantly affect the overall result and are likely to follow the trends of the major sources.

As in the emission study, engine performance has been calculated using the relevant GSP engine model. The engine deteriorations are defined as approximate net thrust losses of 3½ %, 7% and 14%, which correspond to 1%, 2% and 4% deteriorations in each engine component. The noise parameters have been evaluated at nominal conditions corresponding to the three certification points during take-off and landing operations, as indicated in Table 9.5, with the additional constraint of 70% relative humidity. The PNL directivities show the typical effect on the two major sources due to progressive deterioration of the component efficiencies together with the consequences of restoring the thrust.

These relationships, in terms of perceived noise levels, have been determined for the four engine types and the three operating conditions associated with Noise Certification. For the jet noise the changes, due to deterioration, have been taken as the differences in the peaks of the linear noise field-shapes. These and the corresponding fan deltas for full-power are presented in Figure 9.6. Comparisons between the commonly used dBA and PNdB subjective noise metrics have yielded almost identical results, thus for simplicity only the PNdB results have been presented here.

It can be seen that the individual results show odd discrepancies in the trends but these occur with different engines and at different powers. Close examination of the data suggests that these trends are a function of the engine cycle changes linked with the complex nature of the two major sources. These sources are in reality a sum of several individual sub-sources whose balance can be affected by relatively small changes in the input parameters.

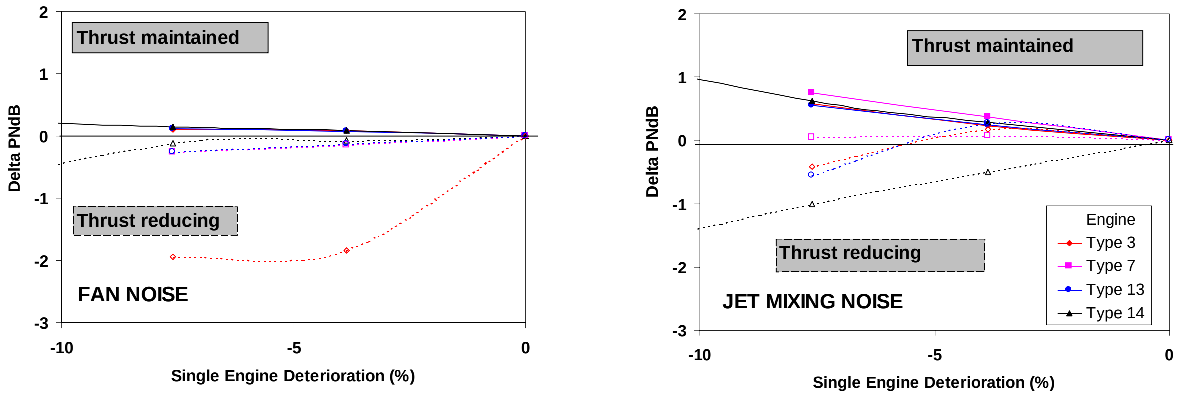

Figure 9.6: Noise changes for main sources at engine full-power.

The bypass ratios of the engines in this study result in the aircraft noise at full power being totally dominated by the jet mixing noise. Thus at this condition the effect on the single engine source noise can be seen to be less than 1 PNdB for a maximum expected deterioration of around 7%. At cutback power, jet mixing and bypass fan noise are comparable but still above that of the background airframe noise. Thus the effect of deterioration is again less than 1 PNdB for the combined fan and jet noise.

At approach powers, although the fan will dominate the other engine sources, the airframe will then be of a comparable level. Thus the small changes in fan noise will become subsumed within the overall aircraft noise and result in little or no source noise change.

9.7.5 Changes due to flight profile

Changes in flight profile due to deteriorated engine power will only impact on the Flyover noise since the propagation distances at Sideline and Approach remain substantially unchanged. Since the total picture must also take into account the source noise changes associated with the deterioration engine, it is best to consider it in two steps. For each of these types, the noise changes due to propagation distance have been computed for the three likely take-off procedures namely, full-power with no cut-back and with ICAO cut-back procedures A and B.

