European Aviation Safety Agency

Notice of Proposed Amendment 2017-01

Implementation of the CAEP/10 amendments on climate change, emissions and noise

RMT.0513 & RMT.0514

EXECUTIVE SUMMARY

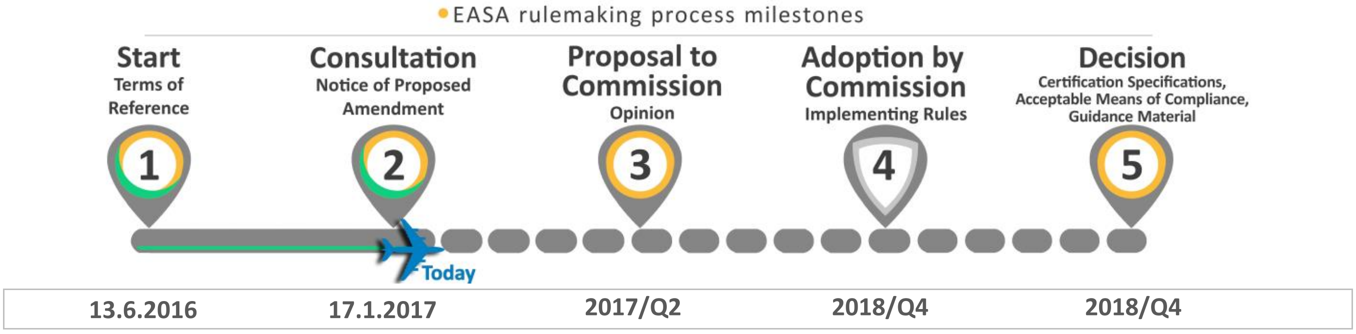
This Notice of Proposed Amendment (NPA) addresses the environmental issues related to the CAEP/10 amendments and their implementation within the European regulatory system.

The International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) agreed in February 2016 on various amendments to ICAO Annex 16 'Environmental Protection' to the Convention on International Civil Aviation (the 'Chicago Convention'). This included general amendments to the existing Volume I 'Aircraft Noise' and Volume II 'Engine emissions' Standards and Recommended Practices (SARPs). CAEP also agreed on two new standards: one on non-volatile particulate matter (nvPM) emissions to be included in Volume II, and an entirely new Volume III for aeroplane CO_2 emissions.

Furthermore, the NPA is linked to ICAO State Letters AN 1/17.14-16/53, AN 1/17.14-16/55 and AN 1/17.14-16/56. It proposes to transpose CAEP/10 amendments into Article 6 of Regulation (EC) No 216/2008, Annex I (Part-21) to Regulation (EU) No 748/2012 and the related acceptable means of compliance (AMC) and guidance material (GM), as well as into the European Aviation Safety Agency (EASA) Certification Specifications (CSs) for 'Aircraft Engine Emissions and Fuel Venting' (CS-34), 'Aircraft Noise' (CS-36) and 'Aeroplane CO_2 Emissions' (CS-CO_2).

The objective of this NPA is to ensure alignment with ICAO provisions. The proposed changes are expected to maintain a high uniform level of environmental protection as well as provide a level playing field for all actors in the aviation sector.

Action area:	Aircraft noise (RMT.0513) & climate change (RMT.0514)		
Affected rules:	— Regulation (EC) No 216/2008; — Part-21 and related AMC/GM; — CS-34; — CS-36; — CS-CO_2 (new)		
Affected stakeholders:	Design and production organisations; design approval holders (DAHs); National Aviation Authorities (NAAs); Member States		
Driver:	Environment	**Rulemaking group:**	No
Impact assessment:	Full (by ICAO CAEP)	**Rulemaking Procedure:**	Standard



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1. About this NPA

1.1. How this NPA was developed

The European Aviation Safety Agency (EASA) developed this NPA in line with Regulation (EC) No 216/2008[1] (hereinafter referred to as the 'Basic Regulation') and the Rulemaking Procedure[2]. This rulemaking activity is included in the EASA 5-year Rulemaking Programme[3] under rulemaking tasks RMT.0513 and RMT.0514. The text of this NPA has been developed by EASA. It is hereby submitted to all interested parties[4] for consultation.

The major milestones of this rulemaking activity to date are provided on the title page.

1.2. How to comment on this NPA

Please submit your comments using the automated **Comment-Response Tool (CRT)** available at **http://hub.easa.europa.eu/crt/**[5].

The deadline for submission of comments is **17 April 2017.**

1.3. The next steps

Following the closing of the public commenting period, EASA will review all comments.

Based on the comments received, EASA will develop an opinion containing the proposed amendments to Regulations (EC) No 216/2008 and (EU) No 748/2012. The opinion will be submitted to the European Commission, which will use it as a technical basis in order to prepare European Union (EU) regulations.

Following the adoption of the regulation, EASA will issue decisions containing the related AMC/GM, as well as the associated CSs (CS-34, CS-36 and CS-CO_2).

The comments received and the EASA responses thereto will be reflected in a comment-response document (CRD), which will be annexed to the opinion.

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[1] Regulation (EC) No 216/2008 of the European Parliament and of the Council of 20 February 2008 on common rules in the field of civil aviation and establishing a European Aviation Safety Agency, and repealing Council Directive 91/670/EEC, Regulation (EC) No 1592/2002 and Directive 2004/36/EC (OJ L 79, 19.3.2008, p. 1) (http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1467719701894&uri=CELEX:32008R0216).

[2] EASA is bound to follow a structured rulemaking process as required by Article 52(1) of the Basic Regulation. Such a process has been adopted by the EASA Management Board (MB) and is referred to as the 'Rulemaking Procedure'. See MB Decision No 18-2015 of 15 December 2015 replacing Decision 01/2012 concerning the procedure to be applied by the Agency for the issuing of opinions, certification specifications and guidance material (http://www.easa.europa.eu/the-agency/management-board/decisions/easa-mb-decision-18-2015-rulemaking-procedure).

[3] http://easa.europa.eu/rulemaking/annual-programme-and-planning.php

[4] In accordance with Article 52 of the Basic Regulation and Articles 6(3) and 7 of the Rulemaking Procedure.

[5] In case of technical problems, please contact the CRT webmaster (crt@easa.europa.eu).

2. In summary — why and what

2.1. Why we need to change the rules — issue/rationale

Following its 10th formal meeting (CAEP/10) from 1 to 12 February 2016, the ICAO CAEP recommended amendments to ICAO Annex 16, Vol I 'Aircraft Noise' and Vol II 'Aircraft Engine Emissions', as well as the creation of a new Vol III 'Aeroplane CO_2 Emissions'. These recommendations are the outcome of work conducted during the three years preceding the meeting in accordance with the CAEP/10 Work Programme. It is further envisaged that these proposed amendments will be adopted, after consultation, by the ICAO Council in 2017/Q1.

The proposed amendments to Vol I of ICAO Annex 16 include updates to the existing aircraft noise measurement specifications. No new standard on aircraft noise was recommended at CAEP/10.

The proposed amendments to Vol II of ICAO Annex 16 include updates to the existing aircraft engine emissions measurement specifications. In addition, a new nvPM-emissions mass concentration standard has been introduced as Chapter 4 into Part III. This is supplemented by Appendix 7 which contains the certification procedures, including measurement methodology, system operation and instrument calibration.

The proposed new Vol III of ICAO Annex 16 introduces an aeroplane CO_2 emissions standard for both new and in-production aeroplane types.

In addition to the amendments to ICAO Annex 16, CAEP/10 approved ICAO Doc 9501 'Environmental Technical Manual' (ETM), Vol I 'Procedures for the Noise Certification of Aircraft', Vol II 'Procedures for the Emissions Certification of Aircraft Engines' and a new Vol III 'Aeroplane CO_2 Emissions'. The updated ETM Vols provide clarifications and additional guidance material to facilitate a harmonised implementation of ICAO Annex 16.

The current EASA rules and measures make a direct reference to the amendments to Vols I and II of ICAO Annex 16, as well as to specific editions of the ETM. These rules and measures need therefore to be amended to ensure that the EU regulations in the field of aviation environmental protection are aligned with the latest international SARPs and associated guidance material.

For a more detailed analysis of the issues addressed by this proposal, please refer to the Section 4.1 'IA'.

2.2. What we want to achieve — objectives

The overall objectives of the EASA system are defined in Article 2 of the Basic Regulation. This proposal will contribute to the achievement of the overall objectives by addressing the issues outlined in Chapter 2.

The specific objective of this proposal is to ensure a high uniform level of environmental protection, as well as to provide a level playing field for all actors in the aviation sector, by aligning the European implementing rules (IRs) and AMC/GM with the ICAO SARPs (ICAO Annex 16) and guidance (ETM).

2.3. How we want to achieve it — overview of the proposals

This NPA proposes amendments to:

- the Basic Regulation;
- Part-21;
- AMC/GM to Part-21;
- CS-34; and
- CS-36.

Additionally, it proposes to create a new CS-CO_2.

The proposed amendments are drafted to reflect the proposed updates in the ICAO SARPs and guidance material, as described hereafter:

ICAO Annex 16, Vol I amendment (see Section 6.1 'Appendix 1')

This amendment addresses technical issues arising from the application of the SARPs and related guidance for aircraft noise certification, and includes miscellaneous editorial changes and corrections to enhance the documents' utility and compatibility with ETM Vol I:

(a) Definition of reference conditions

The amendment aims to ensure consistency in the way each of the Chapters of Vol I define the reference atmosphere in order to improve clarity, thereby providing for a common interpretation. The proposed changes use common text to define the same concept. Moreover, the current situation whereby identical text (e.g. in current Chapter 3, Section 3.6.1.5 and Chapter 8, Section 8.6.1.5) has different intended meanings has been remedied. In addition, references to the ICAO 'standard atmosphere' and to related guidance material in the ETM have been added.

This proposal also includes amendments to the definition of the reference day speed of sound in terms of a temperature lapse rate, and to the derivation of reference power in terms of temperature and pressure lapse rates, as defined by the ICAO 'standard atmosphere'.

(b) Flight path measurement techniques

The amendment proposes to remove references to outdated flight path measurement techniques and align the text of Vol I with the extensively revised guidance material of ETM, Vol I.

(c) Guidelines for noise certification of tilt rotor

The amendment proposes to correct editorial and technical errors in Attachment F 'Guidelines for noise certification of tilt-rotor aircraft' and standardise the terminology and symbols throughout Vol I.

ICAO Annex 16, Vol II amendment (see Section 6.2 'Appendix 2')

This proposed amendment of the SARP in Vol II addresses technical issues arising from the application of the SARP and related guidance for aircraft engine emissions certification, and includes miscellaneous editorial changes and corrections:

(a) Definition of 'engine type certification'

The term 'type-certificated engine' is used in the definition of the 'derivative version' of an engine, and 'engine type certificate' is also used in ETM, Vol II. In that context, a definition of the term 'type certificate' has been added in Part I, Chapter 1.

(b) Update of the sampling-line temperature stability limits

The Vol II, Appendix 3, paragraph 5.1.2 requirements for sampling-line temperature stability are to maintain the line temperature at 160 ± 15°C (with a stability of ± 10 °C). This could be interpreted to allow a range of temperatures of 135 to 185°C, whereas the intent of the current text is to ensure that the line temperature is maintained at 160±15°C (i.e. 145°C to 175°C). To clarify this issue, the amendment proposes the deletion of 'with a stability of ± 10°C', which also aligns the text with Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) 1256D.

(c) Change of the NOx analyser calibration gas to NO

For the NOx analyser, the current Attachment D to Appendix 3 requires a test gas of NO in zero nitrogen and a calibration gas of NOx in zero nitrogen. SAE ARP 1256D recommends NOx for both, test and calibration gases. This inconsistency between ICAO and SAE specifications was discussed within CAEP and SAE, and both groups came to the same conclusion of specifying the use of NO in zero nitrogen for both test and calibration gases.

In practice, the NO bottles contain traces of NO_2 (usually a few ppm). A NOx bottle could be misinterpreted as a true mixture of NO and NO_2 compared to an NO bottle with traces of NO_2. Some bottle providers indicate the NO concentration as well as the NOx concentration to reflect the presence of NO_2 in small quantities. Generally, the NOx analyser can be calibrated by two different approaches depending on the measurement mode being utilised ('NO only' mode or 'NOx' mode). The NO mode is considered as the default mode since NO is what is measured by the NOx analyser. When the NO mode is used, the presence of NO_2 is not desirable. In this case, it is appropriate to require NO in zero nitrogen for both the calibration gas and the test gas, instead of NOx in zero nitrogen. Thus, the calibration and test gas for the NOx analyser in Attachment D to Appendix 3 should be NO in zero nitrogen.

The amendment proposes to change the calibration gas to NO in Attachment D to Appendix 3, and ETM, Vol II provides technical procedural information on the NOx analyser calibration.

(d) Change in the naphthalene content within the test fuel specifications

The current emissions test fuel specification allows naphthalene to be present in the fuel between 1 % vol. and 3.5 %vol. An ICAO/CAEP investigation highlighted that manufacturers and organisations involved in gas turbine emissions measurements have reported difficulties in obtaining fuel that meets the minimum-naphthalene content test fuel specification of Appendix 4. This investigation concluded that the ICAO Annex 16 naphthalene limits are not representative of current, commercially available jet fuel.

When consideration was given to removing the lower limit on the naphthalene content in the emissions test fuel specification (i.e. from 1 % vol. to 0 % vol.), it was concluded that there would be no effect on gaseous emissions levels, and a negligible effect on the 'Smoke Number' (SN) level as long as the aromatic and hydrogen content remains within the current emissions test fuel specification limits. There is no proposal to change the current aromatic and hydrogen limits.

The amendment proposes to change the naphthalene content range of the emissions test fuel specification (Appendix 4) to between 0 % vol. and 3 % vol. (from between 1 % vol. and 3.5 % vol).

(d) Introduction of an aircraft engine nvPM (Chapter 4 and Appendix 7)

Aircraft engines burning hydrocarbon-based fuels emit gaseous and Particulate Matter (PM) emissions as by-products of combustion. At the engine exhaust, particulate emissions mainly consist of ultrafine soot or black carbon emissions. Such particles are called non-volatile PM (nvPM). Compared to traditional diesel engines, non-volatile particles from gas turbine engines are typically smaller in size. Their geometric mean diameter ranges approximately from 15 nanometres (nm) to 60 nm (0.06 micrometres; 10nm = 1/100 000 of a millimetre (mm)). These particles are ultra-fine and invisible to the human eye.

During the CAEP/10 meeting, the first nvPM Standard for aircraft engines was recommended. The proposed amendment includes the new nvPM engine emissions Standard in Chapter 4 as well as the nvPM sampling and measurement system provisions in Appendix 7. The proposed nvPM Standard, which will apply to turbofan and turbojet engines manufactured as from 1 January 2020, is for aircraft engines with rated thrust greater than 26.7 kN.

The regulatory level for the nvPM Standard is the nvPM mass concentration that is equivalent to the current ICAO Annex 16, Vol II SN regulatory level. If an engine meets the current SN Standard, based on the design of the regulatory level, it will also meet the proposed nvPM Standard. Therefore, the proposed CAEP/10 nvPM Standard does not introduce a new stringency.

The purpose of the engine exhaust emission certification is to compare engine technologies and to ensure that the engines produced comply with the prescribed regulatory limits. The nvPM sampling and measurement system requirements, as described in the proposed Appendix 7, standardise the particle losses in the measurement system such that particle losses are minimised and that engine measurements performed by different engine manufacturers and test facilities are directly comparable. The proposed nvPM Standard will allow, for the first time, the technological comparison of different engine type designs in terms of nvPM emissions.

The nvPM sampling and measurement system will lose a portion of the particles when they travel through the sampling lines because of the very small size of the nvPM particles. Therefore, the nvPM emissions measured at the instruments will be lower than the values at the engine exit plane. For emission inventories and impact assessments, nvPM emissions at the engine exit should be estimated through application of a standardised methodology to better reflect real-world emissions. To achieve this, an nvPM system loss correction method is proposed, and the reporting of nvPM system loss correction factors is requested (Part IV and Appendix 8). The proposed Part IV and Appendix 8 request the reporting of particle losses although this is not part of the proposed nvPM certification requirements.

Overall, the proposed nvPM Standard will allow manufacturers to become more familiar with the nvPM measurement certification requirements. It will also provide data to support the development of an nvPM mass and number landing take-off (LTO)-based Standard, aiming for CAEP/11 in 2019, which will be more relevant to health and climate impacts.

(e) Update of ICAO Annex 16, Vol II to include the new nvPM emissions Standard

The amendment proposes to introduce the necessary changes into a large number of Sections in order to incorporate the proposed new nvPM Standard.

ICAO Annex 16, Vol. III — 1st Edition (see Appendix 6.3)

The purpose of the 1st Edition of ICAO Annex 16, Vol III is to implement the new Standard and related guidance for aeroplane CO_2 emissions certification.

Vol. III is applicable to new aeroplane type designs as from 1.1.2020, except for aeroplanes with a maximum take-off mass (MTOM) of less than or equal to 60 t and with a maximum operational passenger seating configuration (MOPSC) of less than or equal to 19 seats, for which the applicability date is 1.1.2023. The requirements for aeroplane type designs that are already in production are also applicable as from 1.1.2023. If an in-production aeroplane type design is changed at a time beyond 1.1.2023 and meets agreed change criteria, then the aeroplane will have to comply with the CO_2 emissions Standard. As from 1.1.2028, there will be a general production cut-off irrespective of whether the type design has been changed, which means that in-production aeroplane types can only continue to be produced if the design meets the Standard. The CO_2 emissions Standard covers subsonic jet aeroplanes with an MTOM of greater than 5 700 kg and propeller-driven aeroplanes with an MTOM of greater than 8 618 kg. The CO_2 emissions Standard is especially stringent for larger aeroplanes with an MTOM of greater than 60 t, where it will have the greatest environmental benefit. This recognises the fact that the designs of larger aeroplanes have had access to the broadest range of CO_2 emissions reduction technologies. For aeroplanes with an MTOM of less than or equal to 60 t, the Standard provides some margin for a sector that has not had access to the most advanced technologies.

Vol. III was designed to be environmentally effective, technically feasible and economically reasonable, while considering environmental interdependencies. The final decision on the CO_2 emissions Standard was supported by a data-informed process that included a cost-effectiveness modelling analysis of various stringency and applicability options.

ICAO Doc 9501 'Environmental Technical Manual', Vol. I 'Procedures for the Noise Certification of Aircraft'

The document was revised during the 10th CAEP cycle[6]. The revision includes various editorial improvements as well as the following changes:

(a) new guidance on the calculation of confidence intervals for interpolation between already approved noise/mass values (Chapter 4.2);

(b) improved guidance to reflect modern aircraft tracking methods using differential global positioning tracking systems (Chapter 3.2);

(c) introduction of guidelines for recertification of aircraft to ICAO Annex 16, Vol I, Chapter 14 (Chapter 9); and

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[6] The latest version is available at http://www.icao.int/environmental-protection/Pages/environment-publications.aspx.

(d) introduction of guidelines on the certification standards for tilt rotors into Annex 16, Vol I, Chapter 13 and Attachment F (Chapter 7).

ICAO Doc 9501 'Environmental Technical Manual', Vol. II 'Procedures for the Emissions Certification of Aircraft Engines'

This document was revised during the 10th CAEP cycle[7]. The revision includes new guidance text associated with:

(a) clarification of the carbon balance check (Appendix 3, paragraph 6);

(b) clarification of the engine type certification definition (Part I, Chapter 1);

(c) clarification of the calibration gases for the NOx analyser (Appendix 3, Attachment D);

(d) guidance text on the possibility to elect to comply with the latest Standard (Part III, Chapter 2);

(e) clarification of the probe temperature (Appendix 3, paragraph 5);

(f) technical and equivalent procedures to meet the fuel venting requirements (Part II, Chapter 2);

(g) guidance on the 'no emissions change' certification process (Part III, Chapter 2);

(h) procedures for the nvPM emissions certification of aircraft engines (Part III, Chapter 4 and Appendix 7); and

(i) miscellaneous editorial changes and corrections to enhance the documents.

ICAO Doc 9501 'Environmental Technical Manual', Vol III 'Procedures for the CO_2 Emissions Certification of Aeroplanes' (see Section 6.3.3 'Appendix 3')

The new Vol III of the ETM was created during the 10th CAEP cycle to complement the new ICAO Annex 16, Vol III.

2.4. What are the expected benefits and drawbacks of the proposals

The expected benefits and drawbacks of the proposal are summarised below. For the full impact assessment of alternative options, please refer to Chapter 4 'IA'.

The Impact Assessment (IA) has highlighted the expected benefits and drawbacks of the two policy options identified, namely: leave current rules unchanged (i.e. 'do nothing') or implement the CAEP/10 amendments. Out of these two options, only Option 2 (implementation of the CAEP/10 amendments) has positive impacts in all identified aspects (environmental, social, economic and harmonisation), while Option 1 ('do nothing') has negative impacts in all these aspects. It is therefore proposed to select Option 2 and proceed with the implementation of the CAEP/10 amendments.

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[7] The latest version is available at http://www.icao.int/environmental-protection/Pages/environment-publications.aspx.

3. Proposed amendments and rationale in detail

The text of the amendment is arranged to show deleted text, new or amended text as shown below:

- deleted text is struck through;
- new or amended text is highlighted in grey;
- an ellipsis '[…]' indicates that the rest of the text is unchanged.

3.1. Draft regulation (Draft EASA opinion)

3.1.1. Draft Articles to be included in the draft amending Regulation amending Regulation (EC) No 216/2008

Article 1

In Article 6 of Regulation (EC) No 216/2008, paragraph 1 is amended as follows:

1. Products, parts and appliances shall comply with the environmental protection requirements contained in the 7th Edition of Volume I as amended by Amendment ~~11-B~~12~~, and in~~ the 3rd Edition of Volume II as amended by Amendment ~~8~~9 and in the 1st Edition of Volume III of Annex 16 to the Chicago Convention as applicable on 1 January 201~~5~~8, except for the Appendices to Annex 16.

Article 2

1. Member States may grant exemptions to production organisations against the aeroplane CO_2 Standard established in Volume III, Part III, Chapter 2, paragraph 2.1.1 (a) to (g) of Annex 16 to the Chicago Convention.

2. Exemptions shall be granted under the following conditions:

   (a) such exemptions shall be granted in consultation with the Agency;

   (b) in the case of new aeroplanes, the maximum exemptions per type certificate shall not be more than:

% Margin to CAEP/10 New Type Regulatory Level	Maximum Exemptions per Aeroplane Type Certificate
0 to 2	40
2 to 4	80 – 20 × percent margin to regulatory level
More than 4	0

   (c) in the case of in-production aeroplanes, the maximum exemptions per type certificate shall not be more than:

% Margin to CAEP/10 In-production Type Regulatory Level	Maximum Exemptions per Aeroplane Type Certificate
0 to 2	75
2 to 10	90 – 7.5 × percent margin to regulatory level
More than 10	15

(d) when considering a request for exemption, the production organisation shall provide the Member State with information such that it can take into account:

  (i) the justification provided by the production organisation responsible for manufacturing the exempted aeroplane, including, but not limited to, considerations of technical issues, adverse economic impacts, environmental effects, impact of unforeseen circumstances, and equity issues;

  (ii) the number of new or in-production aeroplanes affected; and

  (iii) the total number of exemptions granted for that aeroplane type; and

(e) when granting the exemption, the Member State shall specify in the exemption as a minimum:

  (i) the aeroplane's type certificate number; and

  (ii) the maximum number of new or in-production aeroplanes included in the exemption.

3. Organisations responsible for manufacturing aeroplanes under an exemption granted in accordance with this Article shall:

(a) ensure that the aeroplane statement of conformity reads: 'Aeroplane exempted from the First Edition (unamended) of ICAO Annex 16, Volume III, Chapter 2, paragraph 2.1.1.[x]', as relevant to paragraph 1 of this Article;

(b) have a quality control process for maintaining oversight of, and managing the production of, affected aeroplanes; and

(c) provide, on a regular basis, to the Member State that granted the exemption and the organisation responsible for the aeroplane design, details on the exempted aeroplanes produced, including aeroplane type, model and serial number.

4. Member States that granted an exemption shall, without undue delay, communicate to the Agency all data referred to in paragraphs 2(d), 2(e) and 3(c). The Agency shall establish and maintain a register containing such data and make it publicly available.

3.1.2. Part-21

SECTION A — TECHNICAL REQUIREMENTS

SUBPART B — TYPE-CERTIFICATES AND RESTRICTED TYPE-CERTIFICATES

1. 21.A.18 is amended as follows:

21.A.18 Designation of applicable environmental protection requirements and certification specifications

[...]

(b) The applicable fuel venting, smoke, gaseous and particulate matter aircraft engine emissions requirements for the issue of a type-certificate for an aircraft and engine are prescribed according to the provisions of Chapter 1 of Part II and Chapter 1 of Part III of~~in~~ Annex 16, Volume II to the Chicago Convention and:

1. for prevention of intentional fuel venting, in Volume II, Part II, Chapter 2;
2. for smoke and gaseous emissions of turbo-jet and turbofan engines intended for propulsion only at subsonic speeds, in Volume II, Part III, Chapter 2;~~ and~~
3. for smoke and gaseous emissions of turbo-jet and turbofan engines for propulsion only at supersonic speeds, in Volume II, Part III, Chapter 3~~.~~;and
4. for particulate matter emissions of turbojet and turbofan engines intended for propulsion only at subsonic speeds, in Volume II, Part III, Chapter 4.

(c) The applicable aeroplane CO_2 emissions requirements for the issue of a type certificate for an aeroplane are prescribed according to the provisions of Chapter 1 of Part II of Annex 16, Volume III to the Chicago Convention and:

1. for subsonic jet aeroplanes, in Volume III, Part II, Chapter 2; and
2. for propeller-driven aeroplanes, in Volume III, Part II, Chapter 2.

(d) The Agency shall issue, in accordance with Article 19 of Regulation (EC) No 216/2008, certification specifications providing for acceptable means to demonstrate compliance with the noise and the emission requirements laid down in points (a), ~~and~~ (b) and (c) respectively.

2. 21.A.31 is amended as follows:

21.A.31 Type design

(a) The type design shall consist of:

[...]

4. any other data necessary to allow by comparison~~,~~ the determination of the airworthiness~~,~~ and the environmental characteristics ~~of noise, fuel venting, and exhaust emissions~~ (where applicable) of later products of the same type.

3. 21.A.41 is amended as follows:

21.A.41 Type-certificate

The type-certificate and restricted type-certificate are both considered to include the type design, the operating limitations, the type-certificate data sheet for airworthiness and emissions, the applicable type-certification basis and environmental protection requirements with which the Agency records compliance, and any other conditions or limitations prescribed for the product in the applicable certification specifications and environmental protection requirements. The aircraft type-certificate and restricted type-certificate, in addition, shall both include the applicable operational suitability data certification basis, the operational suitability data and the type-certificate data sheet for noise. The aircraft type certificate and restricted type certificate data sheet shall include the record of CO_2 emissions compliance, and t~~T~~he engine type-certificate data sheet shall include the record of exhaust emissions compliance.

SUBPART D — CHANGES TO TYPE-CERTIFICATES AND RESTRICTED TYPE-CERTIFICATES

4. 21.A.91 is amended as follows:

21.A.91 Classification of changes in type-certificate

Changes in type-certificate are classified as minor and major. A 'minor change' is one that has no appreciable effect on the mass, balance, structural strength, reliability, operational characteristics, other characteristics affecting the airworthiness of the product, or environmental ~~characteristicsnoise, fuel venting, exhaust emission, operational suitability data or other characteristics affecting the airworthiness of the product~~. Without prejudice to point 21.A.19, all other changes are 'major changes' under this Subpart. Major and minor changes shall be approved in accordance with points 21.A.95 or 21.A.97, as appropriate, and shall be adequately identified.

SUBPART F — PRODUCTION WITHOUT PRODUCTION ORGANISATION APPROVAL

5. 21.A.130 is amended as follows:

21.A.130 Statement of conformity

[...]

(b) A statement of conformity shall include:

1. for each product, part or appliance, a statement that the product or appliance, conforms to the approved design data and is in condition for safe operation; and
2. for each aircraft, a statement that the aircraft has been ground and flight checked in accordance with 21.A.127(a); and
3. for each engine, or variable pitch propeller, a statement that the engine or propeller has been subjected by the manufacturer to a final functional test, in accordance with point 21.A.128; and
4. additionally, in the case of environmental requirements~~engines,~~:

(i) a statement that the completed engine is in compliance with the applicable NO_X emissions requirements on the date of manufacture of the engine; and

(ii) a statement on whether the aeroplane has been issued with an exemption against the applicable CO_2 emissions requirements.

[...]

SUBPART G — PRODUCTION ORGANISATION APPROVAL

6. 21.A.145 is amended as follows:

21.A.145 Approval requirements

The production organisation shall demonstrate, on the basis of the information submitted in accordance with point 21.A.143 that:

[...]

(b) with regard to all necessary airworthiness and environmental~~, noise, fuel venting and exhaust emissions~~ data:

1. the production organisation is in receipt of such data from the Agency, and from the holder of, or applicant for, the type-certificate, restricted type-certificate or design approval, including any exemption granted against the CO_2 production cut-off requirements, to determine conformity with the applicable design data;

2. the production organisation has established a procedure to ensure that airworthiness and environmental~~, noise, fuel venting and exhaust emissions~~ data are correctly incorporated in its production data; and

3. such data are kept up to date and made available to all personnel who need access to such data to perform their duties;

(c) with regard to management and staff:

1. a manager has been nominated by the production organisation, and is accountable to the competent authority. His or her responsibility within the organisation shall consist of ensuring that all production is performed to the required standards and that the production organisation is continuously in compliance with the data and procedures identified in the exposition referred to in point 21.A.143;

2. a person or group of persons have been nominated by the production organisation to ensure that the organisation is in compliance with the requirements of this Annex I (Part 21), and are identified, together with the extent of their authority. Such person(s) shall act under the direct authority of the accountable manager referred to in point (1). The persons nominated shall be able to show the appropriate knowledge, background and experience to discharge their responsibilities;

3. staff at all levels have been given appropriate authority to be able to discharge their allocated responsibilities and that there is full and effective coordination within the

production organisation in respect of airworthiness and environmental~~, noise, fuel venting and exhaust emission~~ data matters;

[...]

7. 21.A.147 is amended as follows:

21.A.147 Changes to the approved production organisation

(a) After the issue of a production organisation approval, each change to the approved production organisation that is significant to the showing of conformity or to the airworthiness and environmental ~~characteristics of noise, fuel venting, and exhaust emissions~~ of the product, part or appliance, particularly changes to the quality system, shall be approved by the competent authority. An application for approval shall be submitted in writing to the competent authority and the organisation shall demonstrate to the competent authority before implementation of the change, that it will continue to comply with this Subpart.

[...]

SUBPART H — CERTIFICATES OF AIRWORTHINESS AND RESTRICTED CERTIFICATES OF AIRWORTHINESS

8. 21.A.174 is amended as follows:

21.A.174 Application

[...]

(b) Each application for a certificate of airworthiness or restricted certificate of airworthiness shall include:

    1. the class of airworthiness certificate applied for;

    2. with regard to new aircraft:

        (i) a statement of conformity:

            — issued under point 21.A.163(b); or

            — issued under point 21.A.130 and validated by the competent authority; or

            — for an imported aircraft, a statement signed by the exporting authority that the aircraft conforms to a design approved by the Agency;

        (ii) a weight and balance report with a loading schedule; and

        (iii) the flight manual, when required by the applicable certification specifications for the particular aircraft.

    3. with regard to used aircraft:

        (i) originating from a Member State, an airworthiness review certificate issued in accordance with Part M;

        (ii) originating from a non-member State:

- a statement by the competent authority of the State where the aircraft is, or was, registered, reflecting the airworthiness status of the aircraft on its register at time of transfer;
- a weight and balance report with a loading schedule;
- the flight manual when such material is required by the applicable airworthiness code for the particular aircraft;
- historical records to establish the production, modification, and maintenance standard of the aircraft, including all limitations associated with a restricted certificate of airworthiness under point 21.B.327(c);
- a recommendation for the issuance of a certificate of airworthiness or restricted certificate of airworthiness and an airworthiness review certificate following an airworthiness review in accordance with Part M; and
- the CO_2 metric-value data and the date on which the first certificate of airworthiness was issued.

[...]

SUBPART J — DESIGN ORGANISATION APPROVAL

9. 21.A.251 is amended as follows:

21.A.251 Terms of approval

The terms of approval shall identify the types of design work, the categories of products, parts and appliances for which the design organisation holds a design organisation approval, and the functions and duties that the organisation is approved to perform in regard to the airworthiness and environmental~~, operational suitability and~~ characteristics~~ of noise, fuel venting and exhaust emissions~~ of products. For design organisation approval covering type-certification or ETSO authorisation for Auxiliary Power Unit (APU), the terms of approval shall contain in addition the list of products or APU. Those terms shall be issued as part of a design organisation approval.

SECTION B — PROCEDURES FOR COMPETENT AUTHORITIES

SUBPART H — CERTIFICATES OF AIRWORTHINESS AND RESTRICTED CERTIFICATES OF AIRWORTHINESS

10. 21.B.326 is amended as follows:

21.B.326 Certificate of airworthiness

The competent authority of the Member State of registry shall issue a certificate of airworthiness for:

(a) new aircraft:

1. upon presentation of the documentation required by point 21.A.174(b)(2);
2. when the competent authority of the Member State of registry is satisfied that the aircraft conforms to an approved design and is in a condition for safe operation. This may include inspections by the competent authority of the Member State of registry; and

3. when the competent authority of the Member State of Registry is satisfied that the aircraft is in compliance with the applicable CO_2 emissions requirements on the date on which the certificate of airworthiness is first issued.

(b) used aircraft:

1. upon presentation of the documentation required by point 21.A.174(b)(3) demonstrating that:

   (i) the aircraft conforms to a type design approved under a type-certificate and any supplemental type-certificate, change or repair approved in accordance with this Annex I (Part 21); and

   (ii) the applicable airworthiness directives have been complied with; and

   (iii) the aircraft has been inspected in accordance with the applicable provisions of Annex I (Part M) of Regulation (EC) No 2042/2003; and

   (iv) the aircraft was in compliance with the applicable CO_2 emissions requirements on the date on which the certificate of airworthiness was first issued;

2. when the competent authority of the Member State of registry is satisfied that the aircraft conforms to an approved design and is in a condition for safe operation. This may include inspections by the competent authority of the Member State of registry; and

3. when the competent authority of the Member State of Registry is satisfied that the aircraft was in compliance with the applicable CO_2 emissions requirements on the date on which the certificate of airworthiness was first issued.

3.2. Draft certification specifications (Draft EASA decision)

3.2.1. CS-34 — Book 1

Certification Specifications and Acceptable Means of Compliance and Guidance Material for Aircraft Engine Emissions and Fuel Venting

Aircraft Engine Emissions and Fuel Venting Requirements

1. CS 34.1 is amended as follows:

CS 34.1 Fuel venting

(See GM 34.2)

The aircraft must be designed to comply with the applicable fuel venting requirements defined under 21.A.18(b)(1).

2. <u>CS 34.2 is amended as follows</u>:

CS 34.2 Aircraft engine emissions

(See AMC 34.2 and GM 34.2)

The aircraft engine must be designed to comply with the applicable emission requirements defined under 21.A.18(b)(2)~~,~~ and (3) and (4).

3.2.2. CS-34 — Book 2

Acceptable Means of Compliance and Guidance Material

1. <u>AMC 34.2 is amended as follows</u>:

AMC 34.2 Aircraft engine emissions

The acceptable means of compliance for aircraft engine emissions are presented in:

(a) for measurement of reference pressure ratio, Appendix 1 to ICAO Annex 16, Volume II;

(b) for smoke emission evaluation, Appendix 2 to ICAO Annex 16, Volume II;

(c) for instrumentation and measurement techniques for gaseous emissions, Appendix 3~~, except for its attachments,~~ to ICAO Annex 16, Volume II;

(d) for specification for fuel to be used in aircraft turbine engine emission testing, Appendix 4 to ICAO Annex 16, Volume II;

(e) for instrumentation and measurement techniques for gaseous emissions from afterburning gas turbine engines, Appendix 5~~, except for its attachments,~~ to ICAO Annex 16, Volume II;~~ and~~

(f) for compliance procedure for gaseous emissions and smoke, Appendix 6 to ICAO Annex 16, Volume II~~.~~; and

(g) for compliance procedure for particulate matter emissions, Appendix 7 to ICAO Annex 16, Volume II.

2. <u>GM 34.2 is amended as follows</u>:

GM 34.2 Aircraft engine emissions

Guidance material for the application of the certification specifications for aircraft engine emissions is presented in~~:~~

~~(a) for instrumentation and measurement techniques for gaseous emissions, the attachments to Appendix 3 to ICAO Annex 16, Volume II;~~

~~(b) for instrumentation and measurement techniques for gaseous emissions from afterburning gas turbine engines, the attachments to Appendix 5 to ICAO Annex 16, Volume II;~~

~~(c) for definitions and symbols, Part I of the ICAO Environmental Technical Manual, Volume II;~~

~~(d)~~ ICAO Doc 9501 ‘Environmental Technical Manual’, Volume II ‘Procedures for the Emissions Certification of Aircraft Engines’, 2nd Edition, 2014,~~for emissions certification of turbojet and~~

~~turbofan engines intended for propulsion only at subsonic speeds, Part III, Chapter 2 of the ICAO Environmental Technical Manual, Volume II;~~ except for the exemption process from the NOx emissions production cut-off requirements~~;~~

~~(e) for turbojet and turbofan engines intended for propulsion at supersonic speeds, Part III, Chapter 3 of the ICAO Environmental Technical Manual, Volume II;~~

~~(f) for smoke emission evaluation, Appendix 2 to the ICAO Environmental Technical Manual, Volume II;~~

~~(g) for instrumentation and measurement techniques for gaseous emissions, Appendix 3 to the ICAO Environmental Technical Manual, Volume II;~~

~~(h) for specification for HC analyser, Attachment A to Appendix 3 to the ICAO Environmental Technical Manual, Volume II;~~

~~(i) for specification for fuel to be used in aircraft turbine engine emission testing, Appendix 4 to the ICAO Environmental Technical Manual, Volume II;~~

~~(j) for measurement of reference pressure ratio, Appendix 1 to the ICAO Environmental Technical Manual, Volume II;~~

~~(k) for specification for CO and CO2 analysers, Attachment B to Appendix 3 to the ICAO Environmental Technical Manual, Volume II;~~

~~(l) for specification for NOx analyser, Attachment C to Appendix 3 to the ICAO Environmental Technical Manual, Volume II;~~

~~(m) for calibration and test gases, Attachment D to Appendix 3 to the ICAO Environmental Technical Manual, Volume II;~~

~~(n) for calculation of the emissions' parameters, Attachment E to Appendix 3 to the ICAO Environmental Technical Manual, Volume II;~~

~~(o) for specification for additional data, Attachment F to Appendix 3 to the ICAO Environmental Technical Manual, Volume II; and~~

~~(p) for compliance procedure for gaseous emissions and smoke, Appendix 6 to the ICAO Environmental Technical Manual, Volume II.~~

~~References throughout these certification specifications to the ICAO Environmental Technical Manual, Volume II, refer to ICAO Doc 9501 — Environmental Technical Manual, Volume II — Procedures for the Emissions Certification of Aircraft Engines, Second Edition, 2014~~.

3.2.3. CS-36 — Book 2

Certification Specifications and Acceptable Means of Compliance and Guidance Material for Aircraft Noise

Acceptable Means of Compliance and Guidance Material

1. GM 36.1 is amended as follows:

GM 36.1 Aircraft noise

Guidance material for the application of the certification specifications for aircraft noise is presented in:

(a) for equations for the calculation of maximum permitted noise levels as a function of take-off mass, Attachment A to ICAO Annex 16, Volume I;

(b) for evaluating an alternative method of measuring helicopter noise during approach, Attachment D to ICAO Annex 16, Volume I;

(c) for applicability of noise certification standards for propeller-driven aeroplanes, Attachment E to ICAO Annex 16, Volume I;

(d) ~~for general guidelines, Chapter 2 of the ICAO Environmental Technical Manual, Volume I;~~for guidelines for noise certification of tilt rotors, Attachment F to ICAO Annex 16, Volume I; and

(e) ICAO Doc 9501 'Environmental Technical Manual', Volume I 'Procedures for the Noise Certification of Aircraft', CAEP/10 Steering Group 2015-approved revision (based on the 2nd Edition, 2015), except Chapters 1 and 8.

~~(e) for technical procedures applicable for noise certification of all aircraft types, Chapter 3 of the ICAO Environmental Technical Manual, Volume I;~~

~~(f) for guidelines for subsonic jet aeroplanes, propeller-driven aeroplanes over 8 616 kg, and helicopters evaluated under ICAO Annex 16, Volume I, Appendix 2, Chapter 4 of the ICAO Environmental Technical Manual, Volume I;~~

~~(g) for guidelines for propeller-driven aeroplanes not exceeding 8 616 kg evaluated under Appendix 6 to ICAO Annex 16, Volume I, Chapter 5 of the ICAO Environmental Technical Manual, Volume I;~~

~~(h) for guidelines for helicopters not exceeding 3 175 kg evaluated under Appendix 4 to ICAO Annex 16, Volume I, Chapter 6 of the ICAO Environmental Technical Manual, Volume I;~~

~~(i) for guidelines for tilt-rotors evaluated in accordance with Chapter 13 and Attachment F to ICAO Annex 16, Volume I, Chapter 7 of the ICAO Environmental Technical Manual, Volume I; and~~

~~(j) for guidelines for aircraft recertification, Chapter 9 of the ICAO Environmental Technical Manual, Volume I.~~

~~References throughout these certification specifications to the ICAO Environmental Technical Manual, Volume I refer to ICAO Doc 9501 — Environmental Technical Manual, Volume I — Procedures for the Noise Certification of Aircraft, Second Edition, 2015.~~

3.2.4. CS-CO_2

1. New CS-CO_2 is created:

Certification Specifications
and Acceptable Means of Compliance
and Guidance Material
for
Aeroplane CO_2 Emissions

CS-CO_2

Issue 1
xx Month 201x[8]

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[8] For the date of entry into force of Issue 1, please refer to Decision 201x/xxx/R in the **Official Publication** of the Agency.

CONTENTS (general layout)

CS-CO_2

AEROPLANE CO_2 EMISSIONS

BOOK 1 — CO_2 EMISSIONS REQUIREMENTS

BOOK 2 — ACCEPTABLE MEANS OF COMPLIANCE AND GUIDANCE MATERIAL

CS-CO_2

Book 1

Certification Specifications

CS CO2.1 Aeroplane CO_2 emissions

(See AMC CO_2.1 and GM CO_2.1)

The aeroplane must be designed to comply with the applicable CO_2 emissions requirements defined under 21.A.18(c).

CS-CO_2

Book 2

Acceptable Means of Compliance and Guidance Material

AMC CO2.1 Aeroplane CO_2 emissions

For aeroplanes for which Annex 16 to the Chicago Convention[9], Volume III, Part II, Chapter 2 is applicable, the acceptable means of compliance for aeroplane CO_2 emissions are contained in Annex 16, Volume III, Appendices 1 and 2.

GM CO2.1 Aeroplane CO_2 emissions

Guidance material for the application of the certification specifications for aeroplane CO_2 emissions is contained in ICAO Doc 9501 'Environmental Technical Manual', Volume III 'Procedures for the CO_2 Emissions Certification of Aeroplanes', 1st Edition, 2017, except for the exemption process from the CO_2 emissions production cut-off requirements.

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[9] The Convention on International Civil Aviation of 7 December 1944.

3.3. Draft acceptable means of compliance and guidance material (Draft EASA decision)

3.3.1. AMC/GM to Part-21

SECTION A

SUBPART D — CHANGES TO TYPE-CERTIFICATES AND RESTRICTED TYPE-CERTIFICATES

1. Appendix A to GM 21.A.91 is amended as follows:

Appendix A to GM 21.A.91: Examples of Major Changes per discipline

[...]

8. Environment

The introductory text to Appendix A to GM 21.A.91 describes how in Part 21 a negative definition is given of minor changes only. This philosophy is similar to the manner in which the ICAO Standards and Recommended Practices for environmental protection (ICAO Annex 16) and the associated Guidance Material (ICAO Environmental Technical Manual) define changes affecting a product’s environmental characteristics in terms of ‘no-acoustical changes’, ~~and~~ ‘no-emissions changes’ and ‘no-CO_2 changes’ (i.e. changes which do not appreciably affect the product’s environmental characteristics).

Following the general philosophy of this Appendix, however, it is preferred to give examples of changes which might have an appreciable effect on a product’s environmental characteristics (i.e. the effect might be greater than the no-acoustic change and no-emissions change criteria) and might therefore lead to a major change classification.

Where a change is made to an aircraft or aircraft engine, the effect of the change on the product’s environmental characteristics should be taken into account. Examples of changes that might have an appreciable effect on the product’s environmental characteristics, and might therefore be classified as a major change, are listed below. The examples are not exhaustive and will not, in every case, result in an appreciable change to the product’s environmental characteristics, and therefore, will not per-se and in every case result in a major change classification.

An appreciable effect is considered to be one which exceeds the ICAO criteria for a no-acoustical change, ~~or~~ a no-emissions change or a no-CO_2 change. For the definition of a no-acoustical change refer to the section of the ICAO Environmental Technical Manual, Volume I (ICAO Doc 9501, Volume I – Procedures for the Noise Certification of Aircraft) concerning changes to aircraft type designs involving no-acoustical changes (see also the definitions of a ‘derived version’ in ICAO Annex 16, Volume I). For the definition of a no-emissions change refer to the section of the ICAO Environmental Technical Manual, Volume II (ICAO Doc 9501, Volume II – Procedures for the Emissions Certification of Aircraft Engines) concerning no-emissions changes. For the definition of a no-CO_2 change, refer to the Section of ICAO Doc 9501 ‘Environmental Technical Manual’, Volume III ‘Procedures for the CO_2 Emissions Certification of Aeroplanes’ concerning no-CO_2 changes.

(i) Noise: A change that introduces either:

[...]

(iii) CO_2: a change that introduces either:

— an increase in the CO_2 emissions certification level; or

— a decrease in the CO_2 emissions certification levels for which an applicant wishes to take credit.

Examples of CO_2 emission-related changes that may lead to a 'major change' classification are:

— a change to the maximum take-off mass; and

— a change that may affect the aeroplane's specific air range performance, including:

- a change that increases the aircraft's drag;
- a change of engine or, if fitted, propeller type;
- a change in engine thrust rating; and
- a change in the engine combustor design.

— a change to the aeroplane's reference geometric factor (RGF).

2. GM 21.A.101 is amended as follows:

GM 21.A.101 Establishment of the type-certification basis of changed aeronautical products

Foreword

This guidance material (GM) provides guidance for the application of the Changed Product Rule(CPR), 21.A.101 and 21.A.19, for changes made to type-certificated aeronautical products.

Chapter 1. Introduction

1. Purpose

[...]

3. Applicability

a. Reserved.

[…]

f. This GM is not intended to be used to determine the applicable environmental protection requirements (aircraft noise, fuel venting~~, and~~ engine exhaust emissions and aeroplane CO_2 emissions requirements) for changed products.

[...]

SUBPART F — PRODUCTION WITHOUT PRODUCTION ORGANISATION APPROVAL

3. GM No. 2 to 21.A.121 is amended as follows:

GM No. 2 to 21.A.121 Applicability –— Applicable design data

Applicable design data is defined as all necessary drawings, specifications and other technical information provided by the applicant for, or holder of a design organisation approval, TC, STC, approval of repair or minor change design, or ETSO authorisation (or equivalent when Part 21 Section A Subpart F is used for production of products, parts or appliances, the design of which has been approved other than according to Part 21), and released in a controlled manner to the manufacturer producing under Part 21 Subpart F. This should be sufficient for the development of production data to enable manufacture in conformity with the design data.

Prior to issue of the TC, STC, approval of repair or minor change design or ETSO authorisation, or equivalent, design data is defined as ‘not approved’, but parts and appliances may be released with an EASA Form 1 as a certificate of conformity.

After issue of the TC, STC, approval of repair or minor change or ETSO authorisation, or equivalent, this design data is defined as ‘approved’ and items manufactured in conformity are eligible for release on an EASA Form 1 for airworthiness purposes.

For the purpose of Subpart F of Part~~–~~-21, the term ‘applicable design data’ includes~~, in the case of engines and when applicable,~~ the information related to the applicable engine exhaust emissions and aeroplane CO_2 emissions production cut-off requirements.

[...]

4. AMC No. 1 to 21.A.130(b) is amended as follows:

AMC No. 1 to 21.A.130(b) Statement of Conformity for Complete Aircraft

[...]

3 COMPLETION OF THE AIRCRAFT STATEMENT OF CONFORMITY BY THE ORIGINATOR

Block 1

[...]

Block 14 Remarks: Any statement, information, particular data or limitation which may affect the airworthiness of the aircraft. If there is no such information or data, state~~;~~: ‘NONE’. In case the competent authority has endorsed a CO_2 emissions production cut-off exemption, the following record: ‘Aeroplane exempted from 1st Edition (unamended) of Annex 16, Volume III, Part II, Chapter 2, paragraph 2.1.1 [x]’.

[...]

5. AMC 21A.130 (b) (4) is amended as follows:

AMC 21A.130-(b)-(4) Applicable engine exhaust emissions requirements

[...]

6. New AMC 21A.130(b)(5) is inserted as follows:

AMC 21A.130(b)(5) Applicable aeroplane CO_2 emissions requirements

1. General

This determination is made according to the data provided by the aeroplane type certificate holder. This data should allow the determination of whether the aeroplane complies with the CO_2 emissions applicability requirements of Annex 16 to the Chicago Convention, Volume III, Part II, Chapter 2, paragraph 2.1.1.

It should be noted that the competent authority has the possibility to grant exemptions as noted in Volume III, Part II, Chapter 1, paragraph 1.11. This Section summarises the process and criteria for exemptions against the CAEP/10-agreed CO_2 applicability requirements in the 1st Edition of Annex 16, Volume III, Part II, Chapter 2, paragraph 2.1.1 (a) to (g).

2. Process and criteria for exemptions against the CO_2 emissions production cut-off requirements

2.1 Request

The organisation should submit a formal request to the competent authority, signed by an appropriate manager, and copied to all other relevant organisations and involved competent authorities, including the Agency. The letter should include the following information for the competent authority to be in a position to review the application:

(a) administrative information:

name, address and contact details of the applicant organisation;

(b) scope of the request:

(i) aeroplane type (new or in-production type, model designation, type certificate (TC) number, TC date);
(ii) number of individual aeroplane exemptions requested;
(iii) anticipated duration (end date) of continued production of exempted aeroplanes; and
(iv) to whom the aeroplane will be originally delivered; and

(c) justification for exemptions:

when requesting an exemption, the organisation should, to the extent possible, address the following factors, with quantification, in order to support the merits of the exemption request:

(i) technical issues, from an environmental and airworthiness perspective, which may have delayed compliance with the production cut-off requirement;
(ii) economic impacts on the manufacturer, operator(s) and aviation industry at large;

(iii) environmental effects; this should consider the amount of additional CO_2 emissions that will be emitted as a result of the exemption, which may include consideration of the following:

(A) the amount by which the aeroplane model CO_2 emissions exceed the CO_2 emissions standard, taking into account any other aeroplane models in the aeroplane family, covered by the same type-certificate, and their relation to the standard;

(B) the amount of CO_2 emissions that would be emitted by an alternative aeroplane for the same application; and

(C) the impact of changes to reduce CO_2 emissions on other environmental factors, including community noise and NOx emissions;

(iv) impact of unforeseen circumstances and hardship due to business circumstances beyond the manufacturer's control (e.g. employees' strike, supplier disruption or calamitous events);

(v) projected future production volumes and plans for producing a compliant version of the aeroplane model for which exemptions are sought;

(vi) equity issues in administering the production cut-off among economically competing parties (e.g. provide the rationale for granting the exemption when another manufacturer has a compliant engine and does not need an exemption, taking into account the implications for the operator's fleet composition and commonality, as well as related issues in the absence of the engine for which exemptions are sought); and

(vii) any other relevant factors.

2.2 Evaluation

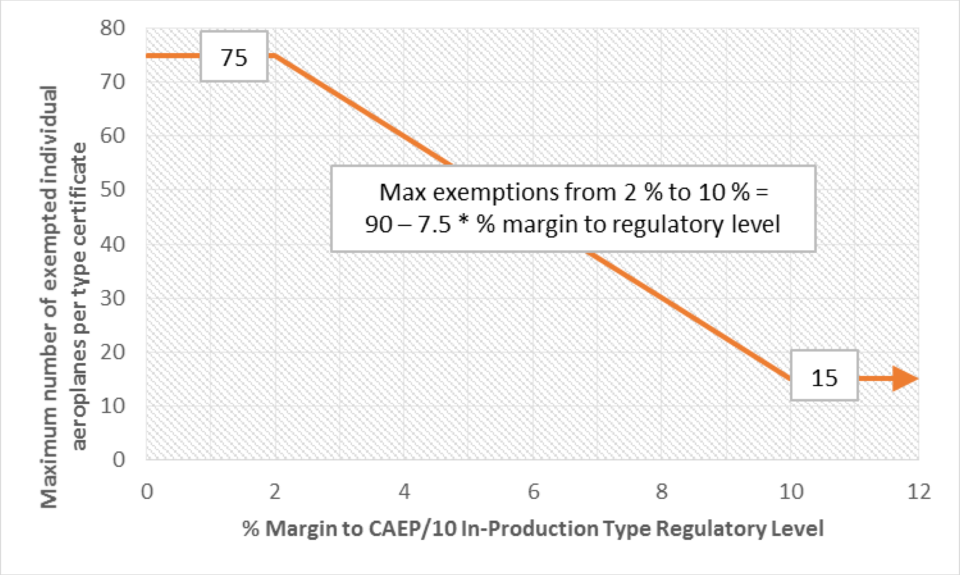
2.2.1. Since the Agency has the overview of the exemptions granted within the Member States and within third countries by contacting the relevant design organisation, the Agency advises the competent authority during the process of granting exemptions. The advice from the Agency should take the form of a letter sent to the competent authority. The approval of exemptions should be communicated to the Member State responsible for the issuance of the aeroplane's initial certificate of airworthiness (CofA).

2.2.2 The evaluation of an exemption request should be based on the justification provided by the organisation.

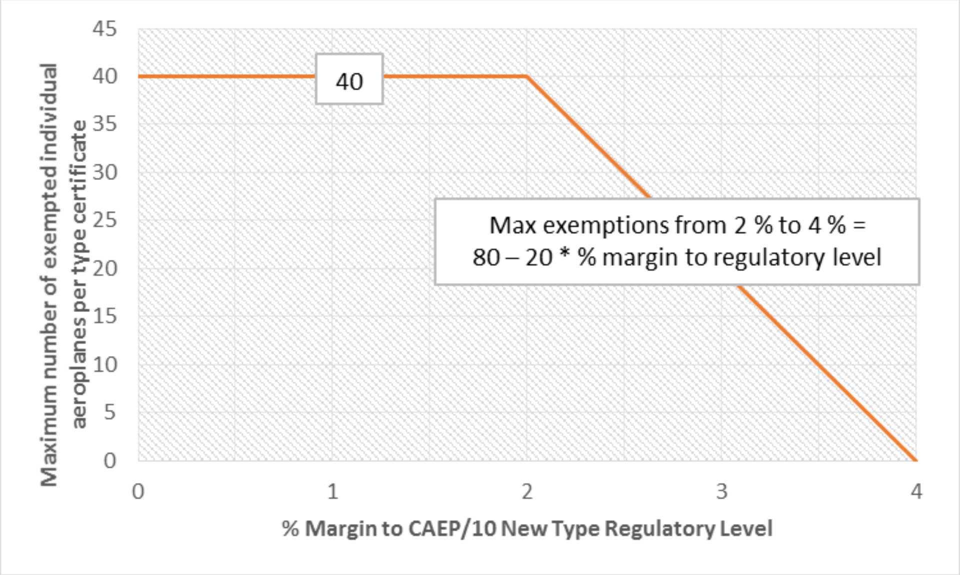
2.2.3 The proposed maximum number of potential exemptions should be inversely proportional to the % margin of the CO_2 metric value from the regulatory level (Volume III, Part II, Chapter 2, paragraph 2.4). Those aeroplane types with a smaller % margin to the regulatory level should be permitted a larger number of exemptions compared to the aeroplane types with a larger % margin.

2.2.4 Following the recommendation in Volume III, Part II, Chapter 1, paragraph 1.11 to use an acceptable process, the number of aeroplanes exempted per type certificate is the proposed maximum number in the tables and figures below:

% Margin to CAEP/10 In-Production Regulatory level	Maximum Exemptions Total
0 to 2	75
2 to 10	90 – 7.5 × % margin to regulatory level
More than 10	15



% Margin to CAEP10 New-Type Regulatory level	Maximum Exemptions Total
0 to 2	40
2 to 4	80 – 20 × % margin to regulatory level
More than 4	0



2.3 Rejection of request

If the competent authority rejects the request for exemption, the response should include a detailed justification.

SUBPART G — PRODUCTION ORGANISATION APPROVAL

7. GM 21.A.131 is amended as follows:

GM 21.A.131 Scope — Applicable design data

[…]

For the purpose of Subpart G of Part-21, the term ‘applicable design data’ includes~~, in case of engines and when applicable,~~ the information related to the applicable engine exhaust emissions and aeroplane CO_2 emissions production cut-off requirements.

8. GM 21.A.145(b)(2) is amended as follows:

GM 21.A.145(b)(2) Approval Requirements –— Airworthiness and environmental protection~~, noise, fuel venting and exhaust emissions /~~production/quality data procedures

1 When a POA holder/applicant is developing its own manufacturing data, such as computer based data, from the design data package delivered by a design organisation, procedures are required to demonstrate the right transcription of the original design data.

2 Procedures are required to define the manner in which airworthiness and environmental~~, noise, fuel venting and exhaust emissions~~ data is used to issue and update the production/quality data, which determines the conformity of products, parts and appliances. The procedure must also define the traceability of such data to each individual product, part or appliance for the purpose of certifying condition for safe operation and issuing a Statement of Conformity or EASA Form 1.

9. AMC No 2 to 21.A.163(c) is amended as follows:

AMC No 2 to 21.A.163(c) Completion of the EASA Form 1

[...]

Examples of data to be entered in this block as appropriate:

- For complete engines, a statement of compliance with the applicable emissions requirements current on the date of manufacture of the engine.
- For ETSO articles, state the applicable ETSO number.
- Modification standard.
- Compliance or non-compliance with airworthiness directives or Service Bulletins.
- Details of repair work carried out, or reference to a document where this is stated.
- Shelf life data, manufacture date, cure date, etc.
- Information needed to support shipment with shortages or re-assembly after delivery.
- References to aid traceability, such as batch numbers.
- In case of an engine, if the ~~C~~competent ~~A~~authority has granted an engine exhaust emissions production cut-off exemption, the record: ‘[~~“~~N~~EW OR SPARE~~New or Spare~~”~~] ~~ENGINE EXEMPTED~~

~~FROM NOx EMISSIONS PRODUCTION CUT-OFF REQUIREMENT~~engine exempted from NOx emissions production cut-off requirement'.

10. AMC 21A.165(c)(3) is amended as follows:

AMC 21A.165(c)(3) Applicable engine exhaust emissions requirements

[...]

11. AMC 21A.165(c)(4) is amended as follows:

AMC 21A.165(c)(4) Applicable aeroplane CO_2 emissions requirements

1. General

This determination is made according to the data provided by the aeroplane type certificate holder. This data should allow the determination of whether the aeroplane complies with the CO_2 emissions applicability requirements of Annex 16 to the Chicago Convention, Volume III, Part II, Chapter 2, paragraph 2.1.1.

It should be noted that the competent authority has the possibility to grant exemptions as noted in Volume III, Part II, Chapter 1, paragraph 1.11. This Section summarises the process and criteria for exemptions against the CAEP/10-agreed CO_2 applicability requirements in the 1st Edition of Annex 16, Volume III, Part II, Chapter 2, paragraph 2.1.1 (a) to (g).

2. Process and criteria for exemptions against the CO_2 emissions production cut-off requirements

2.1 Request

The organisation should submit a formal request to the competent authority, signed by an appropriate manager, and copied to all other relevant organisations and involved competent authorities, including the Agency. The letter should include the following information for the competent authority to be in a position to review the application:

(a) administrative information:

name, address and contact details of the applicant organisation;

(b) scope of the request:

(i) aeroplane type (new or in-production type, model designation, type certificate (TC) number, TC date);
(ii) number of individual aeroplane exemptions requested;
(iii) anticipated duration (end date) of continued production of exempted aeroplanes; and
(iv) to whom the aeroplane will be originally delivered; and

(c) justification for exemptions:

when requesting an exemption, the organisation should, to the extent possible, address the following factors, with quantification, in order to support the merits of the exemption request:

(i) technical issues, from an environmental and airworthiness perspective, which may have delayed compliance with the production cut-off requirement;

(ii) economic impacts on the manufacturer, operator(s) and aviation industry at large;

(iii) environmental effects; this should consider the amount of additional CO_2 emissions that will be produced as a result of the exemption, which may include consideration of the following:

  (A) the amount by which the aeroplane model CO_2 emissions exceed the CO_2 emissions standard, taking into account any other aeroplane models in the aeroplane family, covered by the same type-certificate, and their relation to the standard;

  (B) the amount of CO_2 emissions that would be emitted by an alternative aeroplane for the same application; and

  (C) the impact of changes to reduce CO_2 emissions on other environmental factors, including community noise and NOx emissions;

(iv) impact of unforeseen circumstances and hardship due to business circumstances beyond the manufacturer’s control (e.g. employees’ strike, supplier disruption or calamitous events);

(v) projected future production volumes and plans for producing a compliant version of the aeroplane model for which exemptions are sought;

(vi) equity issues in administering the production cut-off among economically competing parties (e.g. provide the rationale for granting the exemption when another manufacturer has a compliant engine and does not need an exemption, taking into account the implications for the operator’s fleet composition and commonality, as well as related issues in the absence of the engine for which exemptions are sought); and

(vii) any other relevant factors.

2.2 Evaluation

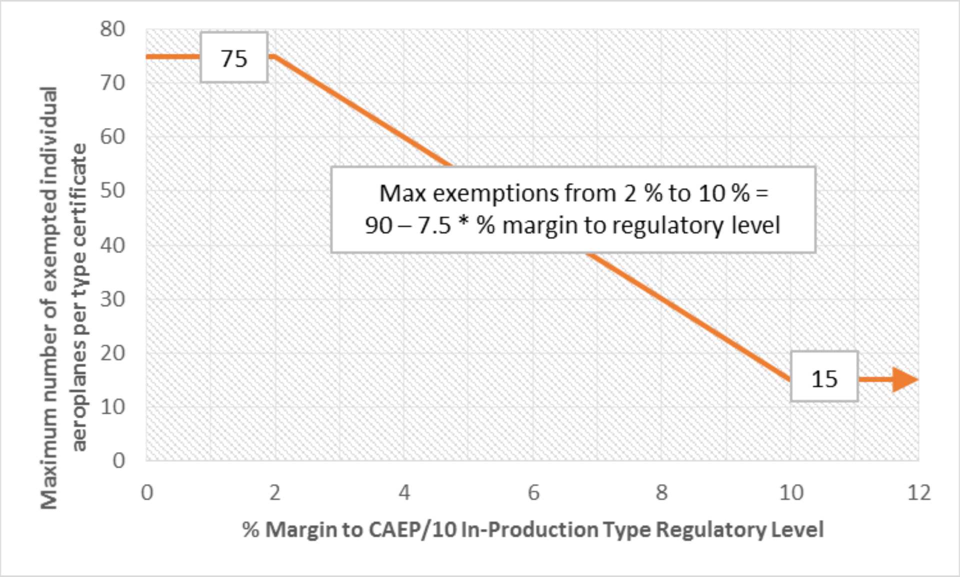
2.2.1. Since the Agency has the overview of the exemptions granted within the Member States and within third countries by contacting the relevant design organisation, the Agency advises the competent authority during the process of granting exemptions. The advice from the Agency should take the form of a letter sent to the competent authority. The approval of exemptions should be communicated to the Member State responsible for the issuance of the aeroplane’s initial certificate of airworthiness (CofA).

2.2.2 The evaluation of an exemption request should be based on the justification provided by the organisation.

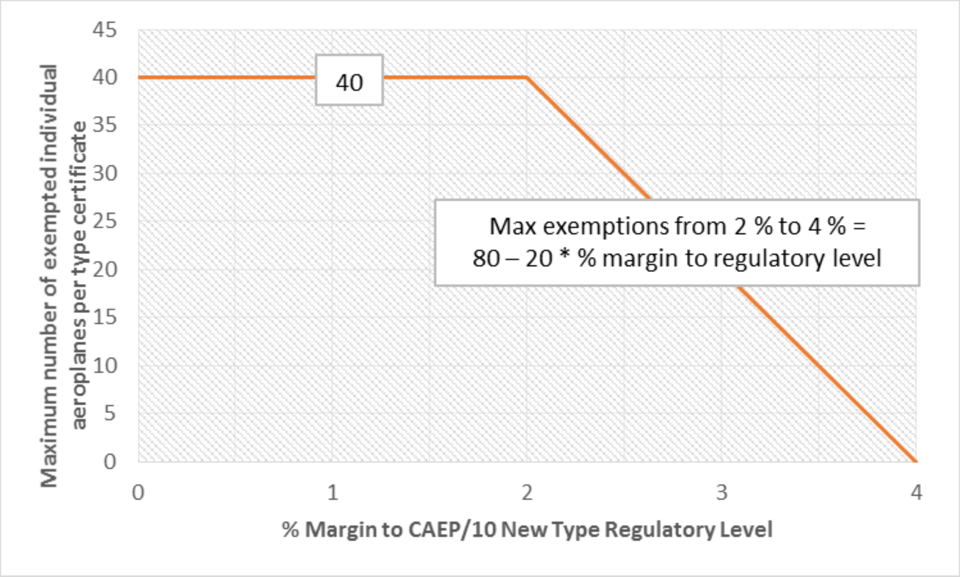
2.2.3 The proposed maximum number of potential exemptions should be inversely proportional to the % margin of the CO_2 metric value from the regulatory level (Volume III, Part II, Chapter 2, paragraph 2.4). Those aeroplane types with a smaller % margin from the regulatory level should be permitted a larger number of exemptions compared to the aeroplane types with a larger % margin.

2.2.4 Following the recommendation in Volume III, Part II, Chapter 1, paragraph 1.11 to use an acceptable process, the number of aeroplanes exempted per type certificate is the proposed maximum number in the tables and figures below:

% Margin to CAEP10 In-Production Regulatory level	Maximum Exemptions Total
0 to 2	75
2 to 10	90 – 7.5 × % margin to regulatory level
More than 10	15



% Margin to CAEP10 New-Type Regulatory level	Maximum Exemptions Total
0 to 2	40
2 to 4	80 – 20 × % margin to regulatory level
More than 4	0



2.3 Rejection of request

If the competent authority rejects the request for exemption, the response should include a detailed justification.

4. Impact assessment (IA)

4.1. What is the issue

At its 10th formal meeting from 1 to 12 February 2016 (CAEP/10), the ICAO CAEP approved amendments to ICAO Annex 16, Vol I 'Aircraft Noise' and Vol II 'Aircraft Engine Emissions'. It also approved a new aircraft engine particulate matter emissions Standard to be contained in ICAO Annex 16, Vol II, and a new aeroplane CO_2 emissions Standard for ICAO Annex 16, Vol III.

To support the ICAO Annex 16 requirements, ICAO Doc 9501 'Environmental Technical Manual' (ETM), Vol I 'Procedures for the Noise Certification of Aircraft', as well as Vol II 'Procedures for the Emissions Certification of Aircraft Engines' were also updated to provide clarifications and additional guidance material on the use of procedures for certification. A new ETM Vol III 'Aeroplane CO_2 Emissions' was also created.

These recommendations resulted from the work conducted during the three years preceding the meeting in accordance with the CAEP/10 Work Programme. The amendments approved at CAEP have been subsequently proposed for adoption by ICAO in State Letters AN 1/17.14-16/53 (Vol I), AN 1/17.14-16/54 (Vol II) and AN 1/17.14-16/56 (Vol III), dated 8 July 2016.

Article 6 of the Basic Regulation makes direct reference to the current amendments of ICAO Annex 16, Vols I and II (7th Edition, Amendment 11-B and 3rd Edition, Amendment 8, respectively). The alignment with the ICAO SARPs and Guidance Material in the area of environmental protection should be maintained. Leaving the current regulatory framework unchanged would lead to an uneven playing field among stakeholders at global level, and would potentially create loopholes in the environmental certification of aircraft and aircraft engines.

4.1.1. Safety risk assessment

No safety risks were identified.

4.1.2. Who is affected

The present rulemaking task affects:

- stakeholders: design and production organisations;
- authorities: NAAs and EASA;
- products: fixed-wing and rotary-wing aircraft as well as tilt rotors; and
- people impacted by aircraft noise and emissions.

4.1.3. How could the issue/problem evolve

Aircraft noise and emissions are expected to grow over the next decades as the projected improvement of aircraft and aircraft engines' environmental performance will be insufficient to compensate for the negative effect of traffic growth in the EU and worldwide. Noise and emissions design standards are one of the key measures in mitigating aviation's environmental impact (reduction at source) and are part of EASA's remit.

Furthermore, it is anticipated that ICAO Contracting States outside the EU will implement the amendments to ICAO Annex 16 proposed for adoption within the ICAO States Letters. Leaving the EU rules unchanged would therefore lead to an uneven playing field among actors operating in the international aviation market, and create major loopholes in the field of environmental protection certification.

4.2. What we want to achieve — objectives

The specific objective of this proposal is to ensure a high uniform level of environmental protection by aligning the EU rules and EASA AMC/GM with the ICAO SARPs (Annex 16) and guidance (ETM), as well as to provide a level playing field for all actors in the aviation sector.

4.3. How it could be achieved — options

The policy options are unchanged compared to the ones identified in the preliminary regulatory impact assessment (Pre-RIA) for this RMT, namely:

Table 1 — Selected policy options

Option No	***Short title***	**Description**
0	Do nothing	Baseline option (no change in rules; risks remain as outlined in the issue analysis).
1	CAEP/10 implementation	To implement the CAEP/10 amendments, as proposed for adoption by the relevant ICAO State Letters.

4.4. Methodology and data

A summary of the methodology and the data used in developing the new nvPM and CO_2 standards are provided in Sections 6.2.5 and 6.3.4, respectively.

4.5. What are the impacts

4.5.1. Safety impact

No safety impacts were identified.

4.5.2. Environmental impact

Out of the two options considered, only Option 1 has a positive impact on the environment. The introduction of new nvPM and CO_2 Standards in ICAO Annex 16 and the ETM ensures that aircraft and aircraft engine designs meet the latest environmental standards which mitigate local air quality and climate change impacts and have a positive benefit for the environment.

Furthermore, the overall ICAO Annex 16 amendments remove ambiguities and inconsistencies. They also provide clarifications, include up-to-date best practices based on the latest technical developments, and introduce technically sound and well-defined specifications.

4.5.3. Social impact

No social impacts are expected from the options in consideration other than the indirect social effect through the mitigation of the environmental impacts (positive impact of Option 1).