The differences due to flight trajectory changes for these two procedures are negligible and consequently they are not differentiated in any of the results presented below. Figure 9.7 shows the partial picture of noise changes due to trajectory changes alone, brought about by the reduced engine power. Note that the impact of a given loss of thrust on one engine is greater on a twin than a four-engined aircraft.

To complete the flyover analysis, the engine source noise changes for a single engine need to be incorporated into the total aircraft (two or four engine) and the impact of trajectory added. For the full power case with no cutback there will be reductions in source noise (jet noise) and for the cutback there will be similar increases due to the requirement to maintain the climb gradient (thrust). The combined impact of these source changes and flight profile is illustrated in Figure 9.8.

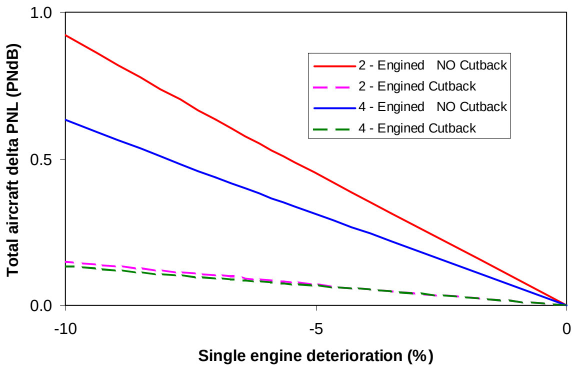

Figure 9.7: Noise changes due to trajectory changes alone (propagation).

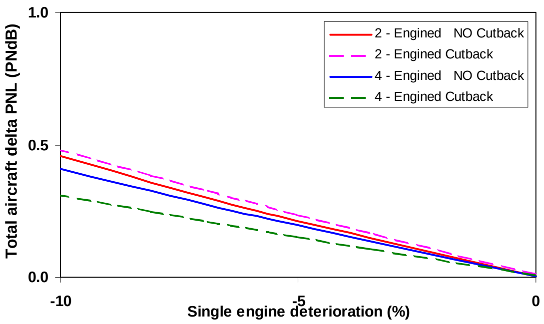

Figure 9.8: Noise changes due to trajectory and source changes.

Thus for the case where the engine thrust is not increased to maintain the original flight path trajectory, increases of less than ½ PNdB in Flyover noise could be expected for both two and four engined aircraft. However, the associated sideline noise levels, because of the reduced power, will be down by a similar amount. Note that the approach levels will not show any change other than a source effect, since the aircraft thrust is dictated by the requirement to follow the ILS beam, typically a 3-degree glide slope.

9.7.6 Liner effects

Table 9.11 shows the various acoustic liner types, with the number of inlets tested. The variation in the numbers of each type reflect the ability to gain access for testing and the number of that type in service with the airline. The individual results presented here represent measurement positions distributed around the cowls and show good consistency, thus implying no tendency for any area to be more susceptible to deteriorating acoustic performance.

Table 9.11: Liner types tested.

Liner Type		*Number tested*
1	Single layer, perforate	32
2	Single layer, linear – low porosity	4
3	Single layer, linear – high porosity	6
4	Double layer, perforate	2

Liner type 1, a single layer perforate, has by far the greatest number of test results because of the greater availability of the aircraft. Cowls with over 70,000 hours are still exhibiting reasonable resistances consistent with the manufacturer’s expectations. Although there are fewer samples of Type 4, the facing sheet construction is similar to the Type 1 and consequently would not be expected to show signs of deterioration.

Of potentially greater concern are the Type 2 liners whose construction, with a low porosity woven or linear facing sheet, would be expected to be more susceptible to blockage due to dust or corrosion from environmental damage than one of a higher porosity. With these types, it has been possible to compare the test results with the manufacturers original acoustic specification and they do not show any significant variation of resistance with operation time and are still within their original specification. The manufacturer’s previous experience is that where acoustic liners have been accidentally contaminated, they generally exhibit a marked increase in acoustic resistance. There is no evidence of any contamination with these Type 2 liners.

The Type 3 liners are also linear but are of greater porosity and hence lower acoustic resistance than the Type 2. They would therefore be expected to show results with less scatter about a target nominal value. Whilst this figure is not known, the results are again consistent with a clean liner.

The tolerance on resistance as defined by the engine manufacturer is consistent with associated aircraft noise levels varying by no more than 0.1 EPNdB. The impedance data collected during these tests, remaining within the typical tolerance band defined for manufacture, therefore supports the conclusion that with increasing age of nacelle inlet acoustic liner treatments, overall aircraft noise levels are principally unaffected.

9.7.7 Changes due to engine deterioration

Since the liner tests indicated little or no effect, the main noise changes due to engine deterioration results from the changes in engine cycle. Thus the changes in certified levels arising from the deterioration (by approximately 7%) of a single engine on the aircraft are summarised in Table 9.12.

Table 9.12: Aircraft noise changes (PNdB) for the deterioration of a single engine.

	2 Engined Aircraft		*4 Engined Aircraft*	
	Maintained Flight path	*Deteriorated Flight Path*	*Maintained Flight path*	*Deteriorated Flight Path*
SIDELINE	< ½	< -½	< ¼	< -¼
FLYOVER without Cutback	< ½	< ½	< ½	< ½
FLYOVER with Cutback	< ¼	< ½	< ¼	< ¼
APPROACH	< ¼	N/A	< ¼	N/A

The magnitudes of the changes in overall aircraft noise resulting from a significantly deteriorated engine are of the same order as the statistical scatter on individual aircraft certification measurements. Thus they would be measurable in certification trials.

9.8 Airframe deterioration

The performance of airframes, like engines, will deteriorate with time and use for a number of reasons. This deterioration will result in increased drag which, to maintain the mission, requires compensation through use of additional thrust. The additional fuel burn carries an emissions and noise penalty. Data available from the airlines have not proved to be suitable to specifically allow the identification of residual airframe deterioration (after that attributable to engines) owing to insufficient quantity of data and, importantly, the absence of weight information. A feel for the likely effect of airframe deterioration can be obtained from simple parametric analysis using typical levels of overall airframe deterioration expected by airlines. It is reasonable to suppose that cumulative deterioration of the airframe from several different sources may represent an overall efficiency loss of perhaps 1% to 2% of fuel burn [Ref. 9-14].

Typical increases in emissions production at cruise when the airframe has suffered deterioration were estimated using GSP. Models for undeteriorated engines were used. Engine thrust was increased to counter the increase in airframe drag due to deterioration (a 1% increase in drag requires a 1% increase in thrust from the engines). Results of the effect on emissions production from new engines at cruise are presented in Tables 9.13 and 9.14.

Table 9.13: Effect of 1% airframe drag increase on emissions production.

Engine Type	*fuel flow (%)*	*mass NOx (%)*	*mass CO (%)*	*mass HC (%)*
3	0.8	1.5	0.1	-1.1
7	0.9	1.7	0.0	0.7
13	0.9	1.4	-0.1	-0.3
14	0.8	1.2	-2.3	0.3
15	0.9	1.3	-2.1	0.3

Table 9.14: Effect of 2% airframe drag increase on emissions production.

Engine Type	*fuel flow (%)*	*mass NOx (%)*	*mass CO (%)*	*mass HC (%)*
3	1.7	3.2	0.4	-2.1
7	1.8	3.4	-0.1	1.3
13	1.8	2.9	-0.1	-0.6
14	1.7	2.4	-4.6	0.5
15	1.8	2.6	-4.0	0.6

In assessing the impact of airframe deterioration on noise, the composition of the aircraft drag, i.e. the balance between form drag and lift induced drag, needs to be understood. In practice it will only be the form drag that will be affected by the airframe deterioration, thus a 2% deterioration in overall drag observed at cruise needs to be translated into the change at take-off. For a typical civil jet transport the take-off drag comprises about 10% form drag and 90% induced drag [Ref. 9-15] but at cruise this changes to 75% and 25%. Thus 2% deterioration in cruise drag, because of the higher proportion of lift drag at take-off, will manifest itself as approximately 0.3% change in overall drag at take-off. For this magnitude of change and reference to Table 9.12 it can clearly be seen that the associated changes in noise for the airport environment is unlikely to be detectable.