4.5.4. Economic impact

Both options have an economic impact.

It should be noted that the costs for stakeholders of designing, producing and operating aircraft compliant with the new CAEP/10 environmental requirements are also present under Option 0 (‘do nothing’) as these requirements will likely be applicable in world regions other than Europe. Furthermore, Option 0 would increase the risk of European products not being acceptable in different parts of the world, with the associated costs that this would incur.

In contrast, as Option 1 improves the harmonisation of environmental protection certification requirements worldwide, it reduces the administrative burden for industry and, therefore, has a positive economic impact.

4.5.5. General Aviation (GA) and proportionality issues

No impacts on small and medium-sized enterprises (SMEs) and/or GA were identified.

4.5.6. Impact on ‘Better Regulation’ and harmonisation

Option 0 would create a misalignment between EU rules and the global ICAO SARPS and guidance in the area of aviation environmental protection.

It would most probably lead to divergence between European and non-European aviation environmental protection standards, creating potential loopholes.

Out of the two options, only Option 1 ensures that EU rules are aligned with the global set of rules proposed for adoption in the ICAO State Letters.

4.6. Conclusion

4.6.1. Comparison of options

Out of the two policy options considered, only Option 1 (implementation of CAEP/10 amendments) has positive impacts in all identified aspects (environmental, social, economic, harmonisation, and no impact on safety). On the other hand, Option 0 (do nothing) has negative impacts in all aspects but safety.

During a three-year work cycle (2013–2016), the proposed amendments to ICAO Annex 16 and the ETM, and, more specifically, the new particulate matter and CO_2 standards were thoroughly discussed in the CAEP working groups by high-level technical experts from aviation authorities (including EASA), industry and non-governmental organisations (NGOs). The amendments, as proposed, reflect the EU objective of improving environmental protection.

The benefits and drawbacks of each option are summarised in the below table:

	Safety	**Environment**	**Economic**	**Social**	**Regulatory harmonisation**
Option 0	0	–	–	–	–
Option 1	0	++	+	+	++

Based on the above, it is recommended to implement the amendments agreed at CAEP/10 and proposed for adoption in the ICAO State Letters, i.e. to follow Option 1.

4.7. Monitoring and evaluation

No specific monitoring or ex post evaluation is planned for this rule.

5. References

5.1. Affected regulations

- Regulation (EC) No 216/2008 of the European Parliament and of the Council of 20 February 2008 on common rules in the field of civil aviation and establishing a European Aviation Safety Agency, and repealing Council Directive 91/670/EEC, Regulation (EC) No 1592/2002 and Directive 2004/36/EC (OJ L 79, 19.3.2008, p. 1).
- Commission Regulation (EU) No 748/2012 of 3 August 2012 laying down implementing rules for the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organisations, and repealing Commission Regulation (EC) No 1702/2003 (OJ L 224, 21.8.2012, p. 1).

5.2. Affected decisions

- Decision No. 2003/3/RM of the Executive Director of the Agency of 17 October 2003 on certification specifications providing for acceptable means of compliance for aircraft engine emissions and fuel venting (‘CS-34’).
- Decision No. 2003/4/RM of the Executive Director of the Agency of 17 October 2003 on certification specifications providing for acceptable means of compliance for aircraft noise (‘CS-36’).
- Decision N° 2012/020/R of the Executive Director of the Agency of 30th October 2012 on Acceptable Means of Compliance and Guidance Material for the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organisations (‘AMC and GM to Part-21’).

5.3. Other reference documents

- ICAO CAEP/10 Working Paper (WP)/92, Report of the 10th meeting of the Committee on Aviation Environmental Protection, February 2016
- ICAO State Letter AN 1/17.14-16/53, ‘Proposals for the amendment of Annex 16, Volume I concerning Standards and Recommended Practices relating to environmental protection — Aircraft noise’, 8 July 2016
- ICAO State Letter AN 1/17.14-16/55, ‘Proposals for the amendment of Annex 16, Volume II concerning Standards and Recommended Practices relating to environmental protection — Aircraft engine emissions’, 8 July 2016
- ICAO State Letter AN 1/17.14-16/56, ‘Proposals for the First Edition of Annex 16, Volume III, concerning Standards and Recommended Practices relating to environmental protection — Aeroplane CO_2 emissions’, 8 July 2016
- Annex 16 ‘Environmental Protection’ to the Convention on International Civil Aviation
- ICAO Doc 9501 ‘Environmental Technical Manual’, Vols I, II and III

6. Appendices

6.1. Appendix 1 — ICAO ANNEX 16, VOL I AMENDMENTS

6.1.1. Excerpt of the summary of presentations, discussions, conclusions, recommendations and proposed general changes to ICAO Annex 16, Vol I from the CAEP/10 Report (Agenda Item 6 'Review of technical proposals relating to aircraft noise')

6.2 PROPOSED AMENDMENTS TO ANNEX 16, VOLUME I AND THE ENVIRONMENTAL TECHNICAL MANUAL, VOLUME I

6.2.1 N.02.01 Definitions; N.02.02 Modification of ETM figures; N.02.04 Nomenclature: Symbols and units; N.02.06 Caretaking of the ETM

6.2.1.1 WG1 recommended changes to the ETM, Volume I and Annex 16, Volume I to enhance the documents' utility and compatibility. Under N.02.06, all miscellaneous editorial changes arising from other N.02 tasks have been included. The maintenance and update task will continue during CAEP/11.

6.2.2 N.02.12 Atmospheric absorption

6.2.2.1 This task is to "Monitor SAE work to update the atmospheric absorption procedure and assess the impact, including the effect on stringency, of its adoption in the Annex". At the 2015 CAEP Steering Group meeting, it was agreed that SAE ARP 5534, for noise certification purposes, would be adopted during the next round of standard-setting at the earliest, pending completion of the technical work. Completion of the technical work is expected during the CAEP/11 cycle.

6.2.3 N.02.14 Confidence interval for interpolation

6.2.3.1 The 2015 CAEP Steering Group meeting endorsed new guidance for applicants and authorities on the calculation of confidence intervals for interpolation between already approved noise/mass values.

6.2.4 N.02.22 Flight path measurement

6.2.4.1 Noise certification flight testing requires that the aircraft's position relative to the microphone(s) be established to a high degree of accuracy. Improved guidance to reflect modern aircraft tracking methods using differential global positioning tracking systems was completed. Related Annex text was aligned with the revised ETM guidance material. These changes were endorsed by the 2015 CAEP Steering Group meeting. Additional work is needed in CAEP/11 to update guidance on photographic scaling methods used by small aircraft.

6.2.5 N.02.25 Recertification taking into account Chapter 14

6.2.5.1 The 2015 CAEP Steering Group meeting endorsed the revisions to the ETM, Volume I, Chapter 9 to introduce guidelines for recertification to Annex 16, Volume I, Chapter 14.

6.2.6 N.02.26 Update of ETM for tilt-rotors

6.2.6.1 The 2015 CAEP Steering Group meeting endorsed guidelines in the ETM for tilt-rotors with reference to the certification standards for tilt-rotors in Annex 16, Volume I, Chapter 13 and the certification guidance for tilt-rotors in Annex 16, Volume I, Attachment F.

Discussion and Conclusions

6.2.7 The meeting congratulated WG1 on its achievements in keeping Annex 16, Volume I up to date and relevant. The meeting approved the amendments to Annex 16, Volume I as presented in Appendix A. The meeting noted the view of a member that a thorough review of the text in Chapter 13 of Annex 16, Volume I is needed and agreed to consider it with future work.

6.2.8 The meeting confirmed the Steering Group Approved Revision (SGAR) of the ETM, Volume I approved by the 2015 CAEP Steering Group meeting.

6.2.9 Recommendation

6.2.9.1 In light of the foregoing discussion, the meeting developed the following recommendation:

RSPP **Recommendation 6/1 — Amendments to Annex 16 — Environmental Protection, Volume I — Aircraft Noise**

That Annex 16, Volume I be amended as indicated in Appendix A to the report on this agenda item.

Recommendation 6/2 — Amendments to the Environmental Technical Manual, Volume I – Procedures for the Noise Certification of Aircraft

That the *Environmental Technical Manual*, Volume I be amended, as indicated in the Report of Working Group 1, and that revised versions approved by subsequent CAEP Steering Groups be made available, free of charge on the ICAO website, pending a final decision on official publication by the ICAO Secretary General.

6.1.2. Proposed general amendments to ICAO Annex 16, Vol I

The text of the amendment is arranged to show deleted text with a line through it and new text highlighted with grey shading, as shown below:

1.	~~Text to be deleted is shown with a line through it.~~	text to be deleted
2.	New text to be inserted is highlighted with grey shading.	new text to be inserted
3.	~~Text to be deleted is shown with a line through it~~ followed by the replacement text which is highlighted with grey shading.	new text to replace existing text

PROPOSAL A

REFERENCE ATMOSPHERE

…

CHAPTER 3.

1.— SUBSONIC JET AEROPLANES — Application for Type Certificate submitted on or after 6 October 1977 and before 1 January 2006

2.— PROPELLER-DRIVEN AEROPLANES OVER 8 618 kg — Application for Type Certificate submitted on or after 1 January 1985 and before 1 January 2006

. . .

3.6 Noise certification reference procedures

. . .

3.6.1.5 The reference procedures shall be calculated under the following reference atmospheric conditions:

a) ~~sea level~~ atmospheric pressure at sea level of 1 013.25 hPa, decreasing with altitude at a rate defined by the ICAO Standard Atmosphere;

b) ambient air temperature at sea level of 25°C,~~ i.e. ISA + 10°C;~~ decreasing with altitude at a rate defined by the ICAO Standard Atmosphere (i.e. 0.65°C per 100 m);

c) constant relative humidity of 70 per cent;

d) zero wind;~~ and~~

e) for the purpose of defining the reference take-off profiles for both take-off and lateral noise measurements, the runway gradient is zero; and

f) the reference atmosphere in terms of temperature and relative humidity is considered to be homogeneous (i.e. ambient temperature 25°C and relative humidity 70 per cent) for the purpose of calculating:

   1) the reference sound attenuation rate due to atmospheric absorption; and

   2) the reference speed of sound used in the calculation of the reference sound propagation geometry.

Note 1.— ~~The reference atmosphere in terms of temperature and relative humidity is homogeneous when used for the calculation of atmospheric absorption coefficients.~~ Details for calculating the *variation of reference atmospheric pressure with altitude are given in the section of the Environmental Technical Manual (Doc 9501), Volume I — Procedures for the Noise Certification of Aircraft, concerning the ICAO Standard Atmosphere.*

Note 2. —The characteristics of the ICAO Standard Atmosphere are provided in the Manual of the ICAO Standard Atmosphere (Doc 7488/3).

. . .

CHAPTER 5. PROPELLER-DRIVEN AEROPLANES OVER 8 618 kg — Application for Type Certificate submitted before 1 January 1985

. . .

5.6 Noise certification reference procedures

. . .

5.6.1.5 The reference procedures shall be calculated under the following reference atmospheric conditions:

a) ~~sea level~~ atmospheric pressure at sea level of 1 013.25 hPa, decreasing with altitude at a rate defined by the ICAO Standard Atmosphere;

b) ambient air temperature at sea level of 25°C, decreasing with altitude at a rate defined by the ICAO Standard Atmosphere (i.e. 0.65°C per 100 m),~~i.e. ISA + 10°C~~ except that at the discretion of the certificating authority, an alternative ~~reference~~ ambient air temperature at sea level of 15°C~~, i.e. ISA~~ may be used;

c) constant relative humidity of 70 per cent;~~ and~~

d) zero wind; and

e) the reference atmosphere in terms of temperature and relative humidity is considered to be homogeneous (i.e. ambient temperature 25°C and relative humidity 70 per cent) for the purpose of calculating:

   1) the reference sound attenuation rate due to atmospheric absorption; and

   2) the reference speed of sound used in the calculation of the reference sound propagation geometry.

Note 1.— Details for calculating the variation of reference atmospheric pressure with altitude are given in the section of the Environmental Technical Manual (Doc 9501), Volume I — Procedures for the Noise Certification of Aircraft, concerning the ICAO Standard Atmosphere.

Note 2. —The characteristics of the ICAO Standard Atmosphere are provided in the Manual of the ICAO Standard Atmosphere (Doc 7488/3).

. . .

CHAPTER 6. PROPELLER-DRIVEN AEROPLANES NOT EXCEEDING 8 618 kg — Application for Type Certificate submitted before 17 November 1988

. . .

6.4 Noise certification reference procedures

The reference procedure shall be calculated under the following reference atmospheric conditions:

a) ~~sea level~~ atmospheric pressure at sea level of 1 013.25 hPa, decreasing with altitude at a rate defined by the ICAO Standard Atmosphere; and

b) ambient air temperature at sea level of 25°C~~, i.e. ISA + 10°C;~~ decreasing with altitude at a rate defined by the ICAO Standard Atmosphere (i.e. 0.65°C per 100 m);

Note 1.— Details for calculating the variation of reference atmospheric pressure with altitude are given in the section of the Environmental Technical Manual (Doc 9501), Volume I — Procedures for the Noise Certification of Aircraft, concerning the ICAO Standard Atmosphere.

Note 2. —The characteristics of the ICAO Standard Atmosphere are provided in the Manual of the ICAO Standard Atmosphere (Doc 7488/3).

. . .

CHAPTER 8. HELICOPTERS

. . .

8.6.1 General conditions

. . .

8.6.1.5 The reference procedures shall be ~~established for~~ calculated under the following reference atmospheric conditions:

a) ~~sea level~~ constant atmospheric pressure of 1 013.25 hPa;

b) constant ambient air temperature of 25°C~~, i.e. ISA + 10°C~~;

c) constant relative humidity of 70 per cent; and

d) zero wind.

…

CHAPTER 10. PROPELLER-DRIVEN AEROPLANES NOT EXCEEDING 8 618 kg — Application for Type Certificate

or Certification of Derived Version submitted on or after 17 November 1988

. . .

10.5.1 General conditions

. . .

10.5.1.4 The reference procedures shall be calculated under the following atmospheric conditions:

a) ~~sea level~~ atmospheric pressure at sea level of 1 013.25 hPa, decreasing with altitude at a rate defined by the ICAO Standard Atmosphere;

b) ambient air temperature at sea level of 15°C, ~~i.e. ISA~~ decreasing with altitude at a rate defined by the ICAO Standard Atmosphere (i.e. 0.65°C per 100 m);

c) constant relative humidity of 70 per cent; and

d) zero wind.

Note 1.— Details for calculating the variation of reference atmospheric pressure with altitude are given in the section of the Environmental Technical Manual (Doc 9501), Volume I — Procedures for the Noise Certification of Aircraft, concerning the ICAO Standard Atmosphere.

Note 2. —The characteristics of the ICAO Standard Atmosphere are provided in the Manual of the ICAO Standard Atmosphere (Doc 7488/3).

10.5.1.5 The acoustic reference atmospheric conditions shall be the same as the reference atmospheric conditions for flight.

…

CHAPTER 11. HELICOPTERS NOT EXCEEDING 3 175 kg MAXIMUM CERTIFICATED TAKE-OFF MASS

. . .

11.5.1 General conditions

. . .

11.5.1.4 The reference procedure shall be established for the following reference atmospheric conditions:

a) ~~sea level~~constant atmospheric pressure of 1 013.25 hPa;

b) constant ambient air temperature of 25°C;

c) constant relative humidity of 70 per cent; and

d) zero wind.

. . .

CHAPTER 13. TILT-ROTORS

. . .

13.6 Noise certification reference procedures

. . .

13.6.1.5 The reference procedures shall be ~~established for~~ calculated under the following reference atmospheric conditions:

a) ~~sea level~~ constant atmospheric pressure of 1 013.25 hPa;

b) constant ambient air temperature of 25°C~~, i.e. ISA + 10°C~~;

c) constant relative humidity of 70 per cent; and

d) zero wind.

. . .

APPENDIX 6. EVALUATION METHOD FOR NOISE CERTIFICATION OF PROPELLER-DRIVEN AEROPLANES NOT EXCEEDING 8 618 kg — Application for Type Certificate or Certification of Derived Version submitted on or after 17 November 1988

Editorial Note. Changes proposed for consistency purposes and to correct errors are included in paragraphs 3 and 5.2 to provide clarity to the presentation of Proposal A.

…

3. NOISE UNIT DEFINITION

The ~~L_{Amax}~~ L_{ASmax} is defined as the maximum level, in decibels, of the A-weighted sound pressure (slow response) with reference to the square of the standard reference sound pressure ~~(P_0)~~, p_0, of 20 micropascals (µPa).

. . .

5.2 Corrections and adjustments

5.2.1 The adjustments take account of the effects of:

a) differences in atmospheric absorption between meteorological test conditions and reference conditions;

b) differences in the ~~noise~~ sound propagation path length between the actual aeroplane flight path and the reference flight path;

c) the change in the helical tip Mach number between test and reference conditions; and

d) the change in engine power between test and reference conditions.

5.2.2 The noise level under reference conditions ~~(L_{Amax}) REF~~, L_{ASmaxR}, is obtained by adding increments for each of the above effects to the test day noise level ~~(L_{Amax}) TEST~~, L_{ASmax}.

~~(L_{Amax}) REF~~ L_{ASmaxR} = ~~L_{Amax} TEST~~ L_{ASmax} $+ \Delta_1 + \Delta_2 + \Delta_3 + \Delta_4$

where

~~Δ(M) is the adjustment for the change in atmospheric absorption between test and reference conditions;~~

Δ_1 is the adjustment for ~~noise~~ sound propagation path lengths;

Δ_2 is the adjustment for helical tip Mach number; ~~and~~

Δ_3 is the adjustment for engine power~~.~~; and

Δ_4 is the adjustment for the change in atmospheric absorption between test and reference conditions;

a) When the test conditions are within those specified in Figure A6-2, no adjustments for differences in atmospheric absorption need be applied, i.e. ~~$\Delta(M)$~~ $\Delta_4 = 0$. If conditions are outside those specified in Figure A6-2 then adjustments must be applied by an approved procedure or by adding an increment ~~$\Delta(M)$~~ Δ_4 to the test day noise levels where:

~~$\Delta(M) = 0.01 (H_T\alpha - 0.2 H_R)$~~

$$\Delta_4 = 0.01 (H \times \alpha_{500} - 0.2 H_R)$$

and where ~~H_T~~ H is the height in metres of the test aeroplane when directly over the noise measurement point, H_R is the reference height of the aeroplane above the noise measurement point, and α_{500} is the rate of absorption at 500 Hz specified in Tables A1-5 to A1-16 of Appendix 1.

b) Measured noise levels should be adjusted to the height of the aeroplane over the noise measuring point on a reference day by algebraically adding an increment equal to Δ_1. When test day conditions are within those specified in Figure A6-2:

~~$\Delta_1 = 22 \log (H_T/H_R)$~~

$$\Delta_1 = 22 \log (H/H_R)$$

When test day conditions are outside those specified in Figure A6-2:

~~$\Delta_1 = 20 \log (H_T/H_R)$~~

$$\Delta_1 = 20 \log (H/H_R)$$

where ~~H_T~~ H is the height of the aeroplane when directly over the noise measurement point, and H_R is the reference height of the aeroplane over the measurement point.

c) No adjustments for helical tip Mach number variations need be made if the propeller helical tip Mach number is:

. . .

~~$\Delta_2 = K_2 \log (M_R/M_T)$~~

$$\Delta_2 = k_2 \log (M_{HR}/M_H)$$

which shall be added algebraically to the measured noise level, where ~~M_T~~ M_H and ~~M_R~~ M_{HR} are the test and reference helical tip Mach numbers respectively. The value of ~~K_2~~ k_2 shall be determined from approved data from the test aeroplane. In the absence of flight test data and at the discretion of the certificating authority a value of ~~K_2~~ $k_2 = 150$ may be used for ~~M_T~~ M_H less than ~~M_R~~ M_{HR}; however, for ~~M_T~~ M_H greater than or equal to ~~M_R~~ M_{HR} no correction is applied.

Note.— The reference helical tip Mach number ~~M_R~~ M_{HR} is the one corresponding to the reference conditions above the measurement point:

where

~~$$M_R = \frac{\left[\left(\frac{D\pi N}{60}\right)^2 + V_T^2\right]^{1/2}}{c}$$~~

$$M_{HR} = \frac{\left[\left(\frac{D\pi N}{60}\right)^2 + V_R^2\right]^{1/2}}{c_{HR}}$$

where D *is the propeller diameter in metres.*

~~V_T~~ V_R *is the true airspeed of the aeroplane in reference conditions in metres per second.*

N *is the propeller speed in reference conditions in rpm. If* N *is not available, its value can be taken as the average of the propeller speeds over nominally identical power conditions during the flight tests.*

~~c~~ c_{HR} *is the reference day speed of sound at the altitude of the aeroplane in metres per second based on the temperature at the reference height assuming ~~an ISA~~ a temperature lapse rate with height defined by the ICAO Standard Atmosphere (i.e. 0.65°C per 100 m).*

d) Measured sound levels shall be adjusted for engine power by algebraically adding an increment equal to:

~~$\Delta_3 = K_3 \log (P_R/P_T)$~~

$$\Delta_3 = k_3 \log (P_0/P)$$

where ~~P_T~~ P and ~~P_R~~ P_0 are the test and reference engine powers respectively obtained from the manifold pressure/torque gauges and engine rpm. The value of ~~K_3~~ k_3 shall be determined from approved data from the test aeroplane. In the absence of flight test data and at the discretion of the certificating authority a value of ~~K_3~~ $k_3 = 17$ may be used. The reference power ~~P_R~~ P_0 shall be that obtained at the reference height ~~pressure and~~ temperature and pressure ~~assuming an ISA temperature lapse rate with height~~ assuming temperature and pressure lapse rates with height defined by the ICAO Standard Atmosphere.

Note 1.— Details for calculating the variation of reference atmospheric temperature and pressure with altitude are given in the section of the Environmental Technical Manual (Doc 9501), Volume I — Procedures for the Noise Certification of Aircraft, concerning the ICAO Standard Atmosphere.

Note 2. —The characteristics of the ICAO Standard Atmosphere are provided in the Manual of the ICAO Standard Atmosphere (Doc 7488/3).

. . .

ATTACHMENT F. GUIDELINES FOR NOISE CERTIFICATION OF TILT-ROTORS

. . .

6.1 General conditions

. . .

6.1.5 The reference procedures should be~~ established for~~ calculated under the following reference atmospheric conditions:

a) ~~sea level ~~constant atmospheric pressure of 1 013.25 hPa;

b) constant ambient air temperature of 25°C~~, i.e. ISA + 10 C~~;

c) constant relative humidity of 70 per cent; and

d) zero wind.

. . .

Proposal A Rationale:

The proposed amendment aims to ensure consistency in the way in which each of the chapters of Annex 16, Volume I defines the reference atmosphere to improve clarity and thereby ensure a common interpretation. The proposed changes use common text to define the same concept. Also the current situation whereby identical text (e.g. in current Chapter 3, 3.6.1.5 and Chapter 8, 8.6.1.5) has different intended meanings has been remedied. In addition, references to the ICAO Standard Atmosphere and to related guidance material in the ETM have been added.

This proposal also includes amendments to the definition of the reference day speed of sound in terms of a temperature lapse rate, and to the derivation of reference power in terms of temperature and pressure lapse rates, as defined by the ICAO Standard Atmosphere

PROPOSAL B

FLIGHT PATH MEASUREMENT TECHNIQUES

APPENDIX 2. EVALUATION METHOD FOR NOISE CERTIFICATION OF:

1.— SUBSONIC JET AEROPLANES — Application for Type Certificate submitted on or after 6 October 1977

2.— PROPELLER-DRIVEN AEROPLANES OVER 8 618 kg — Application for Type Certificate submitted on or after 1 January 1985

3.— HELICOPTERS

4.— TILT-ROTORS

. . .

2.3 Flight path measurement

2.3.1 The aircraft~~ height and lateral~~ spatial position relative to the~~ flight track~~ measurement microphone(s) shall be determined by a method which is approved by the certificating authority and is independent of~~ normal~~ cockpit flight instrumentation~~, such as radar tracking, theodolite triangulation or photographic scaling techniques, to be approved by the certificating authority~~.

Note.— Guidance material on aircraft position measurement systems is provided in the Environmental Technical Manual *(Doc 9501), Volume I* — Procedures for the Noise Certification of Aircraft.

2.3.2 The aircraft position along the flight path shall be~~ related~~ synchronized to the noise recorded at the noise measurement locations by means of time-synchronizing signals over a distance and duration sufficient to assure that adequate data is obtained during the period that the noise is within 10 dB of the maximum value of PNLT.

. . .

APPENDIX 4. EVALUATION METHOD FOR NOISE CERTIFICATION OF HELICOPTERS NOT EXCEEDING 3 175 kg MAXIMUM CERTIFICATED TAKE-OFF MASS

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2.3 Flight path measurement

2.3.1 The helicopter spatial position relative to the~~ flight path reference point~~ measurement microphone shall be determined by a method which is approved by the certificating authority and is independent of~~ normal~~ cockpit flight instrumentation~~, such as radar tracking, theodolite triangulation or~~

~~photographic scaling techniques, approved by the certificating authority~~.

Note.— Guidance material on aircraft position measurement systems is provided in the Environmental Technical Manual *(Doc 9501), Volume I —* Procedures for the Noise Certification of Aircraft.

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APPENDIX 6. EVALUATION METHOD FOR NOISE CERTIFICATION OF PROPELLER-DRIVEN AEROPLANES NOT EXCEEDING 8 618 kg — Application for Type Certificate or Certification of Derived Version submitted on or after 17 November 1988

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2.3 Aeroplane testing procedures

2.3.1 The test procedures and noise measurement procedure shall be ~~acceptable to the airworthiness and noise certificating authorities of the State issuing the certification~~ approved by the certificating authority.

2.3.2 The flight test programme shall be initiated at the maximum take-off mass for the aeroplane, and the mass shall be adjusted to maximum take-off mass after each hour of flight time.

2.3.3 The flight test shall be conducted at ~~V_y~~ V_Y ± 9 km/h (~~V_y~~ V_Y ± 5 kt) indicated airspeed.

2.3.4 The aeroplane spatial position relative to the ~~flight path reference point~~ measurement microphone shall be determined by a method approved by the certificating authority and is independent of ~~normal~~ cockpit flight instrumentation~~, such as radar tracking, theodolite triangulation or photographic scaling techniques, approved by the certificating authority~~.

Note.— Guidance material on aircraft position measurement systems is provided in the Environmental Technical Manual *(Doc 9501), Volume I —* Procedures for the Noise Certification of Aircraft.

2.3.5 The aeroplane height when ~~directly~~ over the microphone shall be measured by an approved technique. The aeroplane shall pass over the microphone within ±10° from the vertical and within ±20 per cent of the reference height (see Figure A6-1).

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Proposal B Rationale:

The proposed amendment removes references to outdated flight path measurement techniques and aligns the text of Annex 16, Volume I with the extensively revised guidance material of the *Environmental Technical Manual* (ETM), Volume I.

PROPOSAL C

CORRECTIONS TO GUIDELINES FOR NOISE CERTIFICATION OF TILT-ROTORS

ATTACHMENT F. GUIDELINES FOR NOISE CERTIFICATION OF TILT-ROTORS

Note.— See Part II, Chapter 13.

~~*Note 1.— These guidelines are applicable to heavier than air aircraft that can be supported in flight chiefly by the reactions of the air on two or more power driven rotors on axes which can be changed from substantially vertical to horizontal.*~~

Note~~ 2~~.— These guidelines are not intended to be used for tilt-rotors that have one or more configurations that are certificated for airworthiness for STOL only. In such cases, different or additional guidelines would likely be needed.

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3. NOISE MEASUREMENT REFERENCE POINTS

A tilt-rotor, when tested in accordance with the reference procedures of Section 6 and the test procedures of Section 7, should not exceed the noise levels specified in Section 4 at the following reference points:

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c) *Approach reference noise measurement points:*

1) a flight path reference point located on the ground 120 m (394 ft) vertically below the flight path defined in the approach reference procedure (see 6.4). On level ground, this corresponds to a position 1 140 m from the intersection of the 6.0°~~ degree~~ approach path with the ground plane;

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4. MAXIMUM NOISE LEVELS

For tilt-rotors specified in Section 1, the maximum noise levels, when determined in accordance with the noise evaluation method of Appendix 2 for helicopters, should not exceed the following:

a) ~~*At the take-off flight path reference point*~~*For take-off*: 109 EPNdB for tilt-rotors in VTOL/conversion mode with maximum certificated take-off mass, at which the noise certification is requested, of 80 000 kg and over and decreasing linearly with the logarithm of the tilt-rotor mass at a rate of 3 EPNdB per halving of mass down to 89 EPNdB after which the limit is constant.

b) ~~*At the overflight path reference point*~~*For overflight:* 108 EPNdB for tilt-rotors in VTOL/conversion mode with maximum certificated take-off mass, at which the noise certification is requested, of 80 000 kg and over and decreasing linearly with the logarithm of the tilt-rotor mass at a rate of 3 EPNdB per halving of mass down to 88 EPNdB after which the limit is constant.

Note 1.— For the tilt-rotor in aeroplane mode, there is no maximum noise level.

Note 2.— VTOL/conversion mode is all approved configurations and flight modes where the design operating rotor speed is that used for hover operations.

c) ~~*At the approach flight path reference point*~~*For approach:* 110 EPNdB for tilt-rotors in VTOL/conversion mode with maximum certificated take-off mass, at which the noise certification is requested, of 80 000 kg and over and decreasing linearly with the logarithm of the tilt-rotor mass at a rate of 3 EPNdB per halving of mass down to 90 EPNdB after which the limit is constant.

Note.— The equations for the calculation of noise levels as a function of take-off mass presented in Section ~~8~~ 7 of Attachment A, for conditions described in Chapter 8, 8.4.1, are consistent with the maximum noise levels defined in these guidelines.

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6.3 Overflight reference procedure

6.3.1 The overflight reference procedure should be established as follows:

a) the tilt-rotor should be stabilized in level flight overhead the flight path reference point at a height of 150 m (492 ft);

b) a constant configuration selected by the applicant should be maintained throughout the overflight reference procedures;

c) the mass of the tilt-rotor should be the maximum take-off mass at which noise certification is requested;

d) in the VTOL/conversion mode, the nacelle angle at the authorized fixed operation point that is closest to the lowest nacelle angle certificated for zero airspeed, a speed of 0.9 V_{CON} and a rotor speed stabilized at the maximum normal operating rpm certificated for level flight should be maintained throughout the overflight reference procedure;

Note.— For noise certification purposes, V_{CON} is defined as the maximum authorized speed for VTOL/conversion mode at a specific nacelle angle.

e) in the aeroplane mode, the nacelles should be maintained on the down-stop throughout the overflight reference procedure, with:

1) rotor speed stabilized at the rpm associated with the VTOL/conversion mode and a speed of 0.9 V_{CON}; and

2) rotor speed stabilized at the normal cruise rpm associated with the aeroplane mode and at the corresponding 0.9 V_{MCP} or 0.9 V_{MO}, whichever is lesser, certificated for level flight.

Note 1.— For noise certification purposes, V_{MCP} is defined as the maximum operating limit airspeed for aeroplane mode corresponding to minimum engine installed, maximum continuous power (MCP) available for sea level pressure (1 013.25 hPa), 25°C ambient conditions at the relevant maximum certificated mass; and V_{MO} is the maximum operating (MO) limit airspeed that may not be deliberately exceeded.

6.3.2 ~~Note 2. —~~The values of V_{CON} and V_{MCP} or V_{MO} used for noise certification should be quoted in the approved flight manual.

6.4 Approach reference procedure

The approach reference procedure should be established as follows:

a) the tilt-rotor should be stabilized and follow a 6.0° ~~degree~~ approach path;

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7. TEST PROCEDURES

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7.4 Adjustments for differences between test and reference flight procedures should not exceed:

a) *for take-off:* 4.0 EPNdB, of which the arithmetic sum of ~~delta 1~~ Δ_1 and the term –7.5 log (QK/Q_rK_r) from ~~delta 2~~ Δ_2 should not in total exceed 2.0 EPNdB; and

. . .

7.5 During the test the average rotor rpm should not vary from the normal maximum operating rpm by more than ±1.0 per cent ~~during~~ throughout the 10 dB-down time period.

7.6 The tilt-rotor airspeed should not vary from the reference airspeed appropriate to the flight demonstration by more than ±9 km/h (±5 kt) throughout the 10 dB-down time period.

7.7 The number of level overflights made with a headwind component should be equal to the number of level overflights made with a tailwind component.

7.8 The tilt-rotor should fly within ±10° ~~degrees~~ or ±20 m (±65 ft), whichever is greater, from the vertical above the reference track throughout the 10 dB-down time period (see Figure 8-1 of Part II, Chapter 8).

7.9 The tilt-rotor height should not vary during overflight from the reference height ~~at the overhead point~~ throughout the 10 dB-down period by more than ±9 m (30 ft).

7.10 During the approach noise demonstration the tilt-rotor should be established on a stabilized constant speed approach within the airspace contained between approach angles of 5.5° ~~degrees~~ and 6.5° ~~degrees~~ throughout the 10 dB-down period.

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Proposal C Rationale:

The proposed amendment deals with corrections to guidelines for noise certification of tilt-rotors to revise editorial and technical errors in Annex 16, Volume I, Attachment F (Guidelines for noise certification of tilt-rotor aircraft) and standardize the terminology and symbols with the rest Annex 16, Volume I.

PROPOSAL D

GENERAL TECHNICAL, NOMENCLATURE AND TYPOGRAPHICAL ISSUES

TABLE OF CONTENTS

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NOMENCLATURE: SYMBOLS AND UNITS

Note.— Many of the following definitions and symbols are specific to aircraft noise certification. Some of the definitions and symbols may also apply to purposes beyond aircraft noise certification.

1.1 Velocity

Symbol	*Unit*	*Meaning*
c_R	m/s	*Reference speed of sound*. Speed of sound at reference conditions.
M_{ATR}	—	*Helicopter rotor reference advancing blade tip Mach number*. The sum of the reference rotor rotational tip speed and the reference speed of the helicopter, divided by the reference speed of sound.
M_H	—	*Propeller helical tip Mach number*. The square root of the sum of the square of the propeller test rotational tip speed and the square of the test airspeed of the aeroplane, divided by the test speed of sound.
M_{HR}	—	*Propeller reference helical tip Mach number*. The square root of the sum of the square of the propeller reference rotational tip speed and the square of the reference speed of the aeroplane, divided by the reference speed of sound.

Best R/C	m/s	*Best rate of climb*. The certificated maximum take-off rate of climb at the maximum power setting and engine speed.
V_{AR}	km/h	*Adjusted reference speed*. On a non-standard test day, the helicopter reference speed adjusted to achieve the same advancing tip Mach number as the reference speed at reference conditions.
V_{CON}	km/h	*Maximum airspeed in conversion mode*. The never-exceed airspeed of a tilt-rotor when in conversion mode.
V_G	km/h	*Ground speed*. The aircraft velocity relative to the ground.
V_{GR}	km/h	*Reference ground speed*. The aircraft true velocity relative to the ground in the direction of the ground track under reference conditions. V_{GR} is the horizontal component of the reference aircraft speed V_R.
V_H	km/h	*Maximum airspeed in level flight*. The maximum airspeed of a helicopter in level flight when operating at maximum continuous power.
V_{MCP}	km/h	*Maximum airspeed in level flight*. The maximum airspeed of a tilt-rotor in level flight when operating in aeroplane mode at maximum continuous power.
V_{MO}	km/h	*Maximum operating airspeed*. The maximum operating limit airspeed of a tilt-rotor that may not be deliberately exceeded.
V_{NE}	km/h	*Never exceed airspeed*. The maximum operating limit airspeed that may not be deliberately exceeded.
V_R	km/h	*Reference speed*. The aircraft true velocity at reference conditions in the direction of the reference flight path. *Note:— This symbol should not be confused with the symbol commonly used for aeroplane take-off rotation speed.*
V_{REF}	km/h	*Reference landing airspeed*. The speed of the aeroplane, in a specific landing configuration, at the point where it descends through the landing screen height in the determination of the landing distance for manual landings.
V_S	km/h	*Stalling airspeed*. The minimum steady airspeed in the landing configuration.
V_{tip}	m/s	*Tip speed*. The rotational speed of a rotor or propeller tip at test conditions, excluding the aircraft velocity component.
V_{tipR}	m/s	Reference tip speed. The rotational speed of a rotor or propeller tip at reference conditions, excluding the aircraft velocity component.

V_Y	km/h	*Speed for best rate of climb*. The test airspeed for best take-off rate of climb.
V_2	km/h	*Take-off safety speed*. The minimum airspeed for a safe take-off.

1.2 Time

Symbol	*Unit*	*Meaning*
t_0	s	*Reference duration*. The length of time used as a reference in the integration equation for computing EPNL, where $t_0 = 10$ s.
t_R	s	*Reference reception time*. The reference time of reception calculated from time of reference aircraft position and distance between aircraft and microphone used in the integrated procedure.
Δt	s	*Time increment.* The equal time increment between one-third octave band spectra, where $\Delta t = 0.5$ s.
δt_R	s	*Reference time increment*. The effective duration of a time increment between reference reception times associated with PNLT points used in the integrated method.

1.3 Indices

Symbol	*Unit*	*Meaning*
i	—	*Frequency band index*. The numerical indicator that denotes any one of the 24 one-third octave bands with nominal geometric mean frequencies from 50 to 10 000 Hz.
k	—	*Time increment index*. The numerical indicator that denotes any one of the 0.5 second spectra in a noise time history. For the integrated method, the adjusted time increment associated with each value of k will likely vary from the original 0.5 second time increment when projected to reference conditions.
k_F	—	*First time increment identifier*. Index of the first 10 dB-down point in the discrete measured PNLT time history.
k_{FR}	—	*Reference first time increment identifier*. Index of the first 10 dB-down point in the discrete PNLT time history for the integrated method.

Symbol	*Unit*	*Meaning*
k_L	—	*Last time increment identifier*. Index of the last 10 dB-down point in the discrete measured PNLT time history.
k_{LR}	—	*Reference last time increment identifier*. Index of the last 10 dB-down point in the discrete PNLT time history for the integrated method.
k_M	—	*Maximum PNLTM time increment index*. Time increment index of PNLTM.
t	s	*Elapsed time*. The length of time measured from a reference zero.
t_1	s	*Time of first 10 dB-down point*. The time of the first 10 dB-down point in a continuous function of time. (See k_F.)
t_2	s	*Time of last 10 dB-down point*. The time of the last 10 dB-down point in a continuous function of time. (See k_L.)

1.4 Noise Metrics

Symbol	*Unit*	*Meaning*
EPNL	EPNdB	*Effective perceived noise level.* A single-number evaluator for an aircraft pass-by, accounting for the subjective effects of aircraft noise on human beings, consisting of an integration over the noise duration of the perceived noise level (PNL) adjusted for spectral irregularities (PNLT), normalized to a reference duration of 10 seconds. (See Appendix 2, Section 4.1 for specifications.)
EPNL_A	EPNdB	*Approach EPNL.* Effective perceived noise level at the aeroplane approach reference measurement points.
EPNL_F	EPNdB	*Flyover EPNL.* Effective perceived noise level at the aeroplane flyover reference measurement points.
EPNL_L	EPNdB	*Lateral EPNL.* Effective perceived noise level at the aeroplane lateral reference measurement points.
L_{AE}	dB SEL	*Sound exposure level (SEL).* A single event noise level for an aircraft pass-by, consisting of an integration over the noise duration of the A-weighted sound level (dBA), normalized to a reference duration of 1 second. (See Appendix 4, Section 3 for specifications.)
L_{AS}	dB(A)	*Slow A-weighted sound level*. Sound level with frequency weighting A and time weighting S for a specified instance in time.

Symbol	*Unit*	*Meaning*
L_{ASmax}	dB(A)	*Maximum Slow A-weighted sound level*. The maximum value of L_{AS} over a specified time interval.
L_{ASmaxR}	dB(A)	*Reference maximum Slow A-weighted sound level*. The maximum value of L_{AS} over a specified time interval corrected to reference conditions.
$LIMIT_A$	EPNdB	*Approach EPNL limit*. The maximum permitted noise level at the aeroplane approach reference measurement points.
$LIMIT_F$	EPNdB	*Flyover EPNL limit*. The maximum permitted noise level at the aeroplane flyover reference measurement points.
$LIMIT_L$	EPNdB	*Lateral EPNL limit*. The maximum permitted noise level at the aeroplane lateral reference measurement points.
n	noy	*Perceived noisiness.* The perceived noisiness of a one-third octave band sound pressure level in a given spectrum.
N	noy	*Total perceived noisiness.* The total perceived noisiness of a given spectrum calculated from the 24 values of n.
PNL	PNdB	*Perceived noise level.* A perception-based noise evaluator representing the subjective effects of broadband noise received at a given point in time during an aircraft pass-by. It is the noise level empirically determined to be equally as noisy as a 1 kHz one-third octave band sample of random noise. (See Appendix 2, Section 4.2 for specifications.)
PNLT	TPNdB	*Tone-corrected perceived noise level.* The value of the PNL of a given spectrum adjusted for spectral irregularities.
$PNLT_R$	TPNdB	*Reference tone-corrected perceived noise level.* The value of PNLT adjusted to reference conditions.
PNLTM	TPNdB	*Maximum tone-corrected perceived noise level.* The maximum value of PNLT in a specified time history, adjusted for the bandsharing adjustment Δ_B.
$PNLTM_R$	TPNdB	*Reference maximum tone-corrected perceived noise level.* The maximum value of $PNLT_R$ in a specified time history, adjusted for the bandsharing adjustment Δ_B in the simplified method and Δ_{BR} in the integrated method.

Symbol	*Unit*	*Meaning*
SPL	dB	*Sound pressure level*. The level of sound, relative to the reference level of 20 μPa, at any instant of time that occurs in a specified frequency range. The level is calculated as ten times the logarithm to the base 10 of the ratio of the time-mean-square pressure of the sound to the square of the reference sound pressure of 20 μPa.
		Note: — Typical aircraft noise certification usage refers to a specific one-third octave band, e.g. SPL(i,k) for the i-th band of the k-th spectrum in an aircraft noise time-history.
SPL_R	dB	*Reference sound pressure level*. The one-third octave band sound pressure levels adjusted to reference conditions.
SPL_S	dB	*Slow-weighted sound pressure level*. The value of one-third octave band sound pressure levels with time weighting S applied.
Δ_1	TPNdB	*PNLTM adjustment.* In the simplified adjustment method, the adjustment to be added to the measured EPNL to account for noise level changes due to differences in atmospheric absorption and noise path length between test and reference conditions at PNLTM.
	dB(A)	For propeller aeroplanes not exceeding 8.618kg, the adjustment to be added to L_{ASmax} to account for noise level changes due to the difference between test and reference aeroplane heights.
Δ_2	TPNdB	*Duration adjustment.* In the simplified adjustment method, the adjustment to be added to the measured EPNL to account for noise level changes due to the change in noise duration caused by differences between test and reference aircraft speed and position relative to the microphone.
	dB(A)	For propeller aeroplanes not exceeding 8.618kg, the adjustment to be added to L_{ASmax} to account for engine power.
Δ_3	TPNdB	*Source noise adjustment.* In the simplified or integrated adjustment method, the adjustment to be added to the measured EPNL to account for noise level changes due to differences in source noise generating mechanisms between test and reference conditions.
	dB(A)	For propeller aeroplanes not exceeding 8.618kg, the adjustment to be added to L_{ASmax} to account for the propeller helical tip Mach number.
Δ_4	dB	*Atmospheric absorption adjustment*. For propeller aeroplanes not exceeding 8.618kg, the adjustment to be added to the measured L_{ASmax} for noise level changes due to the change in atmospheric absorption caused by the difference between test and reference aeroplane heights.

Symbol	*Unit*	*Meaning*
Δ_B	TPNdB	*Bandsharing adjustment*. The adjustment to be added to the maximum PNLT to account for possible suppression of a tone due to one-third octave bandsharing of that tone. PNLTM is equal to the maximum PNLT plus Δ_B.
Δ_{BR}	TPNdB	*Reference bandsharing adjustment*. The adjustment to be added to the maximum $PNLT_R$ in the integrated method to account for possible suppression of a tone due to one-third octave bandsharing of that tone. $PNLTM_R$ is equal to the maximum $PNLT_R$ plus $\Delta_{BR.}$
Δ_{peak}	TPNdB	*Peak adjustment*. The adjustment to be added to the measured EPNL for when the PNLT for a secondary peak, identified in the calculation of EPNL from measured data and adjusted to reference conditions, is greater than the PNLT for the adjusted PNLTM spectrum.

1.5 Calculation of PNL and Tone Correction

Symbol	*Unit*	*Meaning*
C	dB	*Tone correction factor*. The factor to be added to the PNL of a given spectrum to account for the presence of spectral irregularities such as tones.
f	Hz	*Frequency*. The nominal geometric mean frequency of a one-third octave band.
F	dB	*Delta-dB*. The difference between the original sound pressure level and the final broadband sound pressure level of a one-third octave band in a given spectrum.
$\log n(a)$	—	*Noy discontinuity coordinate*. The log n value of the intersection point of the straight lines representing the variation of SPL with log n.
M	—	*Noy inverse slope*. The reciprocals of the slopes of straight lines representing the variation of SPL with log n.
s	dB	*Slope of sound pressure level*. The change in level between adjacent one-third octave band sound pressure levels in a given spectrum.
Δs	dB	*Change in slope of sound pressure level*.
s'	dB	*Adjusted slope of sound pressure level*. The change in level between adjacent adjusted one-third octave band sound pressure levels in a given spectrum.
$\overline{s}$	dB	*Average slope of sound pressure level*.
SPL(a)	dB	*Noy discontinuity level*. The SPL value at the discontinuity coordinate of the straight lines representing the variation of SPL with log n.
SPL(b) SPL(c)	dB	*Noy intercept levels*. The intercepts on the SPL-axis of the straight lines representing the variation of SPL with log n.
SPL(d)	dB	*Noy discontinuity level*. The SPL value at the discontinuity coordinate where log n equals -1.
SPL(e)	dB	*Noy discontinuity level*. The SPL value at the discontinuity coordinate where log n equals log 0.3.
SPL′	dB	*Adjusted sound pressure level*. The first approximation to broadband sound pressure level in a one-third octave band of a given spectrum.

Symbol	*Unit*	*Meaning*
SPL″	dB	*Final broadband sound pressure level.* The second and final approximation to broadband sound pressure level in a one-third octave band of a given spectrum.

1.6 Flight Path Geometry

Symbol	*Unit*	*Meaning*
H	m	*Height*. The aircraft height when overhead or abeam of the centre microphone.
H_R	m	*Reference height*. The reference aircraft height when overhead or abeam of the centre microphone.
X	m	*Aircraft position along the ground track*. The position coordinate of the aircraft along the x-axis at a specific point in time.
Y	m	*Lateral aircraft position relative to the reference ground track*. The position coordinate of the aircraft along the y-axis at a specific point in time.
Z	m	*Vertical aircraft position relative to the reference ground track*. The position coordinate of the aircraft along the z-axis at a specific point in time.
θ	degrees	*Sound emission angle*. The angle between the flight path and the direct sound propagation path to the microphone. The angle is identical for both the measured and reference flight paths.
ψ	degrees	*Elevation angle*. The angle between the sound propagation path and a horizontal plane passing through the microphone, where the sound propagation path is defined as a line between a sound emission point on the measured flight path and the microphone diaphragm.
ψ_R	degrees	*Reference elevation angle.* The angle between the reference sound propagation path and a horizontal plane passing through the reference microphone location, where the reference sound propagation path is defined as a line between a sound emission point on the reference flight path and the reference microphone diaphragm.

1.7 Miscellaneous

Symbol	*Unit*	*Meaning*
antilog	—	*Antilogarithm to the base 10.*
D	m	*Diameter*. Propeller or rotor diameter.
D_{15}	m	*Take-off distance*. The take-off distance required for an aeroplane to reach 15 m height above ground level.
e	—	*Euler's number*. The mathematical constant that is the base number of the natural logarithm, approximately 2.78183.
log	—	*Logarithm to the base 10*.
N	rpm	*Propeller speed.*
N_1	rpm	*Compressor speed*. The turbine engine low pressure compressor first stage fan speed.
RH	%	*Relative humidity*. The ambient atmospheric relative humidity.
T	°C	*Temperature*. The ambient atmospheric temperature.
u	m/s	*Wind speed along-track component*. The component of the wind speed vector along the reference ground track.
v	m/s	*Wind speed cross-track component*. The component of the wind speed vector horizontally perpendicular to the reference ground track.
α	dB/100 m	*Test atmospheric absorption coefficient.* The sound attenuation rate due to atmospheric absorption that occurs in a specified one-third octave band for the measured ambient temperature and relative humidity.
α_R	dB/100 m	*Reference atmospheric absorption coefficient.* The sound attenuation rate due to atmospheric absorption that occurs in a specified one-third octave band for a reference ambient temperature and relative humidity.
μ	—	*Engine noise performance parameter*. For jet aeroplanes, typically the normalized low pressure fan speed, normalized engine thrust, or engine pressure ratio used in the calculation of the source noise adjustment.

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PART I. DEFINITIONS

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~~***Auxiliary power unit***~~ ***Auxiliary power unit (APU).*** A self-contained ~~power unit~~ power unit on an aircraft providing electrical/pneumatic power to aircraft systems during ground operations or in-flight separate from the propulsion engine/s.

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State of Registry. The State on whose register the aircraft is entered.

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CHAPTER 3.

1.— SUBSONIC JET AEROPLANES — Application for Type Certificate submitted on or after 6 October 1977 and before 1 January 2006

2.— PROPELLER-DRIVEN AEROPLANES OVER 8 618 kg — Application for Type Certificate submitted on or after 1 January 1985 and before 1 January 2006

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3.6 Noise certification reference procedures

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3.6.3 Approach reference procedure

The approach reference flight path shall be calculated as follows:

a) the aeroplane shall be stabilized and following a 3° glide path;

b) a steady approach speed of V_{REF} + 19 km/h (V_{REF} + 10 kt), with thrust or power stabilized, shall be maintained over the measurement point;

> *Note.— In airworthiness terms* ~~V_{REF}~~ *V_{REF} is defined as the "reference landing speed". Under this definition reference landing speed means "the speed of the aeroplane, in a specified landing configuration, at the point where it descends through the landing screen height in the determination of the landing distance for manual landings".*

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CHAPTER 6. PROPELLER-DRIVEN AEROPLANES NOT EXCEEDING 8 618 kg — Application for Type Certificate submitted before 17 November 1988

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6.5 Test procedures

6.5.1 Either the test procedures described in 6.5.2 and 6.5.3 or equivalent test procedures approved by the certificating authority shall be used.

6.5.2 Tests to demonstrate compliance with the maximum noise levels of 6.3 shall consist of a series of level flights overhead the measuring station at a height of

~~300 $^{+10}_{-30}$ m (985 $^{+30}_{-100}$ ft)~~

$$300\ ^{+10}_{-30}\ \text{m}\ (984\ ^{+30}_{-100}\ \text{ft})$$

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CHAPTER 8. HELICOPTERS

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8.6.2 Take-off reference procedure

The take-off reference flight procedure shall be established as follows:

a) the helicopter shall be stabilized at the maximum take-off power corresponding to minimum installed engine(s) specification power available for the reference ambient conditions or gearbox torque limit, whichever is lower, and along a path starting from a point located 500 m prior to the flight path reference point, at 20 m (65 ft) above the ground;

b) the best rate of climb speed, ~~V_y~~ V_Y, or the lowest approved speed for the climb after take-off, whichever is the greater, shall be maintained throughout the take-off reference procedure;

c) the steady climb shall be made with the rotor speed stabilized at the maximum normal operating rpm certificated for take-off;

d) a constant take-off configuration selected by the applicant shall be maintained throughout the take-off reference procedure with the landing gear position consistent with the airworthiness certification tests for establishing the best rate of climb speed, ~~V_y~~ V_Y;

e) the mass of the helicopter shall be the maximum take-off mass at which noise certification is requested; and

f) the reference take-off path is defined as a straight line segment inclined from the starting point (500 m prior to the centre microphone location and 20 m (65 ft) above ground level) at an angle defined by best rate of climb and ~~V_y~~ V_Y for minimum specification engine performance.

8.6.3 Overflight reference procedure

8.6.3.1 The overflight reference procedure shall be established as follows:

a) the helicopter shall be stabilized in level flight overhead the flight path reference point at a height of 150 m (492 ft);

b) a speed of 0.9 V_H or 0.9 V_{NE} or 0.45 V_H + 120 km/h (0.45 V_H + 65 kt) or 0.45 V_{NE} + 120 km/h (0.45 V_{NE} + 65 kt), whichever is the least, shall be maintained throughout the overflight reference procedure;

Note.— For noise certification purposes, ~~V_H~~ V_H *is defined as the airspeed in level flight obtained using the torque corresponding to minimum engine installed, maximum continuous power available for sea level pressure (1 013.25 hPa), 25°C ambient conditions at the relevant maximum certificated mass.* ~~V_{NE}~~ V_{NE} *is defined as the not-to-exceed airworthiness airspeed imposed by the manufacturer and approved by the certificating authority.*

c) the overflight shall be made with the rotor speed stabilized at the maximum normal operating rpm certificated for level flight;

d) the helicopter shall be in the cruise configuration; and

e) the mass of the helicopter shall be the maximum take-off mass at which noise certification is requested.

8.6.3.2 The value of V_H and/or V_{NE} used for noise certification shall be quoted in the approved flight manual.

8.6.4 Approach reference procedure

The approach reference procedure shall be established as follows:

a) the helicopter shall be stabilized and following a 6.0° approach path;

b) the approach shall be made at a stabilized airspeed equal to the best rate of climb speed, ~~V_y~~ V_Y, or the lowest approved speed for the approach, whichever is the greater, with power stabilized during the approach and over the flight path reference point, and continued to a normal touchdown;

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CHAPTER 10. PROPELLER-DRIVEN AEROPLANES NOT EXCEEDING 8 618 kg — Application for Type Certificate or Certification of Derived Version submitted on or after 17 November 1988

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10.2 Noise evaluation measure

The noise evaluation measure shall be the maximum A-weighted noise level ~~(L_{Amax})~~, L_{ASmax}, as defined in Appendix 6.

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10.5.2 Take-off reference procedure

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Second phase

a) the beginning of the second phase corresponds to the end of the first phase;

b) the aeroplane shall be in the climb configuration with landing gear up, if retractable, and flap setting corresponding to normal climb throughout this second phase;

c) the speed shall be the best rate of climb speed, ~~V_y~~ V_Y; and

d) take-off power and, for aeroplanes equipped with variable pitch or constant speed propellers, rpm shall be maintained throughout the second phase. If airworthiness limitations do not permit the application of take-off power and rpm up to the reference point, then take-off power and rpm shall be maintained for as long as is permitted by such limitations and thereafter at maximum continuous power and rpm. Limiting of time for which take-off power and rpm shall be used in order to comply with this chapter shall not be permitted. The reference height shall be calculated assuming climb gradients appropriate to each power setting used.

...

10.6 Test procedures

10.6.1 The test procedures shall be acceptable to the airworthiness and noise certificating authorities of the State issuing the certificate.

10.6.2 The test procedures and noise measurements shall be conducted and processed in an approved manner to yield the noise evaluation measure in units of ~~L_{Amax}~~ L_{ASmax} as described in Appendix 6.

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CHAPTER 13. TILT-ROTORS

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13.2 Noise evaluation measure

The noise evaluation measure shall be the effective perceived noise level in EPNdB as described in Appendix 2 of this Annex. The correction for spectral irregularities shall start at 50 Hz (see 4.3.1 of Appendix 2).

Note.— Additional data in SEL and ~~L_{ASmax}~~ L_{ASmax} *as defined in Appendix 4, and one-third octave SPLs as defined in Appendix 2 corresponding to* ~~L_{Amax}~~ L_{ASmax} *should be made available to the certificating authority for land-use planning purposes.*

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13.3 Noise measurement reference points

A tilt-rotor, when tested in accordance with the reference procedures of ~~Section 6~~ 13.6 and the test procedures of ~~Section 7~~ 13.7, shall not exceed the noise levels specified in 13.4 at the following reference points:

. . .

13.6.2 Take-off reference procedure

The take-off reference flight procedure shall be established as follows:

. . .

f) the reference take-off path is defined as a straight line segment inclined from the starting point (500 m (1 640 ft) prior to the centre noise measurement point and 20 m (65 ft) above ground level) at an angle defined by best rate of climb ~~(BRC)~~ and the best rate of climb speed corresponding to the selected nacelle angle and for minimum specification engine performance.

. . .

13.6.3 Overflight reference procedure

13.6.3.1 The overflight reference procedure shall be established as follows:

. . .

d) in the VTOL/conversion mode, the nacelle angle at the authorized fixed operation point that is closest to the lowest nacelle angle certificated for zero airspeed, a speed of ~~$0.9V_{CON}$~~ $0.9\ V_{CON}$ and a rotor speed stabilized at the maximum normal operating rpm certificated for level flight shall be maintained throughout the overflight reference procedure;

Note.— For noise certification purposes, V_{CON} *is defined as the maximum authorized speed for VTOL/conversion mode at a specific nacelle angle.*

e) in the aeroplane mode, the nacelles shall be maintained on the down-stop throughout the overflight reference procedure, with:

  1) rotor speed stabilized at the rpm associated with the VTOL/conversion mode and a speed of ~~$0.9V_{CON}$~~ $0.9\ V_{CON}$; and

  2) rotor speed stabilized at the normal cruise rpm associated with the aeroplane mode and at the corresponding ~~$0.9V_{MCP}$~~ $0.9\ V_{MCP}$ or ~~$0.9V_{MO}$~~ $0.9\ V_{MO}$, whichever is lesser, certificated for level flight.

APPENDIX 2. EVALUATION METHOD FOR NOISE CERTIFICATION OF:

1.— SUBSONIC JET AEROPLANES — Application for Type Certificate submitted on or after 6 October 1977

2.— PROPELLER-DRIVEN AEROPLANES OVER 8 618 kg — Application for Type Certificate submitted on or after 1 January 1985

3.— HELICOPTERS

4.— TILT-ROTORS

Note.— See Part II, Chapters 3, 4, 8, 13 and 14.

1. INTRODUCTION

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Note 3.— A complete list of symbols and units~~, the~~ is included after the Table of Contents of this Annex. The mathematical formulation of perceived noisiness, a procedure for determining atmospheric attenuation of sound, and detailed procedures for correcting noise levels from non-reference to reference conditions are included in Sections~~ 6 to~~ 7 and 8 of this appendix.

. . .

2.2.2 Atmospheric conditions

2.2.2.1 *Definitions and specifications*

For the purposes of noise certification in this section the following specifications apply:

Average crosswind component shall be determined from the series of individual values of the "~~cross track~~cross-track" (v) component of the wind samples obtained during the aircraft test run, using a linear averaging process over 30 seconds or an averaging process that has a time constant of no more than 30 seconds, the result of which is read out at a moment approximately 15 seconds after the time at which the aircraft passes either over or abeam the microphone.

Average wind speed shall be determined from the series of individual wind speed samples obtained during the aircraft test run, using a linear averaging process over 30 seconds, or an averaging process that has a time constant of no more than 30 seconds, the result of which is read out at a moment approximately 15 seconds after the time at which the aircraft passes either over or abeam the microphone. Alternatively, each wind vector shall be broken down into its "~~along track~~along-track" (u) and "cross-track" (v) components. The u and v components of the series of individual wind samples obtained during the aircraft test run shall be separately averaged using a linear averaging process over 30 seconds, or an averaging process that has a time constant of no more than 30 seconds, the result of which is read out at a moment approximately 15 seconds after the time at which the aircraft passes either over or abeam the microphone. The average wind speed and direction (with respect to the track) shall then be calculated from the averaged u and v components according to Pythagorean Theorem and "arctan(v/u)".

Distance constant (or response length). The passage of wind (in metres) required for the output of a wind speed sensor to indicate 100 × (1−1/*e*) per cent (about 63 per cent) of a step-function increase of the input speed.

Maximum crosswind component. The maximum value within the series of individual values of the "~~cross track~~cross-track" (v) component of the wind samples recorded every second over a time interval that spans the 10 dB-down period.

Maximum wind speed. The maximum value within the series of individual wind speed samples recorded every second over a time interval that spans the 10 dB-down period.

Sound attenuation coefficient. The reduction in level of sound within a one-third octave band, in dB per 100 metres, due to the effects of atmospheric absorption of sound. Equations for the calculation of sound attenuation coefficients from values of atmospheric temperature and relative humidity are provided in Section 7.

Time constant (of a first order system). The time required for a device to detect and indicate 100 × (1−1/*e*) per cent (about 63 per cent) of a step function change. (The mathematical constant, ~~e~~*e*, is the base number of the natural logarithm, approximately 2.7183 — also known as Euler's number, or Napier's constant.)

. . .

3.1 Definitions

. . .

***Free-field sensitivity of a microphone system*.** In volts per pascal, for a sinusoidal plane progressive sound wave of specified frequency, at a specified ~~sound incident~~ sound-incidence angle, the quotient of the root-mean-square voltage at the output of a microphone system and the root-mean-square sound pressure that would exist at the position of the microphone in its absence.

. . .

3.7 Analysis systems

3.7.5 When the one-third octave band sound pressure levels are determined from the output of the analyser without SLOW-time-weighting, SLOW-time-weighting shall be simulated in the subsequent processing. Simulated SLOW-weighted sound pressure levels can be obtained using a continuous exponential averaging process by the following equation:

~~$L_s(i,k) = 10 \log [(0.60653)\, 10^{0.1L_s[i,(k-1)]} + (0.39347)\, 10^{0.1L(i,k)}]$~~

$$\mathrm{SPL_s}(i,k) = 10 \log [(0.60653)\, 10^{0.1\mathrm{SPL_s}[i,(k-1)]} + (0.39347)\, 10^{0.1\mathrm{SPL}(i,k)}]$$

where ~~$L_s(i,k)$~~ $\mathrm{SPL_s}(i,k)$ is the simulated SLOW-weighted sound pressure level and ~~$L(i,k)$~~ $\mathrm{SPL}(i,k)$ is the as-measured 0.5 seconds time average sound pressure level determined from the output of the analyser for the k-th instant of time and the i-th one-third octave band. For $k = 1$, the SLOW-weighted sound pressure ~~$L_s[i,(k-1 = 0)]$~~ $\mathrm{SPL_s}[i,(k-1 = 0)]$ on the right-hand side shall be set to 0 dB.

An approximation of the continuous exponential averaging is represented by the following equation for a four sample averaging process for $k = 4$:

~~$L_s(i,k) = 10 \log [(0.13)\, 10^{0.1L[i,(k-3)]} + (0.21)\, 10^{0.1L[i,(k-2)]} + (0.27)\, 10^{0.1L[i,(k-1)]} + (0.39)\, 10^{0.1L[i,k]}]$~~

$$\mathrm{SPL}_s(i,k) = 10 \log [(0.13)\, 10^{0.1\mathrm{SPL}[i,(k-3)]} + (0.21)\, 10^{0.1\mathrm{SPL}[i,(k-2)]} + (0.27)\, 10^{0.1\mathrm{SPL}[i,(k-1)]} + (0.39)\, 10^{0.1\mathrm{SPL}[i,k]}]$$

where ~~$L_s(i,k)$~~ $\mathrm{SPL_s}(i,k)$ is the simulated SLOW-weighted sound pressure level and ~~$L(i,k)$~~ $\mathrm{SPL}(i,k)$ is the as-measured 0.5 seconds time average sound pressure level determined from the output of the analyser for the k-th instant of time and the i-th one-third octave band.

. . .

4.1 General

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4.1.3 The calculation procedure which utilizes physical measurements of noise to derive the EPNL evaluation measure of subjective response shall consist of the five following steps:

a) each of the 24 one-third octave band sound pressure levels in each measured one-half second spectrum is converted to perceived noisiness by the method of Section 4.7. The noy values are combined and then converted to instantaneous perceived noise level, PNL(k) for each spectrum, measured at the k-th instant of time, by the method of Section 4.2;

b) for each spectrum a tone correction factor, ~~$C(k)$~~ $\mathrm{C}(k)$, is calculated by the method of Section 4.3 to account for the subjective response to the presence of spectral irregularities;

c) the tone correction factor is added to the perceived noise level to obtain the tone corrected perceived noise level, PNLT(k), for each spectrum:

$\mathrm{PNLT}(k) = \mathrm{PNL}(k) +$ ~~$C(k)$~~ $\mathrm{C}(k)$;

. . .

4.2 Perceived noise level

. . .

Note.— Perceived noise level, ~~PNL(*k*)~~ *PNL(k), as a function of total perceived noisiness is plotted in the section of the* Environmental Technical Manual *(Doc 9501), Volume I* — Procedures for the Noise Certification of Aircraft, *concerning reference tables used in the manual calculation of effective perceived noise level.*

4.3 Correction for spectral irregularities

4.3.1 Noise having pronounced spectral irregularities (for example, the maximum discrete frequency components or tones) shall be adjusted by the correction factor, ~~*C*(*k*)~~ C(*k*), calculated as follows:

. . .

Table A2-2. Tone correction factors

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Frequency *f*, Hz	Level difference *F*, dB	Tone correction ~~*C*~~C, dB

. . .

Tone corrected perceived noise levels PNLT(*k*) shall be determined by adding the ~~*C*(*k*)~~ C(*k*) values to corresponding PNL(*k*) values, that is:

PNLT(*k*) = PNL(*k*) + ~~*C*(*k*)~~ C(*k*)

For any *i*-th one-third octave band, at any *k*-th increment of time, for which the tone correction factor is suspected to result from something other than (or in addition to) an actual tone (or any spectral irregularity other than aircraft noise), an additional analysis may be made using a filter with a bandwidth narrower than one-third of an octave. If the narrow band analysis corroborates these suspicions, then a revised value for the broadband sound pressure level, SPL′(*i*,*k*), shall be determined from the narrow band analysis and used to compute a revised tone correction factor for that particular one-third octave band.

Note.— Other methods of rejecting spurious tone corrections such as those described in ~~Appendix 2~~ Chapter 4 of the Environmental Technical Manual *(Doc 9501), Volume I* — Procedures for the Noise Certification of Aircraft *may be used.*

. . .

4.4 Maximum tone corrected perceived noise level

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4.4.2 The tone at PNLTM may be suppressed due to one-third octave bandsharing of that tone. To identify whether this is the case, the average of the tone correction factors of the PNLTM spectrum and the two preceding and two succeeding spectra is calculated. If the value of the tone correction factor

~~$C(k_M)$~~ $\mathrm{C}(k_\mathrm{M})$ for the spectrum associated with PNLTM is less than the average value of ~~$C(k)$~~ $\mathrm{C}(k)$ for the five consecutive spectra (k_M–2) through (k_M+2), then the average value ~~C_{avg}~~ C_avg shall be used to compute a bandsharing adjustment, Δ_B, and a value of PNLTM adjusted for bandsharing.

~~$C_{avg} = [C(k_M-2) + C(k_M-1) + C(k_M) + C(k_M+1) + C(k_M+2)] / 5$~~

$\mathrm{C}_\mathrm{avg} = [\mathrm{C}(k_\mathrm{M}–2) + \mathrm{C}(k_\mathrm{M}–1) + \mathrm{C}(k_\mathrm{M}) + \mathrm{C}(k_\mathrm{M}+1) + \mathrm{C}(k_\mathrm{M}+2)] / 5$

If ~~C_{avg}~~ C_avg > ~~$C(k_M)$~~ $\mathrm{C}(k_\mathrm{M})$, then Δ_B = ~~C_{avg}~~ C_avg – ~~$C(k_M)$~~ $\mathrm{C}(k_\mathrm{M})$ and

. . .

4.6 Effective perceived noise level

4.6.1 If the instantaneous tone corrected perceived noise level is expressed in terms of a continuous function with time, PNLT(t), then the effective perceived noise level, EPNL, would be defined as the level, in EPNdB, of the time integral of PNLT(t) over the noise event duration, normalized to a reference duration, ~~T_0~~ t_0, of 10 seconds. The noise event duration is bounded by ~~$t1$~~ t_1, the time when PNLT(t) is first equal to PNLTM – 10, and ~~$t2$~~ t_2, the time when PNLT(t) is last equal to PNLTM – 10.

~~$\mathrm{EPNL} = 10\log\frac{1}{T_0}\int_{t1}^{t2} 10^{0.1\,\mathrm{PNLT}(t)}dt$~~

$$\mathrm{EPNL} = 10\log\frac{1}{\mathrm{t}_0}\int_{t_1}^{t_2} 10^{0.1\,\mathrm{PNLT}(t)}dt$$

4.6.2 In practice PNLT is not expressed as a continuous function with time since it is computed from discrete values of PNLT(k) every half second. In this case the basic working definition for EPNL is obtained by replacing the integral in Section 4.6.1 with the following summation expression:

~~$\mathrm{EPNL} = 10\log\frac{1}{T_0}\sum_{k_F}^{k_L} 10^{0.1\,\mathrm{PNLT}(k)}\Delta t$~~

$$\mathrm{EPNL} = 10\log\frac{1}{\mathrm{t}_0}\sum_{k_\mathrm{F}}^{k_\mathrm{L}} 10^{0.1\,\mathrm{PNLT}(k)}\Delta\mathrm{t}$$

For ~~T_0~~ t_0 = 10 and ~~Δt~~ $\Delta\mathrm{t}$ = 0.5, this expression can be simplified as follows:

$$\mathrm{EPNL} = 10\log\sum_{k_\mathrm{F}}^{k_\mathrm{L}} 10^{0.1\,\mathrm{PNLT}(k)} - 13$$

Note.— 13 dB is a constant relating the one-half second values of ~~PNLT(k)~~ *PNLT(k) to the 10-second reference duration T_0:* 10 log (0.5/10) = –13.

. . .