9.9 Discussion

This Section describes the implications of deteriorations and the changes in emissions and noise, and looks at how these deteriorations are dealt with by operators through regular maintenance and repair.

9.9.1 Data and modelling accuracies

In this study the quality of data received from airlines was adequate and sufficiently consistent to carry out the planned analysis. In the validations of the method for calculating component efficiencies, the engine models and the changes in emissions and noise, it was assumed that all the small errors and assumptions are from statistically independent events and therefore not interrelated. Consequently it has been assumed that the total error is small. Results reported in this study have been consistent with airlines' own data where AEROCERT has had access to this.

9.9.2 Operational issues

In service, it is unlikely that an aircraft would be operating with all its engines in a very high state of deterioration. It has been observed that the average of accrued cycles since overhaul on engines within a fleet is low in comparison to the number of cycles on the highest cycle engines within the fleet. The effects of having engines of dissimilar states of deterioration are different for emissions and noise. The effects of the combinations are additive for fuel burn and emissions and will be reflected by the fleet average cycles and for noise a single highly deteriorated engine tends to dominate the total aircraft noise.

In this study the landing and take-off flight operating points that represent the noise measurement positions have been modelled either by maintaining the profile by restoring thrust or by allowing the profile to change as a result of a reduction of thrust due to deterioration but actual operations probably fall between these two extremes. AEROCERT Work Package 2 provides this information. Operators say that they do fully restore thrust.

9.9.3 Emissions

Fuel burn and emission rates of NO_x (by mass) increase with deterioration during typical cruise. The results of the application of generic levels of deterioration are summarised in Table 9.15. The level of change of fuel burn and NO_x production are dependent on the levels of deterioration of the individual components. For the cruise case, it was possible to carry out a more rigorous analysis which used available efficiency data to calculate emissions changes due to deterioration. The results of this are presented in Table J.

Table 9.15: Summary of estimated impact of deterioration on emissions at cruise.

Deterioration on each component	*Representative deterioration level*	*Δ Fuel flow (%)*	*Δ mass NO_x (%)*
1%	typical	+2½ to +3½	+2 to +4
2%	maximum	+5 to +7	+3 to +8

Table 9.10 provides detailed results of the consequence of deterioration and fuel flow increase on NO_x production. The variation in overall compressor efficiency change and fuel flow increases between the engines is reasonably large with a corresponding variation in percentage increases in NO_x. There is no relation between the fuel flow or NO_x increases and the typical number of cycles the engine will perform or the typical hour/cycle ratio. This implies that engine performance deterioration is a function of engine design rather than operation.

Results for the flight operating points in the vicinity of airports, which are representative of the typical noise operation points, are summarised in Table 9.16. The percentage increases in fuel flow rates are similar to those for cruise, but the increases in mass of NO_x emitted at each of the three flight points are greater in magnitude. Increases in the fuel burn and emissions at these flight points are of much less significance than for the increases at cruise due to the short period of operation at these points.

Table 9.16: Summary of impact of deterioration on emissions at the noise operating points.

		Full-power		Cutback		Approach	
Deterioration on each component	*Representative deterioration level*	*Δ FF (%)*	*Δ mass NO_x (%)*	*Δ FF (%)*	*Δ mass NO_x (%)*	*Δ FF (%)*	*Δ mass NO_x (%)*
1%	typical	3 to 4	4 to 8	3 to 4	4 to 9	4½	7 to 10
2%	maximum	6 to 8	10 to 18	6 to 8	10 to 19	9	15 to 19

Over the complete LTO cycle a deteriorated engine uses more fuel and produces increased amounts of all of the emissions species. For the maximum deterioration level considered, fuel flow and mass of NO_x increased by at least 8% in all cases compared to quoted certification values. Table Q summarises Tables H and I.

Table 9.17: Summary of impact of deterioration on emissions for the emissions certification LTO cycle.

Deterioration on each component	*Representative deterioration level*	*□ FF (%)*	*□ mass NO_x (%)*
1%	typical	4 to 10	4 to 7
2%	maximum	8 to 14	8 to 12

Emissions produced over the LTO cycle are used in the certification of engines. Currently the certification process is generally carried out on new engines, and probably takes no account of the effects of deterioration on emissions production. Most of today's engines comply with the Standards by a significant margin. However, with the demands for more stringent standards, this may become an issue.

9.9.4 Noise

Aircraft noise at full power is totally dominated by the jet mixing noise for the high bypass ratio engines considered in this study. At this condition the effect on the single engine source noise is likely to be less than 1 PNdB for a maximum expected deterioration of around 7%. At cutback power the effect of deterioration is again less than 1 PNdB for the combined fan and jet noise. At approach powers, although the fan will dominate the other engine sources, the airframe will then be of a comparable level. Changes in flight profile due to deteriorated engine power, where thrust is not increased to maintain the original flight path trajectory, only impact Flyover noise and by less than ½ PNdB increase. The acoustic liner measurements showed no significant variation of resistance (a measure of acoustic performance) with operation time for any of the liner types investigated. The impact of high levels of deterioration would be measurable in certification trials as the magnitude of changes in overall aircraft noise are of the same order as the scatter on individual aircraft certification measurements.

9.9.5 Current engine maintenance practices

Engine maintenance is based on a combination of scheduled checks/inspections and 'on-condition' monitoring. ECM reports are analysed by programs provided by the engine manufacturers. Detailed maintenance programmes are originally proposed by the engine manufacturer, but are adjusted by the airlines as experience is gained and maintenance checks are added or eliminated and intervals are similarly affected by operational. All changes have to be accepted by the certification authorities. EGT is usually considered to be the most important parameter from a monitoring point of view, in particular, the 'EGT margin'. Feedback from airlines indicates that it is currently uneconomic to change engines due to high fuel flow. Fuel prices are low enough that the cost of major maintenance action to counter increased fuel burn far outweighs the extra fuel costs incurred.

Some actions, e.g. adjustments and minor replacements, are carried out while engines are on-wing. The reason for removal of an engine could be one or more of a number of causes such as failed inspections/checks, mechanical damages or failure or bad performance, high EGT and fuel consumption. It appears that deterioration is not an over-riding reason to initiate overhaul; this is mainly decided on economic grounds. Within the data-sets supplied by the airlines collaborating with the AEROCERT partners, there is only limited information on the extent of performance restoration through overhaul. Component efficiency improvements of 2-3% seem to be achieved, but it is not possible to determine whether this is the maximum achievable, whether it is typical, or whether the as-new performance has been restored.

9.10 Conclusions

The conclusions of this work package are:

9.10.1 Deterioration

1. The typical deterioration of engine performance encountered in in-service engines, between removal for major overhaul, would result in an approximate overall deterioration in engine thrust of around 3-4% at a consistent throttle setting. Maximum deterioration would lead to substantially higher thrust losses.
2. It will be rare for an aircraft to be operating with both or all its engines in a high state of deterioration. Fleet average engine deterioration is much lower.
3. The rate of deterioration of the performance of an airframe is slow compared to that of an engine. Cumulative deteriorations on an airframe may, in time (many years), represent an overall efficiency loss that equates to up to 2% of cruise fuel burn.

9.10.2 Fuel and emissions changes

4. At cruise, fuel use on a single typically deteriorated engine may increase by up to 3.5%, and mass of NO_x emitted by up to 4%.