Table A2-3. Constants for mathematically formulated noy values

~~BAND (*i*)~~	*f* ~~Hz~~	~~SPL(*a*)~~	~~SPL(*b*)~~	~~SPL(*c*)~~	~~SPL(*d*)~~	~~SPL(*e*)~~	~~*M*(*b*)~~	~~*M*(*c*)~~	~~*M*(*d*)~~	~~*M*(*e*)~~
~~1~~	~~50~~	~~91.0~~	~~64~~	~~52~~	~~49~~	~~55~~	~~0.043478~~	~~0.030103~~	~~0.079520~~	~~0.058098~~
~~2~~	~~63~~	~~85.9~~	~~60~~	~~51~~	~~44~~	~~51~~	~~0.040570~~	↑	~~0.068160~~	~~”~~
~~3~~	~~80~~	~~87.3~~	~~56~~	~~49~~	~~39~~	~~46~~	~~0.036831~~		~~”~~	~~0.052288~~
~~4~~	~~100~~	~~79.0~~	~~53~~	~~47~~	~~34~~	~~42~~	~~”~~		~~0.059640~~	~~0.047534~~
~~5~~	~~125~~	~~79.8~~	~~51~~	~~46~~	~~30~~	~~39~~	~~0.035336~~		~~0.053013~~	~~0.043573~~
~~6~~	~~160~~	~~76.0~~	~~48~~	~~45~~	~~27~~	~~36~~	~~0.033333~~		↑	~~”~~
~~7~~	~~200~~	~~74.0~~	~~46~~	~~43~~	~~24~~	~~33~~	~~”~~			~~0.040221~~
~~8~~	~~250~~	~~74.9~~	~~44~~	~~42~~	~~21~~	~~30~~	~~0.032051~~	↓		~~0.037349~~
~~9~~	~~315~~	~~94.6~~	~~42~~	~~41~~	~~18~~	~~27~~	~~0.030675~~	~~0.030103~~		~~0.034859~~
~~10~~	~~400~~	~~∞~~	~~40~~	~~40~~	~~16~~	~~25~~	~~0.030103~~	↑		↑
~~11~~	~~500~~	↑	~~40~~	~~40~~	~~16~~	~~25~~	↑			
~~12~~	~~630~~		~~40~~	~~40~~	~~16~~	~~25~~				
~~13~~	~~800~~		~~40~~	~~40~~	~~16~~	~~25~~			↓	
~~14~~	~~1 000~~		~~40~~	~~40~~	~~16~~	~~25~~	↓		~~0.053013~~	↓
~~15~~	~~1 250~~		~~38~~	~~38~~	~~15~~	~~23~~	~~0.030103~~		~~0.059640~~	~~0.034859~~
~~16~~	~~1 600~~		~~34~~	~~34~~	~~12~~	~~21~~	~~0.029960~~	~~NOT APPLICABLE~~	~~0.053013~~	~~0.040221~~
~~17~~	~~2 000~~		~~32~~	~~32~~	~~9~~	~~18~~	↑		~~”~~	~~0.037349~~
~~18~~	~~2 500~~		~~30~~	~~30~~	~~5~~	~~15~~			~~0.047712~~	~~0.034859~~
~~19~~	~~3 150~~		~~29~~	~~29~~	~~4~~	~~14~~			~~”~~	↑
~~20~~	~~4 000~~		~~29~~	~~29~~	~~5~~	~~14~~			~~0.053013~~	↓
~~21~~	~~5 000~~	↓	~~30~~	~~30~~	~~6~~	~~15~~	↓	↓	~~”~~	~~0.034859~~
~~22~~	~~6 300~~	~~∞~~	~~31~~	~~31~~	~~10~~	~~17~~	~~0.029960~~	~~0.029960~~	~~0.068160~~	~~0.037349~~
~~23~~	~~8 000~~	~~44.3~~	~~37~~	~~34~~	~~17~~	~~23~~	~~0.042285~~		~~0.079520~~	~~”~~
~~24~~	~~10 000~~	~~50.7~~	~~41~~	~~37~~	~~21~~	~~29~~	~~”~~	~~”~~	~~0.059640~~	~~0.043573~~

BAND (i)	ISO BAND	f Hz	SPL(a)	SPL(b)	SPL(c)	SPL(d)	SPL(e)	$M(b)$	$M(c)$	$M(d)$	$M(e)$
1	17	50	91.0	64	52	49	55	0.043478	0.030103	0.079520	0.058098
2	18	63	85.9	60	51	44	51	0.040570	0.030103	0.068160	0.058098
3	19	80	87.3	56	49	39	46	0.036831	0.030103	0.068160	0.052288
4	20	100	79.0	53	47	34	42	0.036831	0.030103	0.059640	0.047534
5	21	125	79.8	51	46	30	39	0.035336	0.030103	0.053013	0.043573
6	22	160	76.0	48	45	27	36	0.033333	0.030103	0.053013	0.043573
7	23	200	74.0	46	43	24	33	0.033333	0.030103	0.053013	0.040221
8	24	250	74.9	44	42	21	30	0.032051	0.030103	0.053013	0.037349
9	25	315	94.6	42	41	18	27	0.030675	0.030103	0.053013	0.034859
10	26	400	∞	40	40	16	25	0.030103	NOT APPLICABLE	0.053013	0.034859
11	27	500	∞	40	40	16	25	0.030103		0.053013	0.034859
12	28	630	∞	40	40	16	25	0.030103		0.053013	0.034859
13	29	800	∞	40	40	16	25	0.030103		0.053013	0.034859
14	30	1 000	∞	40	40	16	25	0.030103		0.053013	0.034859
15	31	1 250	∞	38	38	15	23	0.030103		0.059640	0.034859
16	32	1 600	∞	34	34	12	21	0.029960		0.053013	0.040221
17	33	2 000	∞	32	32	9	18	0.029960		0.053013	0.037349
18	34	2 500	∞	30	30	5	15	0.029960		0.047712	0.034859
19	35	3 150	∞	29	29	4	14	0.029960		0.047712	0.034859
20	36	4 000	∞	29	29	5	14	0.029960		0.053013	0.034859
21	37	5 000	∞	30	30	6	15	0.029960		0.053013	0.034859
22	38	6 300	∞	31	31	10	17	0.029960	0.029960	0.068160	0.037349
23	39	8 000	44.3	37	34	17	23	0.042285	0.029960	0.079520	0.037349
24	40	10 000	50.7	41	37	21	29	0.042285	0.029960	0.059640	0.043573

. . .

Figure A2-3. ~~Example of perceived noise level corrected for tones as a function of aeroplane flyover time~~Perceived noisiness as a function of sound pressure level

. . .

6. ~~NOMENCLATURE: SYMBOLS AND UNITS~~RESERVED

~~*Symbol*~~	~~*Unit*~~	~~*Meaning*~~
~~antilog~~	~~—~~	~~*Antilogarithm to the base 10.*~~
~~*C*(*k*)~~	~~dB~~	~~*Tone correction factor*. The factor to be added to PNL(*k*) to account for the presence of spectral irregularities such as tones at the *k*-th increment of time.~~
~~*d*~~	~~s~~	~~*Duration time*. The length of the significant noise time history being the time interval between the limits of *t*(1) and *t*(2) to the nearest 0.5 second.~~
~~*D*~~	~~dB~~	~~*Duration correction*. The factor to be added to PNLTM to account for the duration of the noise.~~
~~EPNL~~	~~EPNdB~~	~~*Effective perceived noise level*. The value of PNL adjusted for both the spectral irregularities and the duration of the noise. (The unit EPNdB is used instead of the unit dB.)~~
~~*f*(*i*)~~	~~Hz~~	~~*Frequency*. The geometrical mean frequency for the *i*-th one-third octave band.~~
~~*F*(*i*,*k*)~~	~~dB~~	~~*Delta-dB*. The difference between the original sound pressure level and the final broadband sound pressure level in the *i*-th one-third octave band at the *k*-th interval of time.~~
~~*h*~~	~~dB~~	~~*dB-down*. The level to be subtracted from PNLTM that defines the duration of the noise.~~
~~*H*~~	~~%~~	~~*Relative humidity*. The ambient atmospheric relative humidity.~~
~~*i*~~	~~—~~	~~*Frequency band index*. The numerical indicator that denotes any one of the 24 one-third octave bands with geometrical mean frequencies from 50 to 10 000 Hz.~~
~~*k*~~	~~—~~	~~*Time increment index*. The numerical indicator that denotes the number of equal time increments that have elapsed from a reference zero.~~
~~log~~	~~—~~	~~*Logarithm to the base 10.*~~
~~log *n*(*a*)~~	~~—~~	~~*Noy discontinuity coordinate*. The log *n* value of the intersection point of the straight lines representing the variation of SPL with log *n*.~~
~~*M*(*b*), *M*(*c*), etc.~~	~~—~~	~~*Noy inverse slope*. The reciprocals of the slopes of straight lines representing the variation of SPL with log *n*.~~
~~*n*~~	~~noy~~	~~*Perceived noisiness*. The perceived noisiness at any instant of time that occurs in a specified frequency range.~~

~~*Symbol*~~	~~*Unit*~~	~~*Meaning*~~
~~*n*(*i*,*k*)~~	~~noy~~	~~*Perceived noisiness*. The perceived noisiness at the *k*-th instant of time that occurs in the *i*-th one-third octave band.~~
~~*n*(*k*)~~	~~noy~~	~~*Maximum perceived noisiness*. The maximum value of all of the 24 values of *n*(*i*) that occurs at the *k*-th instant of time.~~
~~*N*(*k*)~~	~~noy~~	~~*Total perceived noisiness*. The total perceived noisiness at the *k*-th instant of time calculated from the 24 instantaneous values of *n*(*i*,*k*).~~
~~*p*(*b*), *p*(*c*), etc.~~	~~—~~	~~*Noy slope*. The slopes of straight lines representing the variation of SPL with log *n*.~~
~~PNL~~	~~PNdB~~	~~*Perceived noise level*. The perceived noise level at any instant of time. (The unit PNdB is used instead of the unit dB.)~~
~~PNL(*k*)~~	~~PNdB~~	~~*Perceived noise level*. The perceived noise level calculated from the 24 values of SPL(*i*,*k*) at the *k*-th increment of time. (The unit PNdB is used instead of the unit dB.)~~
~~PNLM~~	~~PNdB~~	~~*Maximum perceived noise level*. The maximum value of PNL(*k*). (The unit PNdB is used instead of the unit dB.)~~
~~PNLT~~	~~TPNdB~~	~~*Tone corrected perceived noise level*. The value of PNL adjusted for the spectral irregularities that occur at any instant of time. (The unit TPNdB is used instead of the unit dB.)~~
~~PNLT(*k*)~~	~~TPNdB~~	~~*Tone corrected perceived noise level*. The value of PNL(*k*) adjusted for the spectral irregularities that occur at the *k*-th increment of time. (The unit TPNdB is used instead of the unit dB.)~~
~~PNLTM~~	~~TPNdB~~	~~*Maximum tone corrected perceived noise level*. The maximum value of PNLT(*k*). (The unit TPNdB is used instead of the unit dB.)~~
~~PNLT$_r$~~	~~TPNdB~~	~~*Tone corrected perceived noise level* adjusted for reference conditions.~~
~~*s*(*i*,*k*)~~	~~dB~~	~~*Slope of sound pressure level*. The change in level between adjacent one-third octave band sound pressure levels at the *i*-th band for the *k*-th instant of time.~~
~~Δ*s*(*i*,*k*)~~	~~dB~~	~~*Change in slope of sound pressure level*.~~
~~*s*′(*i*,*k*)~~	~~dB~~	~~*Adjusted slope of sound pressure level*. The change in level between adjacent adjusted one-third octave band sound pressure levels at the *i*-th band for the *k*-th instant of time.~~
~~$\bar{s}$(*i*,*k*)~~	~~dB~~	~~*Average slope of sound pressure level*.~~
~~SPL~~	~~dB re 20 µPa~~	~~*Sound pressure level*. The sound pressure level at any instant of time that occurs in a specified frequency range.~~

~~*Symbol*~~	~~*Unit*~~	~~*Meaning*~~
~~SPL(*a*)~~	~~dB re 20 µPa~~	~~*Noy discontinuity coordinate*. The SPL value of the intersection point of the straight lines representing the variation of SPL with log *n*.~~
~~SPL(*b*)~~ ~~SPL(*c*)~~	~~dB re 20 µPa~~	~~*Noy intercept*. The intercepts on the SPL-axis of the straight lines representing the variation of SPL with log *n*.~~
~~SPL(*i*,*k*)~~	~~dB re 20 µPa~~	~~*Sound pressure level*. The sound pressure level at the *k*-th instant of time that occurs in the *i*-th one-third octave band.~~
~~SPL′(*i*,*k*)~~	~~dB re 20 µPa~~	~~*Adjusted sound pressure level*. The first approximation to broadband sound pressure level in the *i*-th one-third octave band for the *k*-th instant of time.~~
~~SPL(*i*)~~	~~dB re 20 µPa~~	~~*Maximum sound pressure level*. The sound pressure level that occurs in the *i*-th one-third octave band of the spectrum for PNLTM.~~
~~$\mathrm{SPL}(i)_r$~~	~~dB re 20 µPa~~	~~*Corrected maximum sound pressure level*. The sound pressure level that occurs in the *i*-th one-third octave band of the spectrum for PNLTM corrected for atmospheric sound absorption.~~
~~SPL″(*i*,*k*)~~	~~dB re 20 µPa~~	~~*Final broadband sound pressure level*. The second and final approximation to broadband sound pressure level in the *i*-th one-third octave band for the *k*-th instant of time.~~
~~*t*~~	~~s~~	~~*Elapsed time*. The length of time measured from a reference zero.~~
~~*t*1, *t*2~~	~~s~~	~~*Time limit*. The beginning and end, respectively, of the significant noise time history defined by *h*.~~
~~Δ*t*~~	~~s~~	~~*Time increment*. The equal increments of time for which PNL(*k*) and PNLT(*k*) are calculated.~~
~~*T*~~	~~s~~	~~*Normalizing time constant*. The length of time used as a reference in the integration method for computing duration corrections, where *T* = 10 s.~~
~~*t* (°C)~~	~~°C~~	~~*Temperature*. The ambient atmospheric temperature.~~
~~α(*i*)~~	~~dB/100 m~~	~~*Test atmospheric absorption*. The atmospheric attenuation of sound that occurs in the *i*-th one-third octave band for the measured atmospheric temperature and relative humidity.~~
~~$\alpha(i)_0$~~	~~dB/100 m~~	~~*Reference atmospheric absorption*. The atmospheric attenuation of sound that occurs in the *i*-th one-third octave band for a reference atmospheric temperature and relative humidity.~~
~~A_1~~	~~degrees~~	~~*First constant* climb angle.*~~
~~A_2~~	~~degrees~~	~~*Second constant** climb angle.*~~

~~*Symbol*~~	~~*Unit*~~	~~*Meaning*~~
~~δ~~ ~~ε~~	~~degrees~~ ~~degrees~~	~~*Thrust cutback angles*. The angles defining the points on the take-off flight path at which thrust reduction is started and ended, respectively.~~
~~η~~	~~degrees~~	~~*Approach angle.*~~
~~η_r~~	~~degrees~~	~~*Reference approach angle.*~~
~~θ~~	~~degrees~~	~~*Noise angle (relative to flight path)*. The angle between the flight path and noise path. It is identical for both measured and corrected flight paths.~~
~~ψ~~	~~degrees~~	~~*Noise angle (relative to ground)*. The angle between the noise paths and the ground. It is identified for both measured and corrected flight paths.~~
~~μ~~	~~degrees~~	~~*Engine noise emission parameter*. (See 9.3.4.)~~
~~Δ_1~~	~~EPNdB~~	~~*PNLT correction*. The correction to be added to the EPNL calculated from measured data to account for noise level changes due to differences in atmospheric absorption and noise path length between reference and test conditions.~~
~~Δ_2~~	~~EPNdB~~	~~*Adjustment to duration correction*. The adjustment to be made to the EPNL calculated from measured data to account for noise level changes due to the noise duration between reference and test conditions.~~
~~Δ_3~~	~~EPNdB~~	~~*Source noise adjustment*. The adjustment to be made to the EPNL calculated from measured data to account for noise level changes due to differences between reference and test engine regime.~~

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~~* Gear up, speed of at least V_2 + 19 km/h (V_2 + 10 kt), take-off thrust.~~
~~**Gear up, speed of at least V_2 + 19 km/h (V_2 + 10 kt), after cutback.~~

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7. SOUND ATTENUATION IN AIR

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7.2 The relationship between sound attenuation, frequency, temperature and humidity is expressed by the following equations:

$$\alpha(i) = 10^{[2.05 \log (f_o/1\,000) + 1.1394 \times 10^{-3} \times \mathrm{T} - 1.916984]} + \eta(\delta) \times 10^{[\log (f_o) + 8.42994 \times 10^{-3} \times \mathrm{T} - 2.755624]}$$

$$\delta = \sqrt{\frac{1010}{f_o}}\, 10^{(\log \cancel{H}\mathrm{RH} - 1.328924 + 3.179768 \times 10^{-2} \cancel{\theta} \times \mathrm{T})} \times 10^{(-2.173716 \times 10^{-4} \cancel{\theta} \times \mathrm{T}^2 + 1.7496 \times 10^{-6} \cancel{\theta} \times \mathrm{T}^3)}$$

where:

$\eta(\delta)$ is given by Table A2-4 and f_o by Table A2-5;

$\alpha(i)$ being the attenuation coefficient in dB/100 m;

~~θ~~ T being the temperature in °C; and

~~H~~ RH being the relative humidity expressed as a percentage.

7.3 The equations given in 7.2 are convenient for calculation by means of a computer.

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8. ADJUSTMENT OF AIRCRAFT FLIGHT TEST RESULTS

8.1 Flight profiles and noise geometry

Flight profiles for both test and reference conditions are described by their geometry relative to the ground, the associated aircraft ground speed, and, in the case of aeroplanes, the associated engine ~~control~~ noise performance parameter(s) used for determining the acoustic emission of the aeroplane. Idealized aircraft flight profiles are described in 8.1.1 for aeroplanes and 8.1.2 for helicopters.

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8.1.2 Helicopter flight profiles

8.1.2.1 *Reference take-off profile characteristics*

Figure A2-7 illustrates the profile characteristics for the helicopter take-off procedure for noise measurements made at the take-off noise measurement point:

a) the helicopter is initially stabilized in level flight at point A at the best rate of climb speed ~~V_y~~ V_Y. The helicopter continues to point B where take-off power is applied, and a steady climb is initiated. A steady climb is maintained through point X and beyond to point F, the end of the noise flight path; and

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8.1.3 Adjustment of measured noise levels from measured to reference profile in the calculation of EPNL

Note.— The "useful portion of the measured flight path" referred to in this section is defined in accordance with the requirements of 2.3.2.

8.1.3.1 For the case of a microphone located beneath the flight path, the portions of the test flight path and the reference flight path which are significant for the adjustment of the measured noise levels from the measured profile to the reference profile in the EPNL calculation are illustrated in Figure A2-10, where:

a) XY represents the useful portion of the measured flight path (Figure A2-10 a)), and X_rY_r that of the corresponding reference flight path (Figure A2-10 b)); and

b) K is the actual noise measurement point and K_r the reference noise measurement point. Q represents the aircraft position on the measured flight path at which the noise was emitted and observed as PNLTM at point K. The angle between QK and the direction of flight along the measured flight path is θ, the ~~acoustic~~ sound emission angle. Q_r is the corresponding position on the reference flight path where the angle between Q_rK_r is also θ. QK and Q_rK_r are, respectively, the measured and reference ~~noise~~ sound propagation paths.

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8.1.3.2 For the case of a microphone laterally displaced to the side of the flight path, the portions of the test flight path and the reference flight path which are significant for the adjustment of the measured noise levels from the measured profile to the reference profile in the EPNL calculation are illustrated in Figure A2-11, where:

a) XY represents the useful portion of the measured flight path (Figure A2-11 a)), and X_rY_r that of the corresponding reference flight path (Figure A2-11 b)); and

b) K is the actual noise measurement point and K_r the reference noise measurement point. Q represents the aircraft position on the measured flight path at which the noise was emitted and observed as PNLTM at point K. The angle between QK and the direction of flight along the measured flight path is θ, the ~~acoustic~~ sound emission angle. The angle between QK and the ground is ψ, the elevation angle. Q_r is the corresponding position on the reference flight path where the angle between Q_rK_r and the direction of flight along the reference flight path is also θ, and the angle between Q_rK_r and the ground is ~~ψ_r~~ ψ_R, where in the case of aeroplanes, the difference between ψ and ~~ψ_r~~ ψ_R is minimized.

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8.1.3.3 In both situations the ~~acoustic~~ sound emission angle θ shall be established using three-dimensional geometry.

8.1.3.4 In the case of lateral full-power noise measurements of jet aeroplanes the extent to which differences between ψ and ψ_r can be minimized is dependent on the geometrical restrictions imposed by the need to maintain the reference microphone on a line parallel to the extended runway centre line.

Note.— In the case of helicopter measurements, there is no requirement to minimize the difference between ψ and ~~ψ_r~~ ψ_R .

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8.2 Selection of adjustment method

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8.2.3 For aeroplanes, either the simplified method, described in 8.3, or the integrated method, described in 8.4, shall be used for the lateral, flyover or approach conditions. The integrated method shall be used when:

a) for flyover, the absolute value of the difference between the value of ~~$EPNL_r$~~ $EPNL_R$, when calculated according to the simplified method described in 8.3, and the measured value of EPNL calculated according to the procedure described in 4.1.3 is greater than 8 EPNdB;

b) for approach, the absolute value of the difference between the value of ~~EPNL_r~~ EPNL_R, when calculated according to the simplified method described in 8.3, and the measured value of EPNL calculated according to the procedure described in 4.1.3 is greater than 4 EPNdB; or

c) for flyover or approach, the value of ~~EPNL_r~~ EPNL_R, when calculated according to the simplified method described in 8.3, is greater than the maximum noise levels prescribed in 3.4 of Part II, Chapter 3, less 1 EPNdB.

Note.— Part II, Chapter 3, 3.7.6, specifies limitations regarding the validity of test data based upon both the extent to which ~~EPNL_r~~ *EPNL_R differs from* ~~EPNL~~ *EPNL, and also the proximity of the final* ~~EPNL_r~~ *EPNL_R values to the maximum permitted noise levels, regardless of the method used for adjustment.*

8.3 Simplified method of adjustment

8.3.1 General

8.3.1.1 The simplified adjustment method consists of the determination and application of adjustments to the EPNL calculated from the measured data for the differences between measured and reference conditions at the moment of PNLTM. The adjustment terms are:

a) Δ_1 — adjustment for differences in the PNLTM spectrum under test and reference conditions (see 8.3.2);

b) ~~Δ_Peak~~ Δ_peak — adjustment for when the PNLT for a secondary peak, identified in the calculation of EPNL from measured data and adjusted to reference conditions, is greater than the PNLT for the adjusted PNLTM spectrum (see 8.3.3);

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8.3.1.2 The coordinates (time, X, Y and Z) of the reference data point associated with the emission of ~~PNLTM_r~~ PNLTM_R shall be determined such that the ~~acoustic~~ sound emission angle θ on the reference flight path, relative to the reference microphone, is the same value as the ~~acoustic~~ sound emission angle of the as-measured data point associated with PNLTM.

8.3.1.3 The adjustment terms described in 8.3.2 to 8.3.5 are applied to the EPNL calculated from measured data to obtain the simplified reference condition effective perceived noise level, ~~EPNL_r~~ EPNL_R as described in 8.3.6.

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8.3.2 Adjustments to spectrum at PNLTM

8.3.2.1 The one-third octave band levels SPL(i) used to construct PNL(k_M) (the PNL at the moment of PNLTM observed at measurement point K) shall be adjusted to reference levels $\text{SPL}_r(i)$ as follows:

~~$SPL_r(i) = SPL(i) + 0.01\,[\alpha(i) - \alpha(i)_0]\,QK$~~
~~$+ 0.01\,\alpha(i)_0\,(QK - Q_rK_r)$~~
~~$+ 20\log(QK/Q_rK_r)$~~

$$\begin{aligned} SPL_R(i) = {} & SPL(i) + 0.01\,[\alpha(i) - \alpha_R(i)]\,QK \\ & + 0.01\,\alpha_R(i)\,(QK - Q_rK_r) \\ & + 20\log(QK/Q_rK_r) \end{aligned}$$

In this expression:

- the term 0.01 [$\alpha(i)$ – ~~$\alpha(i)_0$~~ $\alpha_R(i)$] QK accounts for the effect of the change in sound attenuation due to atmospheric absorption, and $\alpha(i)$ and ~~$\alpha(i)_0$~~ $\alpha_R(i)$ are the coefficients for the test and reference atmospheric conditions, respectively, obtained from Section 7;

- the term 0.01 ~~$\alpha(i)_0$~~ $\alpha_R(i)$ ($QK - Q_rK_r$) accounts for the effect of the change in the ~~noise~~ sound propagation path length on the sound attenuation due to atmospheric absorption;

- the term 20 log (QK/Q_rK_r) accounts for the effect of the change in the ~~noise~~ sound propagation path length due to spherical spreading (also known as the “inverse square” law);

- QK and Q_rK_r are measured in metres, and $\alpha(i)$ and ~~$\alpha(i)_0$~~ $\alpha_R(i)$ are obtained in the form of dB/100 m.

Note.— Refer to Figures A2-10 and A2-11 for identification of positions and distances referred to in this paragraph.

8.3.2.2 The adjusted values of ~~$SPL_r(i)$~~ $SPL_R(i)$ obtained in 8.3.2.1 shall be used to calculate a reference condition PNLT value, ~~$PNLT_r(k_M)$~~ $PNLT_R(k_M)$, as described in 4.2 and 4.3 of this appendix. The value of the bandsharing adjustment, Δ_B, calculated for the test-day PNLTM by the method of 4.4.2, shall be added to this ~~$PNLT_r(k_M)$~~ $PNLT_R(k_M)$ value to obtain the reference condition ~~$PNLTM_r$~~ $PNLTM_R$:

~~$PNLTM_r$~~ $PNLTM_R$ = ~~$PNLT_r(k_M)$~~ $PNLT_R(k_M) + \Delta_B$

An adjustment term, Δ_1, is then calculated as follows:

Δ_1 = ~~$PNLTM_r$~~ $PNLTM_R$ – PNLTM

8.3.2.3 Δ_1 shall be added algebraically to the EPNL calculated from measured data as described in 8.3.6.

8.3.3 Adjustment for secondary peaks

8.3.3.1 During a test flight any values of PNLT that are within 2 dB of PNLTM are defined as “secondary peaks”. The one-third octave band levels for each “secondary peak” shall be adjusted to reference conditions according to the procedure defined in 8.3.2.1. Adjusted values of ~~$PNLT_r$~~ $PNLT_R$ shall be calculated for each “secondary peak” as described in 4.2 and 4.3 of this appendix. If any adjusted peak value of ~~$PNLT_r$~~ $PNLT_R$ exceeds the value of ~~$PNLTM_r$~~ $PNLTM_R$, a ~~Δ_{Peak}~~ Δ_{peak} adjustment shall be applied.

8.3.3.2 ~~Δ_{Peak}~~ Δ_{peak} shall be calculated as follows:

~~$\Delta_{\mathrm{Peak}} = \mathrm{PNLT}_r(MaxPeak) - \mathrm{PNLTM}_r$~~

$$\Delta_{\mathrm{peak}} = \mathrm{PNLT}_{\mathrm{R}}(k_{\mathrm{M2}}) - \mathrm{PNLTM}_{\mathrm{R}}$$

where ~~$\mathrm{PNLT}_r(MaxPeak)$~~ $\mathrm{PNLT}_{\mathrm{R}}(k_{\mathrm{M2}})$ is the reference condition PNLT value of the largest of the secondary peaks; and ~~PNLTM_r~~ $\mathrm{PNLTM}_{\mathrm{R}}$ is the reference condition PNLT value at the moment of PNLTM.

8.3.3.3 ~~Δ_{Peak}~~ Δ_{peak} shall be added algebraically to the EPNL calculated from measured data as described in 8.3.6.

8.3.4 Adjustment for effects on noise duration

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8.3.4.2 Referring to the flight paths shown in Figures A2-10 and A2-11, the adjustment term Δ_2 shall be calculated from the measured data as follows:

$$\Delta_2 = -7.5 \log (QK/Q_r K_r) + 10 \log (V_G/\cancel{V_{Gr}}V_{GR})$$

where:

V_G is the test ground speed (horizontal component of the test airspeed); and

~~V_{Gr}~~ V_{GR} is the reference ground speed (horizontal component of the reference airspeed).

. . .

8.3.5 Source noise adjustments

8.3.5.1 The source noise adjustment shall be applied to take account of differences in test and reference source noise generating mechanisms. For this purpose the effect on aircraft propulsion source noise of differences between the acoustically significant propulsion operating parameters actually realized in the certification flight tests and those calculated or specified for the reference conditions of Chapter 3, 3.6.1.5, is determined. Such operating parameters may include for jet aeroplanes, the engine ~~control~~ noise performance parameter μ (typically normalized low pressure fan speed, normalized engine thrust or engine pressure ratio), for propeller-driven aeroplanes both shaft horsepower and propeller helical tip Mach number and for helicopters, during overflight only, advancing rotor blade tip Mach number. The adjustment shall be determined from manufacturer’s data approved by the certificating authority.

8.3.5.2 For aeroplanes, the adjustment term Δ_3 shall normally be determined from sensitivity curve(s) of EPNL versus the propulsion operating parameter(s) referred to in 8.3.5.1. It is obtained by subtracting the EPNL value corresponding to the measured value of the correlating parameter from the EPNL value corresponding to the reference value of the correlating parameter. The adjustment term Δ_3 shall be added algebraically to the EPNL value calculated from the measured data (see 8.3.6).

Note.— Representative data for jet aeroplanes are illustrated in Figure A2-12 which shows a curve of ~~EPNL~~ *EPNL versus the engine* ~~*control*~~ *noise performance parameter* ~~μ~~ *μ. The* EPNL *data is adjusted to all other relevant reference conditions (aeroplane mass, speed, height and air temperature) and, at each value of* ~~μ~~ *μ, for the difference in noise between the installed engine and the flight manual standard of engine.*

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8.3.5.5 For helicopter overflight, if any combination of the following three factors results in the measured value of an agreed noise correlating parameter deviating from the reference value of this parameter, then source noise adjustments shall be determined from manufacturer's data approved by the certificating authority:

a) airspeed deviations from reference;

b) rotor speed deviations from reference; and/or

c) temperature deviations from reference.

This adjustment should normally be made using a sensitivity curve of ~~$PNLTM_r$~~ $PNLTM_R$ versus advancing blade tip Mach number. The adjustment may be made using an alternative parameter, or parameters, approved by the certificating authority.

Note 1.— If it is not possible during noise measurement tests to attain the reference value of advancing blade tip Mach number or the agreed reference noise correlating parameter, then an extrapolation of the sensitivity curve is permitted, provided the data cover an adequate range of values, agreed by the certificating authority, of the noise correlating parameter. The advancing blade tip Mach number, or agreed noise correlating parameter, shall be computed from as measured data. Separate curves of ~~$PNLTM_r$~~ $PNLTM_R$ *versus advancing blade tip Mach number, or another agreed noise correlating parameter, shall be derived for each of the three certification microphone locations, centre line, left sideline and right sideline, defined relative to the direction of flight of each test run.*

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8.3.6 Application of adjustment terms for simplified method

Determine EPNL for reference conditions, ~~$EPNL_r$~~ $EPNL_R$, using the simplified method, by adding the adjustment terms identified in 8.3.2 through 8.3.5 to the EPNL calculated for measurement conditions as follows:

$$\cancel{EPNL_r}\ EPNL_R = EPNL + \Delta_1 + \cancel{\Delta_{Peak}}\ \Delta_{peak} + \Delta_2 + \Delta_3$$

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8.4 Integrated method of adjustment

8.4.1 General

8.4.1.1 The integrated method consists of recomputing, under reference conditions, points in the PNLT time history corresponding to measured points obtained during the tests, and then computing EPNL directly for the new time history.

8.4.1.2 The emission coordinates (time, X, Y, and Z) of the reference data point associated with each $PNLT_r(k)$ shall be determined such that the ~~acoustic~~ sound emission angle θ on the reference flight path, relative to the reference microphone, is the same value as the ~~acoustic~~ sound emission angle of the as-measured data point associated with $PNLT(k)$.

Note.— As a consequence, and unless the test and reference conditions are identical, the reception *time intervals between the reference data points will typically neither be equally-spaced nor equal to one-half second.*

8.4.1.3 The steps in the integrated procedure are as follows:

a) The spectrum associated with each test-day data point, $\mathrm{PNLT}(k)$, is adjusted for spherical spreading and attenuation due to atmospheric absorption, to reference conditions (see 8.4.2.1);

b) A reference tone-corrected perceived noise level, ~~$\mathrm{PNLT}_r(k)$~~ $\mathrm{PNLT}_\mathrm{R}(k)$, is calculated for each one-third octave band spectrum (see 8.4.2.2);

c) The maximum value, ~~PNLTM_r~~ $\mathrm{PNLTM}_\mathrm{R}$ and first and last 10 dB-down points are determined from the ~~PNLT_r~~ PNLT_R series (see 8.4.2.3 and 8.4.3.1);

d) The effective duration, ~~$\delta t_{\mathrm{R}r}(k)$~~ $\delta t_\mathrm{R}(k)$, is calculated for each ~~$\mathrm{PNLT}_r(k)$~~ $\mathrm{PNLT}_\mathrm{R}(k)$ point, and the reference noise duration is then determined (see 8.4.3.2 and 8.4.3.3);

e) The integrated reference condition effective perceived noise level, ~~$\mathrm{EPNL}_{\mathrm{R}r}$~~ EPNL_R, is determined by the logarithmic summation of ~~$\mathrm{PNLT}_r(k)$~~ $\mathrm{PNLT}_\mathrm{R}(k)$ levels within the noise duration normalized to a duration of 10 seconds (see 8.4.4); and

f) A source noise adjustment is determined and applied (see 8.4.5).

8.4.2 PNLT computations

8.4.2.1 The measured values of $\mathrm{SPL}(i,k)$ shall be adjusted to the reference values ~~$\mathrm{SPL}_r(i,k)$~~ $\mathrm{SPL}_\mathrm{R}(i,k)$ for the differences between measured and reference sound propagation path lengths and between measured and reference atmospheric conditions, by the methods of 8.3.2.1. Corresponding values of ~~$\mathrm{PNL}_r(k)$~~ $\mathrm{PNL}_\mathrm{R}(k)$ shall be computed as described in 4.2.

8.4.2.2 For each value of ~~$\mathrm{PNL}_r(k)$~~ $\mathrm{PNL}_\mathrm{R}(k)$, a tone correction factor ~~$C(k)$~~ $\mathrm{C}_\mathrm{R}(k)$ shall be determined by analysing each reference value ~~$\mathrm{SPL}_r(i,k)$~~ $\mathrm{SPL}_\mathrm{R}(i,k)$ by the methods of 4.3, and added to ~~$\mathrm{PNL}_r(k)$~~ $\mathrm{PNL}_\mathrm{R}(k)$ to obtain ~~$\mathrm{PNLT}_r(k)$~~ $\mathrm{PNLT}_\mathrm{R}(k)$.

8.4.2.3 The maximum reference condition tone corrected perceived noise level, ~~PNLTM_r~~ $\mathrm{PNLTM}_\mathrm{R}$, shall be identified, and a new reference condition bandsharing adjustment, ~~$\Delta_{\mathrm{B}r}$~~ Δ_BR, shall be determined and applied as described in 4.4.2.

Note.— Due to differences between test and reference conditions, it is possible that the maximum $PNLT_R$ *value will not occur at the data point associated with* ~~PNLTM~~ *PNLTM. The determination of* ~~PNLTM_r~~ $PNLTM_R$ *is independent of PNLTM.*

8.4.3 Noise duration

8.4.3.1 The limits of the noise duration shall be defined as the 10 dB-down points obtained from the series of reference condition $\mathrm{PNLT}_r(k)$ values. Identification of the 10 dB-down points shall be performed in accordance with 4.5.1. In the case of the integrated method, the first and last 10 dB-down points shall be designated as ~~$k_{\mathrm{F}r}$~~ k_FR and ~~$k_{\mathrm{L}r}$~~ k_LR.

8.4.3.2 The noise duration for the integrated reference condition shall be equal to the sum of the effective durations, $\delta t_r(k)$, associated with each of the ~~$\mathrm{PNLT}_r(k)$~~ $\mathrm{PNLT}_\mathrm{R}(k)$ data points within the 10 dB-down period, inclusive.

8.4.3.3 The effective duration, ~~$\delta t_r(k)$~~ $\delta t_\mathrm{R}(k)$, shall be determined for each ~~$\mathrm{PNLT}_r(k)$~~ $\mathrm{PNLT}_\mathrm{R}(k)$ reference condition data point as follows:

~~$\delta t_r(k) = [(t_r(k) - t_r(k-1)) + (t_r(k+1) - t_r(k))]/2$~~

$$\delta t_\mathrm{R}(k) = [(t_\mathrm{R}(k) - t_\mathrm{R}(k-1)) + (t_\mathrm{R}(k+1) - t_\mathrm{R}(k))] / 2$$

where:

~~$t_r(k)$~~ $t_\mathrm{R}(k)$ is the time associated with ~~$\mathrm{PNLT}_r(k)$~~ $\mathrm{PNLT}_\mathrm{R}(k)$;

~~$t_r(k-1)$~~ $t_\mathrm{R}(k-1)$ is the time associated with ~~$\mathrm{PNLT}_r(k-1)$~~ $\mathrm{PNLT}_\mathrm{R}(k-1)$, the data point preceding ~~$\mathrm{PNLT}_r(k)$~~ $\mathrm{PNLT}_\mathrm{R}(k)$; and

~~$t_r(k+1)$~~ $t_\mathrm{R}(k+1)$ is the time associated with ~~$\mathrm{PNLT}_r(k+1)$~~ $\mathrm{PNLT}_\mathrm{R}(k+1)$, the data point following ~~$\mathrm{PNLT}_r(k)$~~ $\mathrm{PNLT}_\mathrm{R}(k)$.

Note 1.— Due to differences in flight path geometry, airspeed and sound speed between test and reference conditions, the times, ~~$t_r(k)$~~ $t_R(k)$, *associated with the* ~~$\mathrm{PNLT}_r(k)$~~ $PNLT_R(k)$ *points projected to the reference flight path are likely to occur at varying, non-uniform time intervals.*

Note 2.— Relative values of time ~~$t_r(k)$~~ $t_R(k)$ *for the reference data points can be determined by using the distance between such points on the reference flight path, and the reference aircraft airspeed* ~~V_r~~ V_R.

Note 3.— The Environmental Technical Manual *(Doc 9501), Volume I —* Procedures for the Noise Certification of Aircraft, *provides additional guidance for one method for performing the integrated procedure, including the determination of effective durations,* ~~$\delta t_r(k)$~~ $\delta t_R(k)$, *for the individual data points of the reference time history.*

8.4.4 Calculation of integrated reference condition EPNL

8.4.4.1 The equation for calculating reference condition EPNL using the integrated method, ~~$\mathrm{EPNL}_{\mathrm{R}r}$~~ EPNL_R, is similar to the equation for test-day EPNL given in 4.6. However, the numerical constant related to one-half second intervals is eliminated, and a multiplier is introduced within the logarithm to account for the effective duration of each ~~$\mathrm{PNLT}_r(k)$~~ $\mathrm{PNLT}_\mathrm{R}(k)$ value, ~~$\delta t_r(k)$~~ $\delta t_\mathrm{R}(k)$:

~~$\mathrm{EPNL}_r = 10 \log \frac{1}{T_0} \sum_{k_{Fr}}^{k_{Lr}} 10^{0.1\mathrm{PNLT}_r(k)} \delta t_r(k)$~~

$$\mathrm{EPNL}_\mathrm{R} = 10 \log \frac{1}{\mathrm{t}_0} \sum_{k_\mathrm{FR}}^{k_\mathrm{LR}} 10^{0.1\mathrm{PNLT}_\mathrm{R}(k)}\ \delta\ \mathrm{t}_\mathrm{R}(k)$$

where:

the reference time, ~~T_0~~ t_0, is 10 seconds;

~~k_{Fr}~~ k_FR and ~~k_{Lr}~~ k_LR are the first and last 10 dB-down points as defined in 8.4.3.1; and

~~$\delta t_r(k)$~~ $\delta t_\mathrm{R}(k)$ is the effective duration as defined in 8.4.3.3 of each reference condition ~~$\mathrm{PNLT}_r(k)$~~

$\mathrm{PNLT}_R(k)$ value.

8.4.5 Source noise adjustment

8.4.5.1 Finally, a source noise adjustment shall be determined by the methods of 8.3.5, and added to the ~~EPNL_r~~ EPNL_R determined in 8.4.4.1.

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APPENDIX 3. EVALUATION METHOD FOR NOISE CERTIFICATION OF PROPELLER-DRIVEN AEROPLANES NOT EXCEEDING 8 618 kg — Application for Type Certificate submitted before 17 November 1988

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4.2.2 Correction of noise received on the ground

The noise measurements made at heights different from 300 m (~~985~~984 ft) shall be adjusted to 300 m (~~985~~984 ft) by the inverse square law.

4.2.3 Performance correction

. . .

4.2.3.2 The performance correction shall be calculated by using the following formula:

~~$\Delta\mathrm{dB} = 49.6 - 20\log\left[(3\,500 - D_{15})\frac{R/C}{V_y} + 15\right]$~~

$$\Delta\mathrm{dB} = 49.6 - 20\log\left[(3\,500 - \mathrm{D}_{15})\frac{\text{Best R/C}}{\mathrm{V_Y}} + 15\right]$$

where ~~D_{15}~~D_{15}= Take-off distance to 15 m at maximum certificated take-off mass and maximum take-off power (paved runway)

Best R/C = Best rate of climb at maximum certificated take-off mass and maximum take-off power

~~V_y~~V_Y = Climb speed corresponding to Best R/C at maximum take-off power and expressed in the same units.

. . .

APPENDIX 4. EVALUATION METHOD FOR NOISE CERTIFICATION

OF HELICOPTERS NOT EXCEEDING 3 175 kg MAXIMUM CERTIFICATED TAKE-OFF MASS

. . .

2.4 Flight test conditions

2.4.1 The helicopter shall be flown in a stabilized flight condition over a distance sufficient to ensure that the time-varying sound level is measured during the entire time period that the sound level is within 10 dB(A) of ~~L_{Amax}~~ L_{ASmax}.

Note.— ~~L_{Amax}~~ L_{ASmax} is defined as the maximum of the A-frequency-weighted S-time-weighted sound level measured during the test run.

2.4.2 The helicopter flyover noise test shall be conducted at the airspeed referred to in Part II, Chapter 11, 11.5.2, with such airspeed adjusted as necessary to produce the same advancing blade tip Mach number as associated with the reference conditions.

2.4.3 The reference advancing blade tip Mach number ~~(M_R)~~, M_{ATR}, is defined as the ratio of the arithmetic sum of the blade tip rotational speed ~~n(V_T)~~, V_{tipR}, and the reference helicopter true airspeed ~~V_T~~, V_R, divided by the speed of sound ~~(c_R)~~, c_R, at 25°C such that:

~~$M_R = \frac{(V_T + V_r)}{c_R}$~~

$$M_{ATR} = \frac{(V_{tipR} + V_R)}{c_R}$$

3. NOISE UNIT DEFINITION

3.1 The sound exposure level, L_{AE}, is defined as the level, in decibels, of the time integral of squared A-weighted sound pressure ~~(P_A)~~, p_A, over a given time period or event, with reference to the square of the standard reference sound pressure ~~(P_0)~~, p_0, of 20 μPa and a reference duration of one second.

3.2 This unit is defined by the expression:

~~$L_{AE} = 10 \log \frac{1}{T_0} \int_{t1}^{t2} \left(\frac{P_A(t)}{P_0} \right)^2 dt$~~

$$L_{AE} = 10 \log \frac{1}{t_0} \int_{t_1}^{t_2} \left(\frac{p_A(t)}{p_0} \right)^2 dt$$

where ~~T_0~~ t_0 is the reference integration time of one second and ~~($t2 - t1$)~~ $(t_2 - t_1)$ is the integration time interval.

3.3 The above integral can be approximated from periodically sampled measurement as:

~~$$L_{AE} = 10\ \log\frac{1}{T_0}\sum_{k_F}^{k_L} 10^{0.1L_A(k)}\,\Delta t$$~~

$$L_{AE} = 10\ \log\frac{1}{t_0}\sum_{k_F}^{k_L} 10^{0.1L_{AS}(k)}\,\Delta t$$

where ~~$L_A(k)$~~ $L_{AS}(k)$ is the time varying A-frequency-weighted S-time-weighted sound level measured at the k-th instant of time, k_F and k_L are the first and last increment of k, and ~~Δt~~ Δt is the time increment between samples.

. . .

4.4 Noise measurement procedures

. . .

4.4.4 The A-frequency-weighted sound level of the background noise, including ambient noise and electrical noise of the measurement systems, shall be determined in the test area with the system gain set at levels which will be used for helicopter noise measurements. If the ~~L_{Amax}~~ L_{ASmax} of each test run does not exceed the A-frequency-weighted sound level of the background noise by at least 15 dB(A), flyovers at an approved lower height may be used and the results adjusted to the reference measurement height by an approved method.

. . .

5.2 Corrections and adjustments

. . .

5.2.2 The adjustments for spherical spreading and duration may be approximated from:

$\Delta_1 = 12.5 \log (H/150)$ ~~dB~~

where H is the height, in metres, of the test helicopter when directly over the noise measurement point.

5.2.3 The adjustment for the difference between reference airspeed and adjusted reference airspeed is calculated from:

~~$$\Delta_2 = 10 \log\left(\frac{V_{ar}}{V_r}\right) \text{dB}$$~~

$$\Delta_2 = 10 \log\left(\frac{V_{AR}}{V_R}\right)$$

where Δ_2 is the quantity in decibels that must be algebraically added to the measured SEL noise level to correct for the influence of the adjustment of the reference airspeed on the duration of the measured flyover event as perceived at the noise measurement station. ~~V_r~~ V_R is the reference airspeed as prescribed under Part II, Chapter 11, 11.5.2, and ~~V_{ar}~~ V_{AR} is the adjusted reference airspeed as prescribed in 2.4.2 of this appendix.

. . .

6.3 Validity of results

. . .

Note.— Methods for calculating the 90 per cent confidence interval are given in ~~in~~ the section of the Environmental Technical Manual *(Doc 9501), Volume I* — Procedures for the Noise Certification of Aircraft *concerning the calculation of confidence intervals.*

. . .

APPENDIX 5. MONITORING AIRCRAFT NOISE ON AND IN THE VICINITY OF AERODROMES

. . .

1. INTRODUCTION

. . .

Note 3.— This appendix specifies the measuring equipment to be used in order to measure noise levels created by aircraft in the operation of an aerodrome. The noise levels measured according to this appendix are approximations to perceived noise levels ~~PNL~~ PNL, in PNdB, as calculated by the method described in Appendix 1, 4.2.

. . .

APPENDIX 6. EVALUATION METHOD FOR NOISE CERTIFICATION OF PROPELLER-DRIVEN AEROPLANES NOT EXCEEDING 8 618 kg — Application for Type Certificate or Certification of Derived Version submitted on or after 17 November 1988

…

6.2 Validity of results

6.2.1 The measuring point shall be overflown at least six times. The test results shall produce an average noise level ~~(L_{Amax})~~ value, L_{ASmax}, and its 90 per cent confidence limits, the noise level being the arithmetic average of the corrected acoustical measurements for all valid test runs over the measuring point.

…

ATTACHMENT D. GUIDELINES FOR EVALUATING AN ALTERNATIVE METHOD OF MEASURING HELICOPTER NOISE DURING APPROACH

. . .

2.3 Approach reference procedure

The approach reference procedure shall be established as follows:

a) the helicopter shall be stabilized and following approach paths of 3°, 6° and 9°;

b) the approach shall be made at a stabilized airspeed equal to the best rate of climb speed, ~~V_y~~ V_Y, or the lowest approved speed for the approach, whichever is the greater, with power stabilized during the approach and over the flight path reference point, and continued to a normal touchdown;

. . .

ATTACHMENT F. GUIDELINES FOR NOISE CERTIFICATION OF TILT-ROTORS

. . .

2. NOISE EVALUATION MEASURE

The noise evaluation measure should be the effective perceived noise level in EPNdB as described in Appendix 2 of this Annex.

Note.— Additional data in SEL and ~~L_{Amax}~~ L_{ASmax} *as defined in Appendix 4, and one-third octave SPLs as defined in Appendix 2 corresponding to* ~~L_{Amax}~~ L_{ASmax} *should be made available to the certificating authority for land-use planning purposes.*

. . .

ATTACHMENT H. GUIDELINES FOR OBTAINING HELICOPTER NOISE DATA FOR LAND-USE PLANNING PURPOSES

. . .

2. DATA COLLECTION PROCEDURES

2.1 Data suitable for land-use planning purposes may be derived directly from Chapter 8 noise certification data. Chapter 8 applicants may optionally elect to acquire data suitable for land-use planning purposes via alternative take-off, approach and/or flyover procedures defined by the applicant and approved by the certificating authority. Alternative flyover procedures should be performed overhead the flight path reference point at a height of 150 m (492 ft). In addition, an applicant may optionally elect to provide data at additional microphone locations.

2.2 Chapter 11 noise certification data may be provided for land-use planning purposes. Chapter 11 applicants may optionally elect to provide data acquired via alternative flyover procedures at 150 m (492 ft) above ground level. In acquiring data for land-use planning purposes, Chapter 11 applicants should give consideration to acquiring data from two additional microphones symmetrically disposed at 150 m on each side of the flight path and/or additional take-off and approach procedures defined by the applicant and approved by the certificating authority. In addition, an applicant may optionally elect to provide data at additional microphone locations.

. . .

3. REPORTING OF DATA

. . .

3.2 It is recommended that all data provided for land-use planning purposes be presented in terms of average sound exposure level ~~(L_{AE})~~, L_{AE}, as defined in Appendix 4 of this volume, for left sideline, centre line and right sideline measurement points defined relative to the direction of flight for each test ~~pass~~ run. Additional data in other noise metrics may also be provided and should be derived in a manner that is consistent with the prescribed noise certification analysis procedure.

. . .

Proposal D Rationale:

All the proposed amendments are corrections due to minor technical errors in Annex 16, Volume I or for consistency purposes. This includes an amalgamation of all symbols and units from across Annex 16, Volume I into one new section (*NOMENCLATURE: SYMBOLS AND UNITS*).

— — — — — — — —

6.2. Appendix 2 — ICAO ANNEX 16, VOL II AMENDMENTS

6.2.1. Excerpt of the summary of presentations, discussions, conclusions, recommendations and proposed general changes to ICAO Annex 16, Vol II and ETM Vol II from the CAEP/10 Report (Agenda Item 3 'Review of technical proposals relating to aircraft engine emissions').

3.2 PROPOSED GENERAL AMENDMENTS TO ANNEX 16, VOLUME II

3.2.1 The Co-Rapporteurs of WG3 presented a report on the general proposed amendments to Annex 16, *Environmental Protection*, Volume II – *Aircraft Engine Emissions*. These changes included all proposed general amendments that are outside of the technical amendments associated with the nvPM and CO_2 Standards.

3.2.2 Work item 1: Part I – Definitions

3.2.2.1 It was proposed to add a definition of "engine type certification" in Annex 16, Volume II, Part I, Chapter 1.

3.2.3 Work item 2: Part III, Chapter 1

3.2.3.1 It was proposed to add a definition of "engine derivative versions" into Annex 16, Volume II, Part III, Chapter 1, Paragraph 1.1. This change was in addition to changes due to the proposed new Chapter 4 on nvPM (see Agenda Item 4) and due to a typographical error.

3.2.4 Work item 3: Part III, Chapter 2

3.2.4.1 For consistency purposes with the new proposed Chapter 4 on nvPM, it was proposed to change the title of the four Landing Take-Off (LTO) modes in Annex 16, Volume II, Part III, Chapter 2, paragraph 2.1.4.3, from "phase" to "LTO operating mode".

3.2.5 Work item 4: Appendix 3 – Sampling Line Temperature Stability

3.2.5.1 For clarification purposes, it was proposed to delete the phrase "with a stability of ± 10°C" from the requirement to maintain the line temperature at 160 ± 15 °C (with a stability of ± 10°C) in Annex 16, Volume II, Appendix 3, paragraph 5.1.2.

3.2.6 Work item 4: Appendix 3 – Carbon Balance Check

3.2.6.1 For editorial purposes, it was proposed to delete "within" and to add "with an accuracy of" in Annex 16, Volume II, Appendix 3, paragraph 6.4.

3.2.7 Work item 5: Attachment D to Appendix 3 - Calibration Gas for NOx

3.2.7.1 For the NOx analyser, Annex 16, Volume II requires a test gas of NO in zero nitrogen[10] and a calibration gas of NOx in zero nitrogen. SAE Aviation Recommended Practice (ARP) 1256D recommends NOx for both. Following investigations by WG3 and the SAE E-31 Committee both have recommended to specify the use of nitrogen monoxide (NO) in zero nitrogen for both the test gas and the calibration gas. It was proposed to change the calibration gas to NO in Annex 16, Volume II, Appendix 3, Attachment D.

3.2.8 Work item 6: Appendix 4 – Naphthalene Content

3.2.8.1 It was highlighted that there is an increasing difficulty to find fuels with a naphthalene content of at least 1% in volume as specified in Annex 16, Volume II, Appendix 4. To address this it was proposed to change the emissions test fuel specification from having a naphthalene content from “1-3.5%” to “0.0 to 3.0%”.

3.2.9 Work item 7: Appendix 6

3.2.9.1 Changes were proposed to Annex 16, Volume II, Appendix 6 that include an update to the general requirements, a new compliance procedure for nvPM emissions, coefficients for the nvPM mass characteristic level and a change to the title of Table A6-1. A correction was also proposed to the formulae in Table A6-1.

3.2.10 Work item 8: Typographical

3.2.10.1 It was proposed to replace “NO_x” by “NOx” (“x” subscript by “x” lower case) throughout Annex 16, Volume II. Additionally, some general typographical errors were proposed.

3.2.11 Work item 9: Reference to ISO in the Foreword

3.2.11.1 The certification procedures for the proposed nvPM Standard make extensive use of the specifications developed by ISO. Therefore, it was proposed to add a paragraph in the Foreword to Annex 16, Volume II, indicating this reference.

3.2.12 Work item 10: Consistency for nvPM Chapters

3.2.12.1 It was proposed to correct a number of inconsistencies in the Chapters associated with nvPM. The corrections include changes to definitions and alignment of symbols related to nvPM used throughout Annex 16, Volume II.

3.2.12.2 It was also proposed to add “for engine performance” to Annex 16, Volume II, Chapter 2 paragraphs 2.1.4.1 and Chapter 3, 3.1.5.1 to read: “The reference atmospheric conditions for engine performance shall be ISA at sea level except that the reference absolute humidity shall be 0.00634 kg water/kg dry air.”

---

[10] Zero nitrogen shall be used as the zero gas. The zero gas is the gas used in establishing the zero, or no response, adjustment of an instrument.

Discussion and Conclusions

3.2.13 The meeting noted the importance of the work to maintain Annex 16, Volume II in order to keep it up to date, relevant with regard to current certification practices. The meeting approved the general amendments to Annex 16, Volume II as presented in Appendix A.

3.2.14 Recommendation

3.2.14.1 In light of the foregoing discussion, the meeting developed the following recommendation:

RSPP **Recommendation 3/1 — General Amendments to Annex 16 — *Environmental Protection*, Volume II — *Aircraft Engine Emissions***

That Annex 16, Volume II be amended as indicated in Appendix A to the report on this agenda item.

3.3 GENERAL PROPOSED AMENDMENTS TO THE ENVIRONMENTAL TECHNICAL MANUAL, VOLUME II

3.3.1 The Co-Rapporteurs of WG3 presented proposed amendments to ICAO Doc 9501, Environmental Technical Manual, Volume II – Procedures for Emissions Certification of Aircraft Engines.

3.2.2 Work item 1: Foreword

3.3.2.1 It was proposed to add a Foreword to the ETM, Volume II that is consistent with Volumes I and the proposed Volume III. This Foreword will allow for amendments to the ETM, Volume II be approved by CAEP Steering Group Meetings and be made available, free of charge on the ICAO website, pending a final decision on official publication by the ICAO Secretary General.

3.3.3 Work item 2: Definition of Engine Type Certificate

3.3.3.1 It was proposed to add additional information on the type certificate definition to the ETM, Volume II in order to provide further guidance.

3.3.4 Work item 3: Calibration and Test Gas for the NOx Analyser

3.3.4.1 It was proposed to provide new “technical procedure” information on the NOx analyser calibration that supports the proposed change in the calibration gas to NO in Annex 16, Volume II, Appendix 3, Attachment D (see paragraph x.x.x of this report).

3.3.5 Work item 4: Elect to Comply to a Later Standard

3.3.5.1 It was proposed to provide the engine manufacturers the option to comply with a later Standard, even though at the time of the date of manufacture of the first production model the more stringent Standard is not applicable.

3.3.6 Work item 5: Latest Emission Standard Applied

3.3.6.1 To clarify paragraph 4, “Latest emissions Standard applied” for the “technical procedure” under the ETM, Volume II, Chapter 2, paragraph 2.1.1, it is proposed to add the word “applicable” in the first sentence.

3.3.7 Work item 6: Temperature of the Probe for Gas Measurements

3.3.7.1 Annex 16, Volume II, Appendix 3 neither requires a minimum temperature nor mentions active cooling of the probe for gas or smoke measurements. It was proposed to add an “EXPLANATORY INFORMATION” to the ETM, Volume II, Appendix 3, paragraph 5.1.1 “Sampling probe.”

3.3.8 Work item 7: Carbon Balance Check

3.3.8.1 As some engine manufacturers are using SAE ARP1256 and ARP1533 to perform the carbon balance check, there was a need to explain and assess the differences between Annex 16, Volume II which uses the Air Fuel Ratio (AFR), and the ARP1256 which uses Fuel Air Ratio (FAR). In addition, ARP1533 explains how to calculate a carbon balance and a FAR balance. To clarify, it was proposed to add additional guidance text into the ETM, Vol. II.

3.3.9 Work item 8: Vented Fuel

3.3.9.1 It was proposed to provide technical and equivalent procedures to meet the fuel venting requirements of Annex 16, Volume II, Part II.

3.3.10 Work item 9: No Emissions Change

3.3.10.1 It was proposed to provide additional guidance text to capture the current process involved in the “no emissions change” certification process. The text proposed included a modification to the first bullet to include a reference to Annex 16, Volume II, Appendix 3 instead of using the current equations, to ensure consistency.

3.3.11 Work item 10: Table of Contents Updates

3.3.11.1 It was proposed to update the table of contents in order to accommodate the proposed changes to the ETM, Volume II and additions associated with the proposed nvPM Standard.

Discussion and Conclusions

3.3.12 In approving the proposed amendments to the ETM, Volume II, as presented in the report from the working group, the meeting recognised the work conducted by WG3 in the maintenance of the manual. The meeting agreed that revised versions of the ETM, Volume II, approved by subsequent CAEP Steering Groups be made available, free of charge on the ICAO website, pending a final decision on official publication by the ICAO Secretary General.

3.3.13 Recommendation

3.3.13.1 In light of the foregoing discussion, the meeting developed the following recommendation:

> **Recommendation 3/2 — General Amendments to the Environmental Technical Manual, Volume II**
>
> That the *Environmental Technical Manual*, Volume II be amended and published, and revised versions approved by subsequent CAEP Steering Groups be made available, free of charge on the ICAO website, pending a final decision on official publication by the ICAO Secretary General.

6.2.2. Proposed general amendments to ICAO Annex 16, Vol II (excluding the nvPM Standard)

The text of the amendment is arranged to show deleted text with a line through it and new text highlighted with grey shading, as shown below:

1. ~~Text to be deleted is shown with a line through it.~~	text to be deleted
2. New text to be inserted is highlighted with grey shading	new text to be inserted
3. ~~Text to be deleted is shown with a line through it~~ followed by the replacement text which is highlighted with grey shading.	new text to replace existing text

PROPOSAL A

TYPE-CERTIFICATED ENGINE DEFINITION

. . .

INTERNATIONAL STANDARDS AND RECOMMENDED PRACTICES

PART I. DEFINITIONS AND SYMBOLS

CHAPTER 1. DEFINITIONS

. . .

Derivative version. An aircraft gas turbine engine of the same generic family as an originally type-certificated engine and having features which retain the basic core engine and combustor design of the original model and for which other factors, as judged by the certificating authority, have not changed.

Note.— Attention is drawn to the difference between the definition of ~~A~~“derived version of an aeroplane~~@~~” in Volume I of Annex 16 and the definition of ~~A~~“derivative version~~@~~” in this Volume.

. . .

Exhaust nozzle. In the exhaust emissions sampling of gas turbine engines where the jet effluxes are not mixed (as in some turbofan engines for example) the nozzle considered is that for the gas generator (core) flow only. Where, however, the jet efflux is mixed the nozzle considered is the total exit nozzle.

. . .

Type Certificate. A document issued by a Contracting State to define the design of an aircraft, engine or propeller type and to certify that this design meets the appropriate airworthiness requirements of that State.

Note.— In some Contracting States a document equivalent to a type certificate may be issued for an engine or propeller type.

. . .

Proposal A Rationale:

The proposed amendment adds the definition of “type certificate” in Annex 16, Volume II, Part I, Chapter 1. The “type-certificated engine” term is used in the definition of the “derivative version” of an engine, and “engine type certificate” is also used in the *Environmental Technical Manual* (ETM), Volume II, without any definition in Annex 16, Volume II for type certificate.

PROPOSAL B

SAMPLING LINE TEMPERATURE STABILITY

…

APPENDIX 3. INSTRUMENTATION AND MEASUREMENT TECHNIQUES FOR GASEOUS EMISSIONS

…

5. DESCRIPTION OF COMPONENT PARTS

. . .

5.1.2 Sampling lines

The sample shall be transferred from the probe to the analysers via a line of 4.0 to 8.5 mm inside diameter, taking the shortest route practicable and using a flow rate such that the transport time is less than 10 seconds. The line shall be maintained at a temperature of 160°C ±15°C ~~(with a stability of ±10°C)~~, except for a) the distance required to cool the gas from the engine exhaust temperature down to the line control temperature, and b) the branch which supplies samples to the CO, CO_2, and ~~NO_x~~ NOx analysers. This branch line shall be maintained at a temperature of 65°C ±15°C ~~(with a stability of ±10°C)~~. When sampling to measure HC, CO, CO_2 and ~~NO_x~~ NOx components the line shall be constructed in stainless steel or carbon-loaded grounded PTFE.

. . .

Proposal B Rationale:

The Annex 16, Volume II requirements in Appendix 3, paragraph 5.1.2 for sampling line temperature stability are to maintain the line temperature at 160±15 °C (with a stability of ± 10°C). This could be interpreted to allow a range of temperatures of 135 to 185°C. The intent of the current text in Annex 16, Volume II is to ensure that the line temperature is maintained between 160±15°C (i.e. 145°C to 175°C). To clarify this issue, the proposed amendment proposes the deletion of “with a stability of ± 10°C”. This aligns Annex 16, Vol. II with SAE Aerospace Recommended Practice (ARP) 1256D.

PROPOSAL C

CALIBRATION GAS FOR THE NOX ANALYSER

…

ATTACHMENT D TO APPENDIX 3. CALIBRATION AND TEST GASES

Table of calibration gases

Analyser	*Gas*	*Accuracy**
HC	propane in zero air	±2 per cent or ±0.05 ppm**
CO_2	CO_2 in zero air	±2 per cent or ±100 ppm**
CO	CO in zero air	±2 per cent or ±2 ppm**
~~NO_x~~ NOx	~~NO_x~~NO in zero nitrogen	±2 per cent or ±1 ppm**

* Taken over the 95 per cent confidence interval.
** Whichever is greater.

The above gases are required to carry out the routine calibration of analysers during normal operational use.

Table of test gases

. . .

Analyser	*Gas*	*Accuracy**
~~NO_x~~NOx	NO in zero nitrogen	±1 per cent

* Taken over the 95 per cent confidence interval.

The above gases are required to carry out the tests of Attachments A, B and C.

Carbon monoxide and carbon dioxide calibration gases may be blended singly or as dual component mixtures. Three component mixtures of carbon monoxide, carbon dioxide and propane in zero air may be used, provided the stability of the mixture is assured.

Zero gas as specified for the CO, CO_2 and HC analysers shall be zero air (which includes “artificial” air with 20 to 22 per cent O_2 blended with N_2). For the ~~NO_x~~NOx analyser zero nitrogen shall be used as the zero gas. Impurities in both kinds of zero gas shall be restricted to be less than the following gas concentrations:

1 ppm C
1 ppm CO
100 ppm CO_2
1 ppm ~~NO_x~~NOx

The applicant shall ensure that commercial gases, as supplied, do in fact meet this specification, or are so specified by the vendor.

…

Proposal C Rationale:

For the NOx analyser, the current Attachment D to Appendix 3 requires a test gas of NO in zero nitrogen and a calibration gas of NOx in zero nitrogen. SAE ARP1256D recommends NOx for both, test and calibration gases. This inconsistency between ICAO and SAE specifications was discussed within CAEP and SAE, and both groups came to the same conclusion of specifying the use of NO in zero nitrogen for test and calibration gases.

Practically the NO bottles contain traces of NO_2 (usually below few ppm). A NOx bottle could be misinterpreted as a true mixture of NO and NO_2 compared to an NO bottle with traces of NO_2. Some bottle providers indicate the NO concentration as well as the NOx concentration to reflect the presence of NO_2 in small quantities. Generally, the NOx analyser can be calibrated by two different approaches depending on the measurement mode being utilised (NO only mode or NOx mode). The NO mode is considered as the default mode since NO is what is measured by the NOx analyser. When the NO mode is used, the presence of NO_2 is not desirable. In this case, it is appropriate to require NO in zero nitrogen for both the calibration gas and the test gas, instead of NOx in zero nitrogen. Thus, the calibration and test gas for the NOx analyser in Attachment D to Appendix 3 should be NO in zero nitrogen.

The proposed amendment changes the calibration gas to NO in Attachment D to Appendix 3. The ETM, Volume II provides technical procedural information on the NOx analyser calibration.

PROPOSAL D

EMISSIONS TEST FUEL SPECIFICATION

…

APPENDIX 4. SPECIFICATION FOR FUEL TO BE USED IN AIRCRAFT TURBINE ENGINE EMISSION TESTING

The fuel shall meet the specifications of this Appendix 4, unless a deviation and any necessary corrections have been agreed upon by the certificating authority. Additives used for the purpose of smoke suppression (such as organometallic compounds) shall not be present.

Property	*Allowable range of values*
Density kg/m^3 at 15°C	780 – 820
Distillation temperature, °C	
10% boiling point	155 – 201
Final boiling point	235 – 285
Net heat of combustion, MJ/kg	42.86 – 43.50
Aromatics, volume %	15 – 23
Naphthalenes, volume %	~~1.0 – 3.5~~ 0.0 - 3.0
Smoke point, mm	20 – 28
Hydrogen, mass %	13.4 – 14.3
Sulphur, mass %	less than 0.3~~%~~
Kinematic viscosity at –20°C, mm^2/s	2.5 – 6.5

…

Proposal D Rationale:

The current Annex 16, Vol. II emissions test fuel specification allows naphthalene to be present in the fuel between 1%vol and 3.5%vol. A ICAO/CAEP investigation highlighted that manufacturers and organisations involved in gas turbine emissions measurements have reported difficulties in obtaining fuel that meets the minimum naphthalene content test fuel specification in Annex 16, Volume II, Appendix 4. This investigation concluded that the Annex 16 naphthalene limits are not representative of current commercially available jet fuel.

When consideration was given to removing the lower limit on the naphthalene content in the emissions test fuel specification (i.e. from 1%vol to 0%vol), it was concluded that there would be no effect on gaseous emissions levels, and there would be negligible effect on Smoke Number (SN) level, as long as the aromatic and hydrogen content remains within the current emissions test fuel specification limits. There is no proposal to change the current aromatic and hydrogen limits

The proposed amendment changes the naphthalene content range for the emissions test fuel specification (Annex 16 Vol II, Appendix 4) to between 0%vol and 3%vol (from between 1%vol and 3.5%vol).

PROPOSAL E

GENERAL TECHNICAL, NOMENCLATURE AND TYPOGRAPHICAL ISSUES

…

Table A. Amendments to Annex 16

. . .

4	Fourth Meeting of the Committee on Aviation Environmental Protection	Increased stringency of ~~NO_x~~ NOx emissions limits.	26 February 1999 19 July 1999 4 November 1999
5	Sixth Meeting of the Committee on Aviation Environmental Protection	Increase in stringency of the ~~NO_x~~ NOx emissions Standards.	23 February 2005 11 July 2005 24 November 2005

…

PART III. EMISSIONS CERTIFICATION

…

CHAPTER 2. TURBOJET AND TURBOFAN ENGINES INTENDED FOR PROPULSION ONLY AT SUBSONIC SPEEDS

…

2.1.2 Emissions involved

The following emissions shall be controlled for certification of aircraft engines:

Smoke
Gaseous emissions
  Unburned hydrocarbons (HC);
  Carbon monoxide (CO); and
  Oxides of nitrogen (~~NO_x~~NOx).

2.1.3 Units of measurement

2.1.3.1 The smoke emission shall be measured and reported in terms of Smoke Number (SN).

2.1.3.2 The mass (D_p) of the gaseous pollutant HC, CO, or ~~NO_x~~ NOx emitted during the reference emissions landing and take-off (LTO) cycle, defined in 2.1.4.2 and 2.1.4.3, shall be measured and reported in grams.

…

2.1.4 Reference conditions

2.1.4.1 *Atmospheric conditions*

The reference atmospheric conditions for engine performance shall be ISA at sea level except that the reference absolute humidity shall be 0.00634 kg water/kg dry air.

. . .

2.1.4.3 *Reference emissions landing and take-off (LTO) cycle*

The reference emissions LTO cycle for the calculation and reporting of gaseous emissions shall be represented by the following time in each operating mode.

~~Phase~~LTO operating mode	*Time in operating mode, minutes*
Take-Off	0.7
Climb	2.2
Approach	4.0
Taxi/ground idle	26.0

. . .

2.3.2 Regulatory levels

Gaseous emission levels when measured and computed in accordance with the procedures of Appendix 3 and converted to characteristic levels by the procedures of Appendix 6, or equivalent procedures as agreed by the certificating authority, shall not exceed the regulatory levels determined from the following formulas:

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

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

Oxides of nitrogen (~~NO_x~~NOx):

. . .

APPENDIX 2. SMOKE EMISSION EVALUATION

. . .

2.2.2 Sampling lines shall be as "straight through" as possible. Any necessary bends shall have radii which are greater than 10 times the inside diameter of the lines. The material of the lines shall be such as to discourage build-up of particulate matter or static electricity.

Note.— Stainless steel or ~~carbon loaded~~ carbon-loaded grounded polytetrafluoroethylene (PTFE) meet these requirements.

2.3 Smoke analysis system

. . .

APPENDIX 3. INSTRUMENTATION AND MEASUREMENT TECHNIQUES FOR GASEOUS EMISSIONS

. . .

2. DEFINITIONS

. . .

Gas ~~C~~concentration. The volume fraction of the component of interest in the gas mixture — expressed as volume percentage or as parts per million.

. . .

Parts per million (ppm). The unit volume gas concentration of a gas per million unit volume of the gas mixture of which it is a part.

Parts per million carbon (ppmC). The mole fraction of hydrocarbon multiplied by 10^6 measured on a methane-equivalence basis. Thus, 1 ppm of methane is indicated as 1 ppmC. To convert ppm concentration of any hydrocarbon to an equivalent ppmC value, multiply ppm gas concentration by the number of carbon atoms per molecule of the gas. For example, 1 ppm propane translates as 3 ppmC hydrocarbon; 1 ppm hexane as 6 ppmC hydrocarbon

Reference gas. A mixture of gases of specified and known composition used as the basis for interpreting instrument response in terms of the gas concentration of the gas to which the instrument is responding.

. . .

Response. The change in instrument output signal that occurs with change in sample gas concentration. ~~Also the output signal corresponding to a given sample concentration.~~

. . .

3.1 Gaseous emissions

Gas ~~C~~concentrations of the following emissions shall be determined:

a) Hydrocarbons (HC): a combined estimate of all hydrocarbon compounds present in the exhaust gas.

b) Carbon monoxide (CO).

c) Carbon dioxide (CO_2).

Note.— CO_2 is not a regulated engine emission but ~~its~~ CO_2 concentration is required for calculation and check purposes.

d) Oxides of nitrogen (~~NO_x~~NOx): an estimate of the sum of the two oxides, nitric oxide (NO)

and nitrogen dioxide (NO_2).

e) Nitric oxide (NO).

. . .

3.2 Other information

In order to ~~normalize~~ normalise the emissions measurement data and to quantify the engine test characteristics, the following additional information shall be provided:

. . .

5. DESCRIPTION OF COMPONENT PARTS

. . .

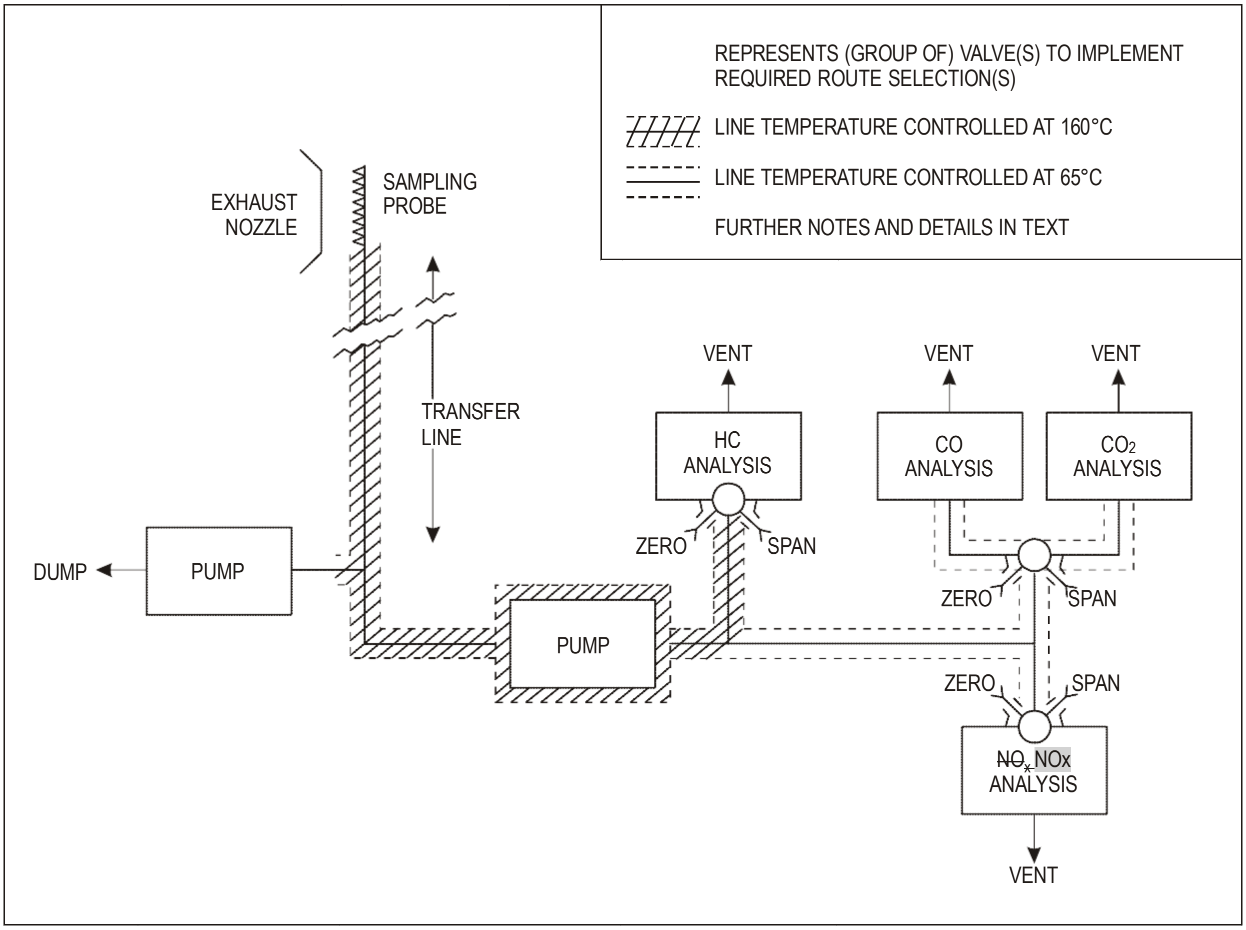

Figure A3-1. Sampling and analysis system, schematic

. . .

5.4 ~~NO_x~~ NOx analyser

The measurement of NO gas concentration shall be by the chemiluminescent method in which the measure of the radiation intensity emitted during the reaction of the NO in the sample with added O_3 is the measure of the NO gas concentration. The NO_2 component shall be converted to NO in a converter of the requisite efficiency prior to measurement. The resultant ~~NO_x~~ NOx measurement system shall include all necessary flow, temperature and other controls and provide for routine zero and span calibration as well as for converter efficiency checks.

Note.— An overall specification is given in Attachment C to this appendix.

. . .

6.2 Major instrument calibration

. . .

6.2.3 The procedure for checking the performance of each analyser shall be as follows (using the calibration and test gases as specified in Attachment D to this appendix):

a) introduce zero gas and adjust instrument zero, recording setting as appropriate;

b) for each range to be used operationally, introduce calibration gas of (nominally) 90 per cent range full-scale deflection (FSD) gas concentration; adjust instrument gain accordingly and record its setting;

c) introduce approximately 30 per cent, 60 per cent, and 90 per cent range FSD gas concentration and record analyser readings;

d) fit a least squares straight line to the zero, 30 per cent, 60 per cent and 90 per cent gas concentration points. For the CO and/or CO_2 analyser used in their basic form without linearization of output, a least squares curve of appropriate mathematical formulation shall be fitted using additional calibration points if judged necessary. If any point deviates by more than 2 per cent of the full scale value (or ±1 ppm*, whichever is greater) then a calibration curve shall be prepared for operational use.

6.3 Operation

. . .

6.3.2 The following procedure shall be adopted for operational measurements:

a) apply appropriate zero gas and make any necessary instrument adjustments;

b) apply appropriate calibration gas at a nominal 90 per cent FSD gas concentration for the ranges to be used, adjust and record gain settings accordingly;

c) when the engine has been stabilized at the required thrust setting, continue to run it and observe pollutant gas concentrations until a stabilized reading is obtained, which shall be recorded;

. . .

6.4 Carbon balance check

Each test shall include a check that the air/fuel ratio as estimated from the integrated sample total carbon gas concentration exclusive of smoke, agrees with the estimate based on engine air/fuel ratio ~~within~~ with an accuracy of ±15 per cent for the taxi/ground idle mode, and ~~within~~ with an accuracy of ± 10 per cent for all other modes (*see* 7.1.2).

. . .

7. CALCULATIONS

7.1 Gaseous emissions

7.1.1 General

The analytical measurements made shall be the gas concentrations of the various gaseous emissions, as detected at their respective analysers for a range of combustor inlet temperatures (T_B) encompassing the four LTO operating modes. Using the calculations of 7.1.2, or the alternative methods defined in Attachment E to this appendix, the measured emissions indices (EI) for each gaseous emission shall be established. To account for deviations from reference atmospheric conditions, the corrections of 7.1.3 shall be applied. Note that these corrections may also be used to account for deviations of the tested engine from the reference standard engine where appropriate (see Appendix 6, paragraph 1 f)). Using combustor inlet temperature (T_B) as a correlating parameter, the emissions indices and fuel flow corresponding to the operation at the four LTO operating modes of a reference standard engine under reference day conditions shall then be established using the procedures of 7.2.

7.1.2 Basic parameters

$$EI_p(\text{emission index for component p}) = \frac{\text{mass of } p \text{ produced in } g}{\text{mass of Fuel used in } kg}$$

$$EI(CO) = \left(\frac{[CO]}{[CO_2]+[CO]+[HC]}\right)\left(\frac{10^3 M_{CO}}{M_C + ({}^{n}/_{m})M_H}\right)\left(1 + [CO_2]\left({}^{P_0}/_{m}\right)\right)$$

$$EI(HC) = \left(\frac{[HC]}{[CO_2]+[CO]+[HC]}\right)\left(\frac{10^3 M_{HC}}{M_C + ({}^{n}/_{m})M_H}\right)\left(1 + [CO_2]\left({}^{P_0}/_{m}\right)\right)$$

$$EI(NOx)\ as\ NO_2 = \left(\frac{[NOx]}{[CO_2]+[CO]+[HC]}\right)\left(\frac{10^3 M_{NO_2}}{M_C + ({}^{n}/_{m})M_H}\right)\left(1 + [CO_2]\left({}^{P_0}/_{m}\right)\right)$$

$$\frac{Air}{Fuel} Ratio = {}^{P_0}/_{m}\left(\frac{M_{AIR}}{M_C + ({}^{n}/_{m})M_H}\right)$$

. . .

MAIR	molecular mass of dry air = 28.966 g or, where appropriate, = (32 ~~*R*~~ $[O_2]_b$ + 28.156 4 ~~*S*~~ $[N_2]_b$ + 44.011 ~~*T*~~ $[CO_2]_b$)g

. . .

~~*R*~~ $[O_2]_b$	gas concentration of O_2 in dry air, by volume = 0.209 5 ~~normally~~
~~*S*~~ $[N_2]_b$	gas concentration of N_2 + rare gases in dry air, by volume = ~~0.709 2~~ 0.790 2 ~~normally~~
~~*T*~~ $[CO_2]_b$	gas concentration of CO_2 in dry air, by volume = 0.000 3 ~~normally~~
[HC]	mean gas concentration of exhaust hydrocarbons vol/vol wet, expressed as carbon

[CO] mean gas concentration of CO in exhaust sample vol/vol, wet

[CO_2] mean gas concentration of CO_2 in exhaust sample vol/vol, wet

[~~NO_x~~NOx] mean gas concentration of ~~NOx~~ NO and NO_2 in exhaust sample vol/vol, wet = [NO + NO_2]

[NO] mean gas concentration of NO in exhaust sample, vol/vol, wet

[NO_2] mean gas concentration of NO_2 in exhaust sample, vol/vol, wet

$$= \frac{([\cancel{NO_x}NOx]_c - [NO])}{\eta}$$

[~~NO_x~~NOx]$_c$ mean gas concentration of NO in exhaust sample after passing through the NO_2/NO converter, vol/vol, wet

. . .

The value of *n/m*, the ratio of the atomic hydrogen to atomic carbon of the fuel used, is evaluated by fuel type analysis. The ambient air humidity, h_{vol}, shall be measured at each set condition. In the absence of contrary evidence as to the characterization (*x*,*y*) of the exhaust hydrocarbons, the values $x = 1$, $y = 4$ are to be used. If dry or semi-dry CO and CO_2 measurements are to be used then these shall first be converted to the equivalent wet gas concentration as shown in Attachment E to this appendix, which also contains interference correction formulas for use as required.

. . .

7.1.3.2 Using the recommended curve fitting technique of 7.2 to relate emission indices to combustor inlet temperature effectively eliminates the exp $((T_{Bref} - T_B)/c)$ term from the generalized equation and for most cases the (FAR_{ref} / FAR_B) term may be considered unity. For the emissions indices of CO and HC many testing facilities have determined that the humidity term is sufficiently close to unity to be eliminated from the expression and that the exponent of the (P_{Bref} / P_B) term is close to unity.

Thus,

EI(CO) corrected = EI derived from (P_B / P_{Bref}) " EI(CO) v. T_B curve

EI(HC) corrected = EI derived from (P_B / P_{Bref}) " EI(HC) v. T_B curve

EI(~~NO_x~~NOx) corrected = EI derived from EI(~~NO_x~~NOx) $(P_{Bref} / P_B)^{0.5}$ exp $(19\ [h_{mass} - 0.00634])$ v. T_B curve

If this recommended method for the CO and HC emissions index correction does not provide a satisfactory correlation, an alternative method using parameters derived from component tests may be used.

Any other methods used for making corrections to CO, HC and ~~NO_x~~ NOx emission indices shall have the approval of the certificating authority.

. ..

ATTACHMENT A TO APPENDIX 3. SPECIFICATION FOR HC ANALYSER

Note 1.— As outlined in 5.2 of Appendix 3, the measuring element in this analyser is the flame ionization detector (FID) in which the whole or a representative portion of the sample flow is admitted into a hydrogen-fuelled flame. With suitably positioned electrodes an ionization current can be established which is a function of the mass rate of hydrocarbon entering the flame. It is this current which, referred to an appropriate zero, is amplified and ranged to provide the output response as a measure of the hydrocarbon gas concentration expressed as ppmC equivalent.

. . .

2. SYNERGISTIC EFFECTS

Note.— In application there are two aspects of performance which can affect the accuracy of measurement:

a) the oxygen effect (whereby differing proportions of oxygen present in the sample give differing indicated hydrocarbon gas concentration for constant actual HC gas concentrations); and

b) the relative hydrocarbon response (whereby there is a different response to the same sample hydrocarbon gas concentrations expressed as equivalent ppmC, dependent on the class or admixture of classes of hydrocarbon compounds).

The magnitude of the effects noted above shall be determined as follows and limited accordingly.

Oxygen response: measure the response with two blends of propane, at approximately 500 ppmC gas concentration known to a relative accuracy of ±1 per cent, as follows:

1) propane in 10 ±1 per cent O_2, balance N_2

2) propane in 21 ±1 per cent O_2, balance N_2

If R_1 and R_2 are the respective ~~normalized~~ normalised responses then ($R_1 - R_2$) shall be less than 3 per cent of R_1.

Differential hydrocarbon response: measure the response with four blends of different hydrocarbons in air, at *gas* concentrations of approximately 500 ppmC, known to a relative accuracy of ±1 per cent, as follows:

a) propane in zero air

b) propylene in zero air

c) toluene in zero air

d) n-hexane in zero air.

If R_a, R_b, R_c and R_d are, respectively, the ~~normalized~~ normalised responses (with respect to propane), then $(R_a - R_b)$, $(R_a - R_c)$ and $(R_a - R_d)$
shall each be less than 5 per cent of R_a.

3. OPTIMIZATION OF DETECTOR RESPONSE AND ALIGNMENT

. . .

3.2 The linearity of each analyser range shall be checked by applying propane in air samples at gas concentrations of approximately 30, 60 and 90 per cent of full scale. The maximum response deviation of any of these points from a least squares straight line (fitted to the points and zero) shall not exceed ±2 per cent of full scale value. If it does, a calibration curve shall be prepared for operational use.

ATTACHMENT B TO APPENDIX 3. SPECIFICATION FOR CO AND CO_2 ANALYSERS

Note 1.— Paragraph 5.3 of Appendix 3 summarizes the characteristics of the analysis subsystem to be employed for the individual measurements of CO and CO_2 gas concentrations in the exhaust gas sample. The instruments are based on the principle of non-dispersive absorption of infrared radiation in parallel reference and sample gas cells. The required ranges of sensitivity are obtained by use of stacked sample cells or changes in electronic circuitry or both. Interferences from gases with overlapping absorption bands may be minimized by gas absorption filters and/or optical filters, preferably the latter.

. . .

CO Analyser

. . .

g) *Interferences:* to be limited with respect to indicated CO gas concentration as follows:

1) less than 500 ppm/per cent ethylene gas concentration

2) less than 2 ppm/per cent CO_2 gas concentration

. . .

CO_2 Analyser

. . .

g) The effect of oxygen (O_2) on the CO_2 analyser response shall be checked. For a change from 0 per cent O_2 to 21 per cent O_2, the response of a given CO_2 gas concentration shall not change by more than 2 per cent of reading. If this limit cannot be met an appropriate correction factor shall be applied.

. . .

CO and CO_2 Analysers

. . .

c) *Calibration curves:*

1) Analysers with a linear signal output characteristic shall be checked on all working ranges using calibration gases at known gas concentrations of approximately 0, 30, 60 and 90 per cent of full scale. The maximum response deviation of any of these points from a least squares straight line, fitted to the points and the zero reading, shall not exceed ±2 per cent of the full scale value. If it does then a calibration curve shall be prepared for operational use.

2) Analysers with a non-linear signal output characteristic, and those that do not meet the requirements of linearity given above, shall have calibration curves prepared for all working ranges using calibration gases at known gas concentrations of approximately 0, 30, 60 and 90 per cent of full scale. Additional mixes shall be used, if necessary, to define the curve shape properly.

ATTACHMENT C TO APPENDIX 3. SPECIFICATION FOR ~~NO_x~~NOx ANALYSER

Note.— See Attachment D for information on calibration and test gases.

1. As indicated in 5.4 of Appendix 3, the measurement of the oxides of nitrogen gas concentration shall be by the chemiluminescent technique in which radiation emitted by the reaction of NO and O_3 is measured. This method is not sensitive to NO_2 and therefore the sample shall be passed through a converter in which NO_2 is converted to NO before the measurement of total ~~NO_x~~NOx is made. Both the original NO and the total ~~NO_x~~NOx gas concentrations shall be recorded. Thus by difference, a measure of the NO_2 gas concentration shall be obtained.

. . .

3. The principal performance specification, determined for the instrument operated in an ambient temperature stable to within 2°C, shall be as follows:

a) *Total range:* 0 to 2 500 ppm in appropriate ranges.

. . .

g) *Interference:* suppression for samples containing CO_2 and water vapour, shall be limited as follows:

1) less than 0.05 per cent reading/per cent CO_2 gas concentration;

2) less than 0.1 per cent reading/per cent water vapour gas concentration.

. . .

j) *Converter:* this shall be designed and operated in such a matter as to reduce NO_2 present in the sample to NO. The converter shall not affect the NO originally in the sample.

The converter efficiency shall not be less than 90 per cent.

This efficiency value shall be used to correct the measured sample NO_2 value (i.e. [~~NO_x~~NOx]$_C$ – [NO]) to that which would have been obtained if the efficiency had not been 100 per cent.

…

ATTACHMENT E TO APPENDIX 3. THE CALCULATION OF THE EMISSIONS PARAMETERS — BASIS, MEASUREMENT CORRECTIONS AND ALTERNATIVE NUMERICAL METHOD

1. SYMBOLS

. . .

K	ratio of gas concentration measured wet to that measured dry (after cold trap)

. . .

~~R~~ $[O_2]_b$	gas concentration of O_2 in dry air, by volume = 0.209 5 ~~normally~~
~~S~~ $[N_2]_b$	gas concentration of N_2 + rare gases in dry air, by volume = ~~0.709 2~~ 0.790 2 ~~normally~~
~~T~~ $[CO_2]_b$	gas concentration of CO_2 in dry air, by volume = 0.000 3 ~~normally~~

. . .

$[CO_2]$	mean gas concentration of CO_2 in exhaust sample vol/vol, wet
[CO]	mean gas concentration of CO in exhaust sample vol/vol, wet
[HC]	mean gas concentration of exhaust hydrocarbons ~~HC~~ ~~in exhaust sample,~~ vol ~~C~~/vol wet, expressed as carbon
[NO]	mean gas concentration of NO in exhaust sample, vol/vol, wet
$[NO_2]$	mean gas concentration of NO_2 in exhaust sample, vol/vol, wet

$$= \frac{([NOx]_c - [NO])}{\eta}$$

[~~NO_x~~NOx] mean gas concentration of NO and NO_2 in exhaust sample vol/vol, wet = [NO + NO_2]

[~~NO_x~~NOx]$_c$ mean gas concentration of NO in exhaust sample, after passing through the NO_2/NO converter, vol/vol, wet

~~$[NO_2]$ mean = $\frac{([NO_x]_c - [NO])}{\eta}$~~

[ ]$_d$ mean gas concentration in exhaust sample after cold trap, vol/vol

[ ]$_m$ mean gas concentration measurement indicated before instrument correction applied, vol/vol

. . .

2. BASIS OF CALCULATION OF EI AND AFR PARAMETERS

2.1 It is assumed that the balance between the original fuel and air mixture and the resultant state of the exhaust emissions as sampled can be represented by the following equation:

C_mH_n + $P0$[~~R~~ $[O_2]_b$ (O2) + ~~S~~ $[N_2]_b$ (N2) + ~~T~~ $[CO_2]_b$ (CO2) + h_{vol} (H2O)] = $P1$(CO2) + $P2$(N2) + $P3$(O2)+ $P4$(H2O) + $P5$(CO) + $P6$(C_xH_y) + $P7$(NO2) + $P8$(NO)

. . .

$$EI(\cancel{NO_x}\,NOx) = (P_7 + P_8)\left(\frac{10^3 M_{NO_2}}{mM_C + nM_H}\right) \text{expressed as } NO_2 \text{ equivalent}$$

. . .

2.2 Values for fuel hydrocarbon composition (m, n) are assigned by fuel specification or analysis. If only the ratio n/m is so determined, the value $m = 12$ may be assigned. The mole fractions of the dry air constituents (~~R~~ $[O_2]_b$, ~~S~~ $[N_2]_b$, ~~T~~ $[CO_2]_b$) are normally taken to be the recommended standard values but alternative values may be assigned, subject to the restriction ~~R~~ $[O_2]_b$ + ~~S~~ $[N_2]_b$ + ~~T~~ $[CO_2]_b$ = 1 and the approval of the certificating authority.

. . .

2.4 Determination of the remaining unknowns requires the solution of the following set of linear simultaneous equations, where (1) to (4) derive from the fundamental atomic conservation relationships and (5) to (9) represent the gaseous product gas concentration relationships.

. . .

m + ~~T~~ $[CO_2]_b$ $P0 = P1 + P5 + xP6$.. (1)

$n + 2h_{vol}P0 = 2P4 + yP6$ .... (2)

(2 ~~R~~ $[O_2]_b$ + 2 ~~T~~ $[CO_2]_b$ + h_{vol})$P0 = 2P1 + 2P3 + P4 + P5 + 2P7 + P8$ .... (3)

2~~*S*~~ $[N_2]_b P0 = 2P2 + P7 + P8$ .... (4)

[~~NO_x~~NOx] $_c P_T = \eta P7 + P8$ .... (8)

. . .

The above set of conditional equations is for the case where all measured gas concentrations are true, that is, not subject to interference effects or to the need to correct for sample drying. In practice, interference effects are usually present to a significant degree in the CO, and NO measurements, and the option to measure CO2 and CO on a dry or partially dry basis is often used. The necessary modifications to the relevant equations are described in 2.5 and 2.6

. . .

2.5 The interference effects are mainly caused by the presence of CO2 and H2O in the sample which can affect the CO and the ~~NO_x~~NOx analysers in basically different ways. The CO analyser is prone to a zero-shifting effect and the ~~NO_x~~NOx analyser to a sensitivity change, represented thus:

$$[CO] = [CO]_m + L[CO2] + M[H2O]$$

and [~~NO_x~~NOx]$_c$ = [~~NO_x~~NOx]$_{cm}$ $(1 + L'[CO2] + M'[H2O])$

which transform into the following alternative equations to (6), (8) and (9), when interference effects require to be corrected,

$[CO]_m P_T + LP1 + MP4 = P5$ …... (6A)

[~~No_x~~NOx]$_{cm}$ $(P_T + L'P1 + M'P4) = \eta P7 + P8$ ….. (8A)

$[NO]_m (P_T + L'P1 + M'P4) = P8$ ….. (9A)

. . .

2.6 The option to measure CO2 and CO gas concentrations on a dry or partially dry sample basis, that is, with a sample humidity reduced to hd, requires the use of modified conditional equations as follows:

$[CO2]_d (P_T - P4)(1 + hd) = P1$ .... (5A)

and

$$[CO]_d (P_T - P4)(1 + hd) = P5$$

However, the CO analyser may also be subject to interference effects as described in 2.5 and so the complete alternative CO measurement gas concentration equation becomes

$[CO]_{md} (Pi - P4)(1 + hd) + LP1 + Mhd (P_T - P4) = P5$ .... (6B)

. . .

3. ANALYTICAL FORMULATIONS

3.1 General

Equations (1) to (10) can be reduced to yield the analytical formulations for the EI and AFR parameters, as given in 7.1 to this appendix. This reduction is a process of progressive elimination of the roots $P0$, $P1$ through $P8$, PT, making the assumptions that all gas concentration measurements are of the “wet” sample and do not require interference corrections or the like. In practice, the option is often chosen to make the CO2 and CO gas concentration measurements on a “dry” or “semi-dry” basis; also it is often found necessary to make interference corrections. Formulations for use in these various circumstances are given in 3.2, 3.3 and 3.4.

3.2 Equation for conversion of dry gas concentration measurements to wet basis

Gas Concentration wet = K × gas concentration dry; that is,

$$[\quad] = K\,[\quad]_d$$

The following expression for K applies when CO and CO2 are determined on a “dry” basis:

$$\{4+(n/m)\,\cancel{T}[CO_2]_b+([n/m]\cancel{T}[CO_2]_b-2h_{vol})\,([NO_2]-(2[HC]/x))+(2+h_{vol})\,\left([y/x]-[n/m]\right)[HC]\}$$

$$K \quad (1+h_d)$$

$$\text{------}\quad (2+h)\,\{2+(n/m)\,(1+h_d)\,([CO_2]_d+[CO]_d)\}-([n/m]\,\cancel{T}[CO_2]_b-2h)\,(1-[1+h_d]\,[CO]_d)$$

. . .

3.3 Interference corrections

The measurements of CO and/or ~~NOx~~NOx and NO may require corrections for interference by the sample CO2 and water concentrations before use in the above analytical equations. Such corrections can normally be expressed in the following general ways:

. . .

$$\eta[NO_2] = ([\cancel{NO_x}NOx]_{cm} - [NO]_m)\,(1 + L'[CO_2] + M'[H_2O])$$

. . .

3.4 Equation for estimation of sample water content

Water concentration in sample

$$[H_2O] = \frac{\left(\left[{}^{n}/_{2m}\right] + h_{vol}\left[{}^{P_0}/_{m}\right]\right)([CO_2] + [CO] + [HC])}{1 + \cancel{T}[CO_2]_b\left({}^{P_0}/_{m}\right)} - \left({}^{y}/_{2x}\right)[HC]$$

4. ALTERNATIVE METHODOLOGY — NUMERICAL SOLUTION

4.1 As an alternative to the analytical procedures summarized in 3, it is possible to obtain readily the emissions indices, fuel/air ratio, corrected wet gas concentrations, etc., by a numerical solution of equations (1) to (10) for each set of measurements, using a digital computer.

4.2 In the equation set (1) to (10) the actual gas concentration measurements are substituted using whichever of the alternative equations (5A), (6A), etc. applies for the particular measuring system, to take account of interference corrections and/or dried sample measurements.

. . .

ATTACHMENT F TO APPENDIX 3. SPECIFICATIONS FOR ADDITIONAL DATA

As required in 3.2 of Appendix 3, in addition to the measured sample constituent gas concentrations, the following data shall also be provided:

. . .

Proposal E Rationale:

All the proposed amendments are corrections due to minor technical errors in Annex 16, Volume II or for consistency purposes.

6.2.3. Excerpt of the summary of CAEP/10 presentations, discussions, conclusions, recommendations and proposed changes to ICAO Annex 16, Vol II from the CAEP/10 Report (Agenda Item 4 'Particulate Matter Standard development').

4.2 PROPOSED NON-VOLATILE PARTICULATE MATTER STANDARD - AMENDMENTS TO ANNEX 16, VOLUME II AND THE ETM, VOLUME II

4.2.1 The Co-Rapporteurs of WG3 presented the stand-alone report on the proposed amendment to Annex 16, Volume II to promulgate a new nvPM certification Standard in Chapter 4, Appendix 7 and associated Attachments A to E. A new Part IV and Appendix 8 are also included on procedures for the estimation of system particle losses.

4.2.2 The new Chapter 4 contains the main elements of the certification requirements, proposed regulatory limit for the nvPM mass concentration and the applicability of the Standard for engines of rated thrust greater than 26.7 kN. Appendix 7 and the associated attachments contain all the certification procedures including the measurement methodology, system operation and instrument calibration. Appendix 7 is based on the Aerospace Information Report (AIR) 6241 published by the SAE Engine Exhaust Measurement Committee (SAE E-31).

4.2.3 Appendix 8 contains the description of the particle loss correction estimation methodology in the sampling measurement system. The sampling system configuration, dimensions and operational parameters recorded during an engine test have to be reported to the Certification Authority in order to prove compliance with Appendix 7. The same information, together with the measured nvPM mass and number concentrations, is used for input into the calculation procedure described in Appendix 8.

4.2.4 The Co-Rapporteurs of WG3 presented the stand-alone report on the proposed amendment to ICAO Doc 9501, *Environmental Technical Manual*, Volume II – *Procedures for Emissions Certification of Aircraft Engines*, related to Chapter 4, Appendix 7 and Attachments A to E pertaining to the proposed CAEP/10 nvPM SARPs.

4.2.5 Several members and observers expressed their support for the proposed CAEP/10 nvPM emissions standard for aircraft engines of rated thrust greater than 26.7 kN, and the procedures for the estimation of system losses. The members committed to the development of an LTO based nvPM mass and number standard during CAEP/11, and supported the work plan to assess the options for the replacement of the smoke number visibility standard for aircraft engines of rated thrust greater than 26.7 kN with a future nvPM mass and number standard that would preserve the invisible plume requirements of the smoke number standard. The members and observers presented a summary of information explaining the nvPM proposed amendments to Annex 16 Volume II, and it was requested that this be included within the Appendix of the CAEP/10 report for this agenda item in order to support the implementation of the proposed nvPM Standard into legislative frameworks.

4.2.6 A member provided full support for the promulgation of the new nvPM emissions certification requirement, the initial nvPM Standard set at the smoke visibility limit, and the procedures for the estimation of system losses for reporting purposes for engines of rated thrust greater than 26.7 kN. The member supported the replacement of the smoke number visibility Standard during CAEP/11 with a future LTO-based nvPM mass and number health-based standard that would preserve the invisible plume requirements of the smoke number Standard. The member encouraged engine manufacturers to submit their respective nvPM emissions information to ICAO's Engine Emissions Databank, which will lead to better characterization of air quality health and climate impacts of aviation.

4.2.7 An observer highlighted that it had put considerable effort and resources into the development of the proposed CAEP/10 nvPM Standard and would continue to support the CAEP work programme going forward. The observer emphasised that there would be a significant amount of work required to achieve the proposed CAEP/11 LTO nvPM Standards for mass and number emissions. A commitment has been made by the manufacturers to measure 25 representative engines by February 2017, and it is believed that the majority of these engines will be measured and data reported for this target date enabling the considerations to go forward. Of the 25 engines, there remain a few that as of yet do not have funding but negotiations are ongoing.

4.2.8 An observer highlighted that establishing an engine nvPM emission Standard to replace the existing smoke number Standard should be one of the top priorities for the CAEP/11 work cycle. The nvPM Standard may provide significant air quality benefits, have climate co-benefits in the form of reduced climate forcing associated with black carbon emissions, and could inform action under consideration by other authorities investigating black carbon emissions from vehicle engines, notably the International Maritime Organization (IMO). The observer looked forward to supporting policy development throughout the CAEP/11 cycle.

Discussion and Conclusions

4.2.9 The meeting discussed the equipment used in the measurement on nvPM measurements. It was clarified that the current Annex 16, Volume II gaseous emissions measurement probe and rake will be used in the nvPM measurements, but the nvPM sampling train is different to that used for gaseous emissions and this has required additional investment from States and industry.

4.2.10 Following a question from a member on whether the proposed CAEP/10 nvPM Standard is of a transitional nature, it was clarified that it is in fact a full regulatory standard, based on the current Smoke Number regulatory level. This can be seen as the first step in setting a more stringent regulatory level for nvPM during CAEP/11, which will involve, as part of the standard setting process, defining stringency options and technology responses for aircraft engines. It was highlighted that the work on the CAEP/11 nvPM Standard will be challenging and there are clear milestones, including the submission of nvPM data from the manufacturers. So that the final result is not jeopardised, WG3 will need to ensure that the milestones are met in a timely manner.

4.2.11 A member requested more details on when the smoke number Standard will be removed following the introduction of the CAEP/11 nvPM Standard for engines greater than 26.7kN. It was clarified that WG3 will work to better understand the confidence level that nvPM measurements uphold the visibility criteria of the current smoke number Standard. Once this has been established, and the nvPM Standard is in place, then proposals will be made to remove the smoke number Standard for engines greater than 26.7kN. The meeting noted that the current smoke number Standard also covers engines <26.7kN.

4.2.12 The meeting thanked the members and observers involved in the nvPM work for the significant resources and dedication. The meeting acknowledged that WG3 has developed an aircraft engine based nvPM mass and number methodology for application as a nvPM mass and number emissions certification requirement. The meeting agreed that the nvPM mass and number emission indices reported as part of the CAEP/10 certification requirement will be used in the development of a new LTO based metric system during CAEP/11 for both nvPM mass and number emissions.

4.2.13 The meeting thanked WG3 for completing its nvPM work during this CAEP cycle, and took note of the significant work conducted by WG3 to develop the new CAEP/10 nvPM Standard based on visibility criterion. As such, the meeting approved the amendments to Annex 16, Volume II, including Chapter 4 and Appendix 7 with Attachments A to E, and Part IV with Appendix 8 on the procedures for the estimation of system losses, as presented in Appendix A to this meeting report. In approving the associated proposed amendments to the ETM, Volume II (pertaining to the new Chapter 4, Appendix 7 and Attachments A to E of Annex 16, Volume II) as presented in the report from the working group, the meeting recognised the work conducted by WG3 to provide guidance material in support of the new nvPM Standard.

4.2.14 The meeting noted the progress toward a CAEP/11 mass and number Standard for turbofan/turbojet engines greater than 26.7kN. The meeting agreed to work towards the retirement of the smoke Standard and replacement with an updated nvPM mass concentration based standard at CAEP/11.

4.2.15 The meeting acknowledged the work of the engine manufacturers in developing the nvPM Standard and encouraged them to submit their respective nvPM emissions information to the PMTG PM Values Database to support the CAEP/11 standard setting process, and once certified, to include nvPM emissions information to the ICAO Engine Emissions Databank.

4.2.16 To aid States in the implementation of the new CAEP/10 nvPM Standard, the meeting approved the summary of information explaining the nvPM proposed amendments to Annex 16, Volume II, as indicated in Appendix B to this Agenda Item.

4.2.17 **Recommendations**

4.2.17.1 In light of the foregoing discussion, the meeting developed the following recommendations:

RSPP

Recommendation 4/1 — Amendments to Annex 16 — *Environmental Protection,* Volume II — *Aircraft Engine Emissions,* to introduce the new CAEP/10 nvPM SARPs

That Annex 16, Volume II be amended to introduce the new non-volatile Particle Matter (nvPM) SARPs as indicated in Appendix A to the report on this agenda item.

Recommendation 4/2 — Amendments to the *Environmental Technical Manual,* Volume II, associated with the new CAEP/10 nvPM SARPs

That the Environmental Technical Manual, Volume II be amended and published, and revised versions approved by subsequent CAEP Steering Groups be made available free of charge on the ICAO website, pending a final decision on official publication by the ICAO Secretary General.

6.2.4. Proposed amendments to ICAO Annex 16, Vol II for the new non-volatile particulate matter engine emissions Standard

The text of the amendment is arranged to show deleted text with a line through it and new text highlighted with grey shading, as shown below:

1.	~~Text to be deleted is shown with a line through it.~~	text to be deleted
2.	New text to be inserted is highlighted with grey shading	new text to be inserted
3.	~~Text to be deleted is shown with a line through it~~ followed by the replacement text which is highlighted with grey shading.	new text to replace existing text

PROPOSAL F

CAEP/10 NON-VOLATILE PARTICULATE MATTER (NVPM) ENGINE EMISSIONS STANDARD

CHAPTER 4. PARTICULATE MATTER EMISSIONS

4.1 General

4.1.1 Applicability

The provisions of this chapter shall apply to all aircraft engines, intended for propulsion only at subsonic speeds, for which an application for type certification is submitted to the certificating authority. Specific provisions for the relevant engine categories shall apply as detailed in section 4.2.

4.1.2 Emissions involved

The purpose of this section is to control non-volatile particulate matter mass ($nvPM_{mass}$) emissions.

4.1.3 Units of measurement

The concentration of nvPM mass ($nvPM_{mass}$) shall be reported in μg/m^3.

4.1.4 Reference conditions

4.1.4.1 *Atmospheric conditions*

The reference atmospheric conditions for the reference standard engine shall be ISA at sea level except that the reference absolute humidity shall be 0.00634 kg water/kg dry air.

4.1.4.2 *Reference emissions landing and take-off (LTO) cycle*

The engine shall be tested at sufficient thrust settings to define the nvPM emissions of the engine so that nvPM mass emission indices (EI_{mass}) and nvPM number emission indices (EI_{num}) can be determined at the following specific percentages of rated thrust and at thrusts producing maximum $nvPM_{mass}$ concentration, maximum EI_{mass} and maximum EI_{num} as agreed by the certificating authority:

LTO operating mode	*Thrust setting*
Take-off	100 per
cent F_{oo} Climb	85
per cent F_{oo}	Approach

30 per cent F_{oo} Taxi/ground idle
7 per cent F_{oo}

4.1.4.3 *Fuel specifications*

The fuel used during tests shall meet the specifications of Appendix 4.

4.1.5 Test conditions

4.1.5.1 The tests shall be made with the engine on its test bed.

4.1.5.2 The engine shall be representative of the certificated configuration (*see* Appendix 6); off-take bleeds and accessory loads other than those necessary for the engine's basic operation shall not be simulated.

4.1.5.3 When test conditions differ from the reference atmospheric conditions in 4.1.4.1, EI_{mass} and EI_{num} shall be corrected to the engine combustor inlet temperature under the reference atmospheric conditions by the method given in Appendix 7.

4.1.5.4 The maximum $nvPM_{mass}$ concentration and EI_{mass} and EI_{num} shall be corrected for thermophoretic losses in the Collection Part of the sampling system by the method given in Appendix 7.

4.2 Non-Volatile Particulate Matter Emissions

4.2.1 Applicability

The provision further specified in 4.2.2 and 4.2.3 shall apply to all turbofan and turbojet engines of a type or model, and their derivative versions, with a rated thrust greater than 26.7 kN and whose date of manufacture of the individual engine is on or after 1 January 2020.

4.2.2 Regulatory Levels

The maximum $nvPM_{mass}$ concentration [µg/m^3] obtained from measurement at sufficient thrust settings, in such a way that the emission maximum can be determined, and computed in accordance with the procedures of Appendix 7 and converted to characteristic levels by the procedures of Appendix 6, or equivalent procedures as agreed by the certificating authority shall not exceed the level determined from the following formula:

$$Regulatory\ limit\ concentration\ of\ nvPM_{mass} = 10^{\left(3 + 2.9\,F_{oo}{}^{-0.274}\right)}$$

4.2.3 Reporting Requirement

The manufacturer shall report the following values of nvPM emissions measured and computed in accordance with the procedures of Appendix 7, or any equivalent procedures as agreed by the certificating authority:

a) characteristic level for the maximum $nvPM_{mass}$ concentration (µg/m^3)
b) fuel flow (kg/s) at each thrust setting of the LTO cycle
c) EI_{mass} (mg/kg of fuel) at each thrust setting of the LTO cycle
d) EI_{num} (particles/kg of fuel) at each thrust setting of the LTO cycle
e) maximum EI_{mass} (mg/kg of fuel)
f) maximum EI_{num} (particles/kg of fuel)

4.3 Information required

Note.— The information required is divided into three groups: 1) general information to identify the engine characteristics, the fuel used and the method of data analysis; 2) the data obtained from the engine test(s); and 3) the results derived from the test data.

4.3.1 General information

The following information shall be provided for each engine type for which emissions certification is sought:

a) engine identification;

b) rated output (in kN);

c) reference pressure ratio;

d) fuel specification reference;

e) fuel hydrogen/carbon ratio;

f) the methods of data acquisition;

g) the method of making corrections for thermophoretic losses in the Collection Part of the sampling system; and

h) the method of data analysis.

4.3.2 Test information

For each test the following information shall be reported:

a) net heat of combustion (MJ/kg);
b) fuel hydrogen content (mass %);
c) fuel total aromatics content (volume %);

- d) fuel naphthalenes (volume %); and
- e) fuel sulfur (mass %).

…

APPENDIX 7. INSTRUMENTATION AND MEASUREMENT TECHNIQUES FOR NON-VOLATILE PARTICULATE MATTER EMISSIONS

1. INTRODUCTION

Note.– The procedures in this appendix provide guidelines for the acquisition of representative turbine engine non-volatile particulate matter (nvPM) exhaust samples, and their transport to, and analysis by, the nvPM sampling and measurement system. The procedures do not apply to engines employing afterburning.

Any equivalent procedures to those contained in this appendix shall only be allowed after prior application to and approval by the certificating authority.

2. DEFINITIONS, ACRONYMS AND SYMBOLS

2.1 Definitions

Where the following expressions are used in this appendix, they have the meanings ascribed to them below:

Accuracy. The closeness with which a measurement approaches the true value established independently.

Aerodynamic diameter of a particle. The diameter of an equivalent sphere of unit density with the same terminal settling velocity as the particle in question, also referred to as “classical aerodynamic diameter”.

Calibration gas. A high accuracy reference gas to be used for alignment, adjustment and periodic checks of instruments.

Catalytic Stripper (CS). A catalytic device that removes volatile species through oxidation.

Competent laboratory. A testing and calibration laboratory which establishes, implements and maintains a quality system appropriate to the scope of its activities, in compliance with the International Organization for Standardization standard ISO/IEC 17025:2005, as amended from time to time, or equivalent standard and for which the programme for calibration of equipment is designed and operated so as to ensure that calibrations and measurements made by the laboratory are traceable to the International System of Units (SI). Formal accreditation of the laboratory to ISO/IEC 17025:2005 is not required.

Cyclone separator. Separation of particles larger than a prescribed aerodynamic diameter via rotational and gravitational means. The specified cut-point aerodynamic diameter is associated with the percent of particles of a particular size that penetrate through the cyclone separator.

Electrical mobility diameter of a particle. The diameter of a sphere that moves with exactly the same mobility in an electrical field as the particle in question.

Elemental carbon (EC). Light absorbing carbon that is not removed from a filter sample heated to 870°C in an inert atmosphere during TOT analysis, excluding char.

Gas concentration. The volume fraction of the component of interest in the gas mixture.

Non-Volatile Particulate Matter (nvPM). Emitted particles that exist at gas turbine engine exhaust nozzle exit plane that do not volatilise when heated to a temperature of 350°C.

Organic carbon (OC). Carbon volatilised in Helium while heating a quartz fibre filter sample to 870°C during TOT analysis. Includes char formed during pyrolysis of some materials.

Particle loss. The loss of particles during transport through a sampling system. This loss is due to various deposition mechanisms, some of which are size dependent.

Particle mass concentration. The mass of particles per unit volume of sample.

Particle mass emission index. The mass of particles emitted per unit of fuel mass used.

Particle number concentration. The number of particles per unit volume of sample.

Particle number emission index. The number of particles emitted per unit of fuel mass used.

Particle size distribution. List of values or a mathematical function that represents particle number concentration according to size.

Parts per million (ppm). The unit volume concentration of a gas per million unit volume of the gas mixture of which it is part.

Penetration fraction. The ratio of particle concentration downstream and upstream of a sampling system element.

Repeatability. The closeness with which a measurement upon a given, invariant sample can be reproduced in short-term repetitions of the measurement with no intervening instrument adjustment.

Quality system. A management system in which the competent laboratory documents its policies, systems, programmes, procedures and instructions to the extent necessary to assure the quality of the test and/or calibration results.

Resolution. The smallest change in a measurement which can be detected.

Response. The change in instrument output signal that occurs with change in sample concentration.

Rise time. The time required for the output signal to pass from 10 per cent to 90 per cent of the final change in the output signal when a reference material is abruptly applied to the automatic measuring system initially in the basic state. (This term is only applicable for an online analyser.)

Stability. The closeness with which repeated measurements upon a given invariant sample can be maintained over a given period of time.

2.2 **Acronyms**

CPC	Condensation Particle Counter
FS	Full Scale range of the analyser
GL	Gas Line
HEPA	High efficiency particle air filter, class H13, which removes at least 99.97 per cent of Dioctyl Phthalate particles (0.3 µm in diameter)
ID	Internal diameter
ISA	International Standard Atmosphere (ISO 2533:1975)
LOD	Limit of Detection
NMI	National Metrology Institute
nvPMmi	Non-volatile particulate matter mass instrument
nvPMni	Non-volatile particulate matter number instrument
nvPM	Non-volatile particulate matter (see definition)
PTFE	Polytetrafluoroethylene
slpm	Standard litres per minute (Litres per minute at STP)
STP	Instrument condition at standard temperature 0°C and pressure 101.325 kPa
TOT	Thermal-optical transmission method
VPR	Volatile Particle Remover

2.3 **Symbols**

$[CO]$	mean gas concentration of CO in exhaust sample, vol/vol, wet
$[CO_2]$	mean gas concentration of CO_2 in undiluted exhaust sample, vol/vol, wet
$[CO_2]_b$	gas concentration of CO_2 in dry air, by volume = 0.0003
$[CO_2]_{dil1}$	mean gas concentration of CO_2 vol/vol after the first dilution stage, wet
$[CO_2]_{dil2}$	mean gas concentration of CO_2 vol/vol after the second dilution stage, wet
$[CO_2]_S$	mean gas concentration of CO_2 vol/vol in undiluted exhaust as sampled, wet, semi-dry or dry

DF	Dilution Factor = (Sample concentration before dilution) / (Sample concentration after dilution) $\frac{\text{Volumeofundilutedsample}}{\text{Volumeofdilutedsample}}$
DF_1	First stage dilution factor $= \frac{[CO_2]}{[CO_2]_{dil1}}$
DF_{1_S}	First stage dilution factor calculated using directly sampled $[CO_2]_S$ and $[CO_2]_{dil1}$
DF_2	Second stage (VPR) dilution factor as per calibration by a Competent Laboratory
D_m	nvPM electrical mobility diameter
D_{xy}, at z nm	Aerodynamic diameter at which xy per cent (detection efficiency) of z size particles are detected
EI_{mass}	nvPM mass emission index corrected for thermophoretic losses, in mg/kg fuel
EI_{num}	nvPM number emission index corrected for thermophoretic losses, in number/kg fuel
[HC]	mean gas concentration of hydrocarbons in exhaust sample, vol/vol, wet, expressed as carbon
$\eta_{VPR}(D_m)$	particle penetration fraction of VPR for particles of D_m
k_{thermo}	Collection Part thermophoretic loss correction factor
[NO]	mean gas concentration of NO in exhaust sample, vol/vol, wet
$[NO_2]$	mean gas concentration of NO_2 in exhaust sample, vol/vol, wet
[NOx]	mean gas concentration of NO and NO_2 in exhaust sample, vol/vol, wet = $[NO]+[NO_2]$
M_C	Atomic mass of carbon = 12.011
M_H	Atomic mass of hydrogen = 1.008
m	number of C atoms in characteristic fuel molecule
n	number of H atoms in characteristic fuel molecule
$nvPM_{mass}$	nvPM mass concentration at instrument STP condition, corrected for dilution and thermophoretic losses in the collection section of the sampling system, µg/m^3
$nvPM_{mass\_STP}$	Diluted nvPM mass concentration at instrument STP condition, µg/m^3
$nvPM_{num\_STP}$	Diluted nvPM number concentration at instrument STP condition, number/cm^3
T_{line}	Sample line wall temperature
T_1	Diluter1 inlet wall temperature °C

T_{EGT} °C	Engine measured or performance-derived engine exhaust nozzle exit plane gas temperature
t_{90}	90 per cent response time (time between change in inlet concentration and the detector reaching 90 per cent of its final signal)
α	Atomic hydrogen-carbon ratio of the fuel = n/m, where C_mH_n is the equivalent hydrocarbon representation of the fuel used in the test and evaluated by reference to the engine fuel type analysis.

3. DATA REQUIRED

3.1 **nvPM Emissions**

3.1.1 In order to calculate the nvPM mass and number emissions, the following concentrations shall be determined:

a) nvPM Mass: $nvPM_{mass\_STP}$

b) nvPM Number: $nvPM_{num\_STP}$

c) Carbon dioxide (CO_2): $[CO_2]$, and $[CO_2]_{dil1}$

d) Carbon monoxide (CO): [CO]

e) Hydrocarbons (HC): [HC]

f) Oxides of Nitrogen (NOx): [NOx], [NO], $[NO_2]$

Note.– Guidance material on the required data is provided in the Environmental Technical Manual (Doc 9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

3.1.2 For system operability check purpose, the concentration of the following emission shall be determined:

- Carbon dioxide (CO_2): $[CO_2]_S$

3.2 **Other information**

In order to normalise the emissions measurement data and to define the engine test characteristics, additional information listed in Attachment F to Appendix 3 and Attachment D to this Appendix shall be provided.

4. GENERAL ARRANGEMENT OF THE NVPM SAMPLING AND MEASUREMENT SYSTEM

4.1 **nvPM sampling and measurement system**

4.1.1 The nvPM sampling and measurement system shall consist of three parts, divided into five sections:

a) Collection Part (Section 1)

b) Transfer Part (Sections 2, 3 and 4)

c) Measurement Part (Section 5)

Note 1.– An overview description of the nvPM sampling and measurement system is provided in Figure A7-1 and Table A7-1.

Note 2 – More detailed requirements and recommendations for each section of the system are provided in Attachments A, B, C and E to this Appendix.

4.1.2 Sections 1 to 4 shall meet the following requirements:

a) The sample lines shall be as straight-through as possible.

b) The total sample line length from probe tip to measurement instrument inlet shall not exceed 35 m. This total length is not equal to the sum of the individual sampling sections maximum allowable lengths. Detailed length requirements are provided in Attachment A to this Appendix and shown in Figure A7-1.

4.1.3 **Recommendation.–** *The following is recommended for Sections 1 to 4:*

a) *The number of fittings should be minimized and should be manufactured from stainless steel material with a smooth bore.*

b) *The number of bulkhead union fittings should be minimized and should be thermally insulated to minimize thermal gradients.*

Note. – Guidance material is provided in the Environmental Technical Manual (Doc 9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

4.1.4 Sections 2 to 4 shall meet the following requirements:

a) Any necessary sampling line bends shall have radii greater than 10 times the ID of the line.

b) There shall not be forward facing step-shoulders greater than 15 per cent of the ID.

c) Changes in sampling line ID greater than 15 per cent shall only occur at a splitter flow path interface.

d) Differences in ID of less than or equal to 15 per cent shall be considered as no change.

e) **Recommendation**.- *The following is recommended for Sections 2 to 4:*

The sampling line should be actively heated across a fitting. If not practical, the sample line should be heated as close as possible to the next heated element and thermally insulated across the fitting.

4.2 **Collection Part**

4.2.1 Section 1 is comprised of the probe/rake hardware and the connection line. It shall meet the following requirements:

a) The sampling probe material shall be stainless steel or any other non-reactive high temperature material.

b) If a sampling probe with multiple sample orifices is used, all sampling orifices shall be of equal diameter. The sampling probe design shall be such that at least 80 per cent of the pressure drop through the sampling probe assembly is taken at the orifices.

c) The number of locations sampled shall not be less than 12.

d) The sampling plane shall be as close to the engine exhaust nozzle exit plane as permitted by considerations of engine performance but in any case shall be within 0.5 nozzle diameter of the exit plane.

e) The applicant shall provide evidence to the certificating authority, by means of detailed traverses that the proposed probe design and position does provide a representative sample for each prescribed thrust setting.

Note. – Guidance material on procedures for representative measurements is provided in the Environmental Technical Manual (Doc9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

4.3 **Transfer Part**

4.3.1 At the inlet to Section 2, the Splitter1 assembly shall split the sample into the Transfer Part line, the gas line (GL) for the measurement of undiluted CO_2, CO, HC, NOx, and the excess sample line.

Note.– This arrangement also allows the GL to be used to measure Smoke Number, if required, as specified in Appendix 2.

4.3.2 The Transfer Part line shall be arranged such that the nvPM sample:

a) passes through Diluter1, an ejector-type diluter, which draws, dilutes and cools the sample;

b) passes through Section 3;

c) passes through a cyclone separator and Splitter2 in Section 4 before entering the Measurement Part in Section 5.

4.4 Measurement Part

4.4.1 nvPM Mass Measurement

The nvPMmi shall meet the requirements in Attachment B to this Appendix.

Each make and model of the nvPMmi shall receive a certificate from the instrument manufacturer or from another competent testing and calibration laboratory confirming that the make and model of the nvPMmi meets the performance specifications listed in Table A7-3 of Attachment B to this Appendix.

4.4.2 nvPM Number Measurement

The nvPM number concentration shall be determined using a system consisting of a Volatile Particle Remover (VPR) and a Condensation Particle Counter (CPC) (nvPMni) in series. The VPR includes a dilution system (DF_2) and a device for the removal of volatile species.

Each make and model of the VPR and CPC shall receive a certificate from the instrument manufacturer or from another competent testing and calibration laboratory confirming that the make and model of each device meets the performance specifications listed in Attachment C to this Appendix.

4.4.3 Make-up flow path

a) The Make-up flow path shall be used to maintain a constant sample flow rate through Section 3 and provide a diluted sample CO_2 concentration measurement.

b) The Make-up flow path shall contain a pump, flow controller, and CO_2 analyser.

c) **Recommendation.–** *A particle filter should be placed upstream of the flow controller to prevent damage to components.*

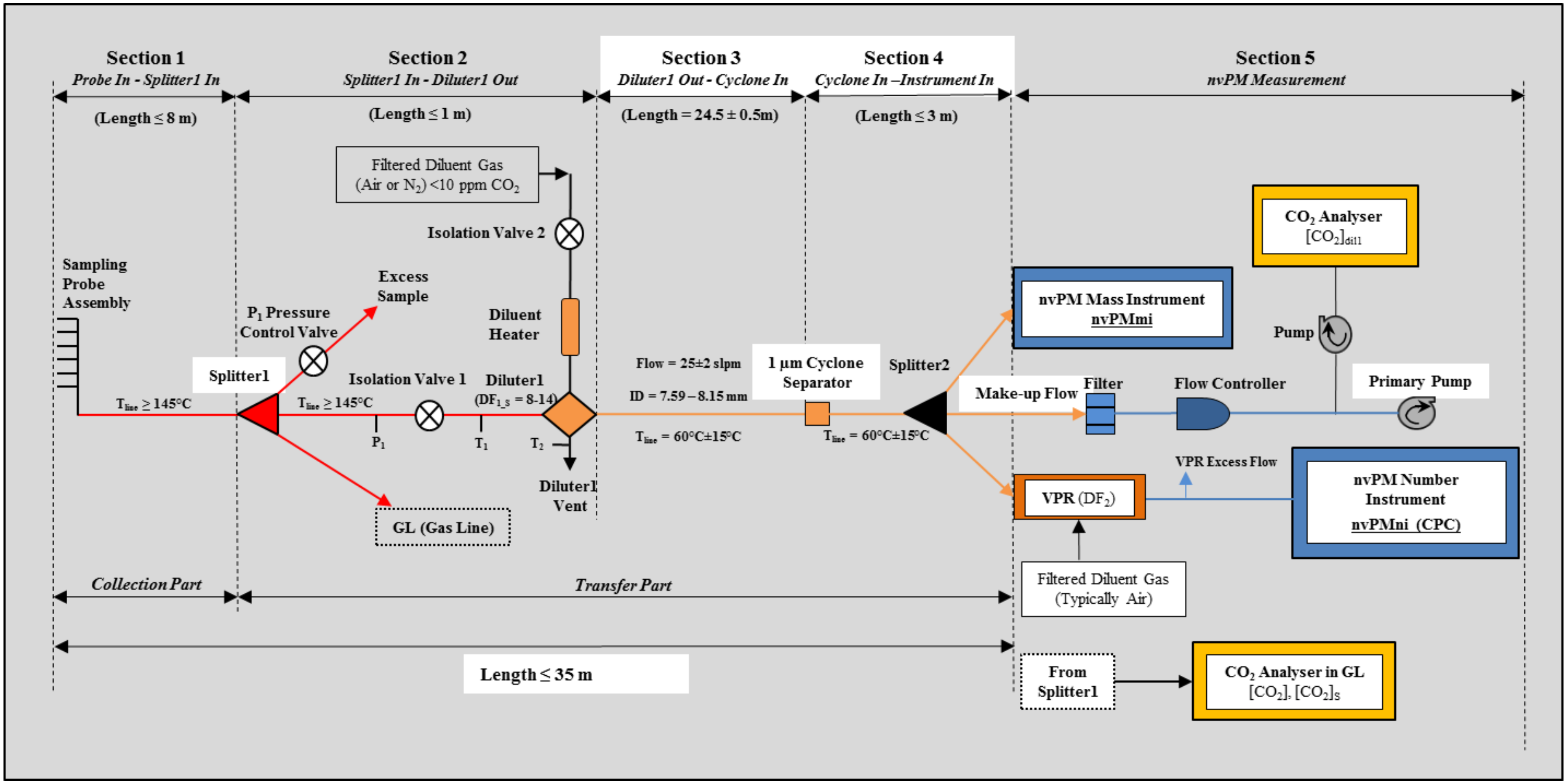

Figure A7-1. Overview schematic of an nvPM sampling and measurement system

Table A7-1. nvPM sampling and measurement system terminology overview

Terminology		Description
Section 1	**Sampling Probe Assembly**	Single or multi-point rake hardware used to obtain representative sample from aircraft engine exhaust.
	Connection Line	Length of tubing to transport sample from Probe to Splitter1 inlet.
Section 2	**Splitter1**	Flow splitter assembly to allow controlled separation of samples to both particle and gas sampling systems. Also provides a flow path (excess sample) to relieve and control sample line pressure.
	P_1 Pressure Control Valve	Valve used to control pressure at Diluter1 inlet.
	P_1	Diluter1 inlet pressure; regulated by the pressure control valve when P_1 is above ambient.
	T_1	Sample tube temperature at Diluter1 inlet needed for thermophoretic particle loss calculation in Sections 1 and 2.
	Isolation Valve 1	Allows isolation of the particle system from the GL sample and allows leakage checks of GL (including probe) and cleanliness check of Transfer Part.
	Isolation Valve 2	Diluent shut-off valve for Diluter1.
	Diluter1	Ejector-type diluter, which provides a near ambient pressure to the inlet of Section 3. Dilutes the nvPM sample early in the Transfer Part (first stage dilution, DF_1) to minimize particle coagulation and reduces sample temperature to minimize thermophoretic losses.
	Filtered Diluent Gas	Compressed gas (Nitrogen or Air) for Diluter1.
	Diluent Heater	Heats the diluent prior to entering the Diluter1. Heater temperature controlled by Diluter1vent temperature (T_2).
	Diluter1 Vent	Allows venting of excess diluted sample to atmosphere to maintain near-ambient pressure at Diluter1 exhaust and prevent over pressuring the Transfer Part.
	T_2	Temperature in vent flow to control Diluter1 outlet temperature.
GL		Gas line. Heated section to transport the exhaust sample for gaseous emissions measurement.
Section 3	**Heated sample line**	Standardised sampling section. Allows measurements at a safe distance from the engine.
Section 4	**1 µm Cyclone Separator**	Removes large particles not generated by combustion and helps to prevent instrumentation blockage.
	Splitter2	Flow splitter assembly to provide sample flow paths for nvPM mass and number concentration

		measurement and a third flow path to ensure that the total system flow rate in Section 3 is maintained.
Section 5	**Filter**	Particle filter to prevent blockage and damage to the flow controller.
	Flow Controller	Maintains constant flow rate in Section 3 by controlling make-up flow.
	Primary Pump	Provides suction for the make-up flow.
	CO_2 Analyser	Measurement of $[CO_2]_{dil1}$ in the diluted sample.
	nvPMmi	nvPM mass instrument
	VPR (DF_2)	Device that removes volatile species and dilutes further the sample (second stage dilution, DF_2) prior to the nvPMni.
	Filtered Diluent Gas	Diluent gas (Nitrogen or Air) for VPR.
	nvPMni (CPC)	nvPM number instrument that is a Condensation Particle Counter.

5. GENERAL TEST PROCEDURE

5.1 Calibration and Maintenance

5.1.1 All instruments shall be maintained conforming to the manufacturer’s guidelines.

5.1.2 The nvPM sampling and measurement system

Calibration and maintenance of the nvPM sampling and measurement system shall be performed as follows at least on an annual basis or as recommended by manufacturer:

a) The cyclone separator collection reservoir shall be emptied and cleaned.

b) Diluter1 orifice nozzle shall be cleaned.

c) Make-up flow controller and inlet flow rates for nvPMmi, nvPMni, VPR shall be calibrated by a NMI-traceable flow meter.

d) **Recommendation.–** *All calibrated flow rates should be within 5 per cent FS.*

e) Pressure transducers shall be calibrated by a NMI-traceable pressure transducer.

f) **Recommendation.–** *All calibrated pressure measurements should be within 2 per cent FS.*

5.1.3 nvPMmi

a) The nvPMmi shall be annually calibrated by a competent laboratory to meet the calibration requirements prescribed in Attachment B to this Appendix.

b) nvPMmi shall demonstrate compliance to performance specifications listed in Table A7-3 of Attachment B to this Appendix after hardware or software changes to the nvPMmi which affects data acquisition and processing.

Note. – Guidance material is provided in the Environmental Technical Manual (Doc 9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

5.1.4 VPR

a) The VPR shall be annually calibrated by a competent laboratory to meet the requirements prescribed in Attachment C to this Appendix.

b) If the VPR contains a catalytic stripper, its replacement interval shall meet the manufacturer guidelines.

5.1.5 nvPMni (CPC)

a) The nvPMni shall be annually calibrated by a competent laboratory to meet the calibration requirements prescribed in Attachment C to this Appendix.

b) The nvPMni working fluid shall be n-butanol and shall be replaced following the manufacturer guidelines.

c) nvPMni shall demonstrate compliance to performance specifications listed in Attachment C to this Appendix after any hardware or software changes to the nvPMni which affects data acquisition and processing.

Note.– Guidance material is provided in the Environmental Technical Manual (Doc 9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

5.1.6 Gas analysers

a) Calibration of the CO_2, CO, HC and NOx analysers shall follow Appendix 3 procedures.

b) The CO_2 impurity of the zero calibration gas for the CO2 analyser downstream of Diluter1 shall be less than 10 ppm.

Note.– The CO_2 impurity specification for the CO_2 analyser downstream of Diluter1is different from Attachment D to Appendix 3.

c) **Recommendation.–** *The diluent for Diluter1 should be the same as the zero calibration gas used for the CO_2 analyser.*

5.2 Engine operation

5.2.1 The engine shall be operated on a static test facility which is suitable and properly equipped for high accuracy performance testing.

5.2.2 The nvPM emissions tests shall be made at the thrust settings prescribed by the certificating authority. The engine shall be stabilised at each setting.

5.3 Carbon balance

Each test shall include a check that the air/fuel ratio as estimated from the integrated sample total carbon concentration exclusive of smoke, agrees with the estimate based on engine air/fuel ratio with an accuracy of ±15 per cent for the taxi/ground idle mode, and with an accuracy of ±10 per cent for all other modes.

Note.– Guidance material on the use of an equivalent procedure is provided in the Environmental Technical Manual (Doc 9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

5.4 Operation of nvPM Sampling and Measurement System

5.4.1 Prior to an engine test series, the following requirements shall be met:

a) Collection Part leakage and cleanliness checks shall be performed using the procedures described in Attachment E to this Appendix.

b) A VPR dilution factor (DF_2) check shall be performed as described in Attachment E.

5.4.2 The following procedure shall be adopted for gaseous measurements on the GL and downstream of Diluter1:

a) Apply appropriate zero calibration gas and make any necessary instrument adjustments.

b) Apply appropriate calibration gas at a nominal 90 per cent FS concentration to span the ranges to be used, adjust and record gain settings accordingly.

5.4.3 During an engine test series, the following requirements shall be met:

a) nvPM measurements shall only be taken after all instruments and sample transfer lines are warmed up and stable.

b) If any component or section of the nvPM sampling system is new, cleaned since last use or used previously for a purpose other than sampling engine exhaust, then the nvPM sampling system shall sample aircraft engine exhaust for a minimum of 30 minutes at any engine power condition prior to obtaining nvPM measurements.

Note. – Removal of soot blockage in the Diluter1 orifice does not constitute a cleaning process as defined in b).

c) The nvPMmi manufacturer-recommended operability checks shall be performed.

d) For nvPM number measurements, the following requirements shall be met:

   1. The VPR heated stage is at 350°C ±15°C.
   2. If a catalytic stripper is used in the VPR, the diluent shall contain at least 10 per cent of O_2.
   3. The nvPMni working fluid is at the level required by the manufacturer.

4. The nvPMni saturator and the condenser have reached correct operating temperatures.

e) The nvPMni manufacturer-recommended operability checks shall be performed.

f) A Transfer Part cleanliness check shall be performed at the beginning and end of an engine test using the procedures described in Attachment E to this Appendix.

Note. – The Transfer Part cleanliness check also serves as an operational nvPM instrumentation zero check.

g) Ambient nvPM measurements shall be performed at the beginning and end of an engine test using the procedures described in Attachment E to this Appendix.

Note. – The ambient measurement also serves as an operational nvPMni response check.

h) Gaseous analyser zero and calibration points shall be rechecked at the end of the test and also at intervals not greater than 1 hour during tests. If either has changed by more than ±2 per cent of FS range, the test shall be repeated after restoration of the instrument to within its specification.

i) **Recommendation.–** *Section 1 back-purging should occur during engine start-up and shut down.*

5.4.4 During engine nvPM measurements, the following requirements shall be met:

a) If P1 is at sub-atmospheric pressure, the P1 Pressure Control Valve shall be closed; and if installed, the optional shut-off valve shall be closed.

b) Both the GL CO_2 concentration and the CO_2 concentration downstream of Diluter1, $[CO_2]_{dil1}$, shall be continuously measured and used for validating and controlling DF_1 in real time (DF_{1_S}) to within the range 8 to 14. DF_{1_S} is defined as:

$$\mathrm{DF}_{1\_S}=\frac{[\mathrm{CO}_2]_S}{[\mathrm{CO}_2]_{dil1}}$$

Note.– The calculation of DF_{1_S} does not require the CO_2 concentration on a wet basis.

c) The sample flow rate of 25 slpm ±2 slpm in Section 3 shall be monitored by summation of the make-up flow and the inlet flow rates of the nvPMmi and the VPR.

d) When the engine operation and measured nvPM and $[CO_2]_{dil1}$ concentrations are stable at the required thrust setting, a minimum of 30 seconds of data shall be averaged and recorded.

e) If the nvPMmi lacks a sample pressure measurement, the pressure shall be measured at a location between the Splitter2 outlet and the make-up flow inlet, and recorded.

f) If the nvPMni lacks a sample pressure measurement, the pressure shall be measured at a location between the VPR outlet and nvPMni inlet, and recorded.

6. CALCULATIONS

5.5 nvPM mass concentration and nvPM mass and number emission indices equations

This procedure is used to calculate nvPM mass concentration and nvPM mass and number emission indices (EIs) from aircraft gas turbine engines burning hydrocarbon fuel in air. All equations utilise the nvPM mass concentration and nvPM number concentration at instrument STP conditions. If this is not the case, the user shall follow recommended procedures per the instrument manufacturer to correct the reported concentrations to STP conditions for the instrument.

5.5.1 nvPM mass concentration

The nvPM mass concentration ($nvPM_{mass}$) represents the mass of particles per unit volume of engine exhaust sample corrected for the first stage dilution factor (DF_1) and the Collection Part thermophoretic particle losses. It is calculated using the following equation:

$$\mathrm{nvPM}_{\mathrm{mass}} = \mathrm{DF}_1 \times \mathrm{nvPM}_{\mathrm{mass\_STP}} \times \mathrm{k}_{\mathrm{thermo}}$$

5.5.2 nvPM mass and number emission indices

The nvPM mass and nvPM number emission indices (EI_{mass} and EI_{num}) represent the mass (in milligrams) and number of engine exhaust particles per mass of fuel burned (in kilograms) corrected for their respective dilution factors and the Collection Part thermophoretic particle losses. They are calculated using the following equations:

$$\mathrm{EI}_{\mathrm{mass}} = \frac{22.4 \times \mathrm{nvPM}_{\mathrm{mass\_STP}} \times 10^{-3}}{\left([\mathrm{CO}_2]_{\mathrm{dil1}} + \frac{1}{\mathrm{DF}_1}\left([\mathrm{CO}] - [\mathrm{CO}_2]_{\mathrm{b}} + [\mathrm{HC}]\right)\right)\left(\mathrm{M}_{\mathrm{C}} + \alpha \mathrm{M}_{\mathrm{H}}\right)} \times \mathrm{k}_{\mathrm{thermo}}$$

$$\mathrm{EI}_{\mathrm{num}} = \frac{22.4 \times \mathrm{DF}_2 \times \mathrm{nvPM}_{\mathrm{num\_STP}} \times 10^{6}}{\left([\mathrm{CO}_2]_{\mathrm{dil1}} + \frac{1}{\mathrm{DF}_1}\left([\mathrm{CO}] - [\mathrm{CO}_2]_{\mathrm{b}} + [\mathrm{HC}]\right)\right)\left(\mathrm{M}_{\mathrm{C}} + \alpha \mathrm{M}_{\mathrm{H}}\right)} \times \mathrm{k}_{\mathrm{thermo}}$$

$[CO_2]$, [CO] and [HC] shall be calculated as shown in Attachment E to Appendix 3.

Note 1.– The constant 22.4 used in the EI equations above is the volume of one mole of air in litres at STP conditions rounded to one decimal place.

Note 2.– Guidance material on the use of an equivalent procedure is provided in the Environmental Technical Manual (Doc 9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

5.6 **Correction factors for nvPM emissions**

5.6.1 Correction for nvPM thermophoretic losses in the Collection Part

The correction for nvPM thermophoretic losses in the Collection Part shall be determined using:

$$k_{thermo} = \left(\frac{T_1 + 273.15}{T_{EGT} + 273.15}\right)^{-0.38}$$

If $T_{EGT} < T_1$, then $k_{thermo} = 1$

Note.– Guidance material is provided in the Environmental Technical Manual (Doc 9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

5.7 **Control parameter functions**

The EI shall be normalised to the combustor inlet temperature of the reference standard engine at ISA sea level conditions.

5.7.1 Definitions

Reference standard engine: An engine substantially configured to the production standard of the engine type, with fully representative operating and performance characteristics.

F_{oo}	Rated thrust (see Part I, Chapter 1, Definitions)
F_n	Thrust at operating mode *n* for reported nvPM emissions (kN)
W_f	Fuel mass flow rate of the reference standard engine under ISA sea level conditions (kg/s)
W_{fn}	Fuel mass flow rate of the reference standard engine under ISA sea level conditions at LTO operating mode *n*
T_B	Combustor inlet temperature

5.7.2 The nvPM mass and number emission indices (EI) shall be obtained for each LTO operating mode at T_B of the reference standard engine. A minimum of three test points shall be required to define the idle mode. For each LTO operating mode, the corresponding fuel flow under ISA conditions shall be obtained. The following relationships shall be determined under ISA reference conditions for nvPM mass and number emission indices:

a) between EI and T_B; and

b) between W_f and T_B; and

c) between F and T_B;

Note 1.— These relationships are illustrated, for example, by Figure A7-2 a), b) and c).

Note 2.— The relationships b) and c) may be established directly from engine test data, or may be derived from a validated engine performance model.