5. During take-off, climb and approach operations in the vicinity of airports engine fuel use may typically increase by up to 4%, while the mass of NO_x emitted may increase by up to 8-10%.
6. Over a simulated certification LTO cycle, engine fuel flow and mass of NO_x increased by between 4 and 10%. Most modern engines would still comply with the current certification Standards with the levels of deterioration reported. However this may not be true if more stringent Standards are adopted.
7. At maximum levels of deterioration, both fuel use and NO_x increases significantly at all conditions.
8. Fuel and emissions changes from deterioration are additive for each engine on the aircraft.
9. Airframe deterioration requiring an increase in cruise fuel burn of up to 2% would lead to an approximate increase in NO_x of 3%.

9.10.3 Noise changes

10. Single engine source noise is likely to increase by less than 1 PNdB for a very highly deteriorated engine at both full- and cutback powers. There will be little or no source noise change during approach.
11. Increases of less than ½ PNdB in Flyover noise could be expected from to flight profile changes due to deteriorated engine power. Differences for the two ICAO cutback-operating procedures are negligible.
12. Acoustic liner measurements showed no significant variation of resistance with operation time, therefore overall aircraft noise levels will be unaffected by the number of hours of acoustic liner use.
13. The magnitude of changes in overall aircraft noise due to deterioration are of the same order as the scatter on individual aircraft certification measurements.
14. A single highly deteriorated engine dominates aircraft noise on multi-engined aircraft.

9.10.4 Maintenance

15. Engine performance deterioration is not an over-riding reason to initiate overhaul; this is mainly decided on economic grounds. However, other reasons for initiation of major engine overhaul will be used as an opportunity to restore performance losses suffered due to deterioration. The extent of the restoration depends on the components affected and the maintenance action taken.
16. A substantial proportion of the performance deterioration is recovered by major overhaul. However, this programme has not been able to determine the extent of performance restoration compared to the performance of newly manufactured engines.

9.11 Recommendations

1. The current programme has examined a limited range of aircraft and engine types operated by some major European airlines. The gaps in this range include some important products and could be filled by acquiring the flight data from a small number of non-European airlines. This would ensure that policy related decisions on any changes to certification requirements are broadly based.

2. It is not clear whether current emission and noise certification standards include any allowance for engine or airframe deterioration in service. This needs to be clarified.
3. While the consequences of performance deterioration of fuel, emissions and noise have been assessed for the sources, i.e. the aircraft, this needs to be translated into impacts both at the local airport level and at the global level.

10 WP 5: Analysis, evaluation and options for improved certification procedures

This work package (5) draws together the earlier ‘fact finding’ activities undertaken by the partners. The deliverables of this Work Package are:

- A compilation of the activities and conclusions of the various work packages. This Final Report is the deliverable of that activity, giving an overview of the activities and conclusions per work package.
- An interactive workshop with partners, airports, EC, JAA and other stakeholders. This activity is reported on in the next sections.

This chapter concludes with some more general conclusions and recommendations.

10.1 Workshop and stakeholders’ views

As part of the Work Package 5, the AEROCERT team has organised a workshop. For this workshop, various stakeholders have been invited. The AEROCERT team has identified a number of stakeholders: aircraft manufacturers, airlines, aircraft and engine maintenance organisations, governmental policy makers, authorities, airports, engine manufacturers.

The aim of the workshop and role within AEROCERT project was twofold:

- To present the stakeholders the project results so far by giving presentation of the approach, (initial) findings, and ideas for options on improvements to the certification of the AEROCERT project. As such, this workshop serves as a means of dissemination.
- To collect the stakeholders’ responses and views on the AEROCERT findings. These responses and views are further discussed in a plenary meeting. The minutes of this workshop are distributed among the partners as well as the stakeholders present at the meeting for further comments. The final version of the minutes are then used to strengthen the work packages reports.

As a result, the feedback of the stakeholders’ views in the AEROCERT project enhances the AEROCERT findings. At the same time, a broad basis has been founded to enhance the general acceptance. It will then broaden AEROCERT results and provide a better view on the options for improvement of current certification regime.