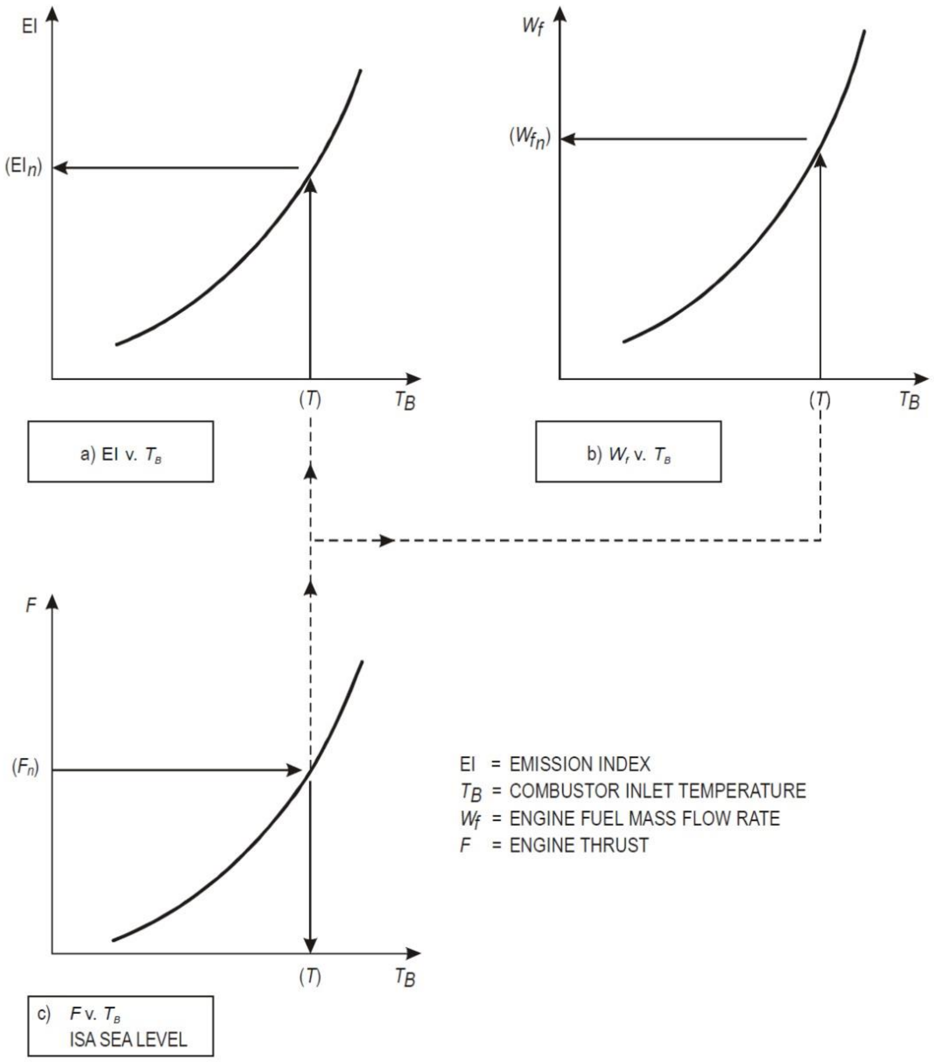

Figure A7-2. Turbine Engine nvPM EI as a function of several engine parameters

5.8 Calculation procedure

The estimation of EI (referenced to T_B) for nvPM mass and number emissions at the reported operating modes shall comply with the following general procedure:

a) determine the combustor inlet temperature (T_B) (Figure A7-2 c)) at the values of F_n corresponding to the reported operating modes, n under reference atmospheric conditions;

b) from the EI/T_B characteristic (Figure A7-2 a)), determine the EI$_n$ value corresponding to T_B;

c) from the W_f /T_B characteristic (Figure A7-2 b)), determine the W_f value corresponding to T_B;

While the methodology described above is the recommended method, the certificating authority may accept equivalent mathematical procedures which utilise mathematical expressions representing the curves illustrated if the expression have been derived using an accepted curve fitting technique.

5.9 Exceptions to the proposed procedures

In those cases where the configuration of the engine or other extenuating conditions exist which would prohibit the use of this procedure, the certificating authority, after receiving satisfactory technical evidence of equivalent results obtained by an alternative procedure, may approve an alternative procedure.

ATTACHMENT A TO APPENDIX 7. REQUIREMENTS AND RECOMMENDATIONS FOR NVPM SAMPLING SYSTEM

1. SECTION 1: PROBE INLET – SPLITTER1 INLET

1.1 Section 1 shall meet the following requirements:

a) The sample shall be transferred from the probe to Section 2 via a line of 4.0 to 8.5 mm inside diameter, taking the shortest route practicable.

b) The sampling line shall be maintained at a temperature greater than or equal to 145°C.

c) The length from probe inlet to the Splitter1 inlet shall be less than or equal to 8 m.

2. SECTION 2: SPLITTER1 INLET – DILUTER1 OUTLET

2.1 Section 2 shall meet the following requirements:

a) Section 2 shall contain Splitter1 and Diluter1.

b) The material of the sample line shall be such as to minimize build-up of particulate matter or static electricity.

Note. – Stainless steel or carbon-loaded electrically grounded polytetrafluoroethylene (PTFE) meet these requirements.

c) The length of Section 2 from the Splitter1 inlet to the Diluter1 outlet shall not exceed 1 m.

d) Section 2 shall contain Isolation Valve 1 in order to perform the leakage check on the gas line (GL).

2.2 The Splitter1 shall meet the following requirements:

a) Splitter1 shall be made of stainless steel.

b) Splitter1 body temperature shall be maintained at greater than or equal to 145 °C.

c) Splitter1 shall separate the engine exhaust sample into three flow paths.

d) The split angles relative to the incoming flow shall be as acute as practical but not exceeding 35°.

e) The nvPM sample flow path shall be as straight-through and short as practical.

f) The Splitter1 internal geometry shall meet the following requirements:

1. No forward facing step-shoulders on the inner wall
2. No change in ID from Splitter1 outlet to Diluter1 inlet
3. GL ID = 4 to 8.5 mm
4. Excess sample line internal cross sectional area shall be greater than or equal to the total inlet area of the probe tips

2.3 The Isolation Valve 1 shall meet the following requirements:

a) The Isolation Valve 1 shall be placed between Splitter1 outlet and Diluter1 inlet.

b) The Isolation Valve 1 shall be full bore with no forward facing step-shoulders greater than 15 per cent of the ID.

c) The seals of the Isolation Valve 1 shall be dry and heat resistant to 175°C.

2.4 The nvPM Section 2 line wall temperature (T1), to within 5 cm of the Diluter1 mixing plane, shall be maintained at greater than or equal to 145°C as shown in Figure A7-3.

2.5 The Diluter1 shall meet the following requirements:

a) Diluter1 shall be an ejector-type diluter.

b) ID of Diluter1 inlet shall be greater than or equal to 7.59 mm.

c) The diluent flow shall be controlled as specified by the manufacturer.

d) The real time Diluter1 dilution factor shall be controlled within the range of 8 to 14.

Note 1.– The minimum dilution factor is required to minimize nvPM coagulation, while the maximum is needed to maintain the diluted sample within the measurement range of the instruments.

Note 2.– DF_1 may be adjusted by controlling P_1 with the pressure control valve on the excess sample flow path or by adjusting the diluent gas flow.

e) The Diluter1 vent shall be open to ambient (equal to engine inlet pressure).

f) The Diluter1 body shall be heated to 60°C ±15°C as shown in Figure A7-3.

g) The diluent shall be nitrogen or air, be HEPA filtered and contain less than 10 ppm CO_2.

h) The diluent shall be heated to provide a diluted nvPM sample temperature of 60 °C ±15 °C at the Diluter1 vent (T_2).

i) The particle penetration of Diluter1 shall meet the minimum requirements as shown in Table A7-2.

j) ***Recommendation****.– To minimize impact on the operable DF1 range, the Diluter1 vent line pressure drop should be kept to a minimum, as practically possible.*

k) ***Recommendation****.– A safety feature should be implemented to prevent the diluent heater from over-heating when the diluent is not flowing.*

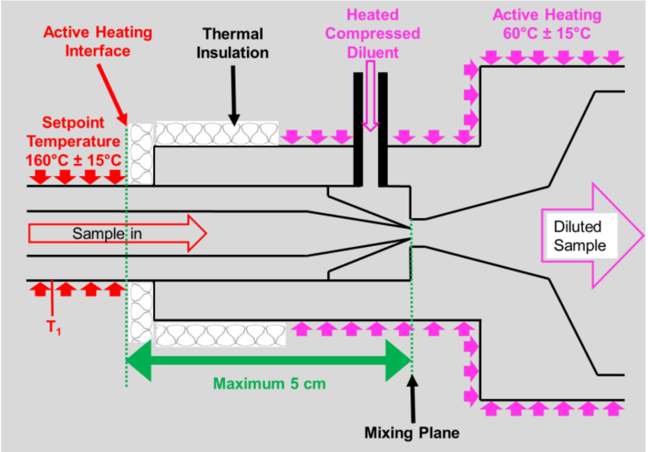

Figure A7-3. Cross section of example ejector-type Diluter1 inlet with heating interface.

Table A7-2: Minimum requirements for particle penetration fractions (transmission efficiencies) of Diluter1

Particle mobility size (diameter)	**15 nm**	**30 nm**	**50 nm**	**100 nm**
Minimum particle penetration fraction	80 per cent	90 per cent	90 per cent	90 per cent

2.6 Gas Line

2.6.1 The GL and gaseous emissions analysers shall meet the specifications in Appendix 3 and Attachments to Appendix 3.

Note.– The Collection Part (Section 1) of the nvPM sampling and measurement system meets the specifications in Appendix 3.

2.6.2 For nvPM EI determination, GL measurements of CO, HC and NOx gaseous concentrations shall be performed simultaneously.

Note.– Guidance material is provided in the Environmental Technical Manual (Doc9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

2.6.3 For determination of DF_{1_S}, a GL measurement of CO_2 concentration (dry, semi-dry or wet) shall be performed simultaneously with the nvPM measurements.

2.7 Excess sample line

2.7.1 The sample line pressure at Diluter1 inlet (P_1) shall be maintained near local ambient air pressure using a suitable Pressure Control Valve with sufficient internal area. When fully closed, the valve shall be capable of holding a vacuum pressure of -75kPa relative to ambient.

2.7.2 **Recommendation.**– *An optional shut-off valve, with sufficient internal area to avoid system backpressure, should be added downstream of the Pressure Control Valve to prevent leakage at sub-atmospheric conditions inside Splitter1.*

3. SECTION 3: DILUTER1 OUTLET – CYCLONE SEPARATOR INLET

3.1 The sampling line shall meet the following requirements:

a) The sampling line material shall be carbon-loaded electrically grounded PTFE.

b) **Recommendation**.– *The sampling line should meet the anti-static specification in ISO 8031.*

c) The sampling line ID shall be between 7.59 mm and 8.15 mm.

Note.– Accounting for manufacturing tolerances, the sampling line ID specification corresponds to commercially available line outer diameter dimensions of 3/8 inch and 7/16 inch, both with 0.035 inch wall thickness; and 10 mm with a 1 mm wall thickness.

d) The line shall be of length 24.5 m ±0.5 m, have no unnecessary fittings and consist of a maximum of three segments.

e) The coiled sample line bend radii shall be greater 0.5 m.

f) The sampling line temperature shall be maintained at 60°C ±15°C through active heating.

g) The sample flow shall be maintained at 25 slpm ±2 slpm.

4. SECTION 4: CYCLONE SEPARATOR INLET – INSTRUMENT INLET

4.1 Cyclone separator

The cyclone separator shall meet the following requirements:

a) The cyclone separator material shall be stainless steel.

b) The cyclone separator shall be heated to 60°C ±15°C.

c) The cyclone separator inlet and outlet IDs shall be less than 15 per cent difference to the inlet and outlet sample line ID.

d) The performances of the cyclone separator at a sample flow rate of 25 slpm shall meet the following specifications:

1. Cut-point: $D_{50} = 1.0\mu m \pm 0.1\ \mu m$
2. Sharpness: $(D_{16}/D_{84})^{0.5}$ less than or equal to 1.25

3. Pressure-drop: ΔP less than or equal to 2 kPa

4.2 **Splitter2**

The Splitter2 shall meet the following requirements:

a) The Splitter2 body material shall be stainless steel

b) The Splitter2 shall be heated to 60°C ±15°C.

c) The Splitter2 shall separate the sample into three flow paths to deliver the diluted nvPM sample to:

   1. nvPMmi
   2. VPR
   3. make-up flow

d) The split angles relative to the incoming flow shall be as acute as practical not exceeding 35°.

e) All nvPM flow paths shall be as straight-through and short as practical.

f) The Splitter2 geometry shall meet the following requirements:

   1. No forward facing shoulders on the inner wall
   2. No change in ID from Splitter2 outlet to nvPMmi inlet
   3. No change in ID from Splitter2 outlet to VPR inlet

4.3 Measurement system interface

The sampling lines to the nvPMmi and VPR shall meet the following requirements:

a) The sampling line material shall be of stainless steel or carbon loaded electrically grounded PTFE.

b) **Recommendation**.– *If the sampling line is carbon loaded electrically grounded PTFE, it should meet the anti-static specification in ISO 8031.*

c) The sampling line shall be heated to 60°C ±15°C.

d) No change in ID between the sampling line and the instrument inlets.

e) Each total line length from cyclone separator inlet to the inlet of the nvPMmi and VPR shall be kept as short as practical and shall not exceed 3m.

5. SECTION 5: – nvPM MEASUREMENT

5.1 Make-up flow

5.1.1 The Make-up flow path components shall meet the following requirements:

a) Primary pump and flow controller to maintain a constant total sample flow rate, (flow rate sum of Make-up flow, nvPMmi, and VPR) of 25 slpm ±2 slpm up to 10 kPa below ambient, through Section 3;

b) CO_2 analyser to measure continuously CO_2 concentration downstream of Diluter1 $[CO_2]_{dil1}$ during the nvPM measurement.

Note 1.– Depending on the sampling configuration, there may be multiple flow controllers and pumps.

Note 2.– Guidance material is provided in the Environmental Technical Manual (Doc9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

c) ***Recommendation.*** *– Particle filters should be placed upstream of flow controllers to prevent damage to components.*

5.1.2 If the nvPMmi lacks a sample pressure measurement, the pressure shall be measured at the Splitter2 outlet to the make-up flow path.

5.1.3 The CO_2 analyser shall meet the following requirements:

a) the CO_2 analyser shall be located after a flow controller;

b) the CO_2 analyser shall meet the performance specifications given in Attachment B to Appendix 3 Paragraphs "CO and CO_2 Analysers" and "CO_2 Analyser" with the exception of a).

c) ***Recommendation.****– The CO_2 analyser Total range should be approximately ten times lower than the CO_2 analyser used on the GL.*

ATTACHMENT B TO APPENDIX 7.

SPECIFICATION FOR NVPM MASS INSTRUMENT AND CALIBRATION

Note 1.– In this Attachment, elemental carbon (EC) mass is being used as a surrogate for nvPM mass. Guidance is provided in the Environmental Technical Manual (Doc9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

Note 2.– A full descriptive text for the Thermal Optical Transmittance (TOT) measurement reference method is provided in paragraph 2. This method is commonly performed by calibration laboratories; it is not expected that the aircraft engine manufacturer would perform this method.

Note 3.– The following ISO reference is used in this Attachment: International Standards Organization, Air Quality - Definition and Determination of Performance Characteristics of an Automatic Measuring System. International Standard 9169, 2006

1. SPECIFICATIONS

Each make and model of the nvPMmi shall receive a certificate from the instrument manufacturer or from another competent testing and calibration laboratory confirming that it meets the specifications:

a) shall have a measurement range of 0 µg/m3 to 1000 µg/m3 or greater;

b) shall have a resolution of 1 µg/m^3 or better;

c) shall be insensitive to volatile particulate matter;

Note 1.– Volatile particulate matter is combustion exhaust material that volatilises at temperatures less than or equal to 350°C.

Note 2.– This specification is met when the nvPMmi meets the Applicability performance specification in Table A7-3.

d) shall meet the performance specifications listed in Table A7-3.

Table A7-3 Performance specifications for nvPM mass instruments

Performance Specification	**Value (equal or less than)**	**Determination Method**
Repeatability	10 µg/m^3	ISO* 6.4.5.3
Zero drift	10 µg/m^3/hr	ISO 6.6 (for C_0 only)
Linearity	15 µg /m^3	ISO* 6.4.5.4
Limit of detection (LOD)	1 µg/m^3	ISO* 6.4.5.5
Rise time	2 seconds	ISO 6.3
Sampling interval	1 second	ISO 2.1.7

Accuracy (Agreement with EC mass concentration determined from TOT)	± 10 per cent	Slope of the linear regression between nvPMmi mass concentration and EC mass concentration determined from TOT after calibration (Table A7-5)
Applicability	±16 per cent	Validation on aircraft turbine exhaust

Note 1.– References to ISO 9169 in the table that are denoted by an asterisk refer to sections for which modifications are applied as described in Paragraph 4 to this Attachment.

Note 2.– The performance specifications reflect the limits of the quantities that can be verified using Thermal-Optical Transmittance (TOT) as the measurement reference method. The TOT method is described in paragraph 2.

Note 3.– Only the Accuracy performance specification is needed and applied in the annual calibration procedure described in paragraph 5 to this Attachment.

Note 4.– Applicability is determined following the procedure provided in Paragraph 3 to this Attachment.

2. THERMAL OPTICAL TRANSMITTANCE (TOT) METHOD

Thermal Optical Transmittance (TOT) shall be the measurement reference method to demonstrate conformity with the performance specifications of each make and model of the nvPMmi and to calibrate the nvPMmi. This method permits the determination of EC and OC in the nvPM samples.

2.1 General

2.1.1 The TOT analyser shall be either a laboratory instrument (with a Flame Ionisation Detector, FID) or semi-continuous instrument (with a Non-Dispersive Infrared detector, NDIR).

2.1.2 The TOT method shall use the temperature profile specified in Table A7-4.

Note.– Guidance material on the TOT method is provided in the Environmental Technical Manual (Doc 9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

2.2 Reagents and Materials

2.2.1 The following reagents shall be used:

a) Aqueous solutions of reagent grade (99 per cent or greater) sucrose, diluted with ultrapure H_2O Type I, or equivalent, to produce 0.1 to 3 mg C per millilitre solution;

b) He – purity 5.0 (greater than 99.999 per cent);

c) H_2 – purity 4.5 (greater than 99.995 per cent);

d) zero air (with less than 0.2 ppm hydrocarbons);

e) A certified mixture of 10 per cent O_2 in He; and

f) A certified mixture of 5 per cent CH_4 in He.

2.2.2 The following material shall be used:

a) For the laboratory instrument, a metal punch provided with the instrument for removal of 1.0 cm^2 or 1.5 cm^2 rectangular portion of filter;

b) For the semi-continuous instrument, a metal punch provided with the instrument for removal of two 2.0 cm^2 circular filters;

c) Pall Tissuquartz™ quartz fibre filters, or equivalent; and

d) Syringe of 10 microlitres

2.2.3 Filter preparation

Depending on the instrument used, the filters shall be prepared as follows:

a) For manual sampling and analysis, all quartz fibre filters shall be pre-fired in a muffle furnace at or greater than 550°C for 12 hours; or, greater than or equal to 800°C for 1 hour to 2 hours before sampling and stored in a sealed container; or

b) For the semi-continuous analyser, the filters for measurement shall be conditioned by performing at least one complete measurement cycle as described in Table A7-4.

2.3 **Sample Preparation**

2.3.1 The sample filter shall be placed on a clean aluminium foil surface.

Note.– Isopropyl alcohol or acetone can be used to clean the foil surface. In this case, allow residual solvent to vaporise from the surface prior to use. Alternatively, the foil can be cleaned by baking in a muffle furnace prior to use.

2.3.2 A representative portion of the filter shall be punched out. Good laboratory practice shall be used in filter handling.

2.4 **Calibration and Quality Control**

2.4.1 The temperature sensor controlling the oven temperature shall be calibrated using a traceable transfer standard within 1 year prior to any TOT analyses being conducted.

2.4.2 If the laboratory instrument is used, the FID response shall be calibrated. The calibration shall meet the following procedure:

a) prepare external calibration standard comprised of a sucrose solution in organic-free water;

b) disperse 10 microlitres of the solution on to punches from a new and clean pre-baked quartz filter;

c) analyse a minimum of three method blank samples and three sucrose solution samples to ensure that instrument calibration shows a percent recovery of 95 per cent to 105 per cent of the theoretical mass of C (µgC measured/µgC dispersed).

2.4.3 If the semi-continuous instrument is used, the NDIR response shall be calibrated. The calibration shall meet the following procedure:

a) prepare external calibration standard comprised of a sucrose solution in organic-free water;

b) disperse 10 microlitres of the solution on to punches from a separate pre-conditioned “boat” filter inserted into the bottom of the quartz semi- tube;

c) analyse a minimum of three method blank samples and three sucrose solution samples to ensure that instrument calibration shows a percent recovery of 95 per cent to 105 per cent of the theoretical mass of C (µgC measured/µgC dispersed).

2.4.4 If the filter analyses require more than one day, each day a single quality control check generally using the stock sucrose solution shall be dispersed to the filter and analysed accordingly. The results shall be within 95 to 105 per cent of the theoretical mass of carbon.

Note.– The method blank is a pre-fired quartz filter without addition of sucrose but handled in the same manner.

2.5 **Measurement**

The measurement shall be obtained using the following procedure:

a) The TOT analyser shall be operated in accordance with manufacturer’s recommendations.

b) Place sample portion into sample oven;

c) Determine EC and OC mass in µg;

Note.– TOT analyser results are reported in µg/cm^2 of carbon.

d) Final sample results shall always be blank-corrected:

1. For the laboratory instrument, the field blank consists of pre-fired quartz fibre filters handled in the same manner as the samples, except that no air is passed through the filter. EC mass loading per unit area greater than or equal to 0.3 µg/cm^2 in the blank samples, represents contamination.
2. For the semi-continuous analyser, a measurement of the internal filter

set shall be performed without any sample gas being passed through the filters.

e) Final sample results shall always be corrected for gas phase OC artefacts. For this correction, the operating conditions (duration and flow rate) shall be identical to those used for sample collection. Depending on the instrument used, the procedure shall be as follows:

1. For the laboratory analyses, a sampling configuration consisting of a Teflon filter followed by a pre-fired back-up quartz filter, or a pre-fired quartz filter followed by a pre-fired back-up quartz filter, shall be employed with the back-up filter analysed as prescribed in Table A7-4. Any OC found on the back-up filters shall be subtracted from the OC found on sample filters.
2. For the semi-continuous analyses, a Teflon filter shall be inserted in the sampling configuration prior to the analyser. Any OC found during this measurement shall be subtracted from the OC found during sample measurement.

2.6 Calculations

For the laboratory instrument:

a) multiply the reported EC loading result (μg/cm^2) by the filter deposit area (cm^2) to calculate total mass of EC (μg) on each filter sample (W_{EC});

b) do the same calculation as in a) for the blanks and calculate the mass found in the average blank (W_b); and

c) calculate the EC mass concentration (C_{EC}) in the air volume sampled at STP conditions, V (in m^3):

$$C_{EC} = \frac{W_{EC} - W_b}{V} \quad (\mu g/m^3)$$

Note 1.– The semi-continuous instrument provides the EC mass concentration as a reported result.

Note 2.– Guidance material on the principle of the TOT method is provided in the Environmental Technical Manual (Doc 9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

Table A7-4 Required temperature profile for the TOT method analysis cycle.

Carrier Gas	**Temperature (°C)**	**Time at Temperature (seconds)**
100 per cent He	310	80
	475	80
	615	80
	870	110
	550	45
10 per cent O_2 in He	550	45
	625	45
	700	45
	775	45
	850	45
	870	60
	930	120

5 per cent CH_4 in He	0	120

3. PROCEDURE TO DEMONSTRATE CONFORMITY TO PERFORMANCE SPECIFICATIONS

Note.– The procedure described in this paragraph is used to demonstrate the conformity to the performance specifications of each make and model of the nvPMmi.

The performance specifications listed in Table A7-3 shall be demonstrated using the TOT method as described in paragraph 2. The measurements shall be performed using the two following sources: a diffusion flame combustion aerosol source and a gas turbine engine exhaust nvPM source.

3.1 Measurement using a diffusion flame combustion aerosol source

3.1.1 The measurement system shall contain:

a) a diffusion flame combustion aerosol source

b) a dilution system using HEPA filtered diluent to control target EC mass concentrations

c) a 1 µm cut-point cyclone separator upstream of the TOT instrumentation and nvPMmi

d) a splitter assembly meeting requirements in paragraph 4.2 d) and f) of Attachment A to this Appendix

Note.– An equivalent procedure is provided in the Environmental Technical Manual (Doc 9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

e) stainless steel or anti-static tubing to connect the manual quartz filter sampler, or a semi-continuous EC/OC analyser, and the nvPMmi. All tubing shall be of the same material, length, and temperature from the split point to the instrument inlets

f) **Recommendation.-** *If anti-static tubing is used, the tubing should meet the anti-static specification in ISO 8031.*

3.1.2 Depending on the instrument used for the TOT measurement, the following requirements shall be met:

a) if manual sampling and laboratory analyser are used, one pre-fired, quartz filter in a stainless steel filter holder having a tapered inlet section with a ≤ 12.5° half-angle operated at a filter face velocity less than or equal to 0.5 m/s at actual operating conditions shall be used. The diameter of the filter deposit shall be large enough to allow at least one punch to be collected from each filter. At least one punch shall be analysed from each quartz filter sample collected; or

b) if a semi-continuous TOT analyser is used it shall be operated at a filter face velocity of less than or equal to 0.5 m/s

3.1.3 Measurements shall be made at tiered levels of target EC mass concentration specified in Table A7-5. Achieved EC mass concentrations shall be within 20 per cent of the target mass concentrations specified.

3.1.4 At each concentration tier level, samples shall be taken for a similar time period to establish a repeatable EC filter loading. The EC filter loading shall be 12 ± 5 µg/cm^2.

3.1.5 The averaging time as defined in ISO 9169 shall be the same as the filter collection time.

3.1.6 The average EC content determined by the TOT method shall be greater than or equal to 80 per cent of total carbon.

3.1.7 EC mass concentrations from the TOT method and the nvPMmi mass concentrations shall be used to determine parameters as specified in paragraph 4 to this Attachment that demonstrate conformity to the performance specifications in Table A7-3.

Table A7-5. EC mass loading parameters for calibration samples.

Target Concentration (µg/m^3)	**Approval Certificate** **No. of Tests**	**Annual Calibration** **No. of Tests**
0 (blank run)	6	3
50	6	0
100	6	3
250	0	3
500	6	3

3.1.8 ***Recommendation****.– 3 points at 50 µg/m3 for annual calibration should be tested.*

3.2 Measurement using a gas turbine engine exhaust nvPM source

3.2.1 Paragraphs 3.1.4 to 3.1.5 shall be repeated for a gas turbine engine exhaust nvPM source using the measurement system specified in paragraphs 3.1.1 c), d), e) and 3.1.2 with a dilution system using HEPA filtered diluent.

Note. – Sufficient dilution should be used to prevent water condensation in the sample line.

3.2.2 A minimum of four data points shall be obtained for a minimum of three different thrust levels with duplicate measurements made at one of the thrust levels using the nvPM sampling system specified above. The measurements shall be conducted at a minimum of three target concentrations, each at least a factor of 1.5 apart from the next, at least one concentration shall be above 120 µg/m^3, and at least one concentration shall be below 120 µg/m^3. The EC filter loading for these four data points shall be between 2.5 µg/cm^2 and 17 µg/cm^2.

3.2.3 EC mass concentrations from the TOT method and the nvPMmi mass concentrations shall be used to determine applicability as specified in Table A7-3 to demonstrate conformity to the performance specifications.

3.2.4 The engine test fuel shall be one of the aviation turbine engine fuels listed in ICAO Doc 9977, Chapter 3, Paragraph 3.2. The same fuel shall be used for the minimum four data points.

4. CALCULATION OF INSTRUMENT PERFORMANCE

4.1 The nvPMmi performance parameters zero drift, rise time and sample rate shall be determined as specified in ISO 9169, paragraphs 6.6, 6.3 and 2.1.7 respectively.

4.2 Repeatability parameter of the nvPMmi at 95 per cent confidence interval shall be determined using 6 consecutive measurements at each concentration level as:

$$s_{r_i}^2 = s_{Y_i}^2 - \Delta^2 \cdot s_{C_i}^2$$

where

$$s_{Y_i}^2 = \frac{\sum_{j=1}^{n}\left(Y_{i,j} - \bar{Y}_i\right)^2}{(n-1)}$$

s_{Ci}	the standard deviation over j of the $C_{i,j}$ for level i
$Y_{i,j}$	the result of measurement by the instrument of the reference material $C_{i,j}$
$C_{i,j}$	the j^th instance of the reference material concentration at level i
Y_i	the average over j of the $Y_{i,j}$
n	number of consecutive measurements at each concentration level (6 minimum)
Δ	the slope of the regression function applied in the lack of fit test determined from the below equations.

$$E_{i,j} = Y_{i,j} - \left(\Gamma + \Delta \times C_{i,j} \right)$$

$$E_i = \frac{\sum_{j=1}^{n} E_{i,j}}{n}$$

where

$E_{i,j}$	the difference between $C_{i,j}$, and $Y_{i,j}$
E_i	the average over j of the $E_{i,j}$
Γ	the intercept of the regression function applied in the lack of fit test

Note. – If the repeatability so determined is negative, indicating that the variance of the measurement could not be discriminated from the variability of the reference material, the test should be repeated with additional attention given to the stability of the reference material source (diffusion flame nvPM source flow and pressure settings) and the accuracy of the determination *of the reference material level (TOT method loadings and procedures). Failing this, the reproducibility can be reported as "significantly better than* $\Delta \cdot s_{C_i}^2$*."*

4.3 Linearity of the nvPMmi shall be determined as specified in ISO 9169, paragraph 6.4.5.4, however with the residual determined by the following:

$$E_i = \frac{\sum_{j=1}^{n} E_{i,j}}{n}$$

4.4 Limit of Detection of the nvPMmi shall be determined as specified in ISO 9169, paragraphs 6.4.5.5. If the instrument does not make a measurement when there are no particles in the sample, then a higher nvPM mass concentration, C_{LOD}, just above zero shall be used such that the instrument produces regular readings. The Limit of Detection in this case shall be determined as:

$$Y_{LOD,0.95} = \bar{Y}_{LOD} - C_{LOD} + 2 \times t_{v,0.95} \times s_{LOD}$$

where

$Y_{LOD,0.95}$	Limit of Detection at 95 per cent confidence interval
$\bar{Y}_{LOD}$	The average of the values $Y_{LOD,j}$
C_{LOD}	The average of the values $C_{LOD,j}$
$t_{v,0.95}$	The two sided Student's factor at 95 per cent confidence, degree $v=n-1$
s_{LOD}	The standard deviation associated with the average Y_{LOD}

Note.– The reference material may not be the same in consecutive measurements taken over the averaging time. Thus, each determination of the reference material's value may be different, albeit well known as determined by the TOT method. ISO 9169 definitions are modified to accommodate such variability.

5. CALIBRATION

5.1 The nvPMmi shall be calibrated annually using the TOT method and a system setup specified in paragraphs 3.1.1 and 3.1.2 to this Attachment.

5.2 Measurements shall be made at tiered levels of target EC mass concentration specified in Table A7-5. Achieved EC mass concentrations shall be within ±20 per cent of target mass concentrations specified.

5.3 At each concentration tier level, samples shall be taken for a similar time period to establish a repeatable EC filter loading. The EC filter loading shall be 12 ± 5 µg/cm^2.

5.4 The averaging time as defined in ISO 9169 shall be the same as the filter collection time.

5.5 EC mass concentrations from the TOT method and the nvPMmi mass concentrations shall be used to establish the best fit for the data points collected from the calibration of the instruments. A linear least squares method shall be used to determine the scale factor b to adjust the nvPM mass concentrations reported by the nvPMmi as follows:

$$b = \frac{\sum x_i y_i}{\sum x_i^2}$$

where

x_i i^{th} nvPMmi measurement

y_i i^{th} TOT EC mass concentration

b Slope of the best fit line

Note 1.– Once the b scaling factor is applied, the slope of a linear regression of the EC assays against the instrument readings adjusted by b is mathematically equal to 1.0, and the requirement on the slope in Table A7-3 will be met by definition.

Note 2.– Because of the expected uncertainties in the repeatability of the TOT EC assays a repeat of the above process at the same or at a different laboratory may produce a different slope without any change in the response of the instrument. The accuracy specifications of Table A7-3 are intended to account for such variability.

5.6 ***Recommendation.–*** *Prior to each annual calibration, the performance of each mass instrument should be assessed in the "as found" condition at an EC mass concentration of 100 µg/m^3 listed in Table A7-5. This assessment will allow traceability to prior calibrations of the instrument and allow comparison of existing and new calibration constants.*

ATTACHMENT C TO APPENDIX 7

SPECIFICATIONS AND CALIBRATION FOR THE VOLATILE PARTICLE REMOVER AND THE NVPM NUMBER INSTRUMENT

1. SPECIFICATIONS

1.1 VPR specifications

Each make and model of the VPR shall receive a certificate from the instrument manufacturer or from another competent testing and calibration laboratory confirming that it meets the performance specifications listed in the following subsections.

1.1.1 The VPR dilution factor (DF_2) shall meet the following requirements:

a) DF_2 shall be adjusted to maintain particle number concentration within CPC single count mode and to reduce sample temperature to between 10°C and 35°C at the CPC inlet.

b) DF_2 variability shall be less than 10 per cent.

1.1.2 The heated section which evaporates volatile species shall be maintained at a temperature of 350°C ±15°C

1.1.3 If the VPR contains multiple heated stages, the additional temperature controls shall be ±15°C of operating temperatures specified by the VPR manufacturer.

1.1.4 The sample pressure control shall meet the following requirements:

a) A pressure control device shall permit to deliver diluted sample to CPC within ±15 kPa of ambient (CPC exhaust) pressure.

b) The pressure shall not exceed 105 kPa.

1.1.5 The minimum allowed particle penetration fractions of the VPR for each dilution setting shall meet the specifications listed in Table A7-6.

Table A7-6: Minimum allowed penetration fractions of the VPR at four particle diameters

Electrical Mobility Particle Diameter, D_m	15 nm	30 nm	50 nm	100 nm
Minimum Penetration fraction, $\eta_{VPR}(D_m)$	0.30	0.55	0.65	0.70

1.1.6 The VPR volatile removal efficiency (VRE) shall be such that more than 99.5 per cent of tetracontane ($CH_3(CH_2)_{38}CH_3$, greater than 95 per cent purity) particles with an inlet concentration of at least 10,000 particles/cm^3 at 30 nm electrical mobility diameter are removed. This VRE shall be demonstrated when the VPR is operated at its minimum dilution setting and manufacturer's recommended operating temperature.

1.1.7 If a catalytic stripper is used in the VPR, the diluent shall contain at least 10 per cent of O_2.

1.2 VPR to CPC Interface

The tube connecting the VPR outlet to the inlet of the CPC shall meet the following requirements:

a) The material shall be electrically conductive.

b) The tube shall have an internal diameter greater than or equal to 4 mm.

c) The sample in the tube shall have a residence time less than or equal to 0.8 seconds.

1.3 CPC specifications

Each make and model of the CPC shall receive a certificate from the instrument manufacturer or from another competent testing and calibration laboratory confirming that it meets the performance specifications listed below.

1.3.1 A coincidence correction function up to a maximum of 10 per cent correction shall be allowed. The coincidence correction function shall not use any algorithm to correct for or define the counting efficiency.

1.3.2 The counting of the particles shall meet the following requirements:

a) The counting mode shall be a single count mode. CPC use in the photometric mode is not allowed. Thus, to ensure single count mode, DF_2 shall be increased as necessary.

b) The counting accuracy shall be of ±10 per cent from 2000 particles/cm^3 to the upper threshold of the single particle count mode against a traceable standard (ISO 27891).

c) The counting efficiency shall be greater than or equal to 50 per cent at 10 nm electrical mobility diameter and greater than or equal to 90 per cent at 15 nm electrical mobility diameter.

d) The counting efficiency shall be established using an Emery oil aerosol.

1.3.3 The data acquisition rate shall be greater than or equal to 1.0 Hz for a minimum interval of 30 seconds once the engine is stabilised.

1.3.4 The particle number concentration shall be reported as particles/cm^3 at STP conditions. If the reported value is not at STP conditions, the CPC absolute inlet pressure shall be measured with an accuracy better than 2 per cent so that the number concentration can be corrected to STP conditions, following manufacturer’s guidelines.

1.3.5 The resolution shall be better than 0.1 particles/cm3 at concentrations below 100 particles/cm3.

1.3.6 The rise time shall be less than 4 seconds.

1.3.7 The sample flow shall be full flow. No internal flow splitting is allowed.

1.3.8 The working fluid shall be n-butanol.

1.3.9 The response shall be linear.

1.4 **System requirement**

The t_{90} from the inlet of the VPR through the CPC shall be equal or less than 10 seconds.

2. CALIBRATION

2.1 **VPR**

Recommendation.– *Prior to each VPR calibration, the VPR should be validated “as* *found" at a single DF_2 setting, typical of that used for measurements on aircraft turbine engines. This validation should include the VPR dilution factor at the selected DF_2 setting, the determination of the penetration fractions and volatile removal efficiency.*

2.1.1 The VPR dilution factor (DF_2) calibration shall meet the following requirements:

a) The DF_2 shall be calibrated at each dilution setting of the VPR, as defined by the VPR manufacturer.

b) **Recommendation**.– *The DF_2 calibration should be performed by a competent laboratory, using either trace gases such as CO_2, or flow measurements.*

2.1.2 VPR particle penetration fractions calibration shall meet the following requirements:

a) The VPR particle penetration fractions shall be measured at 350°C with solid particles of 15 nm, 30 nm, 50 nm and 100 nm electrical mobility diameters for each dilution setting of the VPR. A minimum of 5000 particles/cm^3 across the four particle sizes shall be delivered to the VPR. If soot is used for particle generation then a thermal pre-treatment device heated to 350°C may be needed to deliver only nvPM to the VPR.

b) Particle concentrations shall be measured upstream and downstream of the VPR with a CPC that has at least 90 per cent counting efficiency for particles of an electrical mobility diameter greater than or equal to 15 nm.

c) The VPR penetration fractions shall be determined as follows:

$$\eta_{\mathrm{VPR}}(D_m) = \frac{DF_2 \times N_{out}(D_m)}{N_{in}(D_m)}$$

where

$N_{in}(D_m)$ upstream particle number concentration for particles of D_m

$N_{out}(D_m)$ downstream particle number concentration for particles of D_m

d) $N_{in}(D_m)$ and $N_{out}(D_m)$ shall be referenced to the same T and P conditions.

e) **Recommendation**.– *The VPR should be calibrated as a complete unit.*

2.1.3 VPR Volatile Removal Efficiency (VRE)

a) The VRE shall be determined with a CPC that has at least 90 per cent counting efficiency for particles of an electrical mobility diameter greater than or equal to 15 nm, as follows:

$$\mathrm{VRE}\ (D_{30})=100\times\left[1-\frac{DF_2\times N_{out}(D_{30})}{N_{in}(D_{30})}\right]$$

where

$VRE(D_{30})$	VRE for particles of D_{30}
$N_{in}(D_{30})$	upstream particle number concentration for particles of D_{30}
$N_{out}(D_{30})$	downstream particle number concentration for particles of D_{30}
D_{30}	particle electrical mobility diameter

b) $N_{in}(D_{30})$ and $N_{out}(D_{30})$ shall be referenced to the same T and P conditions.

2.2 **CPC calibration**

2.2.1 The CPC calibration shall be traceable to a standard calibration method (ISO 27891): by comparison the response of the CPC under calibration with that of a calibrated aerosol electrometer when simultaneously sampling electrostatically classified calibration particles.

2.2.2 ***Recommendation**.– Prior to each CPC calibration, the CPC should be validated (“as found”).*

2.2.3 The calibration and validation shall be performed using the procedures described below:

a) The CPC’s detection efficiency shall be calibrated with particles of 10 and 15 nm electrical mobility diameter. The CPC shall have a counting efficiency of greater than or equal to 50 per cent at 10 nm and greater than or equal to 90 per cent at 15 nm.

b) The calibration aerosol shall be Emery oil.

ATTACHMENT D TO APPENDIX 7.

SPECIFICATIONS FOR ADDITIONAL DATA

As required in 3.2 of Appendix 7, the data in Tables A7-7 and A7-8 shall be provided.

Table A7-7. Ambient nvPM Requirements

Data Required	**Units**
Ambient nvPM mass concentration ($nvPM_{mass\_STP}$)	$\mu g/m^3$
Ambient nvPM number concentration ($DF_2 \times nvPM_{num\_STP}$)	particles/cm^3

Table A7-8. nvPM Sampling System and Measurement Parameter Requirements

Parameter	**Unit**
Probe inlet temperature (T_{engine_exit}) (Equivalent to performance-predicted engine exit exhaust gas temperature T_{E}	°C
Measured Diluter1 inlet temperature (T_1)	°C
Individual flow rates (Measured Section 3 & Section 4; Practical estimation Section 1, Section 2)	slpm
Individual pipe inner diameters for Sections 1 to 4	mm
Individual lengths for Sections 1 to 4	m
Individual pipe wall temperatures for Sections 1 to 4	°C
Section 1 total angle of sampling tube bend(s)	degrees
Cyclone separator D_{50} cutpoint (Manufacturer Specification)	nm
Cyclone separator sharpness (Manufacturer Specification)	decimal
Diluter1 four penetration values (Attachment A Table A7-2)	decimal
VPR calibration four penetration values (Attachment C Table A7-6)	decimal
CPC calibration two counting efficiencies	decimal
First stage dilution factor, DF_1	
Second stage (VPR) dilution factor, DF_2	
Particle mass concentration corrected for DF_1: $DF_1 \times nvPM_{massSTP}$	$\mu g/m^3$
Particle number concentration corrected for DF_1 and DF_2:	Particles/cm^3

ATTACHMENT E TO APPENDIX 7

PROCEDURES FOR SYSTEM OPERATION

1. COLLECTION PART AND GAS LINE LEAKAGE CHECK

1.1 Leakage check procedure

Prior to an engine test series, the Collection Part and the GL shall be checked for leakage using the following procedure:

a) isolate the GL from the nvPM Measurement Part using the Isolation Valve 1, the P_1 Pressure Control Valve and, if installed, the optional shut-off valve;

b) isolate the probe and the analysers;

c) connect and operate a vacuum pump to verify the leakage flow rate.

d) The vacuum pump shall have a no-flow vacuum capability of –75 kPa with respect to atmospheric pressure; its full-flow rate shall not be less than 28 L/min at normal temperature and pressure.

1.2 Leakage check requirement

The leakage flow rate shall be less than 0.4 slpm.

2. COLLECTION PART AND GAS LINE CLEANLINESS CHECK

2.1 Cleanliness check procedure

The Collection Part and GL shall be checked for cleanliness using the following procedure:

a) isolate the GL from the nvPM Measurement Part using Isolation Valve 1 and the P_1 Pressure Control Valve;

b) isolate the GL from the probe and connect that end of the sampling line to a source of zero gas;

c) Warm the system up to the operational temperature needed to perform hydrocarbon measurements;

d) Operate the sample flow pump and set the flow rate to that used during engine emission testing;

e) Record the hydrocarbon analyser reading.

2.2 Cleanliness check requirement

2.2.4 The hydrocarbon reading shall not exceed 1 per cent of the engine idle emission level or 1 ppm (both expressed as carbon), whichever is the greater.

2.2.5 ***Recommendation.****– It is recommended to monitor the inlet air quality at the start and end of an engine test and at least once per hour during a test. If HC levels are considered significant, then they should be taken into account.*

3. TRANSFER PART CLEANLINESS/LEAKAGE CHECK

Cleanliness checks can fail due to contaminated Transfer Part components or leaks in the Transfer and/or Measurement Parts.

Note.– A system leakage will result in ambient air particles drawn into the system.

3.1 Cleanliness/leakage check procedure

Prior to an engine test series, the Transfer Part shall be checked for cleanliness and leaks using the following procedure:

a) flow filtered diluent through Diluter1 with the Isolation Valve 1 closed;

b) the flow rates in each Splitter2 path shall be equal to those used during engine testing.

c) Set the DF_2 to the lowest setting of the VPR.

When the measured nvPM mass and number concentrations are stable, record data for a minimum of 30 seconds.

Note. – The flow schematic for the Transfer Part cleanliness check is shown in Figure A7-4

3.2 Cleanliness/leakage check requirement

3.2.1 The 30 seconds averaged nvPM mass concentration (nvPMmass_STP) shall be less than 1 µg/m3.

3.2.2 The 30 seconds averaged nvPM number concentration ($nvPM_{num\_STP}$) shall be less than 2.0 particles/cm^3.

3.2.3 **Recommendation.** – *If the cleanliness check fails, the system should be first inspected for leakage. If no leaks are detected, the cyclone separator collection reservoir should be inspected and cleaned. If the cleanliness check still fails, segments of the sampling system may need cleaning or replacement.*

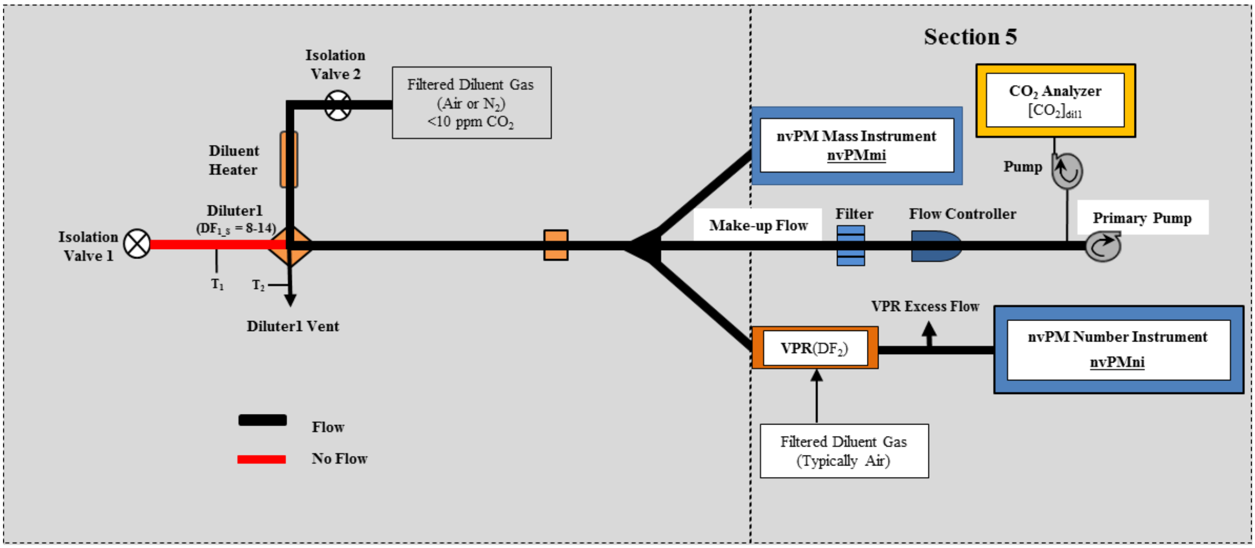

Figure A7-4. Flow schematic for the Transfer Part cleanliness check

4. COLLECTION PART BACK-PURGING

In order to maintain the Section 1 sampling probes and lines clear of unburned fuel, Section 1 shall be back-purged during engine start-up and shutdown as depicted in Figure A7-5.

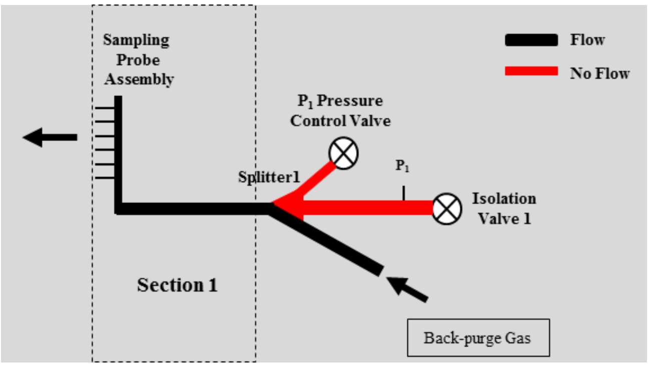

Figure A7-5. Flow schematic for Section 1 back-purge

5. AMBIENT nvPM MEASUREMENT

5.1 General

5.1.1 Ambient nvPM mass and number concentrations representative of engine air inlet shall be obtained before and after an engine test and reported as the average of these two measurements.

5.1.2 **Recommendation. –** *For an enclosed test cell, to achieve representativeness, it is recommended that the ambient particle measurements are obtained while the engine is running, The first ambient measurement should be obtained a minimum of five minutes after engine start-up.*

5.2 Ambient nvPM sampling procedure

The ambient nvPM mass and number concentrations representative of engine air inlet shall be sampled by either:

5.2.1 Method 1 - sampling through Diluter1 vent.

The nvPM Sampling and Measurement system shall be used to sample through Diluter1 vent.

When sampling through the Diluter1 vent the following procedure shall be used:

a) Turn off the diluent flow supply to Diluter1 by closing Isolation Valve 2 and ensure that the Isolation Valve 1 is closed;

b) ***Recommendation.****– The diluent heater should be protected from overheating when the diluent flow is turned off*

c) Ensure flow rates in each Splitter2 flow path are equal to those to be used during engine testing;

d) When the measured nvPM mass and number concentrations are stable, record data for a minimum of three minutes.

Note.– The flow schematic for the method 1 ambient nvPM measurement in shown in Figure A7-6.

This setup shall only be used if the vent exhaust location is representative of engine inlet air.

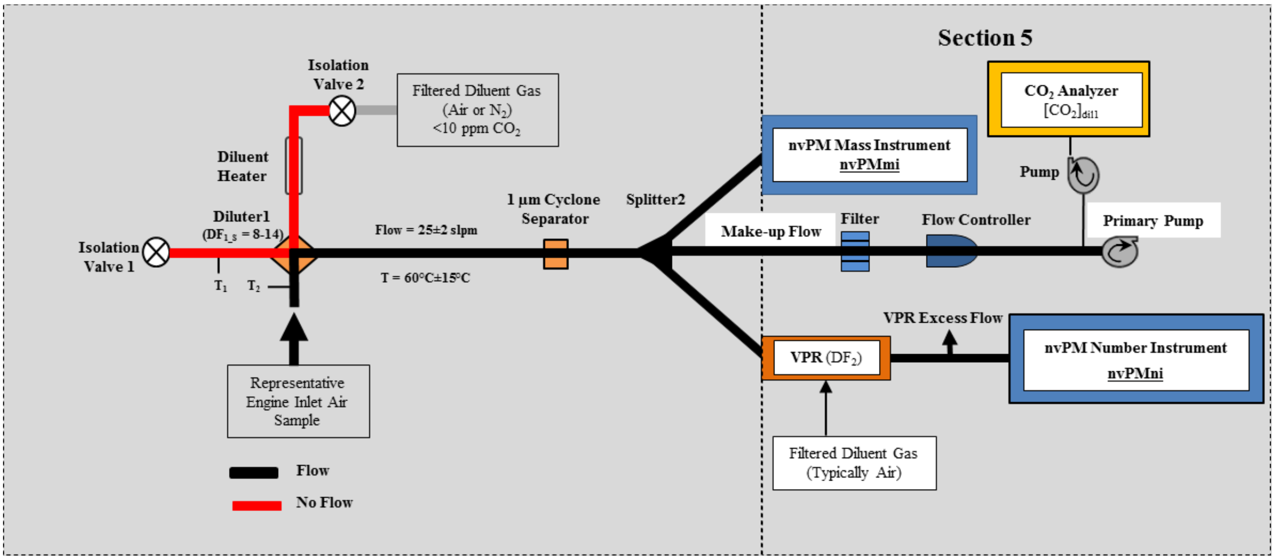

Figure A7-6. Flow schematic for ambient particle air measurement

5.2.2 Method 2 – an additional nvPM measurement system

5.2.2.1 An additional ambient nvPM sampling and measurement system shall meet the following requirements:

a) The ambient nvPM sampling system shall conform to Section 3 and Section 4 sampling system requirements in Attachment A to this Appendix.

b) The nvPMmi, VPR and nvPMni shall comply with Attachments B and Attachment C to this Appendix.

c) The ambient nvPM sampling system inlet shall be located within 50 m of the engine intake plane.

5.2.2.2 When sampling with an additional nvPM sampling and measurement system, the following procedure shall be used:

a) Ensure flow rates in each Splitter2 path are equal to those to be used during engine testing.

b) When the measured nvPM mass and number concentrations are stable, record data for a minimum of three minutes.

5.3 **Ambient particle measurement requirement**

5.3.1 The three minutes averaged nvPM mass concentration ($nvPM_{mass\_STP}$) and nvPM number concentration corrected for DF_2 ($DF_2 \times nvPM_{num\_STP}$) shall be reported.

Note.– The ambient level of nvPM mass concentration may be below the LOD of the nvPMmi.

5.3.2 **Recommendation.** – *The average nvPMni concentration value corrected for DF_2 should be greater than 10 times the value measured for the cleanliness check. If this check fails,* *the system operation should be verified (valve positions, flow rates, pressures and temperatures) and the measurement should be repeated.*

5.3.3 ***Recommendation.*** *– If ambient nvPM levels are considered significant, then they should be taken into account.*

6. VPR DILUTION FACTOR CALIBRATION CHECK

6.1 The VPR dilution factors (DF_2), anticipated during the engine test, shall be checked using the following setup:

a) a CO_2 gas analyser compliant with attachment B to Appendix 3;

b) a certified, high concentration CO_2 gas with purity 2.0 (greater than 99.0 per cent) CO_2;

Note.– Guidance material is provided in the Environmental Technical Manual (Doc9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

c) connect the CO_2 gas analyser to the outlet of the VPR with a tee fitting to prevent over pressurisation of CO_2 sample;
d) connect the high concentration CO_2 gas to the inlet of the VPR using a tee fitting and flow control valve to provide a VPR inlet pressure as on engine test;
e) allow the sample at the inlet of the VPR to have the same flow rate, and pressure as used during an engine test.

Note.– The flow schematic for the VPR dilution factor check is shown in Figure A7-7.

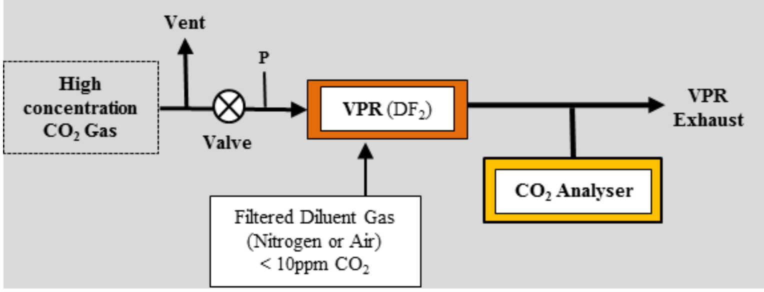

Figure A7-7. VPR Dilution Factor Check Setup

6.2 The VPR dilution factor (DF2) shall be checked using the following procedure:

a) warm-up the VPR and ensure operating temperatures are reached;
b) check that the VPR inlet is pulling a sample flow.
c) warm-up the CO_2 analyser accordingly and prepare for data logging.
d) apply appropriate zero calibration gas to the CO_2 analyser and make any necessary instrument adjustments.
e) apply appropriate calibration gas at a nominal 90 per cent FS concentration to the

CO_2 analyser to span the ranges to be used, adjust and record gain settings accordingly.

f) ensure the sample flow to the CO_2 analyser is adequate (a pump may be required upstream of the CO_2 analyser).

g) flow the high concentration CO_2 gas to the inlet of the VPR, ensuring that there is excess flow at the vent upstream of the VPR inlet.

h) set the VPR to a dilution factor setting.

i) adjust the flow control valve at the VPR inlet, creating a pressure drop to simulate the

sub-ambient sample pressure at the VPR inlet during an engine test nvPMni measurement operation.

j) sample the VPR exhaust flow with the CO_2 gas analyser.

k) when the CO_2 gas analyser reading is stable, record a minimum of seven CO_2 concentration data points within a 3 minute period and calculate the mean.

l) Calculate the mean DF_2 value as a ratio of the mean of CO_2 measurements and the certified CO_2 gas concentration.

m) repeat paragraph 6.2, h) to 6.2, l) to this attachment for each VPR dilution setting to be used during engine testing.

6.3 Calculated DF_2 mean values shall be compared against the results of a Competent Laboratory calibration. If the difference is:

a) less than or equal to ±10 per cent, DF2 values from a Competent Laboratory calibration shall be used.

b) greater than ±10 per cent, the VPR DF2 values shall be re-determined from calibration by a Competent Laboratory.

Note.– Guidance material on the use of an equivalent procedure is provided in the Environmental Technical Manual (Doc 9501), Volume II – Procedures for the Emissions Certification of Aircraft Engines.

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PART IV. NON-VOLATILE PARTICULATE MATTER ASSESSMENT FOR INVENTORY AND MODELLING PURPOSES

Note 1.– The purpose of Part IV is to provide recommendations on how to calculate the nvPM mass and number correction factors for the nvPM system losses other than the Collection Part thermophoretic losses. The nvPM system, the Collection Part and the thermophoretic losses calculation are described in Appendix 7.

Note 2.– The nvPM mass and number system loss correction factors permit an estimation of the concentration of the nvPM mass and number at the exhaust of the aircraft engine from the nvPM mass and number concentration obtained following the procedures described in Appendix 7.

Recommendation 1.– *For inventory and modelling purposes, the aircraft turbine engine manufacturers should determine the nvPM mass and nvPM number system loss correction factors* (k_{SL_mass} *and* k_{SL_num}) *using the methodology described in Appendix 8 and should report these factors to the appropriate authority.*

Recommendation 2.– *For inventory and modelling purposes, the nvPM mass and number concentration obtained following the procedures described in Appendix 7 should be corrected for system losses using the methodology described in Appendix 8.*

APPENDIX 8. PROCEDURES FOR ESTIMATING nvPM SYSTEM LOSS CORRECTIONS

Note 1.– The procedures specified in this Appendix are concerned with the determination of nvPM sampling and measurement system loss correction factors, excluding the Collection Part thermophoretic losses which are included in Appendix 7 data reporting.

Note 2.– Implementation of the nvPM sampling and measurement system requires a long sample line of up to 35m and includes several sampling and measurement system components, which can result in significant particle loss on the order of 50% for nvPM mass and 90% for nvPM number. The particle losses are size dependent and hence are dependent on engine operating condition, combustor technology and possibly other factors. The procedures specified in this Appendix allow for an estimation of the particle losses.

Note 3.– The system loss correction factors are estimated based on the following assumptions: engine exhaust exit plane nvPM have a lognormal distribution, a constant value of nvPM effective density, a fixed value of geometric standard deviation, limiting the nvPM mass concentration to limit of detection, a minimum particle size cut-off of 0.01µm and no coagulation.

Note 4.– The method proposed in this Appendix uses data and measurements as specified in Appendix 7 and Attachments to Appendix 7. Symbols and definitions not defined in this Appendix are defined in Appendix 7 and Attachments.

1. **GENERAL**

1.1 Within the nvPM sampling and measurement system, particles are lost to the sampling system walls by deposition mechanisms. These losses are both size dependent and independent. The size independent Collection Part thermophoretic loss is specified in Appendix 7 paragraph 6.2.1.

1.2 The overall nvPM sampling and measurement system particle loss excluding the Collection Part thermophoretic loss is referred to as system loss.

1.3 The nvPM size distribution needs to be taken into consideration because the loss mechanisms are particle size dependent. These particle size dependent losses are quantified in terms of the fraction of particles of a given size that penetrate through the sampling system.

2. DEFINITIONS, ACRONYMS, AND SYMBOLS

2.1 Definitions

Where the following expressions are used in this appendix, they have the meanings ascribed to them below:

Aerodynamic diameter of a particle. The diameter of an equivalent sphere of unit density with the same terminal settling velocity as the particle in question, also referred to as "classical aerodynamic diameter".

Competent laboratory. A testing and calibration laboratory which establishes, implements and maintains a quality system appropriate to the scope of its activities, in compliance with the International Organization for Standardization standard ISO/IEC 17025:2005, as amended from time to time, or equivalent standard and for which the programme for calibration of equipment is designed and operated so as to ensure that calibrations and measurements made by the laboratory are traceable to the International System of Units (SI). Formal accreditation of the laboratory to ISO/IEC 17025:2005 is not required.

Cyclone separator. Separation of particles larger than a prescribed aerodynamic diameter via rotational and gravitational means. The specified cut-point aerodynamic diameter is associated to the percent of particles that penetrate through the cyclone separator.

Electrical mobility diameter of a particle. The diameter of a sphere that moves with exactly the same mobility in an electrical field as the particle in question.

Non-Volatile Particulate Matter (nvPM). Emitted particles that exist at gas turbine engine exhaust nozzle exit plane that do not volatilise when heated to a temperature of 350°C.

Particle loss. The loss of particles during transport through a sampling system. This loss is due to various deposition mechanisms, some of which are size dependent.

Particle mass concentration. The mass of particles per unit volume of sample.

Particle mass emission index. The mass of particles emitted per unit of fuel mass used.

Particle number concentration. The number of particles per unit volume of sample.

Particle number emission index. The number of particles emitted per unit of fuel mass used.

Particle size distribution. List of values or a mathematical function that represents particle number concentration according to size.

Penetration fraction. The ratio of particle concentration downstream and upstream of a sampling system element.

2.2 Acronyms

CPC	Condensation Particle Counter
nvPMmi	Non-volatile particulate matter mass instrument
nvPMni	Non-volatile particulate matter number instrument

nvPM	Non-volatile particulate matter (see definition)
slpm	Standard litres per minute (Litres per minute at STP)
STP	Instrument condition at standard temperature 0°C and pressure 101.325 kPa
VPR	Volatile Particle Remover

2.3 **Symbols**

C_c	$1+\frac{2\lambda}{D_m}\times(1.165+0.483\times e^{-\frac{0.997D_m}{2\lambda}})$, the dimensionless Cunningham slip correction factor
DF1	first stage dilution factor
DF2	second stage (VPR) dilution factor as per calibration
D	$\frac{k_B\times(273.15+T_i)\times C_c}{3\times\pi\times\mu\times D_m\times10^{-4}}$, the particle diffusion coefficient, cm^2/s
D_m	nvPM electric mobility diameter, µm
D_{mg}	geometric mean diameter, µm
δ	the sum of the square of relative differences between measured and calculated dilution corrected mass and number concentrations
EI_{mass}	nvPM mass emission index corrected for thermophoretic losses, in mg/kg fuel
EI_{num}	nvPM number emission index corrected for thermophoretic losses, in number/kg fuel
ε	convergence criterion (1×10^{-9})
$f_{lgn}(D_m)$	the lognormal distribution function with parameters of geometric standard deviation, σ_g, and geometric mean diameter, D_{mg},
$f_N(D_m)$	the engine exhaust nozzle exit plane particle number lognormal distribution function
ID_{ti}	Inner diameter of the ith segment of the sampling line, mm
k_B	1.3806×10^{-16} $(g\cdot cm^2)/(s^2\cdot K)$
k_{SL_mass}	EImass correction factor for system losses without Collection Part thermophoretic loss correction, µg/m3
k_{SL_num}	EInum correction factor for system losses without Collection Part thermophoretic loss corection, number/cm^3

k_{thermo}	Collection Part thermophoretic loss correction factor, specified in Appendix 7, paragraph 6.2.1
λ	$67.3 \times 10^{-3} \times \left(\frac{273.15+T_i}{296.15}\right) \times \left(\frac{101.325}{P_i}\right) \times \left(\frac{406.55}{T_i+383.55}\right)$, the carrier gas mean free path, µm
$nvPM_{mass\_EST}$	estimated undiluted (i.e., corrected for dilution) instrument mass concentration, µg/m3
$nvPM_{num\_EST}$	estimated undiluted (i.e., corrected for dilution) instrument number concentration, number/cm3
$nvPM_{mass\_EP}$	Estimated engine exhaust nozzle exit plane nvPM mass concentration, specified in Paragraph 4 to this Appendix, not corrected for Collection Part thermophoretic losses.
$nvPM_{num\_EP}$	Estimated engine exhaust nozzle exit plane nvPM number concentration, specified in Paragraph 4 to this Appendix, not corrected for Collection Part thermophoretic losses.
$nvPM_{mass\_STP}$	diluted nvPM mass concentration at instrument STP condition, µg/m^3
$nvPM_{num\_STP}$	diluted nvPM number concentration at instrument STP condition, number/cm^3
ηmass(Dm)	the overall sampling and measurement system penetration fraction for the nvPMmi without Collection Part thermophoretic losses at electrical mobility particle size Dm
ηnum(Dm)	the overall sampling and measurement system penetration fraction for the nvPMni without Collection Part thermophoretic losses at electrical mobility particle size Dm
ηi(Dm)	Penetration fraction for the ith component of the sampling and measurement system
ηbi(Dm)	Penetration fraction for the sampling line bend for ith component of the sampling and measurement system
ρ	the assumed nvPM effective density, g/cm^3
σ_g	the assumed geometric standard deviation of lognormal distribution
Q_i	the carrier gas flow in the ith segment of the sampling line, slpm
Re	$\frac{2\times\rho_{gas}\times Q_i}{3\times\pi\times\mu\times ID_{ti}}$, the carrier gas Reynolds number
T_i	the carrier gas temperature in the ith segment of the sampling line, °C,

3. CORRECTION FACTORS FOR NVPM MASS AND NUMBER EIs

The EI_{mass} correction factor for system losses is the ratio between estimated engine exhaust nozzle exit plane mass concentration without Collection Part thermophoretic loss correction and measured mass concentration and should be calculated as follows:

$$k_{SL\_mass} = \frac{nvPM_{mass\_EP}}{DF_1 \times nvPM_{mass\_STP}}$$

The EI_{num} correction factor for system losses is the ratio between estimated engine exhaust nozzle exit plane number concentration without Collection Part thermophoretic loss correction and measured number concentration and should be calculated as follows:

$$k_{SL\_num} = \frac{nvPM_{num\_EP}}{DF_1 \times DF_2 \times nvPM_{num\_STP}}$$

4. PROCEDURE TO ESTIMATE ENGINE EXHAUST NOZZLE EXIT PLANE MASS AND NUMBER CONCENTRATIONS CORRECTED FOR SYSTEM LOSSES

The engine exhaust nozzle exit plane mass ($nvPM_{mass\_EP}$) and number ($nvPM_{num\_EP}$) should be determined using the following procedure:

a) For a measured $nvPM_{num\_STP}$, begin with an initial value of $nvPM_{num\_EP} = 3 \times DF_1 \times DF_2 \times nvPM_{num\_STP}$.

b) An initial value of 0.02µm should be assumed for the geometric mean diameter, D_{mg}, of the log normal particle size distribution.

c) Starting with initial assumed values of $nvPM_{num\_EP}$ and D_{mg} from a) and b) estimate the nvPM mass ($nvPM_{mass\_EST}$) and number ($nvPM_{num\_EST}$) concentrations using the following equations:

$$nvPM_{mass\_EST} = \sum_{D_m=0.01\mu m}^{1\mu m} \eta_{mass}(\mathrm{D_m}) \times \frac{\rho\pi \mathrm{D_m^3}}{6} \times nvPM_{num\_EP} \times f_{lgn}(\mathrm{D_m}) \times \Delta\ln(\mathrm{D_m})$$

$$nvPM_{num\_EST} = \sum_{D_m=0.01\mu m}^{1\mu m} \eta_{num}(\mathrm{D_m}) \times nvPM_{num\_EP} \times f_{lgn}(\mathrm{D_m}) \times \Delta\ln(\mathrm{D_m})$$

where

$$f_{lgn}(D_m) = \frac{1}{\sqrt{2\pi}\,\ln(\sigma_g)} \times e^{-\frac{1}{2}\left\{\frac{\ln(D_m)-\ln(D_{mg})}{\ln(\sigma_g)}\right\}^2}$$

$\Delta\ln(D_m)$ $= \frac{1}{n} \times \frac{1}{log_{10}(e)}$, is the width of a size bin in base natural logarithm; *e* is the Euler's number, and n is the number of particle size bins per decade

d) Determine the difference, δ, between $nvPM_{num\_STP}$, $nvPM_{mass\_STP}$ and the estimates of the nvPM number concentration ($nvPM_{num\_EST}$) and the nvPM mass concentration ($nvPM_{mass\_EST}$) from the initial engine exhaust nozzle exit plane values using the equation:

$$\delta = \left(\frac{DF_1 \times DF_2 \times nvPM_{num\_STP} - nvPM_{num\_EST}}{DF_1 \times DF_2 \times nvPM_{num\_STP}}\right)^2 + \left(\frac{DF_1 \times nvPM_{mass\_STP} - nvPM_{mass\_EST}}{DF_1 \times nvPM_{mass\_STP}}\right)^2$$

e) Repeat steps c) through d) varying $nvPM_{num\_EP}$ and D_{mg} until δ reduces to less than 1×10^{-9}.

f) Once δ is reduced to less than 1×10^{-9}, the final values of $nvPM_{num\_EP}$ and D_{mg} are those associated with this minimised value of δ

g) Using $nvPM_{num\_EP}$ and D_{mg} from step f), $nvPM_{mass\_EP}$ should be determined using the following expression:

$$\mathrm{nvPM}_{\mathrm{mass\_EP}} = \sum_{D_m=0.01\mu m}^{1\mu m} \frac{\rho\pi \mathrm{D}_{\mathrm{m}}^3}{6} \times \mathrm{nvPM}_{\mathrm{num\_EP}} \times f_{lgn}(\mathrm{D_m}) \times \Delta\ln(\mathrm{D_m})$$

h) ***Recommendation.****– A total of 80 discrete sizes in the particle size range from 0.003 µm to 1 µm should be used in this calculation. In this case the number of size bins per decade, n, is 32 (see the definition for Δln(Dm) above). The sums in the above equations start at 0.01 µm.*

i) ***Recommendation****.– The nvPM effective density should be a constant and equal to 1 g/cm*^{3} *across all particle sizes*

j) ***Recommendation****. – The geometric standard deviation of the lognormal particle number distribution should be equal to 1.8.*

Note 1. – The flow chart shown in figure A8-1 describes this procedure pictorially.

Note 2. – If $nvPM_{mass\_STP}$ *is less than 1 µg/m*^{3}*, a minimum value of 1 µg/m*^{3} *should be used for the procedure to converge.*

Note 3.– The procedure outlined in paragraph 3 is solvable using commercially available software programs.