The plenary workshop discussion has forwarded a number of observations, conclusions and remarks. Many of these have been used to enhance the individual work package reports. Some of the observations, conclusions or remarks are better reported outside of a work package content. These are listed in this chapter, ordered by work package:

10.1.1 WP1: comments and views

WP1 is essentially an overview of the current certification practises and agreed upon. There is no further need for review.

10.1.2 WP2: comments and views

WP2 - operation deals with the actual operations, as derived from the FDR data compared to the certification. The differences between the actual and certification flights are significant enough to identify options for a change in certification. However, it has been stressed by the aircraft manufacturers as well as the regulatory bodies that certification procedures serve to drive the design of aircraft, rather than to drive aircraft operations. As such, it is felt that the current certification procedures do serve that purpose well and do not need adjustments.

From this workshop, it is recommended to issue a statement of environmental performance that is not part of the aircraft certification. Recommended aircraft procedures should state a least-environmental impact variant.

For the LTO emission cycle, various improvements have been suggested in the WP2 and WP3 conclusions. These have been confirmed at the workshop. It has been acknowledged that these modifications have only a small impact on the efforts and costs of certification.

10.1.3 WP3: comments and views

From WP3, the stakeholders have acknowledged that the noise data that is needed to better assess the environmental impacts is available with the aircraft manufacturers. However, it has been noted that in many cases, aircraft manufacturing companies, especially the smaller ones, do not have ownership of the measured data. In such cases, right of ownership lies with the contractor, and only a minimum set of data required for the current noise certification is passed on to the aircraft manufacturer. This poses problems for changes to the noise certification.

For the emissions beyond the current LTO cycle, there is a general lack of sound and solid understanding of the possible impacts. At the workshop, the participants have, in general, confirmed the conclusion that further understanding is required in order to proceed with a certification process. For emissions at cruise and climb conditions, first, it has to be established what has to be protected against what. It is recognised that there is a public pressure to introduce regulation to protect the environment. There is a danger that due to this pressure, some form of certification regime is implemented that does not serve its purpose.

10.1.4 WP4: comments and views

From WP4, the workshop participants have concluded that there is no need for adjustments to change maintenance procedures to counteract any impacts due to engine or airframe deterioration.

10.2 AEROCERT Analysis, Evaluation and Options

The principal aims of the EC AEROCERT (Aircraft Environmental Impacts and Certification Criteria) Research Project, Contract No. AI-97-SC.242, have been to improve the understanding of the effects of flight-operational procedures and in-service deterioration on the (certificated) noise and emissions levels.

To accomplish these aims, AEROCERT has been analysing airline flight and operational data (FDR and ECM), together with associated noise and emissions performance for a range of aircraft types relative to the International Civil Aviation Organisation (ICAO) certification procedures and values. The analysis of many flights, multiple aircraft-engine combinations, and different operators allowed the AEROCERT team to study the diversity of operational procedures. Likewise, monitoring aircraft engines through part of the life cycle, has given the opportunity to study the extent of, and the reason for engine deterioration and the consequences for the noise and emission performance are determined.

10.2.1 Results and Recommendations

The wealth of data retrieved from the analysis has allowed comparison of the well-defined ICAO certification procedures with a diversity of aircraft operations as apparent from the recordings. The data from certification testing is compared with actual noise or emissions operational values.

From the comparisons, many observations have been made. They have led to recommendations regarding better impact assessments of noise and emissions. These recommendations and conclusions are written down in the individual Work Package reports. Condensed versions of the reports are included in this Final Report.