Note 4.– The units for D_m are in µm *which is different from tabulated values given in Appendix 7.*

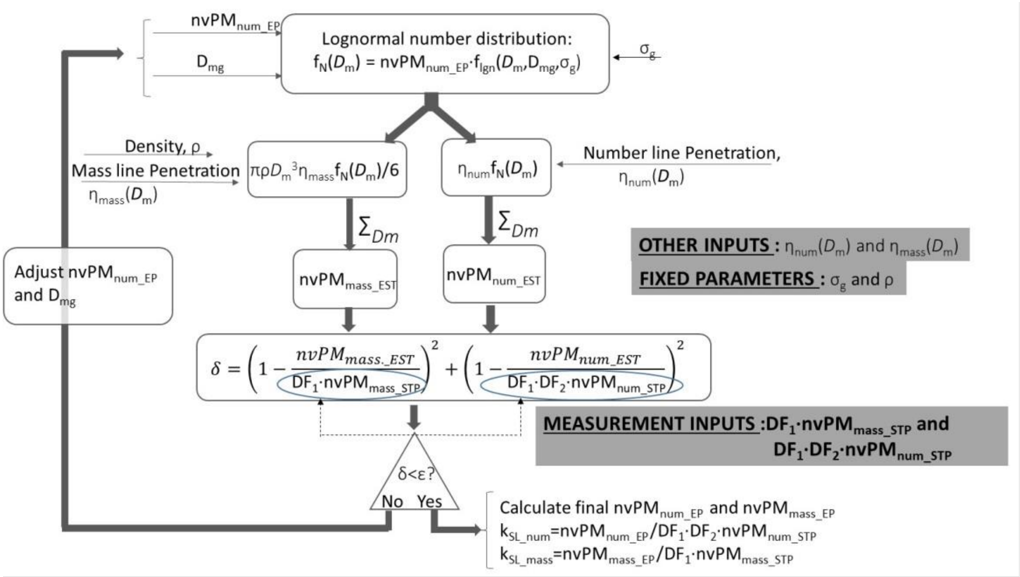

Figure A8-1. Iterative method for calculation of nvPM mass and number corrected for losses other than Collection Part thermophoresis

5. OVERALL SYSTEM PENETRATION FRACTIONS

Note 1.– The particle penetration fractions are different between the nvPM mass concentration measurement and nvPM number concentration measurement because of the difference in sample flow paths after Splitter2.

Note 2.– Penetration fractions may change between different engine condition measurement points because of changing particle size distribution.

Note 3.– Where continuous functions are calculated to estimate penetration fractions or CPC counting efficiency, care should be taken such that they do not go below zero.

Table A8-1. Required nvPM Sampling and Measurement system component penetration fractions

Parameter symbol	Description
$\eta_1(D_m)$	Section 1 – Probe inlet to Splitter1
$\eta_{b1}(D_m)$	Section 1 - Probe inlet to Splitter1 for bends
$\eta_2(D_m)$	Section 2 – Splitter1 to Diluter1 inlet
$\eta_{b2}(D_m)$	Section 2 – Splitter1 to Diluter1 inlet for sampling line bends

$\eta_{dil}(D_m)$	Section 2 – Diluter1
$\eta_3(D_m)$	Section 3 – Diluter1 outlet to Cyclone Separator inlet
$\eta_{b3}(D_m)$	Section 3 – Diluter1 outlet to Cyclone Separator inlet for sampling line bends
$\eta_{cyc}(D_m)$	Cyclone Separator
$\eta_4(D_m)$	Section 4 - Cyclone Separator outlet to Splitter2
$\eta_{b4}(D_m)$	Section 4 - Cyclone Separator outlet to Splitter2 for sampling line bends
$\eta_5(D_m)$	Section 4 – Splitter2 to nvPMmi
$\eta_{b5}(D_m)$	Section 4 – Splitter2 to nvPMmi for sampling line bends
η_{th_m}	Section 5 – Due to thermophoretic loss at the nvPMmi inlet
$\eta_6(D_m)$	Section 4 – Splitter2 to VPR
$\eta_{b6}(D_m)$	Section 4 – Splitter2 to VPR for sampling line bends
$\eta_{VPR}(D_m)$	Section 5 – VPR
$\eta_{CPC}(D_m)$	Section 5 – nvPMni (CPC) counting efficiency
η_{th_n}	Section 5 – Due to thermophoretic loss at the nvPMni inlet

5.1 System Penetration Fraction for nvPM mass

The overall penetration fraction for the nvPM mass, for 80 discrete particle sizes (D_m) in the range from 0.003µm to 1µm, should be calculated by combining system component penetration fractions:

$$\eta_{mass}(D_m) = \eta_1 \times \eta_{b1} \times \eta_2 \times \eta_{b2} \times \eta_3 \times \eta_{b3} \times \eta_{cyc} \times \eta_4 \times \eta_{b4} \times \eta_5 \times \eta_{b5} \times \eta_{th\_m}$$

Where η with subscripts refer to penetration fractions of individual components of the nvPM sampling and measurement system defined in Table A8-1. Procedures to estimate the individual component penetration fractions are defined in Paragraph 6 to this Appendix.

Note.– Depending on the precise geometry of the nvPM sampling system, there can be more individually described components of the nvPM sampling and measurement system than described in Table A8-1.

5.2 System Penetration Fraction for nvPM number

The overall penetration fraction for the nvPM number, for 80 discrete particle sizes (D_m) in the range from 0.003 µm to 1 µm, should be calculated by combining system component penetration fractions:

$$\eta_{num}(\mathrm{D_m}) = \eta_1 \times \eta_{b1} \times \eta_2 \times \eta_{b2} \times \eta_3 \times \eta_{b3} \times \eta_{cyc} \times \eta_4 \times \eta_{b4} \times \eta_6 \times \eta_{b6} \times \eta_{VPR} \times \eta_{CPC} \times \eta_{th\_n}$$

where η with subscripts refer to penetration fractions of individual components of the nvPM sampling and measurement system defined in Table A8-1. Procedures to estimate the individual component penetration fractions are defined in Paragraph 6 to this Appendix.

Note.– Depending on the precise geometry of the nvPM sampling system, there can be more individually described components of the nvPM sampling and measurement system than described in Table A8-1.

6. PROCEDURE TO DETERMINE PENETRATION FRACTIONS OF INDIVIDUAL COMPONENTS OF NVPM SAMPLING AND MEASUREMENT SYSTEM

6.1 Data Required

To calculate transport efficiency for particles over a range of sizes, the characteristics of the flow, the transport line and ambient conditions are required. These parameters defined for each line section are listed in Table A8-2.

Table A8-2. Input Parameters

Parameter symbol	Description	Units
T_i	Temperature of the carrier gas at the entrance of ith segment of the sampling line, except for the Collection Part. Assumed to be equal to the temperature of the wall of each section of the transport line and constant throughout the ith segment of the sampling line	°C
P_i	Pressure of the carrier gas in the ith segment of the sampling line, assumed constant throughout the ith section and equal to 101.325 kPa	kPa
Q_i	Flow rate of the carrier gas through the ith segment of the sampling line	slpm
ID_{ti}	Inside diameter of the ith segment of the sampling line	mm
L_i	Length of of the ith segment of the sampling line	m
θ_{bi}	Total angle of bends in the ith segment of the sampling line	degrees
$\eta_{VPR}(15)$, $\eta_{VPR}(30)$,	VPR penetration fractions at four particle	dimensionless

$\eta_{VPR}(50)$, $\eta_{VPR}(100)$	diameters	
$\eta_{CPC}(10)$, $\eta_{CPC}(15)$	CPC counting efficiency at two particle diameters	dimensionless

6.2 Diffusional Penetration Fractions

Diffusion of particles onto the surface of the sampling system tube walls results in loss of particles entering a segment of the sampling line or a component. Penetration fractions, $\eta_i(D_m)$, for diffusional losses in sections up to the instrument inlets,

$\eta_i(D_m)$, i=1, 2, 3, 4, 5, and 6

are calculated using the expression:

$$\eta_i(D_m) = e^{\frac{-0.6\times\pi\times ID_{ti}\times L_i\times V_{diff}}{Q_i}}$$

where

L_i	length of the ith segment of the sampling line, m
V_{diff}	$1.18 \times Re^{0.875} \times Sc^{0.333} \times \frac{D}{ID_{ti}}$, the deposition speed, cm/s
Sc	$\frac{\mu}{\rho_{gas}D} \times 10^3$, the carrier gas Schmidt number
m_{gas}	29.0 kg/mol , the molecular mass of the carrier gas
P_i	the carrier gas pressure, kPa (assumed to be 101.325 kPa),

Penetration fractions at 80 discrete particle sizes (D_m) in the range from 0.003 μm to 1 μm should be calculated for diffusional losses for each applicable line section.

6.3 Thermophoresis

A constant instrument inlet thermophoretic penetration, $\eta_{th\_m}(D_m) = 1$ should be used for nvPMmi and $\eta_{th\_n}(D_m) = 1$ should be used for nvPMni for all particle sizes.

6.4 Particle Loss in Bends

The penetration faction due to losses in bends

$\eta_{bi}(D_m)$, i=1, 2, 3, 4, 5, and 6

is distinguished for turbulent flow, Re greater than 5000, and laminar flow, Re less than or equal to 5000 where Re is the Reynolds number. For laminar flow when Re less than or equal to 5000 the penetration due to bends in the transport lines should be calculated as

$$\boldsymbol{\eta_{bi} = 1 - 0.01745 \times Stk \times \theta_{bi}}$$

For turbulent flow when Re greater than 5000 the penetration due to bends in the transport lines should be calculated as

$$\boldsymbol{\eta_{bi} = e^{-0.04927 \times Stk \times \theta_{bi}}}$$

where

Stk	$\frac{\boldsymbol{Q_i \times C_c \times \rho \times D_m^2 \times 10^{-3}}}{\boldsymbol{27 \times \pi \times \mu \times ID_{ti}^3}}$, the dimensionless Stokes number
θ_{bi}	Total angle of bends in the of the ith segment of the sampling line, degrees

Penetration fractions at 80 discrete particle sizes (D_m) in the range from 0.003 µm to 1 µm should be calculated for bend losses as applicable for each section of the sampling and measurement system.

6.5 Cyclone Separator Penetration Function

The penetration function of the cyclone separator should be estimated using the following expression:

$$\eta_{cyc}(D_m) = 1 - \int_{x>0}^{D_m} \frac{e^{-\frac{(\ln x - \mu_{cyc})^2}{2\sigma_{cyc}^2}}}{x\sigma_{cyc}\sqrt{2\pi}} dx$$

where

μ_{cyc}	$\ln(D_{50})$, and
σ_{cyc}	$\ln(D_{16}/D_{84})^{0.5}$

Penetration fractions at 80 discrete particle sizes (D_m) in the range from 0.003 µm to 1 µm should be calculated from the cyclone penetration function. The cyclone separator in the nvPM sampling and analysis system has the following specifications:

a) Cut-point: $D_{50} = 1.0$ µm ± 0.1 µm

b) Sharpness: $(D_{16}/D_{84})^{0.5}$ less than or equal to 1.25

Note 1.– Modern computer spreadsheet applications have the cumulative lognormal distribution built into the function library that can be used to generate the penetration function of the cyclone separator.

Note 2.– For most gas turbine engine applications D_m will be less than 0.3 µm*. In such cases the cyclone penetration function will be effectively equal to 1.0.*

6.6 VPR Penetration Function

Note.– A smooth function provided by the calibration laboratory that has goodness of fit results (R^2 greater than 0.95) for the four VPR calibration penetration points (Table A8-3) may be used in place of the function determined from the calculation procedure outlined below.

Particle losses in the VPR are due to both diffusion and thermophoresis. The thermophoretic factor, η_{VPRth}, is a constant. The diffusion factor, η_{VPRdi}, is determined from standard particle losses due to diffusion in a laminar flow. The total VPR penetration function should be estimated using the expression:

$$\eta_{VPR} = \eta_{VPRth} \times \begin{cases} 1 - 5.5 \times \psi^{\frac{2}{3}} + 3.77 \times \phi & \psi < 0.007 \\ 0.819 \times e^{-11.5\psi} + 0.0975 \times e^{-70.1\psi} + 0.0325 \times e^{-179\psi} & \psi > 0.007 \end{cases}$$

where

Ψ	$\frac{6 \times D \times L_{VPR}}{Q_{VPR}}$, the deposition parameter
L_{VPR}	the effective length of the VPR, m
Q_{VPR}	the carrier gas flow in the VPR, slpm
T_{VPR}	the VPR temperature, °C
η_{VPRth}	VPR thermophoretic loss

The VPR penetration function (η_{VPR}) should be fitted to the four measured penetration points by varying the VPR effective length (L_{VPR}) and the thermophoretic loss factor (η_{VPRth}). The R^2 value should be greater than 0.95 to ensure a good fit to the measured penetrations.

Penetration fractions at 80 discrete particle sizes (D_m) in the range from 0.003 µm to 1 µm should be calculated from the VPR continuous function.

Table A8-3. Minimum allowed penetration fractions of the VPR at four particle diameters

Electrical Mobility Particle Diameter, D_m	0.015 µm	0.03 µm	0.05 µm	0.1 µm
Minimum Penetration fraction, $\eta_{VPR}(D_m)$	0.30	0.55	0.65	0.70

6.7 Diluter1 Penetration Fraction

A constant diluter1 penetration, $\eta_{dil}(D_m) = 1$ should be used for all particle sizes.

Penetration fractions at 80 discrete particle sizes (D_m) in the range from 0.003µm to 1µm should be used for the diluter penetration function.

6.8 CPC Counting Efficiency

A continuous function for the CPC counting efficiency should be determined using the two CPC counting efficiencies specified with a two parameter sigmoid function using the expression:

$$\eta_{CPC} = 1 - e^{-\ln(2) \cdot \left[\frac{D_m - D_0}{D_{50} - D_0}\right]}$$

where

$$D_0 = \frac{\alpha_{10} D_{15} - \alpha_{15} D_{10}}{\alpha_{10} - \alpha_{15}}$$

$$D_{50} = \frac{(\alpha_{15}+1)D_{10} + (\alpha_{10} + 1)D_{15}}{\alpha_{15} - \alpha_{10}}$$

$$\alpha_i = \frac{\ln(1 - \eta_{CPC,i})}{\ln(2)}, i = 0.01\ \mu m\ \ or\ 0.015\ \mu m$$

D_{10}	0.01 µm,
D_{15}	0.015 µm,
$\eta_{CPC,10}$	the counting efficiency at 0.01 µm, and
$\eta_{CPC,15}$	the counting efficiency at 0.015 µm.

Penetration fractions at 80 discrete particle sizes (D_m) in the range from 0.003 µm to 1 µm should be calculated from the CPC continuous function.

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Proposal F Rationale:

Aircraft engines burning hydrocarbon-based fuels emit gaseous and particulate matter (PM) emissions as by-products of combustion. At the engine exhaust, particulate emissions mainly consist of ultrafine soot or black carbon emissions. Such particles are called non-volatile PM (nvPM). They are present at the high temperatures at the engine exhaust. Compared to traditional diesel engines, gas turbine engine non-volatile particles are typically smaller in size. Their geometric mean diameter ranges approximately from 15 nanometres (nm) to 60nm (0.06 micrometres; 10nm = 1/100,000 of a millimetre). These particles are ultrafine and are invisible to the human eye.

During the CAEP/10 meeting, the first nvPM Standard for aircraft engines was recommended. The proposed amendment includes the new ICAO nvPM engine emissions Standard (Annex 16, Volume II, Chapter 4) and the nvPM sampling and measurement system requirements (Annex 16, Volume II, Appendix 7). The proposed nvPM Standard, which will apply to turbofan and turbojet engines manufactured from 1 January 2020, is for aircraft engines with rated thrust greater than 26.7kN and is the first of its kind.

The regulatory level for the nvPM Standard is the nvPM mass concentration that is equivalent to the current Annex 16, Volume II Smoke Number (SN) regulatory level. If an engine passes the current smoke number Standard, by design of the regulatory level, it will pass the proposed nvPM Standard. Therefore, a new stringency is not introduced through the proposed CAEP/10 nvPM Standard. Importantly this new proposed Standard sets the stage for health and climate relevant nvPM standards as early as CAEP/11. The proposed nvPM Standard will allow, for the first time, the comparison of engine technology and engine types for nvPM emissions.

The purpose of emission certification is to compare engine technologies and to ensure that the engines produced comply with the prescribed regulatory limits. The nvPM sampling and measurement system requirements as described in the proposed Annex 16, Volume II, Appendix 7, standardise the particle losses in the measurement system such that particle losses are minimised and that engine measurements performed by different engine manufacturers and test facilities can be compared directly.

The nvPM sampling and measurement system will lose a portion of the particles when they travel through the sampling lines because of very small size of the nvPM particles. Therefore, the nvPM emissions measured at the instruments will be lower than the values at the engine exit plane. For emission inventories and impact assessments, nvPM emissions at the engine exit should be estimated through application of a standardized methodology to better reflect real world emissions. To achieve this, an nvPM system loss correction method is proposed and the reporting of nvPM system loss correction factors is requested (Annex 16, Volume II, Part IV and Appendix 8). The proposed Annex 16, Volume II, Part IV and Appendix 8 requests the reporting of particle losses and this is not part of the proposed nvPM certification of engines.

Overall, the proposed nvPM Standard will allow the manufacturers to become more familiar with the ICAO nvPM measurement certification requirements, and will provide ICAO with data to develop a more stringent nvPM mass and number Standard in the future. This is an important step forward and will allow CAEP to develop a CAEP/11 nvPM mass and number Landing Take-off (LTO) based Standard, aiming for 2019.

PROPOSAL G

ANNEX 16, VOLUME II CONSISTENCY WITH THE CAEP/10 NON-VOLATILE PARTICULATE MATTER (NVPM) ENGINE EMISSIONS STANDARD

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FOREWORD

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Editorial practices

The following practice has been adhered to in order to indicate at a glance the status of each statement: *Standards* have been printed in light face roman; *Recommended Practices* have been printed in light face italics, the status being indicated by the prefix ~~Recommendation~~ **Recommendation**; *Notes* have been printed in light face italics, the status being indicated by the prefix *Note*.

It is to be noted that in the English text the following practice has been adhered to when writing the specifications: Standards employ the operative verb “shall” while Recommended Practices employ the operative verb “should”.

The units of measurement used in this document are in accordance with the International System of Units (SI) as specified in Annex 5 to the Convention on International Civil Aviation. Where Annex 5 permits the use of non-SI alternative units, these are shown in parentheses following the basic units. Where two sets of units are quoted it must not be assumed that the pairs of values are equal and interchangeable. It may, however, be inferred that an equivalent level of safety is achieved when either set of units is used exclusively.

Any reference to a portion of this document which is identified by a number includes all subdivisions of that portion.

Coordination with ISO activity

In the provisions related to certification procedures, use is made of the related specifications developed by the International Organization for Standardization (ISO). In most cases, these specifications have been incorporated by direct reference. However, in some cases it has been found necessary to modify the specifications to suit ICAO requirements and in such cases the modified material is included in full in this document. The assistance provided by ISO in the development of detailed specifications is recognised.

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APPENDICES

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INTERNATIONAL STANDARDS AND RECOMMENDED PRACTICES

PART I. DEFINITIONS AND SYMBOLS

CHAPTER 1. DEFINITIONS

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Non-Volatile Particulate Matter (nvPM). Emitted particles that exist at gas turbine engine exhaust nozzle exit plane that do not volatilise when heated to a temperature of 350°C.

. . .

CHAPTER 2. SYMBOLS

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NO_2	Nitrogen dioxide
~~NO_x~~ NOx	Oxides of nitrogen (*see* definition)
nvPM	Non-Volatile Particulate Matter
SN	Smoke Number (*see* definition)

…

PART III. EMISSIONS CERTIFICATION

CHAPTER 1. ADMINISTRATION

1.1 The provisions of 1.2 to ~~1.4~~ 1.5 shall apply to all engines and their derivative versions included in the classifications defined for emission certification purposes in Chapters 2 ~~and~~, 3 and 4 where such engines are fitted to aircraft engaged in international air navigation.

…

APPENDIX 6. COMPLIANCE PROCEDURE FOR GASEOUS EMISSIONS ~~AND~~, SMOKE AND PARTICULATE MATTER EMISSIONS

1. GENERAL

The following general principles shall be followed for compliance with the regulatory levels set forth in Part III, 2.2, 2.3, 3.2 ~~and~~, 3.3 and 4.2:

a) the manufacturer shall be allowed to select for certification testing any number of engines, including a single engine if so desired;

b) all the results obtained during the certification tests shall be taken into account by the certification authority;

c) a total of at least 3 engine tests shall be conducted, so that if a single engine is presented for certification it must be tested at least 3 times;

d) if a given engine (i) is tested several times, the arithmetic mean value (X_i) of the tests shall be considered to be the mean value for that engine (i). The certification result ~~(X)~~ is then the arithmetic mean value of the values (X_i) obtained for each engine tested;

e) the manufacturer shall provide to the certificating authority, the information specified in Part III, 2.4 ~~or~~, 3.4, 4.2 and/or 4.3 as appropriate;

f) the engines submitted for testing shall have emissions features representative of the engine type for which certification is sought. However, at least one of the engines shall be substantially configured to the production standard of the engine type and have fully representative operating and performance characteristics. One of these engines shall be declared to be the reference standard engine. The methods for correcting to this reference standard engine from any other engines tested shall have the approval of the national certificating authority. The methods for correcting test results for ambient effects shall be those outlined in paragraph 7 of Appendix 3, ~~or~~ paragraph 7 of Appendix 5, or paragraph 6 of Appendix 7, as applicable.

2. COMPLIANCE PROCEDURES

2.1 Gaseous emissions and smoke number

The certificating authority shall award a certificate of compliance if the mean of the values measured and corrected (to the reference standard engine and reference atmospheric conditions) for all the engines tested, when converted to a characteristic level using the appropriate factor which is determined by the number of engines tested (i) as shown in ~~the table below~~ Table A6-1, does not exceed the regulatory level.

Note.— The characteristic level of the Smoke Number or gaseous emissions is the mean of the values of all the engines tested, and, for gaseous emissions only, appropriately corrected to the reference standard engine and reference atmospheric conditions, divided by the coefficient corresponding to the number of engines tested, as shown in Table A6-1.

2.2 Particulate matter emissions

The certificating authority shall award a certificate of compliance if the mean of the values of the maximum nvPM mass concentration measured and corrected for thermophoretic losses in the Collection Part of the sampling system for all the engines tested, when converted to a characteristic level using the appropriate factor which is determined by the number of engines tested (i) as shown in Table A6-1, does not exceed the regulatory level.

Note.— The characteristic level of the maximum nvPM mass concentration is the mean of the maximum values of all the engines tested, and appropriately corrected for the thermophoretic losses in the Collection Part of the sampling system, divided by the coefficient corresponding to the number of engines tested, as shown in Table A6-1.

2.3 Characteristic level

The coefficients needed to determine the characteristic levels of engine emissions are given in Table A6-1.

Table A6-1. Coefficients to determine ~~C~~characteristic levels ~~of the Smoke Number or gaseous emissions~~

Number of Engines tested (i)	CO	HC	NO$_x$	SN	nvPM mass concentration
1	0.814 7	0.649 3	0.862 7	0.776 9	0.776 9
2	0.877 7	0.768 5	0.909 4	0.852 7	0.852 7
3	0.924 6	0.857 2	0.944 1	0.909 1	0.909 1
4	0.934 7	0.876 4	0.951 6	0.921 3	0.921 3
5	0.941 6	0.889 4	0.956 7	0.929 6	0.929 6
6	0.946 7	0.899 0	0.960 5	0.935 8	0.935 8
7	0.950 6	0.906 5	0.963 4	0.940 5	0.940 5
8	0.953 8	0.912 6	0.965 8	0.944 4	0.944 4
9	0.956 5	0.917 6	0.967 7	0.947 6	0.947 6
10	0.958 7	0.921 8	0.969 4	0.950 2	0.950 2
~~more than 10~~	~~$1 - \frac{0.130\,59}{\sqrt{i}}$~~	~~$1 - \frac{0.247\,24}{\sqrt{i}}$~~	~~$1 - \frac{0.096\,78}{\sqrt{i}}$~~	~~$1 - \frac{0.157\,36}{\sqrt{i}}$~~	~~i~~

more than 10	$1- \frac{0.13059}{\sqrt{i}}$	$1- \frac{0.24724}{\sqrt{i}}$	$1- \frac{0.09678}{\sqrt{i}}$	$1- \frac{0.15736}{\sqrt{i}}$	$1- \frac{0.15736}{\sqrt{i}}$

3. PROCEDURE IN THE CASE OF FAILURE

Note.— When a certification test fails, it does not necessarily mean that the engine type does not comply with the requirements, but it may mean that the confidence given to the certificating authority in compliance is not sufficiently high, i.e. less than 90 per cent. Consequently, the manufacturer should be allowed to present additional evidence of engine type compliance.

3.1 If an engine type fails a certification test, the certificating authority shall permit the manufacturer, if he/she so wishes, to conduct additional tests on the certification engines. If the total results available still show that the engine type fails the certification requirements, the manufacturer shall be allowed to test as many additional engines as desired. The resulting test results shall then be considered with all previous data.

3.2 If the result is still failure, the manufacturer shall be allowed to select one or more engines for modification. The results of the tests already made on the selected engine(s) while unmodified shall be inspected, and further testing shall be done so that at least three tests are available. The mean of these tests shall be determined for each engine and described as the “unmodified mean”.

3.3 The engine(s) may then be modified, and at least three tests shall be conducted on the modified engine(s), the mean of which shall be described as the “modified mean” in each case. This “modified mean” shall be compared to the “unmodified mean” to give a proportional improvement which shall then be applied to the previous certification test result to determine if compliance has been achieved. It shall be determined before testing of any modified engine is begun that the modification(s) comply with the appropriate airworthiness requirements.

3.4 This procedure shall be repeated until compliance has been demonstrated or the engine type application is withdrawn.

…

Proposal G Rationale:

The proposed amendment makes the necessary consequential changes across Annex 16, Volume II, to reflect the proposed nvPM Standard (Proposal F). These changes are contained in a wide number of sections within Annex 16, Volume II.

6.2.5. Information on the methodology and data used to develop the new non-volatile particulate matter emissions Standard (CAEP/10 Report Agenda Item 4 'Particulate Matter Standard development')

1. BACKGROUND

1.1 Reducing civil aviation's impact on health and climate is one of the critical elements towards achieving ICAO's strategic objective of environmental protection and sustainable development of air transport. CAEP members and observers recognise that nvPM emissions from civil aircraft play a role in adverse impacts to health and climate and they committed to developing a nvPM standard for aircraft engines.

1.2 The new CAEP/10 nvPM standard has not undergone a cost-effectiveness analysis and is based on the correlation of the maximum nvPM mass concentration and the current smoke number (SN) standard. In parallel to this standard, Annex 16, Vol. II requires the reporting of the nvPM mass and number emission indices that would feed the cost-effectiveness analyses and will support the development of nvPM mass and number LTO based standards. Thus the CAEP/10 nvPM standard is considered to be the first stage in the development of future nvPM standards which would enable demonstrating reductions in aircraft engine nvPM emissions over time. The new CAEP/10 nvPM standard and the reporting requirements apply to in-production engines with a rated thrust greater than 26.7kN from 01/01/2020.

2. REGULATORY LEVEL DEVELOPMENT

2.1 The maximum nvPM mass concentration shall not exceed the regulatory level obtained from the following formula which results from the correlation of nvPM mass concentration (in µg/m^3) and the smoke number.

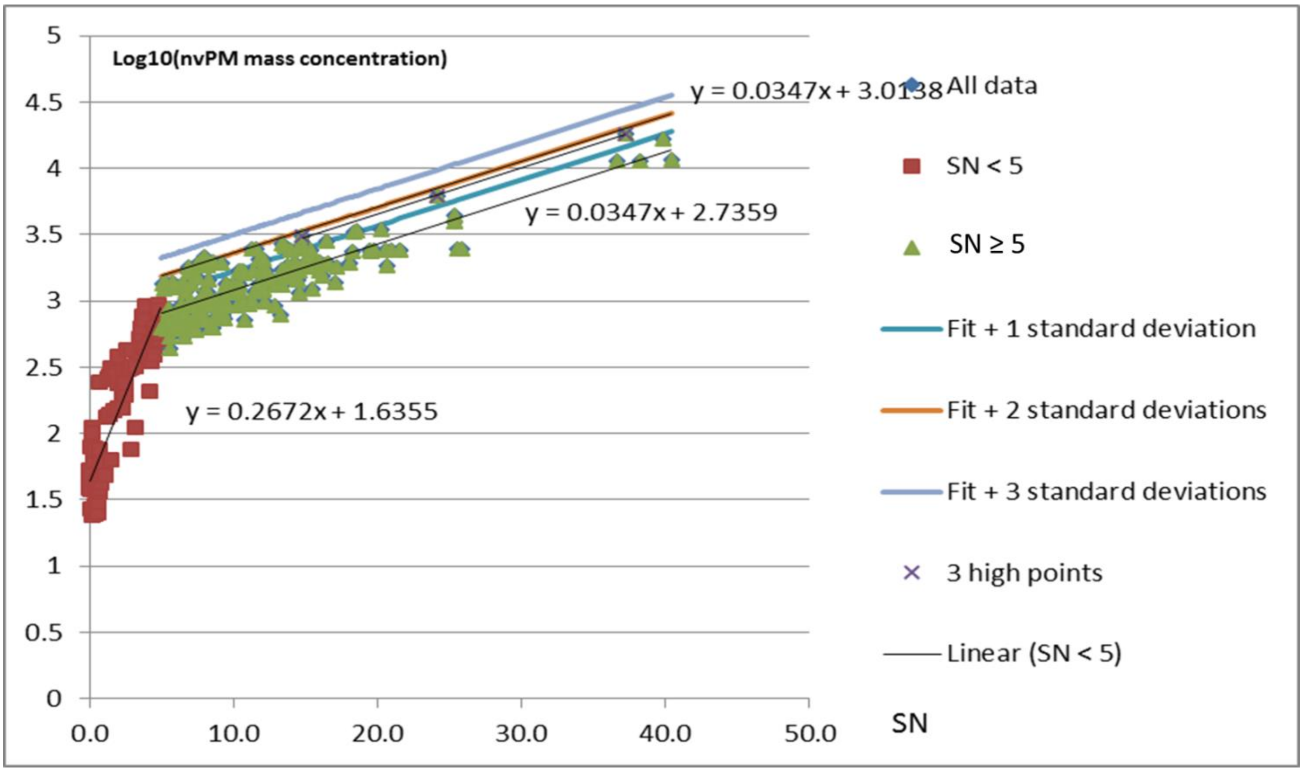
$$nvPM\ mass\ concentration\ limit\ line = 10^{\left\{3+2.9\ \times\ Foo^{-0.274}\right\}}$$

2.2 WG3/PMTG collected and analysed data from a limited number of engine tests that were performed with both nvPM mass and Smoke Number (SN) measurements for engines with a rated thrust greater than 26.7kN. The nvPM mass concentrations and the SN were correlated in a log-linear plot (logarithm of nvPM mass concentration in µg/m^3 versus SN). Only data with a SN greater than 5 were considered since they correspond to realistic rated thrusts (Foo) (SN lower than 5 in the regulatory level equation will result in rated thrust greater than 29132kN). The table below justifies the range of data used in developing the best fit correlation line. The largest allowable SNs for engines greater than 26.7 kN falls at the 26.7 kN cut-off point of 34. The largest engines available today would result in a maximum allowable SN around 15. The data points used in the fit for developing the equation ranged from 5 to 40, which corresponds to a range of thrusts of 14.7 to 29,000 kN of thrust. This fitting range is significantly wider than the range that is relevant from a regulatory perspective and the data fit is very robust within the (narrower) regulatory range where most of data are.

kN thrust	lbs thrust	Max SN
14.7	3,000	40
26.7	6,000	34
529	119,000	15
681	153,000	14

29132	6,549,000	5

2.3 It is assumed that the data are normally distributed in this log-linear space and that Gaussian statistics apply. Thus, the statistical variation in the data can be used to ensure that a line can be drawn that captures a desired fraction of data point based on these statistics. For instance, for a Gaussian distribution, 95.4% of the data points will fall within two standard deviations of the limit line.



Only the points which are no more than two standard deviations above the line are taken into account. These points can be arbitrarily far below the line. In other words, the distribution is being cut off on the high side, but not the low side. Thus, if we chose the line shifted up by two standard deviations, Gaussian statistics indicates that (95.4/2 + 100/2) = 97.7% of the points will be captured below this line. The line shifted up by two standard deviations can be expressed as:

$$\mathrm{Log}_{10}(nvPM\ mass\ concentration[\mu g/m^3]) = 0.0347 \times SN + 3.0138$$

2.4 The nvPM mass concentration regulatory level equation is obtained using this expression and substituting the SN from the SN regulatory level $SN = 83.6 \times Foo^{-0.274}$.

$$nvPM\ mass\ concentration\ limit\ line\ [\mu g/m^3] = 10^{\{3.0138+2.9009 \times Foo^{-0.274}\}}$$

In order to simplify the final expression for regulatory purposes, two approximations are used.

2.4.1 First, the shift by 2 standard deviations resulted in a term of 3.0138. This is close to 3. If the value of 3 is used instead of 3.0138, then the effective shift of the line is smaller. Instead of two standard deviations, using a “rounded-off” value of 3 would be a shift of 1.9

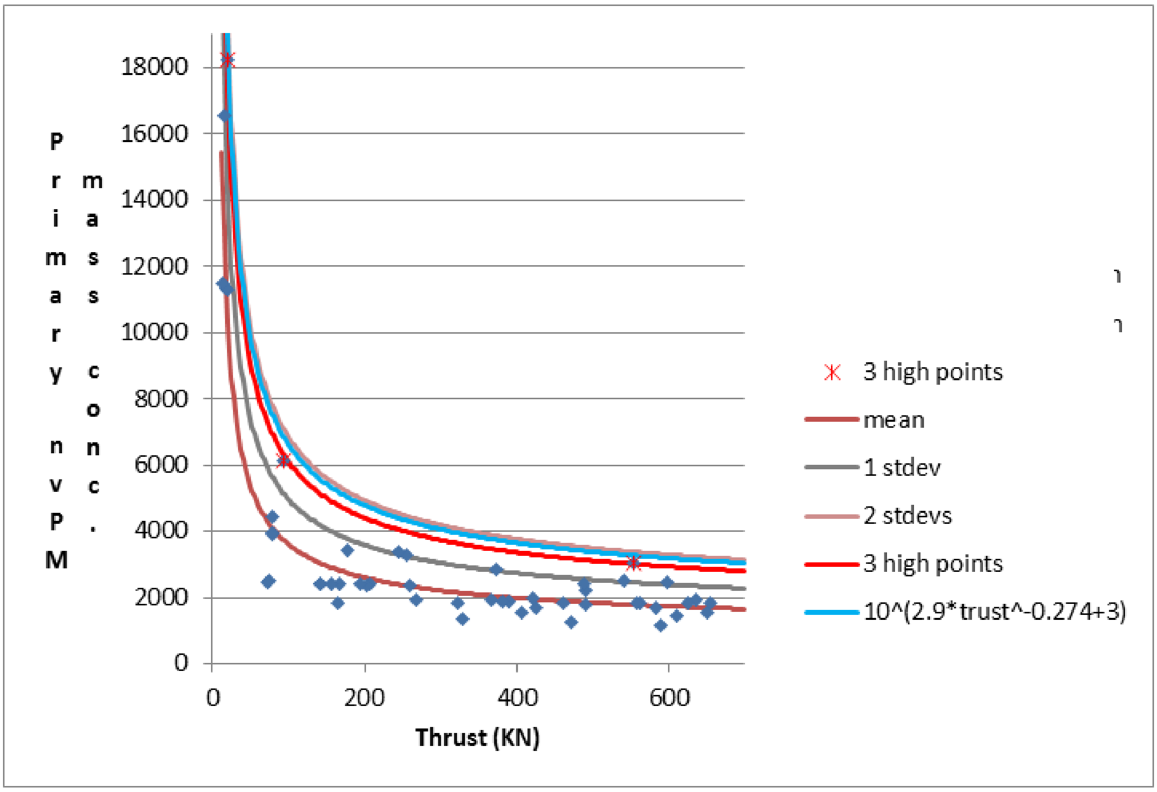
standard deviations. Thus fewer points would be captured by this line with the smaller shift. However, this is a small change, since Gaussian statistics indicate that this 1.9 standard deviation shifted line would capture 97.15% of the data points (again, only a maximum limit, and no minimum imposed), versus 97.7% for the two standard deviation shifted case.

2.4.2 Second, the coefficient in front of Foo in the resulting expression is 0.0347 x 83.6, which equals 2.9009. This is very close to 2.9.

2.4.3 These two numerical values are rounded to the stated values. The other numerical value in the expression is the exponent for Foo itself. The shape of the curve is very sensitive to this exponent, and -0.274 is the exponent used in the regulatory SN limit line. Thus, this Foo exponent numerical value is retained, and the resulting equation for the nvPM mass concentration limit line is given by:

$$nvPM\ mass\ concentration\ limit\ line\ [\mu g/m^3] = 10^{\{3+2.9\times Foo^{-0.274}\}}$$

2.5 This equation can be presented graphically. Each SN/nvPM data pair is assumed to be potentially a maximum value for a given engine and the associated thrust could be calculated using the SN limit line equation. In reality, most engines are not emitting smoke at the maximum SN, so the actual thrust would be greater (i.e. the SN measured is not at a maximum, thus the corresponding thrust would be greater than using the SN limit line expression). So any point plotted using this SN limit line assumption is a worst case, and other data would have a larger margin to the limit line.



The nvPM data is plotted against thrust, as well as the nvPM regulatory level line. Other curves are plotted: for the best fit line (lowest line), the 1 standard deviation shifted line (second line), the 1.9 standard deviation shifted line (corresponding to the regulatory level, second line from the top), and the 2 standard deviation shifted line (top line). Also plotted is a fit through the three highest points identified in the earlier figure (red curve, middle of the five curves). Clearly, the 1.9 and 2 standard deviation lines are very close to one another and capture all of the data points well.

2.6 This nvPM mass concentration regulatory level line can be used for certification purposes for the proposed CAEP/10 standard. Since this regulatory level is based on the existing SN regulatory limit line, the characteristic value and the associated corrections would also follow the existing SN protocol. Thus, the same coefficients, which depend on the number of engines tested, would apply.

A. RATIONALE FOR THE REPORTING OF THE NVPM MASS AND NUMBER EMISSION INDICES

1. In parallel to CAEP/10 nvPM standard, Annex 16, Vol. II requires the reporting of the nvPM mass and number emission indices and other data that would feed the cost-effectiveness analyses and support the development of nvPM mass and number LTO based standards. The requirement applies to all in-production engines with a rated thrust greater than 26.7kN from 01/01/2020.

2. The next nvPM standard should be LTO based and take into account mass and number. The plan is to gather enough data from 25 representative engines by February 2017 for the development of a sensitive standard that would serve as a basis for future stringency options.

3. The nvPM mass and number emission indices reporting in parallel with other useful data is required to guarantee the collection of sufficient data for the assessment of future standard.

B. RATIONALE FOR REPORTING OF NVPM SYSTEM LOSS CORRECTION FACTORS

1. The nvPM sampling and measurement system will lose a portion of the particles when they travel through the sampling lines because of very small size of the nvPM particles. Therefore, the nvPM emissions measured at the instruments will be lower than the values at the engine exit plane.

2. The purpose of emission certification is to compare engine technologies and to ensure that the engines produced comply with the prescribed regulatory limits. The nvPM sampling and measurement system requirements as described in Annex 16, Vol.II, Appendix 7 to Chapter 4 standardise the system such that the particle losses are minimised and that engine measurements performed by different engine manufacturers and test facilities can be compared directly.

3. However, for emission inventories and impact assessments, nvPM emissions at the engine exit should be estimated through application of a standardised methodology to better reflect these emissions. For that purpose Part IV to Annex 16, Vol.II and its related Appendix 8 were created. The recommended methodology for the calculation of the correction factors to estimate system losses is provided in Appendix 8 to Part IV. Part IV recommends that the engine manufacturers report their nvPM system loss correction factors to the appropriate authority using this recommended methodology. Using the same methodology will ensure to get correction factors calculated on a common basis. Getting these emissions factors at the authority level is a first step. There is a need to

discuss a process that will enable modellers to access these factors for their emission inventories and impact assessments.

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6.3. Appendix 3 — ICAO ANNEX 16, VOL III AMENDMENTS

6.3.1. Summary of CAEP/10 presentations, discussions, conclusions, recommendations and proposed 1st Edition of ICAO Annex 16, Vol III from the CAEP/10 Report (Agenda Item 5 'CO2 Standard development).

CO_2 STANDARD DEVELOPMENT

5.1.1 The CO_2 Task Group (CO2TG) co-lead provided an overview of the work undertaken by the CO2TG to develop the ICAO Aeroplane CO_2 Emissions Standard. This included details on the CAEP/10 WG3 CO_2 work programme and on the proposed edits to the draft Annex 16, Volume III approved at CAEP/9, and subsequently published as ICAO Circular 337. This updated version formed the basis of the proposal for the First Edition of Annex 16, Volume III – Aeroplane CO_2 Emissions. This was followed by the presentation of the proposed First Edition of Annex 16, Volume III and ICAO Doc 9501, Environmental Technical Manual (ETM), Volume III. An overview was also provided of potential future ETM, Volume III work items. The CO2TG has continued to investigate the development of the ICAO CO_2 Certification Database and CO2TG has developed a spreadsheet detailing the structure and data requirements for three options, as well as some draft Introduction text for the CO2DB website.

5.1.2 The CO2TG co-lead provided an overview of the work undertaken to develop potential CO_2 applicability options for in-production (InP) aeroplane types. The 2015 CAEP Steering Group (SG2015) had agreed on three potential mandatory in-production applicability options, and these were as follows:

1) Option 1 represents a production cut-off for all InP aeroplane types if they have not been certified to the CO_2 Standard by this date.

2) Option 2 represents applicability being triggered only if an application for a design change for new in-production aeroplanes exceeds a specific CO_2 change criteria.

3) Option 3 represents a hybrid approach, where Option 2 is active for a period of time and is subsequently followed by Option 1.

5.1.3 CO2TG had been requested to develop proposed Annex 16, Volume III text for the three options in preparation for a potential decision at CAEP/10. The CO2TG co-lead provided the proposed edits to Annex 16, Volume III, which could be used to integrate the proposed InP applicability options should they form part of the final decision on a CO_2 Standard.

5.1.4 The meeting discussed the difference between a new type (NT) and InP aeroplane. It was clarified that a NT aeroplane is a new design for which the Type Certificate application was submitted following any applicability date of the CO_2 Standard. InP refers to those aeroplane types which have already submitted an application for, or received, a Type Certificate before any applicability date of the CO_2 Standard. It was added that a derived version of an aeroplane incorporates changes in type design that meet certain criteria. If the changes to an InP aeroplane type are determined to be substantial then the design would be considered a new type design. Following a question from member, it was clarified that a substantial change is challenging to define but there is significant harmonisation on the process to do this across authorities.

5.1.5 The MDG and FESG co-Rapporteurs presented a high level summary of results from the environmental (benefits) and economic (costs) assessment of stringency options (SOs) for a potential CO_2 Standard under consideration by CAEP/10. The information presented was an update to the joint MDG/FESG papers provided to the SG2015, regarding the MDG/FESG analyses for a potential CO_2 Standard under the CAEP/10 work programme. The CO_2 main analysis (CO2ma) has been conducted in accordance with the following framework to consider CO_2 Standard application to NT aeroplanes and new deliveries of InP aeroplane types.

5.1.5.1 NT and InP: Full Technology Response (TR) / Out of Production Case (Case-1): This involved the analysis of CAEP Steering Group agreed SOs at the agreed implementation dates using all technology responses defined by WG3/WG1 –and– aircraft are assumed to go out of production (OoP) at the implementation dates if they cannot be made compliant to a stringency option level.

5.1.5.2 NT-Only: Alternative Response / Production Case (Case-4): This involved the analysis of CAEP Steering Group agreed SOs at agreed implementation dates for NT-only applicability using responses informed by market considerations since manufacturers would not have a legal deadline to bring InP types to levels required under an NT-only standard. Case-4 can be thought of as a range of response scenarios from a voluntary response similar to Case-1 down to an absence of any response by growth and replacement aircraft; and, within that range Case-4 was summarized as follows: Case-4-A included the top 33% most likely families respond and non-compliant families go out of production, unless no aircraft types remain to meet distance band demand, Case-4-B involved repeating Case-4-A with the B767 family remaining in production without a TR, and Case-4-C involved the top 33% most likely families respond and non-compliant families remain in production.

5.1.5.3 Hybrid Applicability: This involved the CO_2 Standard application to NT aeroplanes prior to new deliveries of InP types that allows for potentially combining a higher SOs for NT applicability with a lower SO for InP applicability.

5.1.6 The meeting discussed the impact fuel price has on the results of the CO2ma. Following a question from a member, it was confirmed that when the fuel price is lower the environmental benefit shown for the CO_2 Standard in the analysis will be greater because there is less pressure from the market. It was confirmed that a range of fuel prices had been tested (USD 2.00 to 4.00 per gallon) but this did not include the impact of the current low oil price.

5.1.7 An observer made the assertion, and the FESG co-Rapporteur confirmed, that the additional CO_2 benefits gained beyond SO6 in the hybrid results are smaller than the gains at the lower SOs. A member urged caution with drawing this conclusion and recommended not to focus on one single number in the CO2ma, highlighting that many assumptions had been made that can drive this modelled behaviour. The member commented that CAEP should focus on the breadth of the analysis conducted by MDG/FESG. An observer asked for clarification regarding the high capital cost for SO9 compared to SO8, and the MDG co-rapporteur confirmed that the increase in capital cost was due to a larger aircraft in a CBin dropping out, increasing the purchase of smaller size aircraft to meet demand.

5.1.8 The meeting thanked MDG and FESG for the immense amount of work and dedication in completing the CO2ma. The meeting accepted the results of the CO2ma as presented by MDG and FESG.

5.1.9 The WG1, WG3, MDG, FESG (WMF) coordination group liaison provided an overview of progress against the ICAO CO_2 Standard schedule approved at CAEP/9. All deliverables for CAEP/10 have been met, which were, the CO2ma and sensitivity tests by MDG/FESG; and the Annex 16, VolumeIII amendments, ETM Volume III and InP applicability options. The completion of this substantial body of work should provide CAEP with the information it requires to make a recommendation on the CO_2 Standard. The meeting thanked the WMF coordination group for all the efforts in coordinating the CO_2 Standard work.

5.1.10 The CO_2 Standard Members Group, established at SG2015 to develop and assess various compliance options for the proposed CO_2 Aeroplane Standard, provided a summary of the flexible compliance options for the CO_2 Standard that were discussed by the group. These included exclusions, exemptions, SO Combinations, and different effective dates and InP applicability options. It was highlighted that a face-to-face meeting of the CO_2 Standard Members Group was held in Zurich, Switzerland with the objective to deepen the technical discussions and to give the opportunity to stakeholders and aircraft manufacturers to share their views on the CO_2 Aeroplane Standard.

5.1.11 An observer highlighted that several CAEP members are advocating for a decoupling of stringency lines for aeroplanes whether their MTOM is above or below 60t to additionally mitigate the technical challenges confronted by aeroplanes with MTOM below 60t. To aid the discussions the observer presented views on the selection of the connection methodology between two different SOs. The observer urged CAEP to carefully consider both the selection of SOs and the connection methodology, so as to minimize unintended consequences and because the two are intrinsically intertwined. The observer also offered support to help develop final transition proposals once the SO levels above and below 60t are defined.

5.1.12 A member provided guidance on connecting CO_2 SOs. It was highlighted that with the possibility that SOs may be different below and above the previously established 60t MTOM kink point, the need to better understand how SOs can be connected is crucial. The member offered potential guiding principles and described two methods with examples that may be considered.

5.1.13 Several members and observers presented their views on the different aspects to be considered regarding the CO_2 Standard. They supported, for New Types greater than 60t MTOM, not less than SO7 with an applicability date of 1 January 2020, and for InP aeroplanes, not less than SO6 with an Option 1 applicability trigger in 1 January 2023. These positions allow to have a uniform applicability of the standard across the entire fleet, avoiding any exemptions or adaptations, especially for dedicated freighters. It was recognised that in general aeroplanes less than or equal to 60t MTOM have different challenges compared to aeroplanes above 60t with regards to CO_2 emissions reductions. Some disadvantage to these aeroplanes stem from the technology not being scalable for technical or economic reasons. Several members and observers suggested not less than SO6 with an applicability date of 1 January 2020 for NT aeroplanes less than or equal to 60t MTOM and greater than 19 seats, and in this mass and seat category for InP aeroplanes not less than SO5 with an Option 1 applicability trigger in 1 January 2023 was acceptable. For aeroplanes less than or equal to 60t MTOM and less than or equal to 19 seats (excluding freighters) a NT Standard of SO5 with an applicability date of 1 January 2023 was proposed. For InP aeroplanes, SO4 with an Option 1 applicability trigger in 1 January 2025 was suggested. The several members and observers highlighted that they were open to considering ‘flexible compliance options’ for InP aircraft. These should be of a limited nature in order to ensure that the purpose of the standard is not undermined. After a decision has been taken, it will be crucial that the information can be obtained by the member States for their rulemaking processes.

5.1.13.1 A member asked about the rationale behind the proposal of a particular SO for aeroplanes with less than or equal to 60t MTOM and with less than or equal to 19 seats. It was clarified that this aimed to address concerns with the impact of CO_2 Standard on the business jet market and how this may limit the scope of the chosen SOs for the heavier aeroplanes. It was added that this criteria has also been used in various national and regional regulations.

5.1.14 A member stated that the new ICAO Aeroplane CO_2 Standard should be applied to both NT and InP aeroplanes. It was highlighted that the adoption of a single SO level to NT and InP aeroplanes was unrealistic and the adoption of a single SO level to aeroplanes below and above the 60t MTOM kink could be problematic. The member supported the adoption of SO5 to NT aeroplanes less than or equal to 60t MTOM and SO7 for aeroplanes above the 60 tonne MTOM. The member supported the adoption of SO3 for InP aeroplanes less than or equal to 60t MTOM and SO5 for aeroplanes above 60t MTOM. While the date of 2020 seems to be a reasonable applicability date for NT aeroplanes, for InP aeroplanes, the member supported an applicability date of 2023, using Option 3, with a Production Cut-off date of 2028. The member supported the use of an exclusion criteria in Annex 16, Volume III with procedures included in ETM, Volume III, and supported the inclusion of a mechanism to avoid possible backsliding in fuel efficiency for products that are excluded.

5.1.15 A member expressed concerns over making the CO_2 Standard applicable to InP aeroplanes because the capability to implement the best modern CO_2 emission reduction technologies in InP aeroplane designs is limited. Should CAEP decide to recommend the application of the CO_2 Standard to InP aeroplanes, the member proposed a limit line no stricter than SO2, with an applicability date of 2023 (InP applicability Option 2) or with an applicability date not earlier than 2023 and a production cut-off date not earlier than 2028 (InP applicability Option 3). Regarding the CO_2 Standard for NT aeroplanes, the member proposed a SO no stricter than SO6. Taking into account the specific features of smaller aeroplanes, additional flexible options could be acceptable for such aeroplanes. The member suggested that the basic principles regarding exemptions of aeroplanes from the applicability of the CO_2 Standard, justified by technical reasons, could be described in the ETM, Vol III, and that the final decision should be the responsibility of individual States.

5.1.16 A member presented their views on the CO_2 Standard, supporting for NT aeroplanes above 60t MTOM SO8 or SO9 (maximum) with an applicability date of 1 January 2020, and for less than or equal to 60t MTOM SO5 with an applicability date of 1 January 2020. For InP aeroplanes above 60t MTOM, SO6 with an Option 3 applicability trigger in 1 January 2023 and with a production cut-off date of 1 January 2028 would be acceptable. For less than or equal to 60t MTOM, SO2 with an Option 3 applicability trigger in 1 January 2023 and with a production cut-off date of 1 January 2028 was appropriate. It was added that for aeroplanes less than or equal to 60t MTOM and less than or equal to 19 seats, it should be left to NAAs to adopt more flexible compliance options.

5.1.17 A member supported a separation of regulations above and below the 60t kink point based on technological feasibility. For aeroplanes above 60t MTOM, the member recommended a NT stringency level at SO9 with an applicability date of 2020, and an InP stringency level at SO8 or SO9 with an applicability date of 2023 under applicability Option 1 (production cut off). It was suggested that flexibilities for InP dedicated freighters would be essential for a technologically feasible standard. For aeroplanes less than or equal to 60t MTOM, the member recommended a NT stringency level of SO6 with an applicability date of 2020, and an InP stringency level at SO5 with an applicability date of 2025 under an applicability option of 1 (production cut off). The member stated that the Standard reflects technology innovation and is not to be used as the basis for operational restrictions or charges.

5.1.17.1 In referring to the assertion that the CO_2 Standard should not be used as a basis for operating restrictions or charges, a member questioned whether this would be acceptable if the chosen SO was low. In following up, a member stated that the CO_2 Standard not being the basis for operating restrictions was an important clause. The CO_2 Standard should not restrict access to airports. It is associated with aiming for sustainable development of international civil aviation.

5.1.17.2 The meeting discussed flexibilities for InP dedicated freighters and it was suggested by an observer, and accepted by a member, that Option 3 from the InP applicability options could form part of the construct on InP freighters.

5.1.18 A member supported SO9 for NT aeroplanes at greater than 60t MTOM with an applicability date of 2020, and for less than or equal to 60t MTOM SO6 with an applicability date of 2020. For InP aeroplanes greater than 60t MTOM SO8 or greater with an trigger date of 2023 was supported. For less than or equal to 60t MTOM and greater than 19 seats, this should be SO5 with an applicability date of 2023 and for less than or equal to 19seats, SO3 with an applicability date of 2023 was agreeable. The member supported InP Option 3 with applicability dates of 2023 and 2028.

5.1.19 A member commented that the environmental benefit analysis conducted by MDG is comprehensive. Concerns were however raised over the economic analyses and it was suggested that above SO5 the modelled costs are questionable. The member continued to present further views on the CO_2 Standard, supporting for NT aeroplanes above 60t MTOM SO5 with an applicability date of 2020 and for less than or equal to 60t MTOM SO5 with an applicability date of 2023. For InP aeroplanes, for all MTOMs, SO2 with an applicability date of 2023, option 3, with a production cut-off in 2028 was proposed.

5.1.20 An observer provided its perspective on the NT and InP CO_2 standard, and potential exceptions / exemptions. The observer proposed for aeroplanes with an MTOM greater than or equal to 70.265t the adoption of the SO6 stringency level for NT aeroplanes with an applicability date of 1 January 2020. For aeroplanes with a MTOM less than 70.265t, the adoption of SO5 stringency level for NT with an implementation date set at 1 January 2023 was acceptable. The observer suggested that when developing future updates of the CO_2 emissions standard, for business jet aeroplanes, a review of the implications of the CAEP/10 CO2 certification requirement on aeroplane designs should be performed. If deemed necessary, for an InP CO_2 Standard a limit line of no higher than SO2 was acceptable, with Option 2 beginning on 1 January 2023. The observer highlighted that if a production cut-off was agreed, then Option 3 beginning on 1 January 2023 with an end date of 1 January 2028 was appropriate. The observer recommended that if exemptions are granted for InP certifications, the process must follow unambiguous and published rules to be included in Annex 16, Volume III.

5.1.21 A member raised a concern that setting an InP CO_2 Standard with a limit line of no higher than SO2 would not meet the CAEP tenet of delivering environmental benefit. Regarding the suggestion to set the kink point at 70.265 MTOM, it was clarified that this aimed to minimise market distortions and was the result of joining two SOs together. The observer clarified that other kink points may be required depending on the selection of the SOs.

5.1.22 The meeting discussed exemptions and it was highlighted by an observer that these can be effective but should only be used as method of last resort. Members added that the use of exemptions is common place across aviation regulations (e.g. airworthiness) and can be successfully to address particular issues of members and observers as long as they are carefully constructed.

5.1.23 An observer recommended that for NT aeroplanes below approximately 60t MTOM, SO5, applicable no earlier than 1 January, 2023 was acceptable. It was stated that in the event of a difference in stringency between aeroplanes above and below 60t, a smooth and continuous transition should be employed between the two stringency lines, minimizing potential market distortions for aeroplanes in and around the transition area. The observer suggested that if the CAEP/10 meeting decides that InP applicability is necessary, a change-based InP standard (Option 2 with no production cut-off) set at SO2 would be appropriate, which covers the entire scope of MTOM values, applicable no earlier than 1 January, 2020.

5.1.24 The meeting took note of all the positions and technical information provided by the member and observers thus far. The Chairperson highlighted that with this solid basis, the CAEP/10 meeting should be able to move forward to make a decision on the CO_2 Standard.

5.1.25 An observer considered the aeroplane CO_2 emissions Standard to be an essential step to continually improving the environmental performance of the aviation industry. The observer underlined the importance that the Standard meet the CAEP's Terms of Reference (TORs) and described its position on potential accommodations for aeroplane categories, which may set unwise precedents, have unintended consequences, and unfairly shift the burden of the CO_2 Standard. CAEP was urged to ensure the impact on operators is fully taken into account when setting the CO_2 Standard. The observer also urged CAEP to recommend that States should not adopt CO_2 emissions standards that deviate from any agreed ICAO standard and to not restrict the operation of aircraft that are not subject to or comply with the agreed ICAO CO_2 Standard. The observer highlighted that for a NT CO_2 Standard greater than 60t SO8 at 2020 was appropriate, and for less than or equal to 60t the preferred choice was SO6 at 2020. For an InP CO_2 Standard, greater than 60t SO5 and for less than or equal to 60t SO4, both in 2023 with Option 3 (2028), were the preferred choices.

5.1.26 The meeting discussed how the CO_2 Standard might impact operators and how this impact was calculated. The observer clarified that policymakers should recognize that "economic reasonableness" encompasses economic effects other than "bottom line" costs and to weigh these effects carefully. For example, where a standard unduly limits aircraft availability and/or capability, aircraft operators will have more difficulty matching their aircraft purchases and fleets to efficiently serve market demands. The observer clarified that the analysis of the impact on operators was based on data from the CO2ma. The member raised a concern regarding the use of older (~5 years) economic data to underpin the cost analysis in the CO2ma and highlighted that the economic analysis could be more robust. The meeting noted these concerns while acknowledging that the best available data had been used by MDG/FESG in the CO2ma to aid the decision of CAEP on the CO_2 Standard. The meeting agreed that consistency should be ensured with all elements of the CAEP Terms of Reference during the development of the CO_2 Standard.

5.1.27 An observer noted that new certification standards should push forward aircraft technological improvements and should not imply or result in operating or operational restrictions.

5.1.28 An observer suggested that in order to provide demonstrable environmental benefit, ICAO's CO_2 Standard must require additional efficiency improvements from future aeroplanes beyond that expected due to market forces alone. The observer made recommendations on the standard stringency, flexibility, applicability, and data transparency to support an environmentally-effective CAEP/10 CO_2 Standard. These include: SO10 for all NT aeroplanes, to be applied from 2020; SOs 10 and 8 for new InP aircraft above and below 60t MTOM, respectively, to be applied from 2023; the application of the Standard to InP aeroplanes via a production cut off; and the "detailed" option for data to be included in the ICAO CO_2 Certification Database.

5.1.29 A member highlighted that for a NT CO_2 Standard greater than 60t SO8 in 2020 was appropriate, and for less than or equal to 60t her preferred choice was SO6 in 2020. The member highlighted that for InP applicability greater than 60t at SO8 and less than or equal to 60t SO5, both in 2023 and with applicability Option 3 in 2028 was appropriate.

5.1.30 A member highlighted his position on the CO_2 Standard as, for NT aeroplanes greater than 60t at SO9 in 2020, and less than or equal to 60t at SO6 in 2020. For InP applicability, greater than 60t at SO8 and less than or equal to 60t at SO5, both in 2023 and with applicability Option 3 in 2028 was acceptable. Another member stated his bottom line (minimum), for NT aeroplanes greater than 60t SO7 and less than or equal to 60t at SO6, both in 2020 was acceptable. For InP applicability, greater than 60t at SO6 and less than or equal to 60t at SO5, both with applicability Option 1 in 2023 was appropriate.

5.1.31 Several members commented on the objectives of the CO_2 Standard, and it was made clear that aviation must do its fair share in reducing global CO_2 emissions. They agreed that it was therefore important to set a NT and InP CO_2 Standard as soon as possible for aeroplanes greater than 60 MTOM. The CO_2 Standard should be ambitious but fair. A member raised a concern over the impact of employing higher SOs greater than 60T MTOM, stating the impact of a production cut off must be fully understood. Several members highlighted that consideration of a limited set of flexible compliance options should be given consideration. One member was convinced that market driven forces will continue to be an important incentive for the industry to produce more fuel efficient aircraft types and that some of the lower SO would result in a Standard that would not show any environmental benefit at all or an effectiveness that would quickly diminish.

5.1.32 An observer added that airports and the aviation industry requires ICAO to have a roadmap on addressing aviation CO_2 emissions that is effective, comprehensive and environmentally-beneficial and the CO_2 Standard is a key part of this. The observer supported having both NT and InP applicability and any InP production cut off requirement should be unambiguous.

5.1.33 The WMF liaison presented an overview of work following the 2015 Steering Group meeting to define the content of the information on Annex 16 amendments which could be made public following the CAEP meeting to support the rulemaking processes of all ICAO Member States. The high-level State requirements for information from some States have been identified and processes for potential release of information have been examined by the Group. The result of the group discussions was to recommend that the material required for release be agreed by CAEP, and included in the CAEP/10 Report.

5.1.34 The ICAO Secretariat presented an overview of a draft summary of the input material to the CO_2 Standard-setting process in order support the public rulemaking processes of a number of ICAO Member States. The draft has been reviewed by the WMF group. If agreed by the CAEP/10 meeting, this summary, as well as any additions agreed by the meeting, could be included as part of the CAEP/10 meeting report.

5.1.35 The meeting discussed the draft material to support the public rulemaking processes on the ICAO CO_2 Aeroplane Standard. The meeting showed its appreciation for the work and several members voiced their support for the document to be included in the CAEP/10 report. However, many members cautioned that the material would need review after the Standard stringency was set to ensure the relevance and accuracy of the material. It was agreed that a review by the CAEP/10 meeting should be conducted and the working group co-Rapporteurs should review the material and inform the meeting accordingly.

Discussion and Conclusions

5.1.36 The Chairman summarised, stating that the meeting had heard all the positions from the members and observers and highlighted that the aim of this meeting was to reach a consensus on an environmentally beneficial and cost effective ICAO CO_2 emissions certification Standard. The CO_2 Standard is a critical element of the basket of measures that aim to limit or reduce the impact of aviation greenhouse gas emissions on the global climate.

5.1.37 Following an extensive discussion amongst the CAEP Members, a consensus was reached on the overall package for the ICAO CO_2 emissions certification Standard. The meeting agreed to the following:

- for New Type aeroplanes greater than 60t MTOM, a stringency level of SO8.5 with an applicability date of 2020;
- for New Type aeroplanes less than or equal to 60t MTOM, a stringency level of SO5.0 with an applicability date of 2020, and a later applicability date of 2023 for aeroplane type designs with a passenger seating capacity of equal to or less than 19 seats;
- for in-production aeroplanes greater than 60t MTOM, a stringency level of SO7.0 with applicability trigger option 3, an applicability date of 2023 and production cut-off of 2028.
- for in-production aeroplanes less than or equal to 60t MTOM, a stringency level of SO3.0 with applicability trigger option 3, an applicability date of 2023 and production cut-off of 2028.

5.1.38 Regarding the different stringency levels for InP and NT respectively, the meeting agreed that these stringency levels will be connected using a "plateau" approach (i.e. a horizontal line). The horizontal line will start at 60t MTOM and end at the intersection of the associated stringency level above 60t MTOM.

5.1.39 To provide flexibility for certain aeroplanes with low volume production the members decided on sensible exemption criteria. This will allow certificating authorities to exempt low volume production aeroplanes in exceptional circumstances, taking into account environmental assessment, cost, social responsibility and circumstances of force majeure. It was also agreed that in addition of initial SARPS in Annex 16 and guidance on the ETM, specific exemption criteria will be defined by WG3 in time for the 2016 Steering Group meeting (SG2016).

5.1.40 Recognizing the ongoing and continuous improvement of aircraft technologies and the importance of reflecting technology developments in the ICAO standard-setting process, the meeting agreed that CAEP will, as is done with other standards, periodically review aircraft technology and assess the stringency level of the CO_2 Standard, with the first technology review being initiated in 2016 and concluding by CAEP/11 in 2019.

5.1.41 The meeting recalled the principles and purpose of the CO_2 Standard and specifically that the CO_2 emissions certification Standard of Annex 16, Vol. III is a technical comparison of aviation technologies designed to be used for CO_2 certification processes. The meeting recognised that the Standard was not designed to serve as a basis for operating restrictions or emissions levies.

5.1.42 The meeting agreed that, in a similar way to noise and engine emissions, an ICAO CO_2 Certification Database (CO2DB) should be developed. The meeting confirmed that it should be public and that the United States would host it on behalf of ICAO. The meeting recognised the information submitted by WG3 on the data approaches for the CO2DB (i.e. Metric Value, SAR and Detailed approaches) and that technical discussions in WG3 had progressed as far as they could. However, there was a need for WG3 to consider how to incorporate information on exempted aeroplanes in the CO2DB and this should be reported to SG2017, where a decision would be taken on the CO2DB data approach.

5.1.43 To aid States in the implementation of the new ICAO CO_2 Standard, the meeting approved a summary of information detailing the input provided to the meeting in order to facilitate the decision on the new Annex 16, Volume III, as indicated in Appendix C to this Agenda Item.

5.1.44 **Recommendations**

5.1.44.1 In light of the foregoing discussion, the meeting developed the following recommendations:

RSPP **Recommendation 5/1 —Amendments to Annex 16 — *Environmental Protection*, Volume III — *Aeroplane CO_2 Emissions***

That Annex 16 be amended to include the First Edition of Annex 16, Volume III, entitled *Aeroplane CO_2 Emissions*, as indicated in Appendix A to the report on this agenda item.

Recommendation 5/2 — First Edition of the *Environmental Technical Manual*, Volume III - *Procedures for the CO_2 Emissions Certification of Aeroplanes*

That the *Environmental Technical Manual*, Volume III be published, as indicated in Appendix B to the report on this agenda item, and revised versions approved by subsequent CAEP Steering Groups be made available, free of charge on the ICAO website, pending a final decision on official publication by the ICAO Secretary General.

Recommendation 5/3 — Use of the CO_2 Emissions Standard

That States recognise that the CO_2 emissions certification Standard of Annex 16, Volume III is a technical comparison of aviation technologies designed to be used for CO_2 emissions certification processes. The Standard was not designed to serve as a basis for operating restrictions or emissions levies.

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6.3.2. Proposed 1st Edition of ICAO Annex 16, Vol III

INTERNATIONAL STANDARDS
AND RECOMMENDED PRACTICES

ENVIRONMENTAL PROTECTION

ANNEX 16
TO THE CONVENTION ON INTERNATIONAL CIVIL AVIATION

VOLUME III
AEROPLANE CO_2 EMISSIONS

TABLE OF CONTENTS

FOREWORD

Historical background

Standards and Recommended Practices for Environmental Protection were first adopted by the Council on 2 April 1971 pursuant to the provisions of Article 37 of the Convention on International Civil Aviation (Chicago, 1944) and designated as Annex 16 to the Convention. This Volume III to Annex 16 was developed in the following manner:

At the 36th Session of the ICAO Assembly in 2007, Contracting States adopted Assembly Resolution A36-22 *Consolidated statement of continuing ICAO policies and practices related to environmental protection.* This resolution provided for the establishment of a process which led to the development and recommendation to the Council a Programme of Action on International Aviation and Climate Change and a common strategy to limit or reduce greenhouse gas emissions attributable to international civil aviation.

The development of an aeroplane CO_2 standard as part of the range of measures for addressing greenhouse gas emissions from international aviation was one of the recommended elements within the ICAO Programme of Action on International Aviation and Climate Change. This was subsequently endorsed by the ICAO High-level Meeting on International Aviation and Climate Change in October 2009.

In line with the ICAO Programme of Action, the Eighth Meeting of the Committee on Aviation Environmental Protection (CAEP/8) in February 2010 agreed to develop International Standards and Recommended Practices for Aeroplane CO_2 Emissions. This was approved by the ICAO Council in May 2010. Subsequently the 37^{th} Session of the ICAO Assembly in 2010 adopted resolutions A37-18 and A37-19, requesting that the Council develop a global CO_2 Standard for aircraft. The CAEP developed draft International Standards and Recommended Practices for aeroplane CO_2 emissions and, after amendment following the usual consultation with the Contracting States of the Organisation, this Annex 16, Volume III was adopted by the Council.

Table A shows the origin of amendments to the Annex 16 Volume III over time together with a list of the principal subjects involved and the dates on which the Annex and the amendments were adopted by the Council, when they became effective and when they became applicable.

Applicability

Part I of Volume III of Annex 16 contains definitions and symbols. Part II contains Standards and Recommended Practices for certification of aeroplane CO_2 emissions based on the consumption of fuel applicable to the classification of aeroplanes specified in Part II of Volume III of Annex 16, where such aeroplanes are engaged in international air navigation.

Action by Contracting States

Notification of differences. The attention of Contracting States is drawn to the obligation imposed by Article 38 of the Convention by which Contracting States are required to notify the Organization of any differences between their national regulations and practices and the International Standards contained in this Annex and any amendments thereto. Contracting States are invited to extend such notification to any differences from the Recommended Practices contained in this Annex, and any amendments thereto, when the notification of such differences is important for the safety of air navigation. Further, Contracting States are invited to keep the

Organization currently informed of any differences which may subsequently occur, or of the withdrawal of any differences previously notified. A specific request for notification of differences will be sent to Contracting States immediately after the adoption of each amendment to this Annex.

The attention of States is also drawn to the provisions of Annex 15 related to the publication of differences between their national regulations and practices and the related ICAO Standards and Recommended Practices through the Aeronautical Information Service, in addition to the obligation of States under Article 38 of the Convention.

Use of the Annex text in national regulations. The Council, on 13 April 1948, adopted a resolution inviting the attention of Contracting States to the desirability of using in their own national regulations, as far as is practicable, the precise language of those ICAO Standards that are of a regulatory character and also of indicating departures from the Standards, including any additional national regulations that were important for the safety or regularity of international air navigation. Wherever possible, the provisions of this Annex have been written in such a way as to facilitate incorporation, without major textual changes, into national legislation.

Status of Annex components

An Annex is made up of the following component parts, not all of which, however, are necessarily found in every Annex; they have the status indicated:

1.— *Material comprising the Annex proper:*

a) *Standards* and *Recommended Practices* adopted by the Council under the provisions of the Convention. They are defined as follows:

Standard: Any specification for physical characteristics, configuration, material, performance, personnel or procedure, the uniform application of which is recognized as necessary for the safety or regularity of international air navigation and to which Contracting States will conform in accordance with the Convention; in the event of impossibility of compliance, notification to the Council is compulsory under Article 38.

Recommended Practice: Any specification for physical characteristics, configuration, material, performance, personnel or procedure, the uniform application of which is recognized as desirable in the interest of safety, regularity or efficiency of international air navigation, and to which Contracting States will endeavour to conform in accordance with the Convention.

b) *Appendices* comprising material grouped separately for convenience but forming part of the Standards and Recommended Practices adopted by the Council.

c) *Provisions* governing the applicability of the Standards and Recommended Practices.

d) *Definitions* of terms used in the Standards and Recommended Practices which are not self-explanatory in that they do not have accepted dictionary meanings. A definition does not have an independent status but is an essential part of each Standard and Recommended Practice in which the term is used, since a change in the meaning of the term would affect the specification.

e) Tables and Figures which add to or illustrate a Standard or Recommended Practice and which are referred to therein, form part of the associated Standard or Recommended Practice and have the same status.

2.— *Material approved by the Council for publication in association with the Standards and Recommended Practices:*

a) *Forewords* comprising historical and explanatory material based on the action of the Council and including an explanation of the obligations of States with regard to the application of the Standards and Recommended Practices ensuing from the Convention and the Resolution of Adoption.

b) *Introductions* comprising explanatory material introduced at the beginning of parts, chapters or sections of the Annex to assist in the understanding of the application of the text.

c) *Notes* included in the text, where appropriate, to give factual information or references bearing on the Standards or Recommended Practices in question, but not constituting part of the Standards or Recommended Practices.

d) *Attachments* comprising material supplementary to the Standards and Recommended Practices, or included as a guide to their application.

Selection of language

This Annex has been adopted in six languages — English, Arabic, Chinese, French, Russian and Spanish. Each Contracting State is requested to select one of those texts for the purpose of national implementation and for other effects provided for in the Convention, either through direct use or through translation into its own national language, and to notify the Organization accordingly.

Editorial practices

The following practice has been adhered to in order to indicate at a glance the status of each statement: *Standards* have been printed in light face roman; *Recommended Practices* have been printed in light face italics, the status being indicated by the prefix **Recommendation**; *Notes* have been printed in light italics, the status being indicated by the prefix *Note*.

It is to be noted that in the English text the following practice has been adhered to when writing the specifications: Standards employ the operative verb “shall” while Recommended Practices employ the operative verb “should”.

The units of measurement used in this document are in accordance with the International System of Units (SI) as specified in Annex 5 to the Convention on International Civil Aviation. Where Annex 5 permits the use of non-SI alternative units these are shown in parentheses following the basic units. Where two sets of units are quoted it must not be assumed that the pairs of values are equal and interchangeable. It may, however, be inferred that an equivalent level of safety is achieved when either set of units is used exclusively.

Any reference to a portion of this document which is identified by a number includes all subdivisions of that portion.

Table A. Amendments to Volume III of Annex 16

Amendment	*Source(s)*	*Subject(s)*	*Adopted* *Effective* *Applicable*
1st Edition	Tenth Meeting of the Committee on Aviation Environmental Protection		xx March 20xx xx July 20xx xx November 20xx

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INTERNATIONAL STANDARDS AND RECOMMENDED PRACTICES

PART I. DEFINITIONS AND SYMBOLS

CHAPTER 1. DEFINITIONS

Aeroplane. A power-driven heavier-than-air aircraft, deriving its lift in flight chiefly from aerodynamic reactions on surfaces which remain fixed under given conditions of flight.

Cockpit crew zone. The part of the cabin that is exclusively designated for flight crew use.

Derived version of a non-CO_2-certified aeroplane. An individual aeroplane that conforms to an existing Type Certificate, but which is not certified to Annex 16 Volume III, and to which changes in type design are made prior to the issuance of the aeroplane's first certificate of airworthiness that increase its CO_2 emissions evaluation metric value by more than 1.5% or are considered to be significant CO_2 changes.

Derived version of a CO_2-certified aeroplane. An aeroplane which incorporates changes in type design that either increase its maximum take-off mass, or that increase its CO_2 emissions evaluation metric value by more than:

a) 1.35% at a maximum take-off mass of 5 700 kg, decreasing linearly to;
b) 0.75% at a maximum take-off mass of 60 000 kg, decreasing linearly to;
c) 0.70% at a maximum take-off mass of 600 000 kg; and
d) a constant 0.70% at maximum take-off masses greater than 600 000 kg.

Note.— Where the certificating authority finds that the proposed change in design, configuration, power or mass is so extensive that a substantially new investigation of compliance with the applicable airworthiness regulations is required, the aeroplane will be considered to be a new type design rather than a derived version.

Equivalent procedure. A test or analysis procedure which, while differing from the one specified in this volume of Annex 16, in the technical judgement of the certificating authority yields effectively the same CO_2 emissions evaluation metric value as the specified procedure.

Maximum passenger seating capacity. The maximum certificated number of passengers for the aeroplane type design.

Maximum take-off mass. The highest of all take-off masses for the type design configuration.

Performance model. An analytical tool or method validated from corrected flight test data that can be used to determine the SAR values for calculating the CO_2 emissions evaluation metric value at the reference conditions.

Optimum conditions. The combinations of altitude and airspeed within the approved operating envelope defined in the aeroplane flight manual that provides the highest specific air range value at each reference aeroplane mass.

Reference geometric factor. An adjustment factor based on a measurement of aeroplane fuselage size derived from a two-dimensional projection of the fuselage.

Specific air range. The distance an aeroplane travels in the cruise flight phase per unit of fuel consumed.

State of design. The State having jurisdiction over the organization responsible for the type design.

Subsonic aeroplane. An aeroplane incapable of sustaining level flight at speeds exceeding a Mach number of 1.

Type Certificate. A document issued by a Contracting State to define the design of an aircraft, engine or propeller type and to certify that this design meets the appropriate airworthiness requirements of that State.

Note.— In some Contracting States a document equivalent to a type certificate may be issued for an engine or propeller type.

CHAPTER 2. SYMBOLS

Where the following symbols are used in Volume III of this Annex, they have the meanings, and where applicable the units, ascribed to them below:

AVG	Average
CG	Centre of gravity
CO_2	Carbon dioxide
g_0	Standard acceleration due to gravity at sea level and a geodetic latitude of 45.5 degrees, 9.80665 (m/s^2)
Hz	Hertz (cycles per second)
MTOM	Maximum take-off mass (kg)
OML	Outer mould line
RGF	Reference geometric factor
RSS	Root sum of squares
SAR	Specific air range (km/kg)
TAS	True air speed (km/h)
W_f	Total aeroplane fuel flow (kg/h)
δ	Ratio of atmospheric pressure at a given altitude to the atmospheric pressure at sea level

PART II. CERTIFICATION STANDARD FOR AEROPLANE CO_2 EMISSIONS BASED ON THE CONSUMPTION OF FUEL

CHAPTER 1. ADMINISTRATION

1.1 The provisions of 1.2 to 1.11 shall apply to all aeroplanes included in the classifications defined for CO_2 emissions certification purposes in Chapter 2 of this part where such aeroplanes are engaged in international air navigation.

1.2 CO_2 emissions certification shall be granted or validated by the State of Registry of an aeroplane on the basis of satisfactory evidence that the aeroplane complies with requirements that are at least equal to the applicable Standards specified in this Annex.

1.3 Contracting States shall recognize as valid a CO_2 emissions certification granted by another Contracting State provided that the requirements under which such certification was granted are at least equal to the applicable Standards specified in this Annex.

1.4 The amendment of this volume of the Annex to be used by a Contracting State shall be that which is applicable on the date of submission to that Contracting State for either a Type Certificate in the case of a new type, approval of a change in type design in the case of a derived version, or under equivalent application procedures prescribed by the certificating authority of that Contracting State.

Note.— As each new edition and amendment of this Annex becomes applicable (according to Table A of the Foreword) it supersedes all previous editions and amendments.

1.5 Unless otherwise specified in this volume of the Annex, the date to be used by Contracting States in determining the applicability of the Standards in this Annex shall be the date the application for a Type Certificate was submitted to the State of Design, or the date of submission under an equivalent application procedure prescribed by the certificating authority of the State of Design.

1.6 An application shall be effective for the period specified in the airworthiness regulations appropriate to the aeroplane type, except in special cases where the certificating authority grants an extension. When the period of effectivity is extended the date to be used in determining the applicability of the Standards in this Annex shall be the date of issue of the Type Certificate, or approval of the change in type design, or the date of issue of approval under an equivalent procedure prescribed by the State of Design, less the period of effectivity.

1.7 For derived versions of non-CO_2-certified aeroplanes and derived versions of CO_2-certified aeroplanes, the applicability provisions concerning the Standards of this Annex refer to the date on which “the application for the certification of the change in type design” was made. The date to be used by Contracting States in determining the applicability of the Standards in this Annex shall be the date on which the application for the change in type design was submitted to the Contracting State that first certified the change in type design.

1.8 Where the provisions governing the applicability of the Standards of this Annex refer to the date on which the certificate of airworthiness was first issued to an individual aeroplane, the date to be used by Contracting States in determining the applicability of the Standards in this Annex shall be the date on which the first certificate of airworthiness was issued by any Contracting State.

1.9 The certificating authority shall publish the certified CO_2 emissions evaluation metric value granted or validated by that authority.

1.10 The use of equivalent procedures in lieu of the procedures specified in the Appendices of this Volume of Annex 16 shall be approved by the certificating authority.

Note.- Guidance material on the use of equivalent procedures is provided in the Environmental Technical Manual (Doc 9501), Volume III – Procedures for the CO2 Emissions Certification of Aeroplanes.

1.11 Contracting States shall recognize valid aeroplane exemptions granted by an authority of another Contracting State responsible for production of the aeroplane provided that an acceptable process was used.

Note.- Guidance on acceptable processes and criteria for granting exemptions is provided in the Environmental Technical Manual (Doc 9501),Volume III — Procedures for the CO_2 *Emissions Certification of Aeroplanes.*

CHAPTER 2.

1.—SUBSONIC JET AEROPLANES OVER 5 700 kg

2.—PROPELLER-DRIVEN AEROPLANES OVER 8 618 kg

2.1 Applicability

Note.— See also Chapter 1, 1.4, 1.5, 1.6, 1.7, 1.8 and 1.11.

2.1.1 The Standards of this chapter shall, with the exception of amphibious aeroplanes, aeroplanes initially designed or modified and used for specialised operational requirements, aeroplanes designed with zero RGF, and those aeroplanes specifically designed or modified and used for fire-fighting purposes, be applicable to:

a) subsonic jet aeroplanes, including their derived versions, of greater than 5 700 kg maximum take-off mass for which the application for a type certificate was submitted on or after 1 January 2020, except for those aeroplanes of less than or equal to 60 000 kg maximum take-off mass with a maximum passenger seating capacity of 19 seats or less;

b) subsonic jet aeroplanes, including their derived versions, of greater than 5 700 kg and less than or equal to 60 000 kg maximum take-off mass with a maximum passenger seating capacity of 19 seats or less, for which the application for a type certificate was submitted on or after 1 January 2023;

c) all propeller-driven aeroplanes, including their derived versions, of greater than 8 618 kg maximum take-off mass, for which the application for a type certificate was submitted on or after 1 January 2020;

d) derived versions of non-CO_2-certified subsonic jet aeroplanes of greater than 5 700 kg maximum certificated take-off mass for which the application for certification of the change in type design was submitted on or after 1 January 2023;

e) derived versions of non-CO_2 certified propeller-driven aeroplanes of greater than 8 618 kg maximum certificated take-off mass for which the application for certification of the change in type design was submitted on or after 1 January 2023;

f) individual non-CO_2-certified subsonic jet aeroplanes of greater than 5 700 kg maximum certificated take-off mass for which a certificate of airworthiness was first issued on or after 1 January 2028; and

g) individual non-CO_2-certified propeller-driven aeroplanes of greater than 8 618 kg maximum certificated take-off mass for which a certificate of airworthiness was first issued on or after 1 January 2028.

Note. – Aeroplanes initially designed or modified and used for specialised operational requirements refer to aeroplane type configurations which, in the view of the certificating authority, have different design characteristics to meet specific operational needs compared to typical civil aeroplane types covered by the scope of this Volume of Annex 16, and which may result in a very different CO_2 emissions evaluation metric value.

2.1.2 Notwithstanding 2.1.1, it may be recognized by a Contracting State that aeroplanes on its registry do not require demonstration of compliance with the provisions of the

Standards of Annex 16, Volume III for time-limited engine changes. These changes in type design shall specify that the aeroplane may not be operated for a period of more than 90 days unless compliance with the provisions of Annex 16, Volume III, is shown for that change in type design. This applies only to changes resulting from a required maintenance action.

2.1.3 The granting of an exemption for an aeroplane against applicability requirements specified in 2.1.1 shall be noted on the aeroplane statement of conformity issued by the certificating authority. Certificating authorities shall take into account the numbers of exempted aeroplanes that will be produced and their impact on the environment. Exemptions shall be reported by aeroplane serial number and made available via an official public register.

Note. - Further guidance on issuing exemptions is provided in the Environmental Technical Manual (Doc 9501), Volume III — Procedures for the CO_2 Emissions Certification of Aeroplanes.

2.2 CO_2 emissions evaluation metric

The metric shall be defined in terms of the average of the 1/SAR values for the three reference masses defined in 2.3 and the RGF defined in Appendix 2. The metric value shall be calculated according to the following formula:

$$\mathrm{CO_2\ emissions\ evaluation\ metric\ value} = \frac{\left({}^{1}\!/_{\mathrm{SAR}}\right)_{\mathrm{AVG}}}{(\mathrm{RGF})^{0.24}}$$

Note 1. — The metric value is quantified in units of kg/km.

Note 2. —The CO_2 emissions evaluation metric is a SAR based metric adjusted to take into account fuselage size.

2.3 Reference aeroplane masses

2.3.1 The 1/SAR value shall be established at each of the following three reference aeroplane masses, when tested in accordance with these Standards:

a) high gross mass: 92% MTOM

b) mid gross mass: Simple arithmetic average of high gross mass and low gross mass

c) low gross mass: $(0.45 \times \mathrm{MTOM}) + (0.63 \times (\mathrm{MTOM}^{0.924}))$

Note.— MTOM is expressed in kilograms.

2.3.2 CO_2 emissions certification for MTOM also represents the certification of CO_2 emissions for take-off masses less than MTOM. However, in addition to the mandatory certification of CO_2 metric values for MTOM, applicants may voluntarily apply for the approval of CO_2 metric values for take-off masses less than MTOM.

2.4 Maximum permitted CO_2 emissions evaluation metric value

2.4.1 The CO_2 emissions evaluation metric value shall be determined in accordance with the evaluation methods of Appendix 1.

2.4.2 The CO_2 emissions evaluation metric value shall not exceed the value defined in the following paragraphs:

a) For aeroplanes specified in 2.1.1 a), b) and c) with a maximum take-off mass less than or equal to 60 000 kg:

$$\text{Maximum permitted value} = 10^{(-2.73780+ (0.681310 * \mathrm{log10}(\mathrm{MTOM})) + (-0.0277861 * (\mathrm{log10}(\mathrm{MTOM}))^\wedge 2))}$$

b) For aeroplanes specified in 2.1.1 a) and c) with a maximum take-off mass greater than 60 000 kg, and less than or equal to 70 395 kg:

$$\text{Maximum permitted value} = 0.764$$

c) For aeroplanes specified in 2.1.1 a) and c) with a maximum take-off mass of greater than 70 395 kg:

$$\text{Maximum permitted value} = 10^{(-1.412742 + (-0.020517 * \mathrm{log10}(\mathrm{MTOM})) + (0.0593831 * (\mathrm{log10}(\mathrm{MTOM}))^\wedge 2))}$$

d) For aeroplanes specified in 2.1.1 d), e), f) and g) with a maximum certificated take-off mass less than or equal to 60 000 kg:

$$\text{Maximum permitted value} = 10^{(-2.57535 + (0.609766 * \mathrm{log10}(\mathrm{MTOM})) + (-0.0191302 * (\mathrm{log10}(\mathrm{MTOM}))^\wedge 2))}$$

e) For aeroplanes specified in 2.1.1 d), e), f) and g) with a maximum certificated take-off mass greater than 60 000 kg, and less than or equal to 70 107 kg:

$$\text{Maximum permitted value} = 0.797$$

f) For aeroplanes specified in 2.1.1 d), e), f) and g) with a maximum take-off mass of greater than 70 107 kg:

$$\text{Maximum permitted value} = 10^{(-1.39353 + (-0.020517 * \mathrm{log10}(\mathrm{MTOM})) + (0.0593831 * (\mathrm{log10}(\mathrm{MTOM}))^\wedge 2))}$$

2.5 Reference conditions for determining aeroplane specific air range

2.5.1 The reference conditions shall consist of the following conditions within the approved normal operating envelope of the aeroplane:

a) the aeroplane gross masses defined in 2.3;

b) a combination of altitude and airspeed selected by the applicant for each of the specified reference aeroplane gross masses;

Note.— These conditions are generally expected to be the combination of altitude and airspeed that results in the highest SAR value, which is usually at the maximum range cruise Mach number at the optimum altitude. The selection of conditions other than optimum conditions will be to the detriment of the applicant because the SAR value will be adversely affected.

c) steady (un-accelerated), straight, and level flight;

d) aeroplane in longitudinal and lateral trim;

e) ICAO standard day atmosphere[11];

f) gravitational acceleration for the aeroplane travelling in the direction of true North in still air at the reference altitude and a geodetic latitude of 45.5 degrees, based on g_0;

g) fuel lower heating value equal to 43.217 MJ/kg (18 580 BTU/lb);

h) a reference aeroplane CG position selected by the applicant to be representative of a mid-CG point relevant to design cruise performance at each of the three reference aeroplane masses;

Note.— For an aeroplane equipped with a longitudinal CG control system, the reference CG position may be selected to take advantage of this feature.

i) a wing structural loading condition selected by the applicant for representative operations conducted in accordance with the aeroplane’s payload capability and manufacturer standard fuel management practices;

j) applicant selected electrical and mechanical power extraction and bleed flow relevant to design cruise performance and in accordance with manufacturer recommended procedures;

Note.— Power extraction and bleed flow due to the use of optional equipment such as passenger entertainment systems need not be included.

k) engine handling/stability bleeds operating according to the nominal design of the engine performance model for the specified conditions; and

l) engine deterioration level selected by the applicant to be representative of the initial deterioration level (a minimum of 15 take-offs or 50 engine flight hours).

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[11] ICAO Doc 7488/3 entitled “Manual of the ICAO Standard Atmosphere”.

2.5.2 If the test conditions are not the same as the reference conditions, then corrections for the differences between test and reference conditions shall be applied as described in Appendix 1.

2.6 Test procedures

2.6.1 The SAR values that form the basis of the CO_2 emissions evaluation metric value shall be established either directly from flight tests or from a performance model validated by flight tests.

2.6.2 The test aeroplane shall be representative of the configuration for which certification is requested.

2.6.3 The test and analysis procedures shall be conducted in an approved manner to yield the CO_2 emissions evaluation metric value, as described in Appendix 1. These procedures shall address the entire flight test and data analysis process, from pre-flight actions to post-flight data analysis.

Note.— The fuel used for each flight test should meet the specification defined in either ASTM D1655-15[12]*, DEF STAN 91-91 Issue 7, Amendment 3*[13] *or equivalent.*

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[12] ASTM D1655-15 entitled "Standard Specification for Aviation Turbine Fuels".

[13] Defence Standard 91-91, Issue 7, Amendment 3, entitled "Turbine Fuel, Kerosene Type, Jet A-1".

APPENDIX 1. DETERMINATION OF THE AEROPLANE CO_2 EMISSIONS EVALUATION METRIC VALUE

1.— SUBSONIC JET AEROPLANES OVER 5 700 kg

2.— PROPELLER-DRIVEN AEROPLANES OVER 8 618 kg

1. INTRODUCTION

The process for determining the CO_2 emissions evaluation metric value includes:

a) the determination of the reference geometric factor (see Appendix 2);

b) the determination of the certification test and measurement conditions and procedures for the determination of SAR (see Section 3), either by direct flight test or by way of a validated performance model, including:

   1) the measurement of parameters needed to determine SAR (see Section 4);

   2) the correction of measured data to reference conditions for SAR (see Section 5); and

   3) the validation of data for calculation of the certified CO_2 emissions evaluation metric value (see Section 6);

c) calculation of the CO_2 emissions evaluation metric value (see Section 7); and

d) reporting of data to the certificating authority (see Section 8).

Note.— The instructions and procedures ensure uniformity of compliance tests, and permit comparison between various types of aeroplanes.

2. METHODS FOR DETERMINING SPECIFIC AIR RANGE

2.1 Specific air range may be determined by either direct flight test measurement of SAR test points, including any corrections of test data to reference conditions, or by the use of a performance model approved by the certificating authority. A performance model, if used, shall be validated by actual SAR flight test data.

2.2 In either case the SAR flight test data shall be acquired in accordance with the procedures defined in this Standard and approved by the certificating authority.

Recommendation.—*Validation of the performance model should only need to be shown for the test points and conditions relevant to showing compliance with the standard. Test and analysis methods, including any algorithms that may be used, should be described in sufficient detail.*

3. SPECIFIC AIR RANGE CERTIFICATION TEST AND MEASUREMENT CONDITIONS

3.1 General

This section prescribes the conditions under which SAR certification tests shall be conducted and the measurement procedures that shall be used.

Note.— Many applications for certification of a CO_2 emissions metric value involve only minor changes to the aeroplane type design. The resultant changes in the CO_2 emissions metric value can often be established reliably by way of equivalent procedures without the necessity of resorting to a complete test.

3.2 Flight test procedure

3.2.1 Pre-flight

The pre-flight procedure shall be approved by the certificating authority and shall include the following elements:

a) **Aeroplane conformity**. The test aeroplane shall be confirmed to be in conformance with the type design configuration for which certification is sought.

b) **Aeroplane weighing**. The test aeroplane shall be weighed. Any change in mass after the weighing and prior to the test flight shall be accounted for.

c) **Fuel lower heating value**. A sample of fuel shall be taken for each flight test to determine its lower heating value. Fuel sample test results shall be used for the correction of measured data to reference conditions. The determination of lower heating value and the correction to reference conditions shall be subject to the approval of the certificating authority.

1) **Recommendation.**— *The fuel lower heating value should be determined in accordance with methods which are at least as stringent as those defined in ASTM specification D4809-13*[14].

2) **Recommendation.**— *The fuel sample should be representative of the fuel used for each flight test and should not be subject to errors or variations due to fuel being uplifted from multiple sources, fuel tank selection or fuel layering in a tank.*

d) **Fuel specific gravity and viscosity**. A sample of fuel shall be taken for each flight test to determine its specific gravity and viscosity when volumetric fuel-flow meters are used.

Note.— When using volumetric fuel-flow meters the fuel viscosity is used to determine the volumetric fuel flow from the parameters measured by a volumetric fuel flow meter. The fuel specific gravity (or density) is used to convert the volumetric fuel flow to a mass fuel flow.

1) Recommendation. — *The fuel specific gravity should be determined in accordance with methods which are at least as stringent as those defined in ASTM specification D4052-11*[15].

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[14] ASTM D4809-13 entitled “Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)”.

[15] ASTM D4052-11 entitled “Standard Test Method for Density and Relative Density of Liquids by Digital Density Meter”.

2) Recommendation.— *The fuel kinematic viscosity should be determined in accordance with methods which are at least as stringent as those defined in ASTM specification D445-15*[16]*.*

3.2.2 Flight test method

3.2.2.1 The flight tests shall be performed in accordance with the following flight test method and the stability conditions described in 3.2.3.

3.2.2.2 Test points shall be separated by a minimum duration of two minutes, or separated by an exceedance of one or more of the stability criteria limits in 3.2.3.1.

3.2.2.3 **Recommendation**.— *During the test conditions flown to determine SAR the following criteria should be adhered to:*

a) the aeroplane is flown at constant pressure altitude and constant heading along isobars to the extent that is practicable;

b) the engine thrust/power setting is stable for un-accelerated level flight;

c) the aeroplane is flown as close as practicable to the reference conditions to minimize the magnitude of any corrections;

d) there are no changes in trim or engine power/thrust settings, engine stability and handling bleeds, and electrical and mechanical power extraction (including bleed flow). Any changes in the use of aeroplane systems that may affect the SAR measurement should be avoided; and

e) movement of on-board personnel is kept to a minimum.

3.2.3 Test condition stability

3.2.3.1 For a SAR measurement to be valid, the following parameters shall be maintained within the indicated tolerances for a minimum duration of 1 minute during which the SAR data is acquired:

a) Mach number within ±0.005;

b) ambient temperature within ±1°C;

c) heading within ±3 degrees;

d) track within ±3 degrees;

e) drift angle less than 3 degrees;

f) ground speed within ±3.7 km/h (±2 kt);

g) difference in ground speed at the beginning of the test condition from the ground speed at the end of the test condition within ±2.8 km/h/min (±1.5 kt/min); and

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[16] ASTM D445-15 entitled “Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)”.

h) pressure altitude within ±23 m (±75 ft).

3.2.3.2 Alternatives to the stable test condition criteria listed above may be used provided that stability can be sufficiently demonstrated to the certificating authority.

3.2.3.3 Test points that do not meet the stable test criteria defined in 3.2.3.1 should normally be discarded. However, test points that do not meet the stability criteria of 3.2.3.1 may be acceptable subject to the approval of the certificating authority, and would be considered as an equivalent procedure.

3.2.4 Verification of aeroplane mass at test conditions

3.2.4.1 The procedure for determining the mass of the aeroplane at each test condition shall be subject to the approval of the certificating authority.

3.2.4.2 **Recommendation**.— *The mass of the aeroplane during a flight test should be determined by subtracting the fuel used (i.e. integrated fuel flow) from the mass of the aeroplane at the start of the test flight. The accuracy of the determination of the fuel used should be verified by weighing the test aeroplane on calibrated scales either before and after the SAR test flight, or before and after another test flight with a cruise segment provided that flight occurs within one week or 50 flight hours (at the option of the applicant) of the SAR test flight and with the same, unaltered fuel flow meters.*

4. MEASUREMENT OF AEROPLANE SPECIFIC AIR RANGE

4.1 Measurement System

4.1.1 The following parameters shall be recorded at a minimum sampling rate of 1 Hz:

a) airspeed;

b) ground speed;

c) true airspeed;

d) fuel flow;

e) engine power setting parameter (e.g. fan speed, engine pressure ratio, torque, shaft horse power);

f) pressure altitude;

g) temperature;

h) heading;

i) track; and

j) fuel used (for the determination of gross mass and CG position).

4.1.2 The following parameters shall be recorded at a suitable sampling rate:

a) latitude;

b) engine bleed positions and power off-takes; and

c) power extraction (electrical and mechanical load).

4.1.3 The value of each parameter used for the determination of SAR, except for ground speed, shall be the simple arithmetic average of the measured values for that parameter obtained throughout the stable test condition (see 3.2.3.1).

Note.— The rate of change of ground speed during the test condition is to be used to evaluate and correct any acceleration or deceleration that might occur during the test condition.

4.1.4 The resolution of the individual measurement devices shall be sufficient to determine that the stability of the parameters defined in 3.2.3.1 is maintained.

4.1.5 The overall SAR measurement system is considered to be the combination of instruments and devices, including any associated procedures, used to acquire the following parameters necessary for the determination of SAR:

a) fuel flow;

b) Mach number;

c) altitude;

d) aeroplane mass;

e) ground speed;

f) outside air temperature;

g) fuel lower heating value; and

h) centre of gravity

4.1.6 The accuracy of the individual elements that comprise the overall SAR measurement system is defined in terms of its effect upon SAR. The cumulative error associated with the overall SAR measurement system is defined as the root sum of squares (RSS) of the individual accuracies.

Note.— Parameter accuracy need only be examined within the range of the parameter needed for showing compliance with the CO_2 emissions standard.

4.1.7 If the absolute value of the cumulative error of the overall SAR measurement system is greater than 1.5 per cent a penalty equal to the amount that the RSS value exceeds 1.5 per cent shall be applied to the SAR value corrected to reference conditions (see section 5). If the absolute value of the cumulative error of the overall SAR measurement system is less than or equal to 1.5 per cent no penalty shall be applied.

5. CALCULATION OF REFERENCE SPECIFIC AIR RANGE FROM MEASURED DATA

5.1 Calculation of SAR

5.1.1 SAR is calculated from the following equation:

$$SAR = TAS/W_f$$

where:

TAS is the true air speed; and

W_f is total aeroplane fuel flow.

5.2 Corrections from test to reference conditions

5.2.1 Corrections shall be applied to the measured SAR values to correct to the reference conditions specified in 2.5 of Part II, Chapter 2. Corrections shall be applied for each of the following measured parameters that is not at the reference conditions:

Apparent gravity. Acceleration, caused by the local effect of gravity, and inertia, affects the test weight of the aeroplane. The apparent gravity at the test conditions varies with latitude, altitude, ground speed, and direction of motion relative to the Earth’s axis. The reference gravitational acceleration is the gravitational acceleration for the aeroplane travelling in the direction of true North in still air at the reference altitude, a geodetic latitude of 45.5 degrees, and based on g_0.

Mass/δ. The lift coefficient of the aeroplane is a function of mass/δ and Mach number, where δ is the ratio of the atmospheric pressure at a given altitude to the atmospheric pressure at sea level. The lift coefficient for the test condition affects the drag of the aeroplane. The reference mass/δ is derived from the combination of the reference mass, reference altitude and atmospheric pressures determined from the ICAO standard atmosphere.

Acceleration/deceleration (energy). Drag determination is based on an assumption of steady, unaccelerated flight. Acceleration or deceleration occurring during a test condition affects the assessed drag level. The reference condition is steady, unaccelerated flight.

Reynolds number. The Reynolds number affects aeroplane drag. For a given test condition the Reynolds number is a function of the density and viscosity of air at the test altitude and temperature. The reference Reynolds number is derived from the density and viscosity of air from the ICAO standard atmosphere at the reference altitude and temperature.

CG position. The position of the aeroplane centre of gravity affects the drag due to longitudinal trim.

Aeroelastics. Wing aeroelasticity may cause a variation in drag as a function of aeroplane wing mass distribution. Aeroplane wing mass distribution will be affected by the fuel load distribution in the wings and the presence of any external stores.

Fuel lower heating value. The fuel lower heating value defines the energy content of the fuel. The lower heating value directly affects the fuel flow at a given test condition.

Altitude. The altitude at which the aeroplane is flown affects the fuel flow.

Temperature. The ambient temperature affects the fuel flow. The reference temperature is the standard day temperature from the ICAO standard atmosphere at the reference altitude.

Engine deterioration level. When first used, engines undergo a rapid, initial deterioration in fuel efficiency. Thereafter, the rate of deterioration significantly decreases. Engines with less deterioration than the reference engine deterioration level may be used, subject to the approval of the certificating authority. In such a case, the fuel flow shall be corrected to the reference engine deterioration level using an approved method. Engines with more deterioration than the reference engine deterioration level may be used. In this case a correction to the reference condition shall not be permitted.

Electrical and mechanical power extraction and bleed flow. Electrical and mechanical power extraction and bleed flow affects the fuel flow.

Note.— Post-flight data analysis includes the correction of measured data for data acquisition hardware response characteristics (e.g. system latency, lag, offset, buffering, etc.).

5.2.2 Correction methods are subject to the approval of the certificating authority. If the applicant considers that a particular correction is unnecessary then acceptable justification shall be provided to the certificating authority.

5.3 Calculation of specific air range

5.3.1 The SAR values for each of the three reference masses defined in 2.3 of Chapter 2, Part II, shall be calculated either directly from the measurements taken at each valid test point adjusted to reference conditions, or indirectly from a performance model that has been validated by the test points. The final SAR value for each reference mass shall be the simple arithmetic average of all valid test points at the appropriate gross mass, or derived from a validated performance model. No data acquired from a valid test point shall be omitted unless agreed by the certificating authority.

Note.— Extrapolations consistent with accepted airworthiness practices to masses other than those tested may be allowable using a validated performance model. The performance model should be based on data covering an adequate range of lift coefficient, Mach number, and thrust specific fuel consumption such that there is no extrapolation of these parameters.

6. VALIDITY OF RESULTS

6.1 The 90 per cent confidence interval shall be calculated for each of the SAR values at the three reference masses.

6.2 If clustered data is acquired independently for each of the three gross mass reference points, the minimum sample size acceptable for each of the three gross mass SAR values shall be six.

6.3 Alternatively SAR data may be collected over a range of masses. In this case the minimum sample size shall be twelve and the 90 per cent confidence interval shall be calculated for the mean regression line through the data.

6.4 If the 90 per cent confidence interval of the SAR value at any of the three reference aeroplane masses exceeds ±1.5 per cent, the SAR value at that reference mass may be used, subject to the approval of the certificating authority, if a penalty is applied to it. The penalty shall be equal to the amount that the 90 per cent confidence interval exceeds ±1.5 per cent. If the 90 per cent confidence interval of the SAR value is less than or equal to ±1.5 per cent no penalty need be applied.

Note.— Methods for calculating the 90 per cent confidence interval are given in ICAO Doc 9501 Volume III.

7. CALCULATION OF THE CO_2 EMISSIONS EVALUATION METRIC VALUE

7.1 The CO_2 emissions evaluation metric value shall be calculated according to the formula defined in 2.2 of Part II, Chapter 2.

8. REPORTING OF DATA TO THE CERTIFICATING AUTHORITY

Note.— The information required is divided into: 1) general information to identify the aeroplane characteristics and the method of data analysis; 2) list of reference conditions used; 3) the data obtained from the aeroplane test(s); 4) the calculations and corrections of SAR test data to reference conditions, and 5) the results derived from the test data.

8.1 General information

The following information shall be provided for each aeroplane type and model for which CO_2 certification is sought:

a) designation of the aeroplane type and model;

b) general characteristics of the aeroplane, including centre of gravity range, number and type designation of engines and, if fitted, propellers;

c) maximum take-off mass;

d) the relevant dimensions needed for calculation of the reference geometric factor; and

e) serial number(s) of the aeroplane(s) tested for CO_2 certification purposes and, in addition, any modifications or non-standard equipment likely to affect the CO_2 characteristics of the aeroplane.

8.2 Reference conditions

The reference conditions used for the determination of specific air range (see Part II, Chapter 2, 2.5) shall be provided.

8.3 Test data

The following measured test data, including any corrections for instrumentation characteristics, shall be provided for each of the test measurement points.

a) airspeed, ground speed and true airspeed;

b) fuel flow;

c) pressure altitude;

d) static air temperature;
e) aeroplane gross mass and centre of gravity for each test point;

f) levels of electrical and mechanical power extraction and bleed flow;

g) engine performance:

  1) for jet aeroplanes, engine power setting;

  2) for propeller-driven aeroplanes, shaft horsepower or engine torque and propeller rotational speed.

h) fuel lower heating value;

i) fuel specific gravity and kinematic viscosity if volumetric fuel flow meters are used (see 3.2.1d);

j) the cumulative error (RSS) of the overall measurement system (see 4.1.6);

k) heading, track and latitude;

l) stability criteria (see 3.2.3.1);

m) description of the instruments and devices used to acquire the parameters necessary for the determination of SAR, and their individual accuracies in terms of their effect on SAR (see 4.1.5 and 4.1.6);

8.4 Calculations and corrections of SAR test data to reference conditions

The measured SAR values, corrections to the reference conditions, and corrected SAR values shall be provided for each of the test measurement points.

8.5 Derived data

The following derived information shall be provided for each aeroplane tested for certification purposes:

a) the specific air range (km/kg) for each reference aeroplane mass and the associated 90 per cent confidence interval;

b) the average of the inverse of the three reference mass specific air range values;

c) the reference geometric factor ; and

d) the CO_2 emissions evaluation metric value.

APPENDIX 2. REFERENCE GEOMETRIC FACTOR

1. The reference geometric factor (RGF) is a non-dimensional parameter used to adjust $(1/SAR)_{AVG}$. RGF is based on a measure of fuselage size normalised with respect to 1 m^2, and is derived as follows:

a) for aeroplanes with a single deck determine the area of a surface (expressed in m^2) bounded by the maximum width of the fuselage outer mould line (OML) projected to a flat plane parallel with the main deck floor; and

b) for aeroplanes with an upper deck determine the sum of the area of a surface (expressed in m^2) bounded by the maximum width of the fuselage outer mould line (OML) projected to a flat plane parallel with the main deck floor, and the area of a surface bounded by the maximum width of the fuselage OML at or above the upper deck floor projected to a flat plane parallel with the upper deck floor is determined; and

c) determine the non-dimensional RGF by dividing the areas defined in 1(a) or 1(b) by 1 m^2.

2. The RGF includes all pressurised space on the main or upper deck including aisles, assist spaces, passage ways, stairwells and areas that can accept cargo and auxiliary fuel containers. It does not include permanent integrated fuel tanks within the cabin or any unpressurized fairings, nor crew rest/work areas or cargo areas that are not on the main or upper deck (e.g. ‘loft’ or under floor areas). RGF does not include the cockpit crew zone.

3. The aft boundary to be used for calculating RGF is the aft pressure bulkhead. The forward boundary is the forward pressure bulkhead except for the cockpit crew zone.

4. Areas that are accessible to both crew and passengers are excluded from the definition of the cockpit crew zone. For aeroplanes with a cockpit door, the aft boundary of the cockpit crew zone is the plane of the cockpit door. For aeroplanes having optional interior configurations that include different locations of the cockpit door, or no cockpit door, the boundary shall be determined by the configuration that provides the smallest cockpit crew zone. For aeroplanes certified for single-pilot operation, the cockpit crew zone shall extend half the width of the cockpit.

5. Figures A2-1 and A2-2 provide a notional view of the RGF boundary conditions.

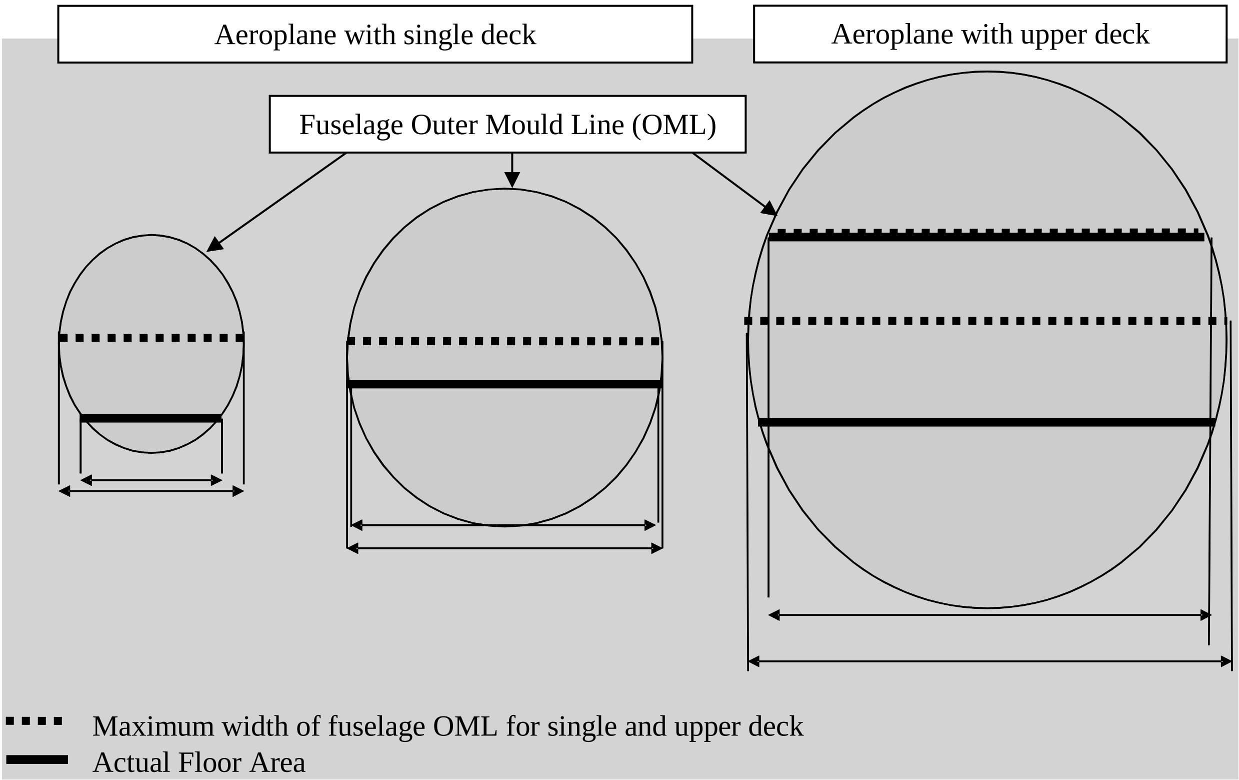


Figure A2-1. Cross-sectional View

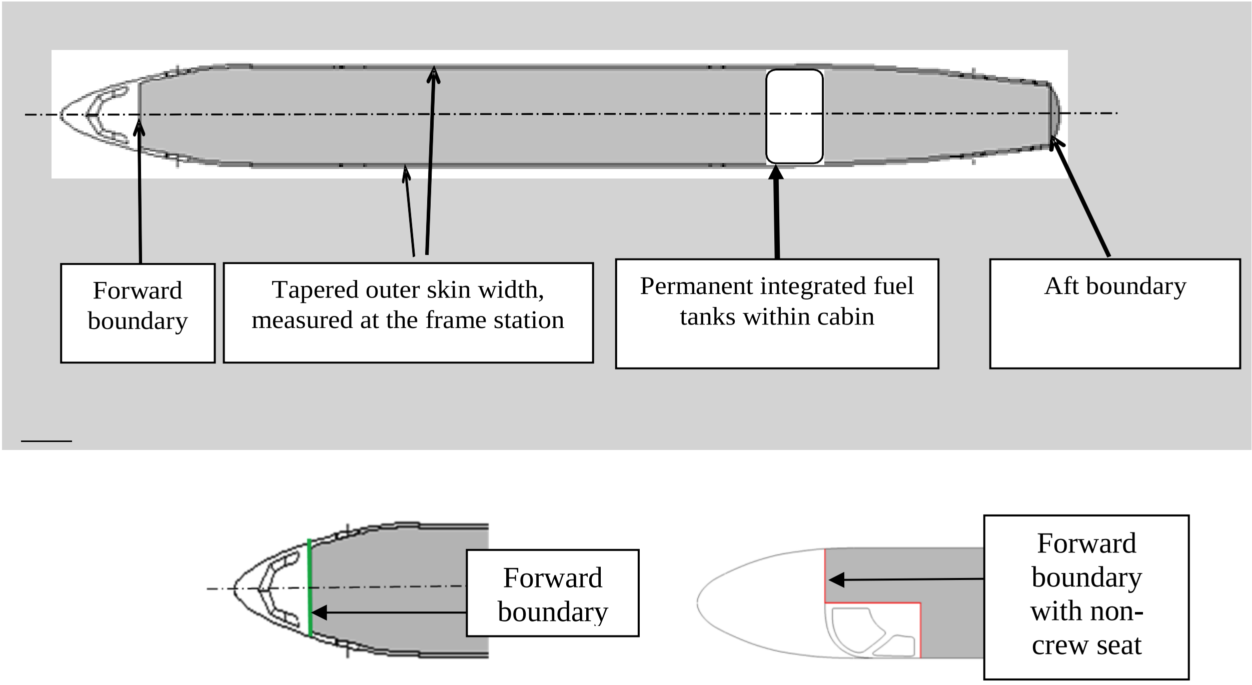


Figure A2-2. Longitudinal View

6.3.3. CAEP Steering Group 2016 approved revision of the Environmental Technical Manual (ETM), Vol III

Environmental Technical Manual

Volume III
Procedures for the CO_2 Emissions Certification of Aeroplanes

International Civil Aviation Organization
Committee on Aviation Environmental Protection

FOREWORD

ICAO Doc 9501, Volume III, First Edition, includes material which has been approved by the ICAO Committee on Aviation Environmental Protection (CAEP) Steering Group during their tenth meeting (CAEP/10) in February 2016. This manual is to be periodically revised under the supervision of the CAEP Steering Group and is intended to make the most recent information available to certificating authorities, aeroplane certification applicants and other interested parties in a timely manner, aiming at achieving the highest degree of harmonisation possible. The technical procedures and equivalent procedures described in this approved revision of the ETM Volume III are consistent with currently accepted techniques and modern instrumentation. This revision and subsequent revisions that may be approved by the CAEP Steering Group will be posted on the ICAO website (http://www.icao.int/) under “publications” until the latest approved revision is submitted to CAEP for formal endorsement and subsequent publication by ICAO.

Comments on this manual, particularly with respect to its application and usefulness, would be appreciated from all States. These comments will be taken into account in the preparation of subsequent editions. Comments concerning this manual should be addressed to:

The Secretary General
International Civil Aviation Organization
999 Robert-Bourassa Boulevard
Montréal, Quebec H3C 5H7
Canada

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS

Acronym or Abbreviation	Meaning	Unit
A	Area	m^2
A16V3	Annex 16 Volume III	-
C_D	Drag coefficient	-
C_L	Lift coefficient	-
CG	Centre of gravity	-
CI	Confidence interval	-
CO_2	Carbon dioxide	-
ETMV3	Environmental technical manual volume III	-
g	Gravitational acceleration	m/s^2
h	Altitude	m
LHV	Lower heating value	MJ/kg
M	Mach number	-
MAC	Mean aerodynamic chord	cm
MTOM	Maximum take-off mass	kg
OML	Outer mould line	-
R_e	Radius of the Earth	m
RE	Reynolds number	-
RGF	Reference geometric factor	-
SAR	Specific air range	km/kg
T	Temperature	K
TAS	True air speed	km/h
TOM	Take-off mass	kg
V	Speed	m/s
W_f	Total aeroplane fuel flow	kg/h
W	Weight	N
WV	Weight variant	-
δ	Ratio of atmospheric pressure at a given altitude to the atmospheric pressure at sea level	-
Φ	Latitude	degrees
ρ	Density	kg/m^3
σ	Ground track angle	degrees

Chapter 1 – INTRODUCTION

1.1 PURPOSE

1.1.1 The aim of this manual is to promote uniformity of implementation of the technical procedures of Annex 16 — Environmental Protection, Volume III — Aeroplane CO_2 Emissions by providing: (1) guidance to certificating authorities, applicants and other interested parties regarding the intended meaning of the Standards in the current edition of the Annex; (2) guidance on specific methods that are deemed acceptable in demonstrating compliance with those Standards; and (3) equivalent procedures resulting in effectively the same CO_2 emissions evaluation metric that may be used in lieu of the procedures specified in the Appendices of Annex 16 Volume III.

1.2 DOCUMENT STRUCTURE

1.2.1 Chapter 1 provides general information regarding the use of this Environmental Technical Manual Volume III. Chapter 2 provides general guidelines on the interpretation of Annex 16 Volume III. Chapter 3 brings technical guidelines for the certification of aeroplanes against Annex 16 Volume III, including equivalent procedures.

1.2.2 Guidance is provided in the form of explanatory information, acceptable methods for showing compliance, and equivalent procedures.

1.3 EQUIVALENT PROCEDURES

1.3.1 The procedures described in the Annex, as supplemented by the means of compliance information provided in this manual, shall be used unless an equivalent procedure is approved by the certificating authority. Equivalent procedures should not be considered as limited only to those described herein, as this manual will be expanded as new equivalent procedures are developed. Also, their presentation does not infer limitation of their application or commitment by certificating authorities to their further use.

1.3.2 The use of equivalent procedures may be requested by applicants for many reasons, including:

1) to make use of previously acquired or existing data for the aeroplane; and
2) to minimize the costs of demonstrating compliance with the requirements of Annex 16, Volume III, by keeping aeroplane test time and equipment and personnel costs to a minimum.

1.4 EXPLANATORY INFORMATION

1.4.1 Explanatory information has the following purpose:

a) explains the intent of the Annex 16 Volume III Standards;
b) states current policies of certificating authorities regarding compliance with the Annex; and
c) provides information on critical issues concerning approval of applicants' compliance methodology proposals.

1.5 CONVERSION OF UNITS

1.5.1 Conversions of some non-critical numerical values between U.S. Customary (English) and SI units are shown in the context of acceptable approximations.

1.6 REFERENCES

1.6.1 Unless otherwise specified, references throughout this document to “the Annex” relate to Annex 16 to the Convention on International Civil Aviation (Environmental Protection), Volume III (Aeroplane CO_2 Emissions), First Edition**.**

1.6.2 References to sections of this manual are defined only by the section number to which they refer. References to documents other than the Annex are numbered sequentially (e.g., Reference 1, Reference 2, etc.). A list of these documents is provided in Appendix 1 of this manual, and a bibliography can be found in Appendix 2.

Chapter 2 - GENERAL GUIDELINES

2.1 APPLICABILITY OF ANNEX 16, VOLUME III

2.1.1 The Chicago Convention Article 3 specifically states that it is not applicable to state aircraft and provides some examples (see below), but this can also include specific flights carrying official government representatives:

" a) This Convention shall be applicable only to civil aircraft, and shall not be applicable to state aircraft.

b) Aircraft used in military, customs and police services shall be deemed to be state aircraft."

2.1.2 In addition, Annex 16 Vol. III, Part II, Chapter 2, para. 2.1 excepts amphibious aeroplanes; aeroplanes initially designed or modified for specialized operational requirements and used as such; aeroplanes designed with zero RGF; and those aeroplanes specifically designed or modified and used for fire-fighting purposes. These are typically special categories of aeroplanes which are limited in numbers and have specific technical characteristics resulting in very different CO2 metric values compared to all other aeroplane types in the proposed applicability scope.

2.1.3 Examples of specialized operational requirements include:

a) aeroplanes that are initially certified as civil aeroplanes during the production process but immediately converted to military aeroplanes;
b) a required capacity to carry cargo that is not possible by using less-specialised aeroplanes (e.g. ramped, with back cargo door);
c) a required capacity for very short or vertical take-offs and landings;
d) a required capacity to conduct scientific, research, or humanitarian missions exclusive of commercial service; or
e) similar factors.

2.1.4 Type design configurations which shall be certified

2.1.4.1 Annex 16 Volume III defines in Part I, Chapter 1 the *"Maximum take-off mass" (MTOM)* as being *"the highest of all take-off masses for the type design configuration"*. Part II, Chapter 2, section 2.3 defines the three reference masses at which the 1/SAR value shall be established, and these masses are calculated based on the MTOM.

2.1.4.2 Applicants may develop multiple TOM variants of a specific type design configuration (i.e., combination of airframe/engine) for operational purposes. As stated above, only the highest Maximum Take-off Mass of a specific airframe/engine combination is required to be certified against Annex 16 Volume III. As stated in Annex 16, Volume III, Part II, Chapter II, paragraph 2.3.2, certification at MTOM also certifies all TOM variants. These TOM variants would have the same CO_2 emissions evaluation metric value as the MTOM.

2.1.4.3 Annex 16, Volume III, Part II, Chapter II, paragraph 2.3.2, also states that *"The applicant may also apply for the approval of CO_2 metric values at take-off masses lower than the highest of all maximum take-off masses"*. The purpose of this statement is to allow the applicant to apply for approval of a separate CO_2 emissions evaluation metric value for a TOM lower than the MTOM. In that case, the reference aeroplane masses, and the maximum permitted CO_2 emissions evaluation metric value, would be based on the TOM instead of the MTOM. The CO_2 emissions evaluation metric value for this TOM could then also be used for any TOM variant of even lower mass. Applicants can apply for approval for separate CO_2 emissions evaluation metric values for as many or as few TOM variants as they desire.

2.1.4.4 Example of type design configurations to be certified.

Assuming an applicant applies for the approval of the following type design configurations:

a) Two fuselage lengths: Model A and Model B;
b) Two engine options: Engine X and Engine Y;
c) Two weight variants (WV) for each fuselage length: WV01 and WV02 for Model A and WV11 and WV12 for Model B.

The possible combinations are summarised in Table 2.1-1 below:

Model A	Engine X	WV01
		WV02
	Engine Y	WV01
		WV02
Model B	Engine X	WV11
		WV12
	Engine Y	WV11
		WV12

Table 2.1-1 - Type Design Configuration combinations

The type design configurations that shall be certified against Annex 16 Volume III are the ones that have the highest MTOM. Each combination of fuselage length and engine option is a separate type design configuration. Assuming WV01 and WV11 have higher maximum take-off masses than WV02 and WV12, the following combinations shall be certified:

a) Model A – Engine X – WV01;
b) Model A – Engine Y – WV01;
c) Model B – Engine X – WV11;
d) Model B – Engine Y – WV11.

The combinations with WV02 and WV12 would be assigned the same CO_2 emissions evaluation metric value as the combinations with WV01 and WV11, respectively. At the applicant's option, the combinations with WV02 and/or WV12 could also be certified to obtain a different CO_2 emissions evaluation metric value for those combinations.

2.1.5. Appropriate margin to regulatory level

2.1.5.1 If an applicant chooses to voluntarily certify a lower TOM variant, as discussed in paragraph 2.1.4 above, it should be kept in mind that an underlying principle in applying the CO_2 standard is that the highest weight variant (MTOM) has the lowest margin to the regulatory limit level. The 1/SAR value used in the CO_2 metric system is calculated as an average of three reference masses (high, medium, and low).

2.1.5.2 In establishing the reference conditions for SAR determination, it is expected that the highest SAR value will be sought at the maximum range cruise condition at the optimum altitude (Annex 16, Volume III, Chapter 2, Paragraph 2.5). It is noted that a greater non-linearity in the 1/SAR vs. mass relationship could be introduced by a constraint unrelated to the aerodynamic and propulsive efficiency of the aeroplane (e.g., an altitude pressurisation limitation). In this instance, particular care should be taken that the principle of the highest weight variant having the lowest margin to the regulatory limit level continues to hold.

2.2 CHANGES TO CO_2 APPROVED AEROPLANE TYPE DESIGNS

Editorial Note: Sections 2.2.1 and 2.2.2 have been updated based on the agreement reached at Steering Group 2016 (SG2016). The associated SG2016 agreed amendments to Annex 16, Volume III will be considered for inclusion by the Council following the Eleventh meeting of CAEP (CAEP/11) in February 2019.

2.2.1 Part I, Chapter I includes the following definition:

> "***Derived version of a CO2-certified aeroplane.*** An aeroplane which incorporates changes in type design that either increase its maximum take-off mass, or that increase its CO_2 emissions evaluation metric value by more than:
>
> a) 1.35% at a maximum take-off mass of 5 700 kg, decreasing linearly to;
> b) 0.75% at a maximum take-off mass of 60 000 kg, decreasing linearly to;
> c) 0.70% at a maximum take-off mass of 600 000 kg; and
> d) a constant 0.70% at maximum take-off masses greater than 600 000 kg.
>
> *Note.— In some States, where the certificating authority finds that the proposed change in design, configuration, power or mass is so extensive that a substantially complete investigation of compliance with the applicable airworthiness regulations is required, the aeroplane is defined as a new type design rather than a derived version.*"

2.2.2 The note clarifies that it is the airworthiness regulations that determine whether or not an aeroplane model is a New Type design (ref. ANAC RBAC 21.19, EASA Part 21.A.19, FAA: Title 14 of the Code of Federal Regulations, Chapter I, Subchapter C, Part 21.19, IAC AP-21 Subpart B para. 21/19, TCCA CAR 521.153). If it is a New Type for airworthiness, then it is also a New Type design from CO2 emissions certification perspective.
Conversely, if the airworthiness requirements do not determine an aeroplane model to be a New Type, then it is a Derived Version for the CO2 requirements. In this case the CO2 certification basis is the same as the aeroplane model from which it is derived, or any later amendment at the option of the applicant.

2.2.3 Consequently, any change to a CO_2 certified aeroplane type design that increases its maximum take-off mass shall be considered a derived version, and the applicant shall demonstrate compliance with Annex 16 Volume III. In addition, any change to a CO_2 certified aeroplane type design that increases its certified CO_2 emissions evaluation metric value by more than the abovementioned thresholds shall be considered a derived version, and the applicant shall demonstrate compliance with Annex 16 Volume III.

2.2.4 Changes to a CO_2-certified aeroplane type design that do not increase its maximum take-off mass or its CO_2 emissions evaluation metric by more than the abovementioned thresholds are considered no-CO_2 changes, and the CO_2 emissions evaluation metric value of the changed type design configuration shall be considered the same as the parent type design. This definition of the no-CO_2 change thresholds is also referred to as the "No-CO_2-Change Criterion".

2.2.5 The evaluation of some changes can be done by simpler equivalent procedures, as detailed in 3.4.2 – Approval based on back-to-back testing or 3.4.3 – Approval of changes based on analysis.

2.2.6 Visualization of the No-CO_2-Change Criterion thresholds is provided in Figure 2.2-1. The trend line equations may be used to evaluate what the no-CO_2 change threshold is for any MTOM.

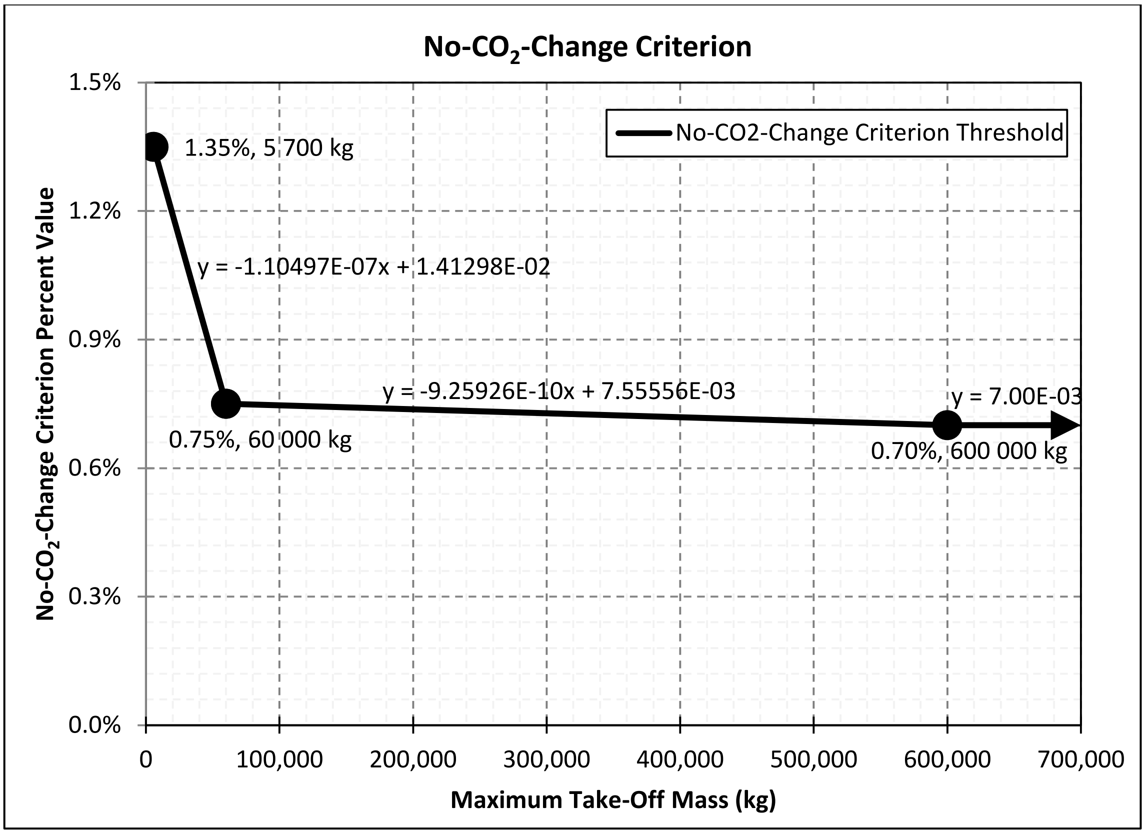


Figure 2.2-1 – Visualization of the No-CO_2-Change Criterion

2.3 CO_2 EMISSIONS EVALUATION METRIC COMPLIANCE DEMONSTRATION PLANS

2.3.1 Prior to undertaking a CO_2 certification demonstration, the applicant should submit to the certificating authority a CO_2 compliance demonstration plan. This plan contains a complete description of the methodology and procedures by which an applicant proposes to demonstrate compliance with the CO_2 certification Standards specified in Annex 16 Volume III. Approval of the plan and the proposed use of any equivalent procedures or technical procedures not included in the Annex remains with the certificating authority. CO_2 compliance demonstration plans should include the following types of information:

a) *Introduction.* A description of the aeroplane CO_2 certification basis.

b) *Aeroplane description.* Type, model number and the specific configuration to be certificated.

Note.— The certificating authority should require that the applicant demonstrate and document the conformity of the test aeroplane, particularly with regard to those parts which might affect its CO_2 emissions evaluation metric.

c) *Aeroplane CO_2 certification methodology.* Means of compliance, equivalent procedures from this ETM and technical procedures from Annex 16 Volume III.

d) *Plans for tests.* The plans for test should include:

1) *Test description.* Test methods to comply with the test environment and flight path conditions of the Annex, as appropriate.

Note— Plans for tests shall either be integrated into the basic CO_2 compliance demonstration plan or submitted separately and referenced in the basic plan.

e) Deliverables. List the documents that should show compliance with Annex 16 Volume III (test and analysis reports, including RGF determination).

2.4 ENGINE INTERMIX

2.4.1 Applicants will typically demonstrate compliance with the Standard of Chapter 2 of Annex 16 Volume III for an aeroplane type configuration where all engines are of the same design. However an applicant may wish to demonstrate compliance of an aeroplane type configuration where not all the engines are of the same design. Such a configuration is commonly referred to as an “engine intermix” configuration.

2.4.2 In such a case the applicant may, subject to the approval of the certificating authority, demonstrate compliance in one of three ways:

a) In accordance with the test procedures defined in paragraph 2.6 of Chapter 2 of the Annex and for which the test aeroplane shall be representative of the intermix configuration for which certification is requested; or

b) In cases where the CO_2 metric value has been established for aeroplanes on which each of the intermix engine models has been exclusively installed, compliance can be demonstrated on the basis of either:

1) the average of the CO_2 emissions evaluation metrics for aeroplanes on which each of the intermix engine models has been exclusively installed; or

2) the highest CO_2 emissions evaluation metric of the aeroplanes on which each of the intermix engine models has been exclusively installed.

Note.− Paragraph 2.1.2 of Chapter 2 of Annex 16, Volume III, states that in the case of time-limited engine changes Contracting States may not require a demonstration of compliance with the Standards of Annex 16, Volume III.

2.5 EXEMPTIONS

2.5.1 Introduction

2.5.1.1 Annex 16, Volume III, Part II, Chapter 2, paragraph 2.1.3 raises the possibility for certificating authorities to exempt aeroplane units from the applicability requirements in the First Edition of Annex 16, Volume III, Part II, Chapter 2, paragraph 2.1.1 (a) to (g).

2.5.1.2 In addition Part II, Chapter 1 paragraph 1.11, indicates that Contracting States shall recognise valid exemptions agreed by another Contracting State provided that the process for granting exemption is acceptable. It is recommended to follow the acceptable process and criteria as described in this ETM. For example, certificating authorities may decide to exempt low volume production aeroplanes in exceptional circumstances, taking into account the justifications listed in 2.5.2.1 c).

2.5.1.3 In order to promote a harmonized global approach to the granting, implementing and monitoring of these exemptions, this section provides guidelines on the process and criteria for issuing exemptions from the CO_2 standard agreed at CAEP/10 (Part II, Chapter 2, paragraph 2.4).

2.5.2 Exemption process

2.5.2.1 Application

The applicant should submit to the competent authority a formal application letter for the manufacture of the exempted aeroplanes, and copied to all other relevant organizations and involved competent authorities. The letter should include the following information in order for the competent authority to be in a position to review the application:

a) Administration

name, address and contact details of the applicant.

b) Scope of application for exemptions

1) aeroplane type (e.g. new or in-production type, model designation, type certificate (TC) number, TC date);
2) number of aeroplane exemptions requested;
3) anticipated duration (end date) of continued production of exempted aeroplanes;
4) designation of to whom the aeroplanes will be originally delivered.

c) Justification for the exemptions. In applying for an exemption, an applicant should, to the extent possible, address the following factors, with quantification, in order to support the merits of the exemption request:

1) technical issues, from an environmental and airworthiness perspective, which may have delayed compliance;
2) economic impacts on the manufacturer, operator(s) and the aviation industry at large;
3) environmental effects. This should consider the amount of additional CO_2 that will be emitted as a result of the exemption, including items such as the amount that the aeroplane model exceeds the Standard, taking into account any other aeroplane models in the aeroplane family covered by the same type certificate and their relation to the Standard;
4) interdependencies. The impact of changes to reduce CO_2 on other environmental factors, including community noise, NOx, nvPM, HC and CO emissions;
5) the impact of unforeseen circumstances and hardship due to business circumstances beyond the manufacturer's control (e.g. employee strike, supplier disruption or calamitous event);
6) projected future production volumes and plans for producing a compliant version of the aeroplane model for which exemptions are sought;
7) for NT aeroplanes only, provide a demonstration that the maximum use of fuel efficient technology relative to CAEP/10 NT regulatory limit was reasonably applied to the design to the aeroplane;
8) equity issues in granting exemptions among economically competing parties (e.g. provide the rationale for granting an exemption when another manufacturer has a compliant aeroplane and does not need an exemption, taking into account the implications for operator fleet composition, commonality and related issues in the absence of the aeroplane for which exemptions are sought); and
9) any other relevant factors.

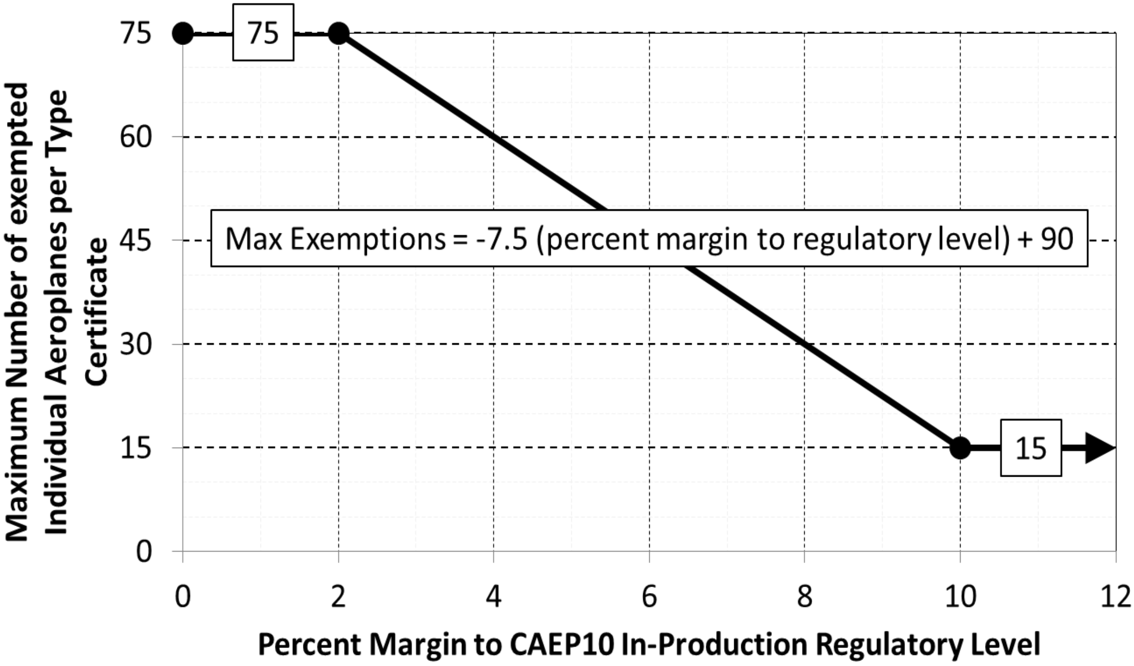
2.5.2.2 Evaluation Criteria

The evaluation of an exemption application should be based on the justification provided. The total number of exempted aeroplanes should be agreed at the time the application is approved and based on the considerations explained in 2.5.2.1 c).

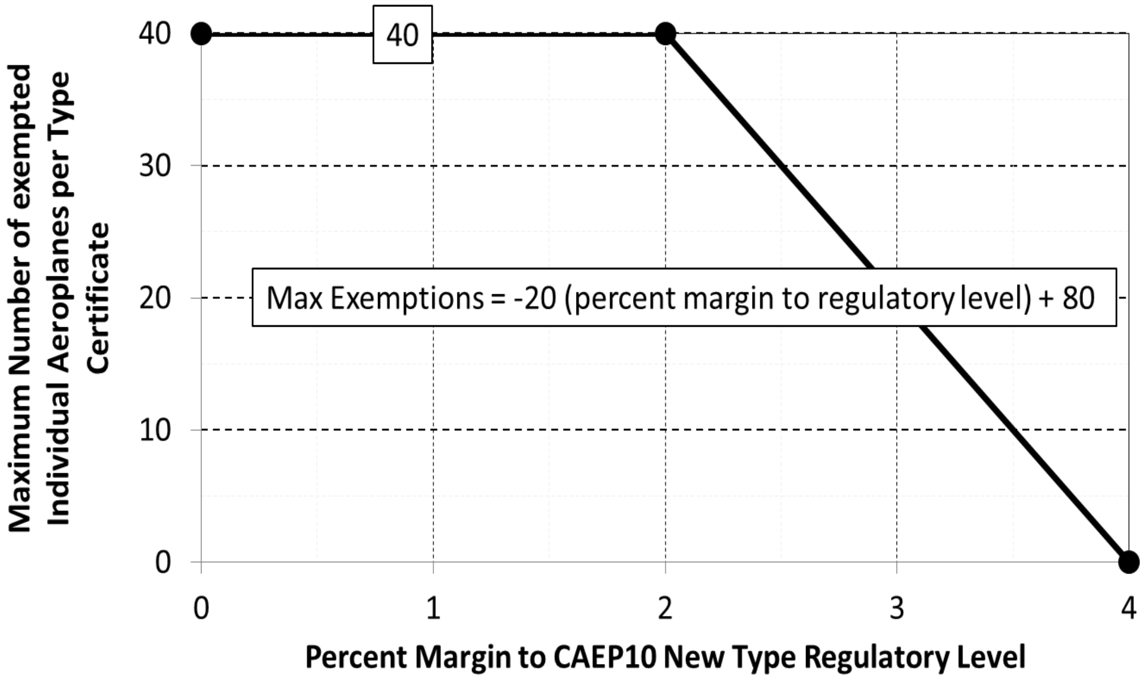
The proposed maximum number of potential exemptions should be inversely proportional to the % margin of the CO_2 metric value from the regulatory level (Part II, Chapter 2, paragraph 2.4). Those aeroplane types with a smaller % margin to the regulatory level should be permitted a larger number of exemptions compared to the aeroplane types with a larger % margin.

Following the recommendation in Part II, Chapter 1, paragraph 1.11 to use an acceptable process, the number of aeroplanes exempted per type certificate would normally not exceed the proposed maximum number in the tables and figures below..

% Margin to CAEP10 In-Production Regulatory level	Maximum Exemptions Total
0 to 2	75
2 to 10	-7.5 × (percent margin to regulatory level)+90
More than 10	15



% Margin to CAEP10 New Type Regulatory level	Maximum Exemptions Total
0 to 2	40
2 to 4	-20 × (percent margin to regulatory level)+80
More than 4	0



The maximum number of exemptions should be reviewed during the CAEP/13 cycle (2022-2025).

2.5.2.3 Review

The competent authority should review, in a timely manner, the application using the information provided in 2.5.2.1 and the evaluation criteria in 2.5.2.2. The analysis and conclusions from the review should be communicated to the applicant in a formal response. If the application is approved, the response should clearly state the scope of the exemptions which have been granted. If the application is rejected, then the response should include a detailed justification.

2.5.3 Registration and communication

2.5.3.1 Oversight of the granted exemptions should include the following elements:

a) The competent authority should publish details of the exempted aeroplanes in an official public register, including aeroplane model and maximum number of permitted exemptions.

b) The applicant should have a quality control process for maintaining oversight of and managing the production of aeroplanes which have been granted exemptions.

c) An exemption should be recorded in the aeroplane statement of conformity[17] which states conformity with the type certificate. Proposed standard text: "Aeroplane exempted from the First Edition of Annex 16, Volume III, Chapter 2, paragraph 2.1.1 [x][18]".

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[17] For Example: European Aviation Safety Agency (EASA) Form 52, United States Federal Aviation Administration (FAA) Form 8130-4 or equivalent forms from other competent authorities.