In broad, general terms (the AEROCERT team recommends to read the work package conclusions and recommendations) the following conclusions and recommendations are found:

- Assessing noise impact based on certification data relies upon a few basic methods, with a large numbers of derivative methods. Significant improvements regarding accuracy of impact assessment are possible if additional noise data could be made available to the public domain.
- The investigation of flight profiles has found a large variation in thrust settings at take-off, especially for large twin aircraft that offer many opportunities for using flexed thrust in take-off, intersection take-offs and earlier turns. It has been found that weight is a highly influential factor in noise production as well, both for landing and take-off. Therefore, significant differences between the individual flight profiles in the recorded flights are apparent. Naturally, this also implies significant differences between the profiles of certification and recorded flights.
- The flight profiles and the resulting noise that are deemed characteristic for the day to day traffic have been compared to the certification flight profiles as well as the certification noise test data. From this comparison, it has shown that for wide-body short haul operations, noise at the lower flyover point may be significantly lower than the certification values, but at the same time, no direct relation between flyover noise and contour areas is apparent. Narrow body aircraft and twin-engine, long haul operations generate more noise at take-off than certification values indicate. Four-engined, long-haul operations appear to be quieter than certification values. Based on these observations, a better impact assessment can be made if the flight profiles used for impact assessment reflect the day to day operations better.
- The above observations do not imply a recommendation to change the noise certification procedures, rather to secure certification noise map data that can be used for noise assessment purposes.
- Regarding emissions at and around airports, a better impact assessment can be made by having information available on more species and obtaining certification data for additional thrust levels applied in actual operations. The current Landing and Take-off (LTO) cycle is regarded as a worst case situation for the aircraft emissions at airports and is still a viable means of certification. Times in mode for the LTO cycle are generally found to be less than specified in the certification test regime.
- Regarding gaseous emissions impact on the global atmosphere and at higher altitudes, the current state of the art technology is not yet capable of providing well-proven and well-

accepted methods for impact assessments. Although there are models to calculate emissions at (higher) altitudes at reasonable accuracy, the transition from emissions to immissions is still not fully understood. Further research, especially into impact assessments is highly recommended. ICAO/CAEP considers the issue currently a priority work item.

- The flight data recordings and engine condition monitoring data show appreciable reduction in engine component efficiency and commensurate fuel burn increase over the on-wing maintenance cycle. From acoustic liner measurements, and the monitoring of engine health over many flights, it is observed that the evident in-service deterioration of engine components does not significantly change the noise performance. No justification has been found to represent deterioration effects in the noise certification procedures.
- Regarding emissions, the deterioration effects of acoustic liners are indeed noticeable. At maximum levels of deterioration, both fuel use and NO_x emission increase significantly at all conditions. It is recommended that the consequences of deterioration of fuel and emissions need to be translated into impacts both at the local airport level and at the global level. Only after such an assessment, it will be possible to rule out including deterioration effects into emissions certification.

10.3 AEROCERT Overall Conclusion and Future Work

The AEROCERT consortium has analysed the noise and emissions of a significant number of recorded flights for a number of representative aircraft. Comparison of these flights with each other and with for equivalent certification flights has shown marked variation in aircraft operations for a certain type or mission and, at the same time, has shown significant differences relative to certification flight test conditions.

The observations and conclusions, drawn from the wealth of flight data in this project, are an excellent starting point for future research on tools, models and data required for improved impact assessment and certification. At the same time the certification data is put into perspective when it comes to impact assessment based on certification criteria.

A number of AEROCERT findings have already been identified as relevant to ongoing analysis within the noise work programme of ICAO/CAEP and its working group 1 (noise technical) and WG3. Specifically comparisons between certificated and actual noise performance are of interest to the JET-10 group, which is looking at noise certification requirements.

At the workshop it has become evident that AEROCERT reporting could benefit developments on ICAO Annex 16, FAR 34 and the JAR 34. It has been strongly recommended to bring the AEROCERT findings forward drawing, as far as possible, on the available supporting data.

It is expected that several ongoing projects in the field of aviation operations, in relation to noise, emissions and others, may benefit from the AEROCERT findings.

There was, and still is, a large need for basic flight data for various aircraft types and engines. Already during the project the data were used, within the agreements with the data supplying airlines, to support working groups mentioned above.

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