[18] Relevant applicability paragraph letter (a to g) would need to be filled for the exempted aeroplane.

d) The applicant should provide to the competent authority, on a regular basis and appropriate to the limitation of the approval, details on the actual exempted aeroplanes which have been produced (e.g. model, aeroplane type and serial number).

e) Exemptions for new aeroplanes should be processed and approved by the competent authority for the production of the exempted aeroplanes in coordination with the competent authorities responsible for the design of the aeroplane and the issuance of the initial certificate of airworthiness.

Chapter 3 - SAR DETERMINATION PROCEDURES

3.1. SAR MEASUREMENT PROCEDURES

3.1.1. FLIGHT TEST PROCEDURES

3.1.1.1 Fuel properties

3.1.1.1.1 One of the important factors when determining the CO_2 emissions of an aeroplane according to Annex 16 Volume III is the fuel used in the flight tests.

3.1.1.1.2 Section *2.6.3* of the Annex states:

> *"Note. — The fuel used for each flight test shall meet the specification defined in either ASTM International D1655, DEF STAN 91-91 or equivalent.*"

Equivalent fuel specifications accepted for the purposes of CO_2 emissions certification are the following:

a) Brazil: CNP-08, QAV-1;

b) China: GB6537 Number 3 Jet Fuel;

c) France: DCSEA 134;

d) Russia: GOST 10227-86 or 52050-2006, RT;

e) USA: ASTM International D1655[1] "Standard Specification for Aviation Turbine Fuels", Jet-A1;

f) UK: DEF STAN 91-91[2] "Turbine Fuel, Kerosene Type, Jet A-1";

g) Similar specifications from other member states, subject to the approval of the certificating authority.

3.1.1.1.3 Section 2.5.1 of the Annex specifies the reference conditions to which the test conditions shall be corrected. The reference fuel lower heating value is specified as 43.217 MJ/kg (18 580 BTU/lb). Recommendation 1 to paragraph 3.2.1c) of Appendix 1 of the Annex states that the fuel lower heating value should be determined in accordance with methods that are at least as stringent as ASTM International D4809-09A[3], "Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)." This method is estimated to have an accuracy level of the order of 0.23%.

3.1.1.1.4 Paragraph 3.2.1(d) of Appendix 1 of the Annex states that a sample of fuel shall be taken for each flight test to determine its specific gravity and viscosity when volumetric fuel-flow meters are used. The fuel's specific gravity and viscosity need not be determined if volumetric fuel-flow meters are not used.

3.1.1.1.5 Examples of acceptable methods to determine the fuel's specific gravity and viscosity are ASTM International D4052[4], entitled "Standard Test Method for Density and Relative Density of Liquids by Digital Density Meter" and ASTM International D445[5], entitled "Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)". Other methods may be used, subject to the approval of the certificating authority.

3.2 SAR DATA ANALYSIS

3.2.1 DATA SELECTION

Selection of data used to show compliance to the standard encompasses both the selection of flight test data gathered during each test condition used to obtain an individual SAR point, as well as the distribution of the resulting corrected SAR points in relation to the three reference masses and the reference conditions.

3.2.1.1 Selection of Flight Test Data

3.2.1.1.1 There are multiple methods employed by aeroplane manufacturers in selecting flight test data for analysis, reflecting a variety of tools and practices. Whichever method is chosen, the flight test data encompassed within the selected range of time is expected to meet the stability criteria detailed in Annex 16 Volume III, Appendix 1, paragraph 3.2.3.1, or alternative stability criteria approved by the certificating authority under paragraph 3.2.3.2 of that Annex 16 Volume III appendix. Test data that do not meet these stability criteria should normally be discarded. However, if such test data appears to be valid when compared with data that meet the stability criteria, and the overall stability of the conditions is reasonably bounded, these data can be retained, subject to approval of the certificating authority.

3.2.1.1.2 One acceptable method is to employ an algorithm that automatically selects the data that meets all the stability criteria, and discards data that does not. This method could be used to select the longest possible duration SAR point that meets the required stability criteria, or could be used to select multiple SAR points of the minimum requirement duration (one minute) providing these points are separated by a minimum of two minutes or by an exceedance of the stability criteria as specified in paragraph 3.2.2.2 of Annex 16 Volume III, Appendix 1. Using a defined algorithm to select data in an automated process allows repeatable and consistent application to other SAR points. This method may also yield a greater number of SAR points to be used in defining the CO_2 metric value and should represent a good statistical distribution. However, because the amount of test data included in each SAR point is maximized, the resulting SAR points could exhibit more scatter than if additional selection criteria are used.

3.2.1.1.3 Another method is to more closely examine the collected flight test data and select the timeframe to be used to define the SAR point, by choosing the best or most stable data available and ignoring less stable data that technically still meets the stability criteria. Examples of this are presented in Figures 3.2-1 and 3.2-2.

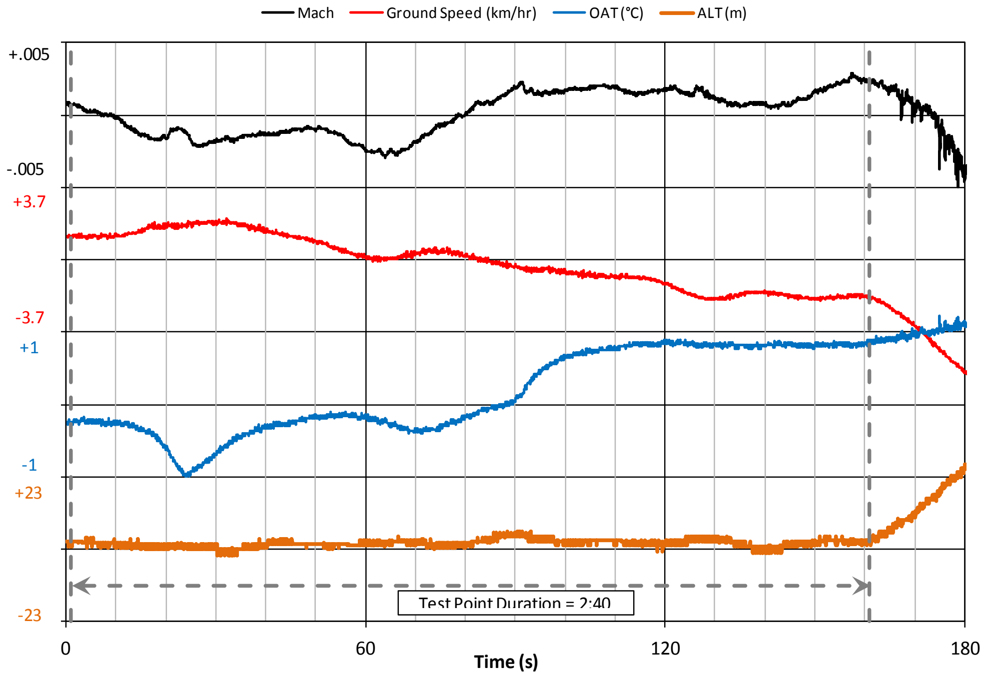

Figure 6.3.3-1 – Flight test data time interval selection – Example 1

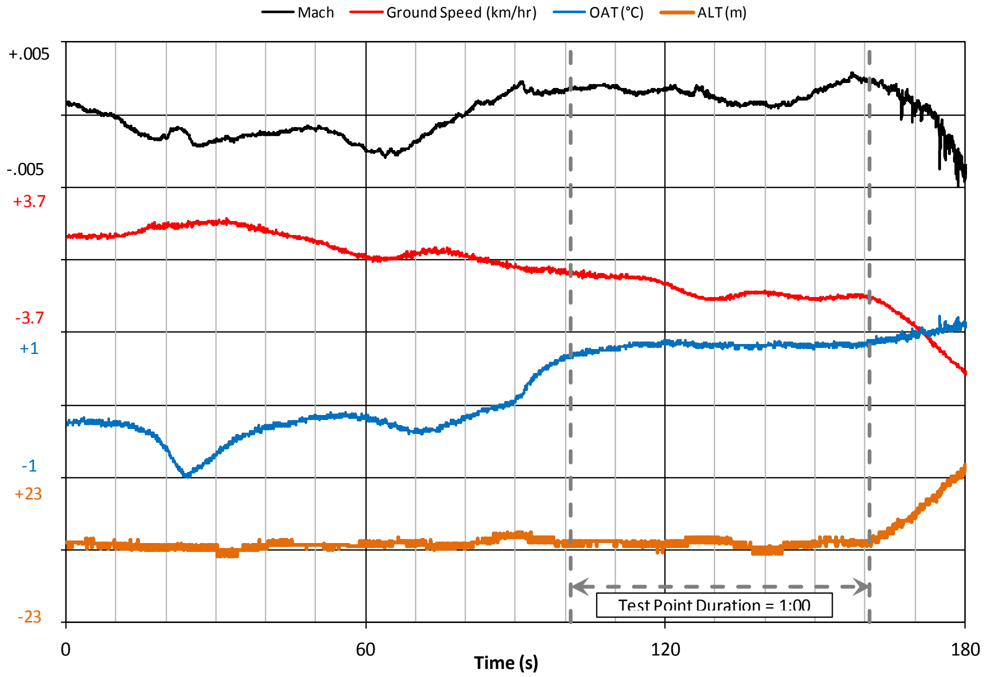

Figure 6.3.3-2 – Flight test data time interval selection – Example 2

3.2.1.1.4 The first graph shows that the plotted parameters stay within the tolerances allowed by the stability criteria for the duration of the test condition. (The changing altitude after the end of the condition reflects pilot input to leave steady flight and transition to the next test condition.) While all parameters are within the required tolerances, fluctuations in ambient temperature and Mach are evident. The second graph shows the same data, but with a manually selected range of shorter duration where the parameters are more stable.

3.2.1.1.5 Selecting data that meets more demanding stability criteria, instead of using all data that meets the Annex 16 Volume III stability criteria, may allow the applicant to filter out observed instabilities caused by air quality, changing environmental conditions, flight control inputs, and aeroplane system dynamics. This could result in a SAR point that is actually more representative of actual aeroplane performance.

3.2.1.1.6 Whichever approach is taken to select data to define SAR points, it is important the methodology be applied as consistently as possible, to minimize potential unseen bias in the resulting distribution of SAR points.

3.2.1.1.7 Another important aspect to consider when selecting data is to ensure that the time interval chosen is representative of the aeroplane's performance, and not indicative of a larger trend. For example, the first plot in Figure 3.2-3 shows a trend line drawn through ground speed data over a 60 second time interval. This ground speed data meets the stability criteria, and taken alone would indicate the need for an energy correction. However, if the ground speed data trace was continued over a longer time interval, it becomes apparent that it exhibits cyclic behaviour. Cyclic data need not be discarded necessarily, but the applicant should ensure that an appropriate time interval is selected such that the arithmetic average is representative. In the example shown in Figure 3.2-3, an energy correction would be inappropriate.

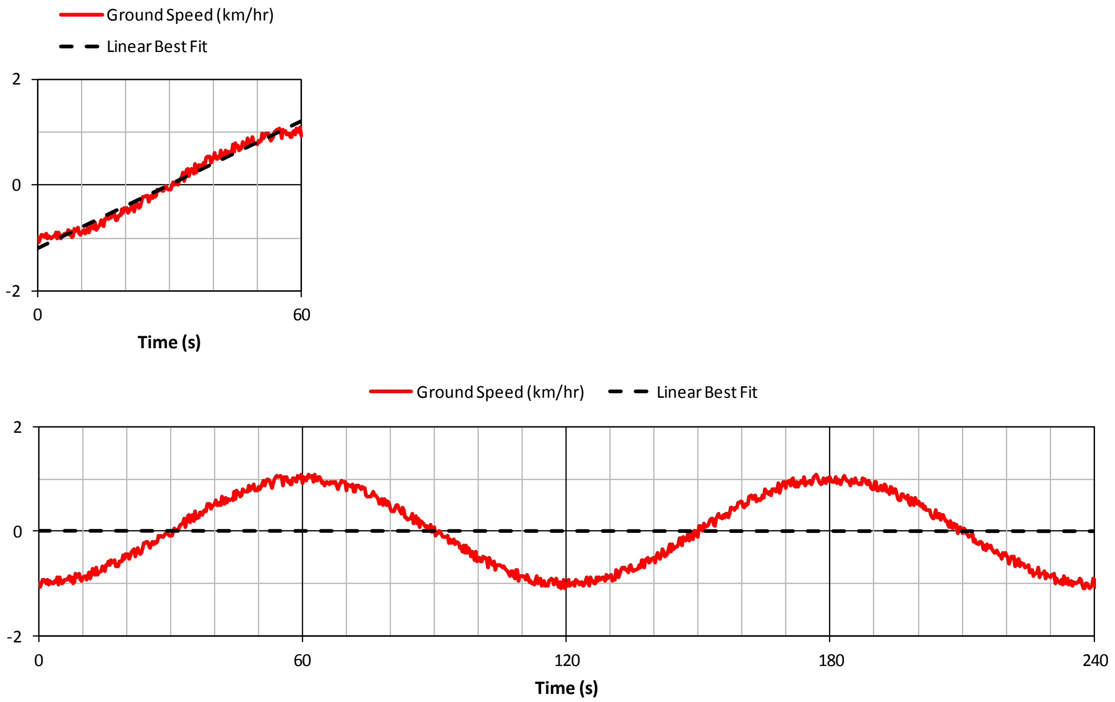

Figure 6.3.3-3 – Cyclic behavior example

3.2.1.2 Distribution of Resulting SAR points

3.2.1.2.1 Once the individual SAR points have been selected and corrected to reference conditions, they should be examined to ensure they present an accurate representation of aeroplane performance.

3.2.1.2.2 For example, if direct flight test is being used to collect 6 SAR points targeting one reference mass, those 6 points when corrected to reference conditions should result in a reasonable grouping. If 5 of the points form a reasonable grouping and one point is a clear outlier, the offending point may require closer scrutiny to ensure it is actually representative. In such a situation, collection of additional data may be warranted, or, if appropriate, and subject to approval by the certificating authority, the offending data point could be discarded.

3.2.1.2.3 If the applicant conducts tests across a range of weights to build a regression line of SAR versus weight, the collected SAR points should be reasonably distributed across the weight range. If a large portion of the regression line is unsupported by data, or is anchored by a single SAR point, then the SAR determined for one of the reference masses may be suspect. This is an important aspect to consider during the development of the certification plan and flight test programme. As with the direct test method, if a single SAR point appears to be an outlier compared to the rest of the data points, it should be examined more closely and could potentially be discarded.

3.2.1.2.4 The applicant should investigate the collection of SAR points for potential sources of unintended bias, for example if all of the data points collected were during periods where groundspeed was increasing. If all of the test points require a large energy correction in one direction, resulting in all SAR point being significantly increased (or decreased), further scrutiny may be required to ensure a bias is not introduced, depending on the test data and correction techniques being used.

3.2.2 CORRECTIONS TO REFERENCE CONDITIONS

3.2.2.1 General. The guidance provided here represents one set of methods, but not the only acceptable methods, for correcting the specific air range test data to the reference conditions specified in paragraph 2.5 of Annex 16 Volume III Part II.

3.2.2.1.1 Care needs to be taken not to inadvertently account for a correction twice when making any of the corrections below. For example, when adjusting to the reference Mass/δ from the test Mass/δ, a drag correction is introduced to account for the change in lift coefficient (C_L). This change in C_L, at a constant Mach number, also changes the reference Reynolds number and the reference mass. However, these additional changes may already be accounted for in the drag adjustments for off-nominal Reynolds number and aeroelastics depending on the correction methods used.

3.2.2.1.2 The corrections identified in paragraphs 3.2.2.2 through 3.2.2.12 cover corrections that should be made to the tested values of aeroplane mass, drag, and fuel flow. These corrected values of aeroplane mass, drag, and fuel flow should then be used to determine SAR for the reference conditions in the following manner:

3.2.2.1.2.1 Determine the aeroplane mass corrected to reference conditions per paragraph 3.2.2.2. Use this mass as the reference mass in paragraphs 3.2.2.3.2, 3.2.2.4.1, and 3.2.2.7.1, and as the mass for determining the aeroplane drag in paragraph 3.2.2.1.2.2.

3.2.2.1.2.2 Determine the aeroplane drag for the test condition using the mass corrected for gravitational acceleration. Determine all of the drag corrections per paragraphs 3.2.2.3, 3.2.2.4, 3.2.2.5, 3.2.2.6, and 3.2.2.7. Sum these drag corrections and add to the aeroplane drag for the test condition to obtain the aeroplane drag corrected to the reference conditions.

3.2.2.1.2.3 Use the drag level corrected to reference conditions from paragraph 3.2.2.1.2.2 as a thrust level (thrust = drag) to determine the total engine fuel flow for these conditions from an engine performance model. Correct this engine fuel flow to reference conditions per paragraphs 3.2.2.8, 3.2.2.9, 3.2.2.10, 3.2.2.11, and 3.2.2.12.

3.2.2.1.2.4 The SAR value corrected to reference conditions is given by the following relationship:

$$SAR_{ref} = \left(\frac{TAS}{Fuel\ Flow_{ref}}\right)$$

Where SAR_{ref} *is the specific air range for the reference conditions in kilometers/kilogram,*

TAS is the aeroplane true airspeed for the test condition in kilometers/hour, and

Fuel $Flow_{ref}$ *is the engine fuel flow for the reference conditions (from paragraph 3.2.2.1.2.3) in kilograms/hour.*

3.2.2.2 Apparent gravity. Acceleration, caused by the local effect of gravity, and inertia, affects the test weight of the aeroplane. The apparent gravity at the test conditions varies with latitude, altitude, ground speed, and direction of motion relative to the Earth's axis. The reference gravitational acceleration is the gravitational acceleration for the aeroplane travelling in the direction of true North in still air at the reference altitude, a geodetic latitude of 45.5 degrees, and based on g_0.

3.2.2.2.1 Since the mass of the aeroplane during each test condition cannot be directly measured, it is determined from the test weight that has been corrected for gravitational acceleration. The test mass corrected for gravitational acceleration, which is to be used in paragraphs 3.2.2.3.2, 3.2.2.4.1, and 3.2.2.7.1, should be determined from the following equation:

$$Mass_{grav} = \left(\frac{W_t + \Delta W_{grav}}{g_0}\right)$$

$Mass_{grav}$ is the average mass of the aeroplane during the test condition corrected for gravitational acceleration in kilograms,

W_t is the average weight of the aeroplane during the test condition in newtons, and

g_0 is the standard gravitational acceleration = 9.80665 meters/second^2.

3.2.2.2.2 The following corrections are based on the World Geodetic System 84 Ellipsoidal Gravity definition. Other formulations and simplifications may provide essentially equivalent results.

3.2.2.2.3 The correction to the test weight for the effect of the variation in gravitational acceleration from the reference gravitational acceleration, can be determined from the following equation:

$$\Delta W_{grav} = W_t \left(\frac{g_{\emptyset,alt} + \Delta g_{cent} + \Delta g_{Coriolis} - g_{Ref}}{g_{ref}}\right)$$

Where ΔW_{grav} is the weight correction in newtons for being off the reference gravitational acceleration,

W_t is the average weight of the aeroplane during the test condition in newtons,

$g_{\phi,alt}$ is the gravitational acceleration at the test altitude and latitude in meters/second^2,

Δg_{cent} is the change in the gravitational acceleration due to centrifugal effect in meters/second^2,

$\Delta g_{Coriolis}$ is the change in the gravitational acceleration due to Coriolis effect in meters/second^2, and

g_{ref} is the reference gravitational acceleration in meters/second^2.

3.2.2.2.4 The gravitational acceleration for the test altitude and latitude, $g_{\phi,alt}$, is determined as follows:

a. First determine the gravitational effect of latitude at sea level from the following equation:

$$g_{\emptyset} = \left(9.7803267714 \; \frac{1 + 0.00193185138639\, sin^2\emptyset}{\sqrt{1 - 0.00669437999013\, sin^2\emptyset}}\right)$$

Where Φ is the test latitude in degrees.

b. The gravitational acceleration for the test altitude and latitude is then determined from the following equation:

$$g_{\emptyset,alt} = g_{\emptyset}\left(\frac{r_e}{r_e + h}\right)^2$$

Where g_ϕ is the gravitational acceleration at the test latitude at sea level (from paragraph 3.2.2.2.4.a),

h is the test altitude in meters, and

r_e is the radius of the Earth at the test latitude, which is determined from the following equation:

$$r_e = \sqrt{\frac{(a^2 cos\,\emptyset)^2 + (b^2 sin\,\emptyset)^2}{(a\, cos\,\emptyset)^2 + (b\, sin\,\emptyset)^2}}$$

Where a is the Earth’s radius at the equator = 6378137 meters,

b is the Earth’s radius at the pole = 6356752 meters, and

3.2.2.2.5 The change in the gravitational acceleration due to centrifugal effect, Δg_{cent}, is determined from the following equation:

$$\Delta g_{cent} = -\frac{{V_g}^2}{r_e + h}$$

Where V_g is the ground speed in meters/second,

r_e is the radius of the Earth in meters at the test latitude, which is determined from the following equation:

$$r_e = \sqrt{\frac{(a^2 cos\, \emptyset)^2 + (b^2 sin\, \emptyset)^2}{(a\, cos\, \emptyset)^2 + (b\, sin\, \emptyset)^2}}\text{ , and}$$

h is the test altitude in meters.

3.2.2.2.6 The change in the gravitational acceleration due to Coriolis effect, $g_{Coriolis}$, can be found from the following equation:

$$g_{Coriolis} = -2\, \omega_E\, V_g\, cos\, \emptyset \sin \sigma$$

Where ω_E is the Earth's rotation rate = 7.29212 x 10^{-5} radians/second,

V_G is the aeroplane's ground speed in meters/second,

Φ is the test latitude in degrees, and

σ is the ground track angle of the aeroplane in degrees.

3.2.2.2.7 The reference gravitational acceleration, g_{ref}, is the gravitational acceleration for the aeroplane travelling in the direction of true North in still air at the reference altitude and a geodetic latitude of 45.5 degrees. Because the reference gravitational acceleration condition is for the aeroplane travelling in the direction of true North, the reference gravitational acceleration does not include any Coriolis effect. Because the reference condition is for the aeroplane travelling in still air, the effect of the centrifugal effect on the reference gravitational acceleration is determined using the aeroplane's true airspeed (i.e. zero wind ground speed). The reference gravitational acceleration can be determined as follows:

3.2.2.2.7.1 Determine the reference gravitational acceleration for the reference altitude and latitude using the process defined in paragraph 3.2.2.2.4, using the reference altitude and 45.5 degrees latitude as the test altitude and latitude, respectively.

3.2.2.2.7.2 Determine the change in the reference gravitational acceleration due to centrifugal effect using the process defined in 3.2.2.2.5, using the aeroplane's true airspeed as the ground speed.

3.2.2.2.7.3 The reference gravitational acceleration, g_{ref}, is the sum of the reference gravitational acceleration for the reference altitude determined in 3.2.2.2.7.1 and the change in the reference gravitational acceleration due to centrifugal effect determined in 3.2.2.2.7.2.

3.2.2.3 Mass/*δ*:. The lift coefficient of the aeroplane is a function of mass/δ and Mach number, where δ is the ratio of the atmospheric pressure at a given altitude to the atmospheric pressure at sea level. The lift coefficient for the test condition affects the drag of the aeroplane. The reference mass/δ is derived from the combination of the reference mass, reference altitude, and atmospheric pressures determined from the ICAO standard atmosphere.

3.2.2.3.1 The effect on drag of the test condition mass/δ being different than the reference mass/δ can be determined from the drag equation:

$$\Delta D_{Mass/_{\delta}} = \frac{1}{2} \rho\, V^2 \left(C_{D\, Ref\, Mass/_{\delta}} - C_{D\, Test\, Mass/_{\delta}} \right) A$$

Where $\Delta D_{Mass/\delta}$ is the drag correction in newtons due to the test mass/δ being different than the reference mass/δ, ρ is the density of air at the test altitude and test temperature in kilograms/meter^3,

V is the aeroplane's average true airspeed during the test condition in meters/second,

A is the aeroplane's reference wing area in meters^2,

$C_{D\ Ref\ Mass/\delta}$ is the drag coefficient from the aeroplane's drag model at the reference mass/δ, and

$C_{D\ Test\ Mass/\delta}$ is the drag coefficient from the aeroplane's drag model at the test mass/δ.

3.2.2.3.2 The aeroplane's drag coefficient in the aeroplane's drag model is a function of the lift coefficient. Given the lift coefficient, the drag coefficient can be determined. The lift coefficients at the reference mass/δ and test mass/δ can be determined from the lift equation:

$$C_L = \left(\frac{Mass/\delta}{7232.4\ M^2 A}\right)$$

Where C_L is the lift coefficient,

Mass/δ is the mass/δ of the aeroplane in kilograms (either the test mass/δ after correcting the test mass for gravitational acceleration, or the reference mass/δ, depending on which C_L value is being determined. (Note: δ is the ratio of the ambient air pressure at a specified altitude (reference or test) to the ambient air pressure at sea level)),

M is the aeroplane's average Mach number during the test condition, and

A is the aeroplane's reference wing area in meters^2.

3.2.2.4 ***Acceleration/deceleration (energy).*** *D*rag determination is based on an assumption of steady, unaccelerated flight. Acceleration or deceleration occurring during a test condition affects the assessed drag level. The reference condition is steady, unaccelerated flight.

3.2.2.4.1 The correction for the change in drag force resulting from acceleration during the test condition can be determined from the following equation:

$$\Delta D_{accel} = -M_{grav}\left(\frac{dV_G}{dT}\right)$$

Where ΔD_{accel} is the drag correction in newtons due to acceleration occurring during the test condition,

M_{grav} is the average mass of the aeroplane during the test condition corrected for gravitational acceleration in kilograms, and

(dV_G/dT) is the change in ground speed over time during the test condition in meters/second^2.

3.2.2.5 ***Reynolds number.*** The Reynolds number affects aeroplane drag. For a given test condition the Reynolds number is a function of the density and viscosity of air at the test altitude and temperature. The reference Reynolds number is derived from the density and viscosity of air from the ICAO standard atmosphere at the reference altitude and temperature.

3.2.2.5.1 The value of the drag coefficient correction for being off the reference Reynolds number condition during the test can be expressed as:

$$\Delta C_{D\ RE} = -B\ log \left[\frac{\frac{1}{M}\left(\frac{RE}{meters}\right)_{test}}{\frac{1}{M}\left(\frac{RE}{meters}\right)_{Ref}} \right]$$

Where $\Delta C_{D\ RE}$ is the change in drag coefficient due to being off the reference Reynolds number,

B is a value representing the variation of drag with Reynolds number for the specific aeroplane (see paragraph 3.2.2.5.2),

M is Mach number, and

RE is Reynolds number.

3.2.2.5.2 One method to obtain B is to use a drag model to obtain the incremental drag variation in response to changing Mach and altitude from a reference cruise condition. The value for B is the value of a single representative slope of a plot of the drag variation, ΔDrag versus $\text{Log}_{10}\left[\frac{1}{M}\left(\frac{RE}{meter}\right) x10^{-6}\right]$.

3.2.2.5.3 The term $\left[\frac{\frac{1}{M}\left(\frac{RE}{meter}\right)_{test}}{\frac{1}{M}\left(\frac{RE}{meter}\right)_{Ref}}\right]$ is the term $\frac{1}{M}\left(\frac{RE}{meter}\right)$ determined at the temperature and altitude for the test condition divided by the same term determined at the standard day temperature and the reference altitude for the test mass/δ using the following equation:

$$\frac{1}{M}\frac{RE}{meter} = 4.7899\ x\ 10^5\ P_S \left(\frac{T_S + 110.4}{T_S^2}\right)$$

Where RE/meter is Reynolds number per meter,

P_S is static pressure in pascals, and

T_S is static termperature in Kelvin.

3.2.2.5.4 The effect on aeroplane drag can then be determined from $\Delta C_{D\ RE}$ and the aeroplane drag equation as follows:

$$\Delta D_{RE} = \frac{1}{2} \rho\ V^2 \Delta C_{D\ RE}\ A$$

Where ΔD_{RE} is the aeroplane drag correction in newtons due to the test Reynolds number being different than the reference Reynolds number,

ρ is the density of air at the test altitude and test temperature in kilograms/meter^3,

V is the aeroplane’s average true airspeed during the test condition in meters/second,

A is the aeroplane’s reference wing area in meters^2, and

$\Delta C_{D\ RE}$ is the change in drag coefficient due to being off the reference Reynolds number from paragraph 3.2.2.5.1.

3.2.2.6 ***CG position.*** The position of the aeroplane centre of gravity affects the drag due to longitudinal trim.

3.2.2.6.1 The drag correction for being off the reference CG position during the test is the difference between the drag at the reference CG position and the drag at the test CG position. This drag correction can be determined by: (1) determining the lift coefficient at the reference and test CG positions; (2) using the aeroplane's drag model with the lift coefficients for the test and reference CG positions to determine the respective drag coefficients; and (3) using the drag equation with the test and reference CG drag coefficients to determine difference in aeroplane drag between the reference and test CG positions.

3.2.2.6.2 The lift coefficient at the test CG position can be determined by using the lift equation in paragraph 3.2.2.3.2. The lift coefficient at the reference CG position can be determined from the following equation:

$$C_{L\ Ref\ CG} = C_{L\ Test}\ [1 + (MAC/L_t)\ (CG_{Ref} - CG_{Test})]$$

Where MAC is the length of the wing mean aerodynamic chord in centimeters,

L_t is the length of the horizontal stabilizer arm (normally measured between the wing 25 percent MAC and the stabilizer 25 percent MAC) in centimeters,

CG_{Ref} is the reference CG position in percent MAC/100, and

CG_{Test} is the CG position in percent MAC/100 during the test condition.

3.2.2.6.3 Once the drag coefficients are determined from the aeroplane drag model using the lift coefficients above, the aeroplane drag for the reference and test CG positions can be determined from the drag equation:

$$\Delta D_{CG} = \frac{1}{2} \rho\, V^2 \left(C_{D\ Test\ CG} - C_{D\ Ref\ CG}\right) A$$

Where ΔD_{CG} is the aeroplane drag correction in newtons due to the test CG being different than the reference CG,

ρ is the density of air at the test altitude and test temperature kilograms/meter^3,

V is the aeroplane's average true airspeed during the test condition in meters/second,

A is the aeroplane's reference wing area in meters^2, and

$C_{D\ Test\ CG}$ and $C_{D\ Ref\ CG}$ are the drag coefficient from the aeroplane's drag model at the test condition CG and reference CG positions, respectively.

3.2.2.7 ***Aeroelastics.*** Wing aeroelastics may cause a variation in drag as a function of aeroplane wing mass distribution. Aeroplane wing mass distribution will be affected by the fuel load distribution in the wings and the presence of any external stores.

3.2.2.7.1 There are no simple analytical means to correct for different wing structural loading conditions. If necessary, corrections to the reference condition should be developed by flight test or a suitable analysis process.

3.2.2.7.2 The reference condition for the wing structural loading is to be selected by the applicant based on the amount of fuel and/or removable external stores to be carried by the wing based on the aeroplane's payload capability and the manufacturer's standard fuel management practices. The reference to the aeroplane's payload capability is to establish the zero fuel mass of the aeroplane, while the reference to the manufacturer's standard fuel management practices is to establish the distribution of that fuel and how that distribution changes as fuel is burned.

3.2.2.7.3 The reference condition for the wing structural loading reference condition should be based on an operationally representative empty weight and payload, which defines the zero fuel mass of the aeroplane. The total amount of fuel loaded for each of the three reference masses would be the reference mass minus the zero fuel mass. Standard fuel management practices will determine the amount of fuel present in each fuel tank. An example of standard fuel management practice is to load the main (wing) fuel tanks before loading the center (body) fuel tanks and to first empty fuel from the center tanks before using the fuel in the main tanks. This helps keep the cg aft, and reduces trim drag.

3.2.2.7.4 Commercial freighters may be designed from scratch, but more often are derivatives of, or are converted from passenger models. For determining aeroelastic effects, it is reasonable to assume that the reference loading for a freighter is the same as the passenger model it was derived from. If there is no similar passenger model, the reference zero-fuel-mass of a freighter can be based on its payload design density. The payload design density is defined by the full use of the volumetric capacity of the freighter and the highest mass it is designed to carry in this configuration, expressed in kg/m^3. For example, a typical payload design density for large commercial freighters is 160 kg/m^3.

3.2.2.7.5 Using a reference payload significantly lower the passenger interior limits or structural limited payload could potentially provide a more beneficial aeroelastic effect. An applicant would need to justify the reference payload assumptions in the context of the capability of the aeroplane and what could be considered typical for the configuration.

3.2.2.8 ***Fuel lower heating value.*** The fuel lower heating value defines the energy content of the fuel. The lower heating value directly affects the fuel flow at a given test condition.

The fuel flow measured during the flight test is corrected to the fuel flow for the reference lower heating value as follows:

$$Fuel\ Flow_{Corr\ LHV} = Fuel\ Flow_{test\ LHV}\left(\frac{LHV_{test}}{LHV_{Ref}}\right)$$

Where $Fuel\ Flow_{Cor\ r\ LHV}$ *is the fuel flow in kilograms/hour corrected for the reference fuel lower heating value,*

$Fuel\ Flow_{test\ LHV}$ *is the measured fuel flow in kilograms/hour during the test (at the test fuel lower heating value,*

LHV_{test} *is the fuel lower heating value of the fuel used for the test in MJ/kg, and*

LHV_{Ref} *is the reference fuel lower heating value = 43.217 MJ/kg.*

3.2.2.9 ***Altitude***. The altitude at which the aeroplane is flown affects the fuel flow.

3.2.2.9.1 The engine model should be used to determine the difference between the fuel flow at the test altitude and the fuel flow at the reference altitude. The fuel flow at the test altitude should be corrected by this value so that it represents the fuel flow that would have been obtained at the reference altitude.

3.2.2.10 ***Temperature.*** The ambient temperature affects the fuel flow. The reference temperature is the standard day temperature from the ICAO standard atmosphere at the reference altitude.

3.2.2.10.1 The engine model should be used to determine the difference between the fuel flow at the test temperature and the fuel flow at the reference temperature. The fuel flow at the test temperature should be corrected by this value so that it represents the fuel flow that would have been obtained at the reference temperature.

3.2.2.11 ***Engine deterioration level.*** *When first used, e*ngines undergo a rapid, initial deterioration in fuel efficiency. Thereafter, the rate of deterioration significantly decreases. Engines with less than the reference deterioration level may be used, subject to the approval of the certification authority. In such a case, the fuel flow shall be corrected to the reference engine deterioration level, using an approved method. Engines with more deterioration than the reference engine deterioration level may be used. In this case a correction to the reference condition shall not be permitted.

3.2.2.11.1 As stated above, a correction should not generally be made for engine deterioration level. If an applicant proposes to use an engine or engines with less than the reference deterioration level for testing, it may be possible to establish a conservative correction level to apply to the test fuel flow to represent engines at the reference deterioration level. Such a correction should be substantiated by engine fuel flow deterioration data from the same engine type or family.

3.2.2.12 ***Electrical and mechanical power extraction and bleed flow.*** Electrical and mechanical power extraction and bleed flow affects the fuel flow.

3.2.2.12.1 The engine model should be used to determine the difference between the fuel flow at the test power extraction and bleed flow and the fuel flow at the reference power extraction and bleed flow. The fuel flow at the test power extraction and bleed flow should be corrected by this value so that it represents the fuel flow that would have been obtained at the reference power extraction and bleed flow.

3.3. VALIDITY OF RESULTS - CONFIDENCE INTERVAL

3.3.1 INTRODUCTION

3.3.1.1 Sections 3.3.2 to 3.3.4 provide an insight into the theory of confidence interval evaluation. Application of this theory and some worked examples are provided in 3.3.4. A suggested bibliography is provided in Appendix 2 to this manual for those wishing to gain a greater understanding.

3.3.2 DIRECT FLIGHT TESTING

3.3.2.1 If n measurements of SAR $y_1, y_2, ..., y_n$ are obtained under approximately the same conditions and it can be assumed that they constitute a random sample from a normal population with true population mean, μ, and true standard deviation, σ, then the following statistics can be derived:

$$\bar{y} = estimate\ of\ the\ mean = \frac{1}{n}\left\{\sum_{i=1}^{i=n} y_{(i)}\right\}$$

$$s = estimate\ of\ the\ standard\ deviation\ of\ the\ mean = \sqrt{\frac{\sum_{i=1}^{i=n}(y_i - \bar{y})^2}{n-1}}$$

From these and the Student's t-distribution, the confidence interval, CI, for the estimate of the mean, $\bar{y}$ can be determined as:

$$\mathrm{CI} = \bar{y} \pm t_{\left(1-\frac{\alpha}{2},\zeta\right)} \frac{s}{\sqrt{n}}$$

Where $t_{\left(1-\frac{\alpha}{2},\zeta\right)}$ denotes the $\left(1-\frac{\alpha}{2}\right)$ percentile of the single-sided Student's t-test with ζ degrees freedom (for a clustered data set $\zeta = n-1$) and where α is defined such that $100(1-\alpha)$ per cent is the desired confidence level for the confidence interval. In other words it denotes the probability with which the interval will contain the unknown mean, µ. For CO2 certification purposes, 90 per cent confidence intervals are generally desired and thus $t_{.95,\zeta}$ is used. See Table 3.3-1 for a listing of values of $t_{.95,\zeta}$ for different values of ζ.

3.3.3 REGRESSION MODEL

3.3.3.1 If n measurements of SAR ($y_1, y_2, ..., y_n$) are obtained under significantly varying values of mass ($x_1, x_2, ..., x_n$) respectively, then a polynomial can be fitted to the data by the method of least squares. For determining the mean SAR, μ, the following polynomial regression model is assumed to apply:

$$\mu = B_0 + B_1 x + B_2 x^2 + ... + B_k x^k .$$

The estimate of the mean line through the data of the SAR is given by:

$$y = b_0 + b_1 x + b_2 x^2 + ... + b_k x^k .$$

Each regression coefficient (B_i) is estimated by b_i from the sample data using the method of least squares in a process summarized as follows.

Each observation $\left(x_i, y_i\right)$ satisfies the equations:

$$y_i = B_0 + B_1 x_i + B_2 x_i^{\,2} + . \quad .+ B_k x_i^{\,k} +.\varepsilon_i$$

$$= b_0 + b_1 x_i + b_2 x_i^{\,2} + ... + b_k x_i^{\,k} + e_i \,,$$

where ε_i and e_i are, respectively, the random error and residual associated with the SAR. The random error ε_i is assumed to be a random sample from a normal population with mean zero and standard deviation σ. The residual (e_i) is the difference between the measured value and the estimate of the value using the estimates of the regression coefficients and x_i. Its root mean square value (s) is the sample estimate for σ. These equations are often referred to as the normal equations.

Table 3.3-1. Student's t-distribution (for 90 per cent confidence) for various degrees of freedom

Degrees of freedom (ζ)	$t_{.95,\,\zeta}$
1	6.314
2	2.920
3	2.353
4	2.132
5	2.015
6	1.943
7	1.895
8	1.860
9	1.833
10	1.812
12	1.782
14	1.761
16	1.746
18	1.734
20	1.725
24	1.711
30	1.697
60	1.671

Degrees of freedom (ζ)	$t_{.95,\zeta}$
>60	1.645

The *n* data points of measurements $\left(x_i, y_i\right)$ are processed as follows:

Each elemental vector $\left(\underline{x}_i\right)$ and its transpose $\left(\underline{x}'_i\right)$ are formed such that:

$$\underline{x}_i = \begin{pmatrix} 1 & x_i & x_i^2 & . & . & x_i^k \end{pmatrix}, \text{ a row vector; and}$$

$$\underline{x}'_i = \begin{pmatrix} 1 \\ x_i \\ x_i^2 \\ . \\ . \\ x_i^k \end{pmatrix}, \text{ a column vector.}$$

A matrix $\underline{X}$ is formed from all the elemental vectors $\underline{x}_i$ for *i* = 1, ….., *n*. $\underline{X}'$ is the transpose of $\underline{X}$. A matrix $\underline{A}$ is defined such that $\underline{A} = \underline{X}'\underline{X}$ and a matrix $\underline{A}^{-1}$ is the inverse of $\underline{A}$. In addition, $\underline{y} = (y_1\ y_2 \ldots y_n)$, and $\underline{b} = (b_0\ b_1 \ldots b_2)$, with $\underline{b}$ determined as the solution of the normal equations:

$$\underline{y} = \underline{X}\,\underline{b} \text{ and } \underline{X}'\underline{y} = \underline{X}'\underline{X}\,\underline{b} = \underline{A}\underline{b},$$

to give

$$\underline{b} = \underline{A}^{-1}\,\underline{X}'\underline{y}.$$

The 90 per cent confidence interval CI_{90} for the mean value of the SAR estimated with the associated value of the mass x_0 is then defined as:

$$\mathrm{CI}_{90} = \bar{y}\left(x_0\right) \pm t_{.95,\zeta}\ s\ v\left(x_0\right),$$

where $v\left(x_0\right) = \sqrt{\underline{x}_0\underline{A}^{-1}\underline{x}'_0}$.

Thus $\mathrm{CI}_{90} = \bar{y}\left(x_0\right) \pm t_{.95,\zeta}\ s\ \sqrt{\underline{x}_0\underline{A}^{-1}\underline{x}'_0}$,

where:

— $\underline{x}_0 = \left(1\, x_0\ x_0^2 \ldots\ x_0^k\right)$;

— $\underline{x}'_0$ is the transpose of $\underline{x}_0$;

— $\bar{y}\left(x_0\right)$ is the estimate of the mean value of the SAR at the associated value of the mass x_o;

— $t_{.95,\zeta}$ is obtained for ζ degrees of freedom. For the general case of a multiple regression analysis involving K independent variables (i.e. $K + 1$ coefficients) ζ is defined as $\zeta = n - K - 1$ (for the specific case of a polynomial regression analysis, for which k is the order of curve fit, there are k variables independent of the dependent variable, and so $\zeta = n - k - 1$); and

— $s = \sqrt{\dfrac{\sum_{i=1}^{i=n} (y_i - \bar{y}(x_i))^2}{n-K-1}}$, the estimate of σ, the true standard deviation.

3.3.4 WORKED EXAMPLES OF THE DETERMINATION OF 90 PER CENT CONFIDENCE INTERVALS

3.3.4.1 Direct Flight Testing

3.3.4.1.1 Example 1: the Confidence Interval is less than the confidence interval limit

Let’s consider the following set of 6 independent measurements of SAR obtained by flight test around one of the three reference masses of the CO2 emissions evaluation metric. After correction to reference conditions, the following clustered data set of SAR values is obtained:

Measurement number	*Corrected SAR (km/kg)*
1	0.38152
2	0.38656
3	0.37988
4	0.38011
5	0.38567
6	0.37820

Table 3.3-2 - Measurements of SAR – Example 1

- The number of data points (n) = 6
- The degrees of freedom (n-1) = 5
- The Student’s t-distribution for 90 per cent confidence and 5 degrees of freedom ($t_{(.95,5)}$) = 2.015 (see Table 3.3-1)

Note: 6 is the minimum number of test points requested by Appendix 1 of Annex 16 Volume 3, §6.2.

Estimate of the mean SAR ($\overline{SAR}$) for the clustered data set

$$\overline{SAR} = \frac{1}{n}\left\{\sum_{i=1}^{i=n} SAR_{(i)}\right\} = 0.38282\ km/kg$$

Estimate of the standard deviation (s)

$$s = \sqrt{\frac{\sum_{i=1}^{i=n}\left(SAR_{(i)} - \overline{SAR}\right)^2}{n-1}} = 0.00344\ km/kg$$

Confidence Interval determination

The 90 per cent confidence interval (CI_{90}) is calculated as follows (see §3.3.2):

$$\boxed{CI90 = \overline{SAR} \pm t_{(.95,n-1)} \frac{s}{\sqrt{n}} = 0.38282 \pm 2.015 \text{ x } \frac{0.00344}{\sqrt{6}} = 0.38282 \pm 0.00283\ km/kg}$$

Check of confidence interval limits

The confidence interval extends to ±0.00283 km/kg around the mean SAR value of the clustered data set (0.38282 km/kg). This represents ±0.74 per cent of the mean SAR value, which is below the confidence interval limit of 1.5 per cent defined in Annex 16 Volume 3 Appendix 1 §6.4.

As a result, the SAR value of 0.38282 km/kg associated to one of the reference masses of the CO2 emissions evaluation metric can be used for the metric determination.

3.3.4.1.2 Example 2: the confidence Interval exceeds the confidence interval limit

Let's consider the following set of 6 independent measurements of SAR obtained by flight test around one of the three reference masses of the CO2 emissions evaluation metric. After correction to reference conditions, the following clustered data set of SAR values is obtained:

Measurement number	*Corrected SAR (km/kg)*
1	0.15208
2	0.15795
3	0.15114
4	0.15225
5	0.15697
6	0.15834

Table 3.3-3 – Measurements of SAR – Example 2

- The number of data points (n) = 6
- The degrees of freedom (n-1) = 5
- The Student's t-distribution for 90 per cent confidence and 5 degrees of freedom ($t_{(.95\ ,5)}$) = 2.015 (see Table 3.3-1)

Estimate of the mean SAR ($\overline{SAR}$) for the clustered data set

$$\overline{SAR} = \frac{1}{n}\left\{\sum_{i=1}^{i=n} SAR_{(i)}\right\} = 0.15479\, km/kg$$

Estimate of the standard deviation (s)

$$s = \sqrt{\frac{\sum_{i=1}^{i=n}\left(SAR_{(i)} - \overline{SAR}\right)^2}{n-1}} = 0.0033\, km/kg$$

Confidence Interval determination

The 90 per cent confidence interval (CI_{90}) is calculated as follows (see §3.3.2):

$$\boxed{CI90 = \overline{SAR} \pm t_{(.95,n-1)} \frac{s}{\sqrt{n}} = 0.15479 \pm 2.015 \text{ x } \frac{0.0033}{\sqrt{6}} = 0.15479 \pm 0.00271\, km/kg}$$

Check of confidence interval limits

The confidence interval extends to ±0.00271 km/kg around the mean SAR value of the clustered data set (0.15479 km/kg). This represents ±1.75 per cent of the mean SAR value, which is above the confidence interval limit of 1.5 per cent defined in Annex 16 Volume 3 Appendix 1 §6.4.

In such a case, a penalty equal to the amount that the 90 per cent confidence interval exceeds ±1.5 per cent shall be applied to the mean SAR value, i.e. (1.75-1.50)=0.25 per cent. The mean SAR value shall therefore be penalized by an amount of 0.25 per cent as follows:

$$\overline{SAR} = (1 - \frac{0.25}{100})\, x\ 0.15479 = 0.15440\, km/kg$$

As a result, the SAR value of 0.15440 km/kg associated to one of the reference masses of the CO2 emissions evaluation metric can be used for the metric determination.

3.3.4.2 Regression model

3.3.4.2.1 Example 3: the confidence Interval at each of the three reference masses of the CO2 emissions evaluation metric is less than the confidence interval limit

Let's consider the following set of 12 measurements of SAR obtained by flight test at optimum speed and optimum altitude as a function of the aeroplane gross mass. After SAR correction to reference conditions, the following data set is obtained:

Measurement Number & Reference Mass	*Gross Mass (m_i) (kg)*	*Corrected SAR (SAR_i) (km/kg)*
1	17800	0.928
Low Mass (*)	17825	
2	17970	0.905
3	18400	0.908
4	18850	0.884
5	19500	0.850
6	19950	0.845
Mid Mass (*)	19953	
7	20180	0.833
8	20350	0.818
9	21000	0.792
10	21500	0.781
11	21870	0.779
High Mass (*)	22080	
12	22150	0.771

Table 3.3-4 – Measurements of SAR – Example 3

(*) *Low, Mid and High mass represent the reference masses of the CO2 emissions evaluation metric defined in Annex 16, Volume 3, Chapter 2, §2.3.*

The number of data points (n) = 12

Note: 12 is the minimum number of test points requested by Appendix 1 of Annex 16 Volume 3, §6.3.

A representation of above measurement points is proposed in below figure 3.3-1.

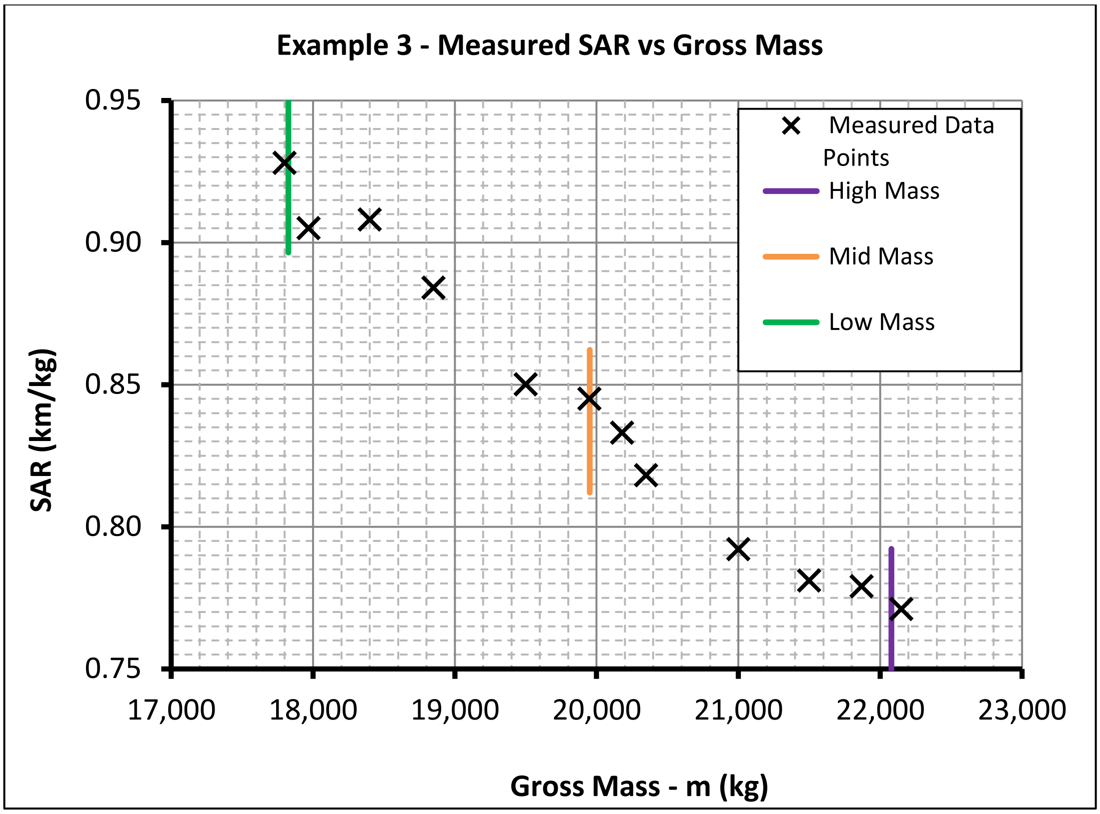

Figure 3.3-1 – Measured SAR vs Gross Mass – Example 3

<u>Estimate of the mean SAR model by polynomial regression</u>

In order to estimate the SAR model (SAR_{av}) as a function the aeroplane gross mass (m), a polynomial regression of second order is proposed, so that:

$$SAR_{av} = B_0 + B_1\,m + B_2\,m^2$$

Each observation (m_i, SAR_i), for i = 1, …, 12 satisfies the equation:

$$SAR_{(i)} = b_0 + b_1\,m_i + b_2\,m_i^2 + e_i$$

where e_i = residual error (difference between the measured SAR value and its estimate).

This gives under a matrix form:

$$\begin{pmatrix} SAR1 \\ SAR2 \\ SAR3 \\ \vdots \\ SAR12 \end{pmatrix} = \begin{pmatrix} 1 & m1 & m1^2 \\ 1 & m2 & m2^2 \\ 1 & m3 & m3^2 \\ \vdots & \vdots & \vdots \\ 1 & m12 \cdots & m12^2 \end{pmatrix} \begin{pmatrix} b0 \\ b1 \\ b2 \end{pmatrix} + \begin{pmatrix} e1 \\ e2 \\ e3 \\ \vdots \\ e12 \end{pmatrix}$$

$$\underline{SAR} = \underline{M}\,\underline{b} + \underline{e}$$

Where:

$$\underline{SAR} = \begin{pmatrix} 0.928 \\ 0.905 \\ 0.908 \\ 0.884 \\ 0.850 \\ 0.845 \\ 0.833 \\ 0.818 \\ 0.792 \\ 0.781 \\ 0.779 \\ 0.771 \end{pmatrix} \qquad \underline{M} = \begin{pmatrix} 1 & 17800 & 17800^2 \\ 1 & 17970 & 17970^2 \\ 1 & 18400 & 18400^2 \\ 1 & 18850 & 18850^2 \\ 1 & 19500 & 19500^2 \\ 1 & 19950 & 19950^2 \\ 1 & 20180 & 20180^2 \\ 1 & 20350 & 20350^2 \\ 1 & 21000 & 21000^2 \\ 1 & 21500 & 21500^2 \\ 1 & 21870 & 21870^2 \\ 1 & 22150 & 22150^2 \end{pmatrix} \qquad \underline{b} = \begin{pmatrix} b0 \\ b1 \\ b2 \end{pmatrix} \qquad \underline{e} = \begin{pmatrix} e1 \\ e2 \\ e3 \\ \vdots \\ e\mathrm{n} \end{pmatrix}$$

The least square principle consists in looking for the parameter values of vector $\underline{B}$ minimising the sum of the squares of residuals, i.e.:

$$\mathrm{Min} \sum_{i=1}^{i=12} e\mathrm{i}^2 = \min \sum_{i=1}^{i=12} (SAR(\mathrm{i}) - b0 - b1\, m\mathrm{i} - b2\, m\mathrm{i}^2)^2$$

It is equivalent to look for the solutions of $\frac{\partial(\sum e\mathrm{i}^2)}{\partial b\mathrm{j}} = 0$ for j= (0, 1, 2)

The solution $\underline{B} = \begin{pmatrix} B0 \\ B1 \\ B2 \end{pmatrix}$ is given by $\underline{A^{-1}}\,\underline{M'}\,\underline{SAR}$ (see §3.3.3), where:

- $\underline{M'}$ = transpose of $\underline{M}$

- $\underline{A^{-1}} = (\underline{M'}\,\underline{M})^{-1}$ = Inverse of $(\underline{M'}\,\underline{M})$

Finally, $\underline{B} = \begin{pmatrix} 2.402921963 \\ -0.000120515 \\ 2.10695\, x10 - 09 \end{pmatrix}$ and

$$\boxed{\mathrm{SAR}_{av} = 2.402921963 - 0.000120515\ \mathrm{m} + 2.10695.10^{-9}\ \mathrm{m}^2}$$

The following figure 3.3-2 provides a representation of the mean SAR model as a function of the aeroplane gross mass:

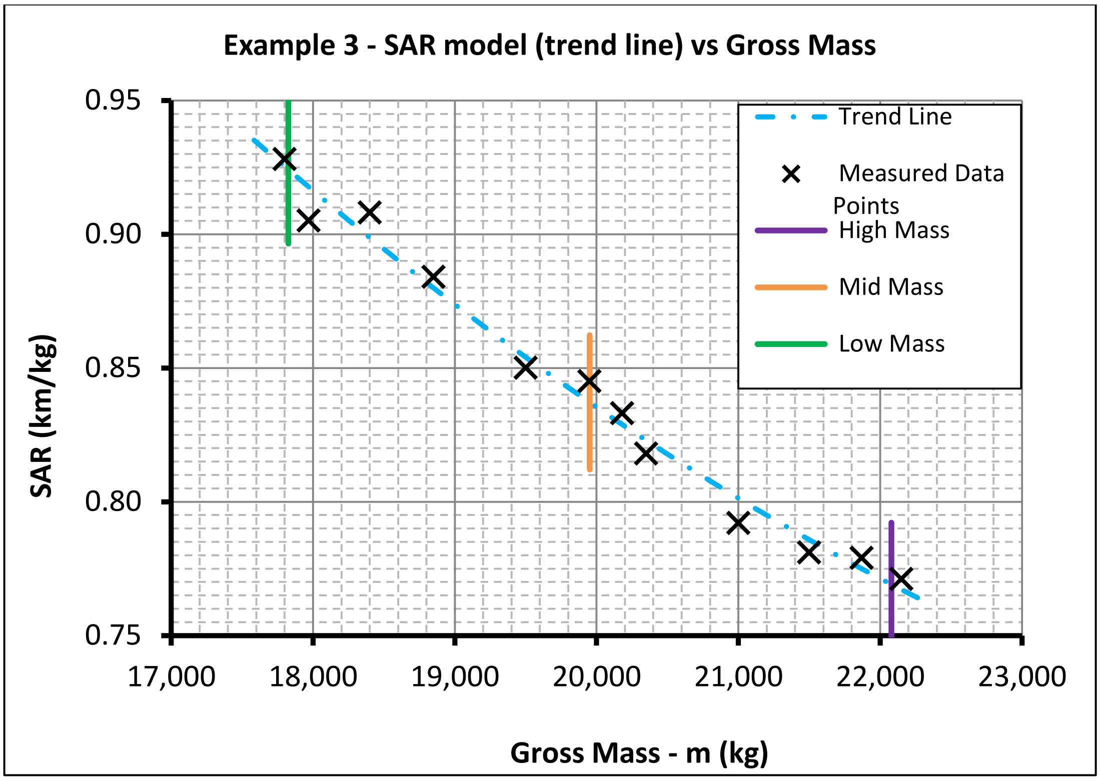

Figure 3.3-2 – SAR model (trend line) vs Gross Mass – Example 3

The mean SAR values at each of the three reference gross masses of the CO2 emissions evaluation metric are as follows:

Reference mass	*Mass value (kg)*	*Mean SAR value (km/kg)*
Low Mass	17825	0.92418
Mid Mass	19953	0.83710
High Mass	22080	0.76914

Table 3.3-5 – Mean SAR values – Example 3

Estimate of the standard deviation (s)

$$s = \sqrt{\frac{\sum_{i=1}^{i=n}(SAR_i - SARav(i))^2}{n-K-1}} = 0.00765\ km/kg$$

Where
- The number of data points (n) = 12
- K = 2 for a second order polynomial regression (See §3.3.3)
- The degrees of freedom (n-K-1) = 9

Confidence Interval determination

The 90 per cent confidence interval (CI_{90}) at an aeroplane gross mass m_0 is calculated as follows (see §3.3.3):

$$\boxed{CI90 = SARav(m0) \pm t_{(.95\,,n-K-1)}\, s\, \sqrt{\underline{m0}\ \underline{A-1}\ \underline{m0'}}}$$

Where:

- The Student's t-distribution for 90 per cent confidence and 9 degrees of freedom $t_{(.95,\,9)} = 1.833$ (see Table 3.3-1).

- $\underline{m_0} = (1\ \ m_0\ \ m_0^2)$ and $\underline{m_0}' = \begin{pmatrix} 1 \\ m0 \\ m0^2 \end{pmatrix}$

- $\underline{A}^{-1} = (\underline{M'}\ \underline{M})^{-1}$ = Inverse of $(\underline{M'}\ \underline{M})$

The following figure 3.3-3 provides a representation of the 90% confidence interval as a function of aeroplane gross mass:

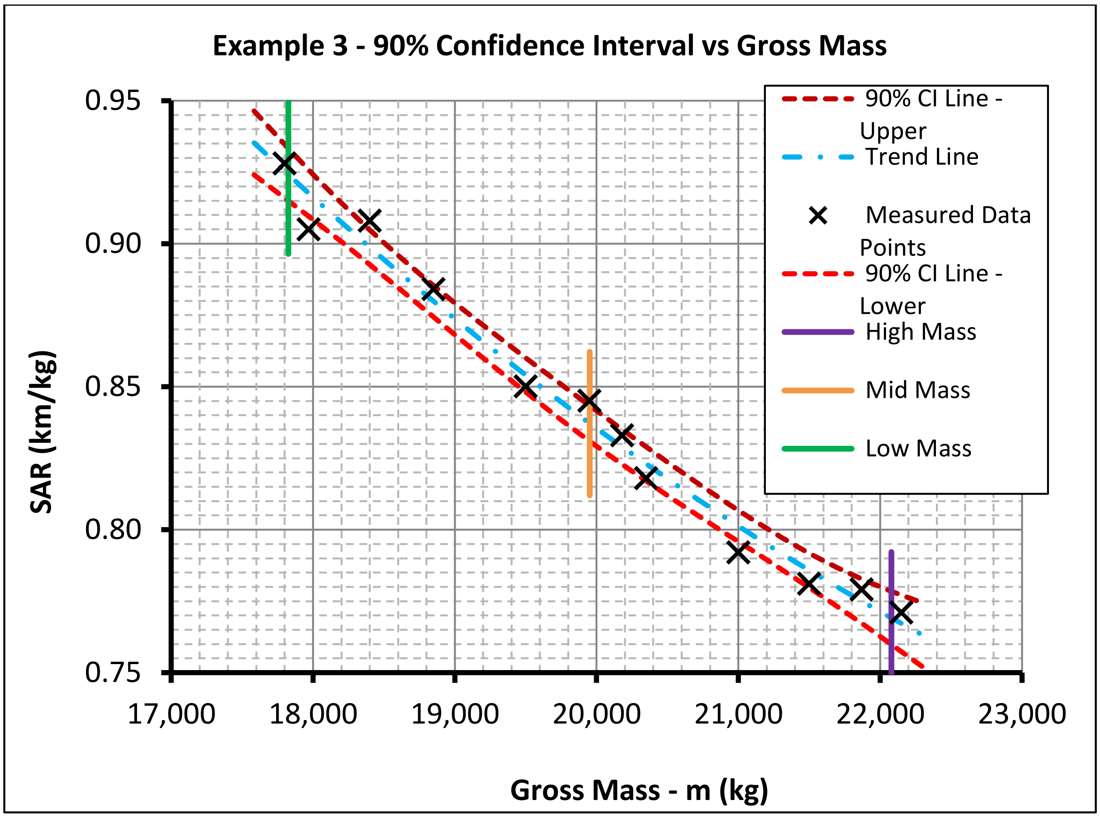

Figure 3.3-3 – 90% Confidence Interval vs Gross Mass – Example 3

The 90% confidence intervals at each of the three reference gross masses of the CO2 emissions evaluation metric are as follows:

Reference mass	*Mass value (kg)*	*90% Confidence Interval (kg/km)*
Low Mass	17825	$CI_{90} = 0.92418 \pm 0.00915$
Mid Mass	19953	$CI_{90} = 0.83710 \pm 0.00619$
High Mass	22080	$CI_{90} = 0.76914 \pm 0.00925$

Table 3.3-6 – Confidence intervals – Example 3

<u>Check of confidence interval limits</u>
For each of the three reference gross masses of the CO2 emissions evaluation metric, the confidence interval extends around the mean SAR value to an amount in percent provided in below table.

Reference mass	*Mass value (kg)*	*90% Confidence Interval (percentage of mean SAR)*
Low Mass	17825	(0.00915/0.92418) x 100 = 0.99%
Mid Mass	19953	(0.00619/0.83710) x 100 = 0.74%
High Mass	22080	(0.00925/0.76914) x 100 = 1.2%

Table 3.3-7 – Check of confidence intervals – Example 3

The 90 per cent Confidence Intervals at each of the three reference gross masses of the CO2 emissions evaluation metric are all below the confidence interval limit of 1.5 per cent defined in Annex 16 Volume 3 Appendix 1 §6.4.

As a result, the following mean SAR values associated to each of the three reference masses of the CO2 emissions evaluation metric can be used for the metric determination.

Reference mass	*Mass value (kg)*	*Mean SAR value (km/kg)*
Low Mass	17825	0.92418
Mid Mass	19953	0.83710
High Mass	22080	0.76914

Table 3.3-8 – Mean SAR values – Example 3

3.3.4.2.2 Example 4: the Confidence Interval of at least one of the three reference masses of the CO2 emissions evaluation metric exceeds the confidence interval limit

Let’s consider the following set of 12 measurements of SAR obtained by flight test at optimum speed and optimum altitude as a function of the aeroplane gross mass. After SAR correction to reference conditions, the following data set is obtained:

Measurement Number & Reference Mass	*Gross Mass (m_i) (kg)*	*Corrected SAR (SAR_i) (km/kg)*
1	17800	0.932
Low Mass (*)	17825	
2	18200	0.925
3	18620	0.913
4	18890	0.889
5	19350	0.868
6	19610	0.848
Mid Mass (*)	19953	
7	19920	0.838
8	20510	0.830
9	20790	0.806
10	21220	0.815
11	21480	0.779
High Mass (*)	22080	
12	22100	0.788

Table 3.3-9 – Measurements of SAR – Example 4

(*) *Low, Mid and High mass represent the reference masses of the CO2 emissions evaluation metric defined in Annex 16, Volume 3, Chapter 2, §2.3.*

The number of data points (n) = 12 (minimum requested by Appendix 1 of Annex 16 Volume 3, §6.3).

A representation of above measurement points is proposed in below figure 3.3-4.

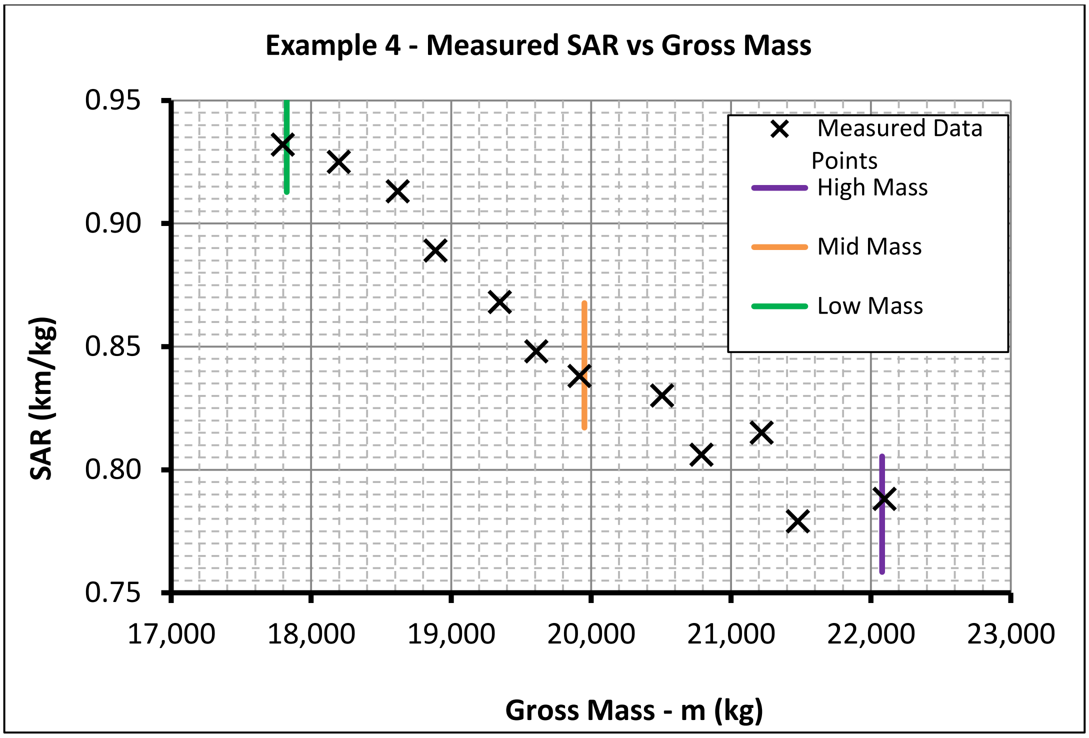

Figure 3.3-4 – Measured SAR vs Gross Mass – Example 4

Estimate of the mean SAR model by polynomial regression

In order to estimate the SAR model (SAR_{av}) as a function the aeroplane gross mass (m), a polynomial regression of second order is proposed, so that:

$$SAR_{av} = B_0 + B_1\, m + B_2\, m^2$$

Each observation (m_i, SAR_i), for i = 1, …, 12 satisfies the equation:

$$SAR_{(i)} = b_0 + b_1\, m_i + b_2\, m_i^2 + e_i$$

With e_i = residual error (difference between the measured SAR value and its estimate).

This gives under a matrix form:

$$\begin{pmatrix} SAR1 \\ SAR2 \\ SAR3 \\ \vdots \\ SAR12 \end{pmatrix} = \begin{pmatrix} 1 & m1 & m1^2 \\ 1 & m2 & m2^2 \\ 1 & m3 & m3^2 \\ \vdots & \vdots & \vdots \\ 1 & m12 \cdots & m12^2 \end{pmatrix} \begin{pmatrix} b0 \\ b1 \\ b2 \end{pmatrix} + \begin{pmatrix} e1 \\ e2 \\ e3 \\ \vdots \\ e12 \end{pmatrix}$$

$$\underline{SAR} = \underline{M}\,\underline{b} + \underline{e}$$

Where:

$$\underline{\text{SAR}} = \begin{pmatrix} 0.932 \\ 0.925 \\ 0.913 \\ 0.889 \\ 0.868 \\ 0.848 \\ 0.838 \\ 0.830 \\ 0.806 \\ 0.815 \\ 0.779 \\ 0.788 \end{pmatrix} \qquad \underline{\text{M}} = \begin{pmatrix} 1 & 17800 & 17800^2 \\ 1 & 18200 & 18200^2 \\ 1 & 18620 & 18620^2 \\ 1 & 18890 & 18890^2 \\ 1 & 19350 & 19350^2 \\ 1 & 19610 & 19610^2 \\ 1 & 19920 & 19920^2 \\ 1 & 20510 & 20510^2 \\ 1 & 20790 & 20790^2 \\ 1 & 21220 & 21220^2 \\ 1 & 21480 & 21480^2 \\ 1 & 22100 & 22100^2 \end{pmatrix} \qquad \underline{\text{b}} = \begin{pmatrix} b0 \\ b1 \\ b2 \end{pmatrix} \qquad \underline{\text{e}} = \begin{pmatrix} e1 \\ e2 \\ e3 \\ \vdots \\ e\text{n} \end{pmatrix}$$

The least square principle consists in looking for the parameter values of vector $\underline{\text{B}}$ minimising the sum of the squares of residuals, i.e.:

$$\text{Min} \sum_{i=1}^{i=12} e\text{i}^2 = \min \sum_{i=1}^{i=12} (SAR(\text{i}) - b0 - b1\, m\text{i} - b2\, m\text{i}^2)^2$$

It is equivalent to look for the solutions of $\frac{\partial(\sum e\text{i}^2)}{\partial b\text{j}} = 0$ for j= (0, 1, 2)

The solution $\underline{\text{B}} = \begin{pmatrix} B0 \\ B1 \\ B2 \end{pmatrix}$ is given by $\underline{\text{A}^{-1}}\ \underline{\text{M'}}\ \underline{\text{SAR}}$ (see §3.3.3), where:

$\underline{\text{M'}}$ = transpose of $\underline{\text{M}}$

$\underline{\text{A}^{-1}} = (\underline{\text{M'}}\ \underline{\text{M}})^{-1}$ = Inverse of $(\underline{\text{M'}}\ \underline{\text{M}})$

Finally, $\underline{\text{B}} = \begin{pmatrix} 3.26727172 \\ -0.000205692 \\ 4.21798\, x10 - 09 \end{pmatrix}$ and

$$\boxed{\text{SAR}_{\text{av}} = 3.26727172 - 0.000205692\ \text{m} + 4.21798.10^{-9}\ \text{m}^2}$$

The following figure 3.3-5 provides a representation of the mean SAR model as a function of the aeroplane gross mass:

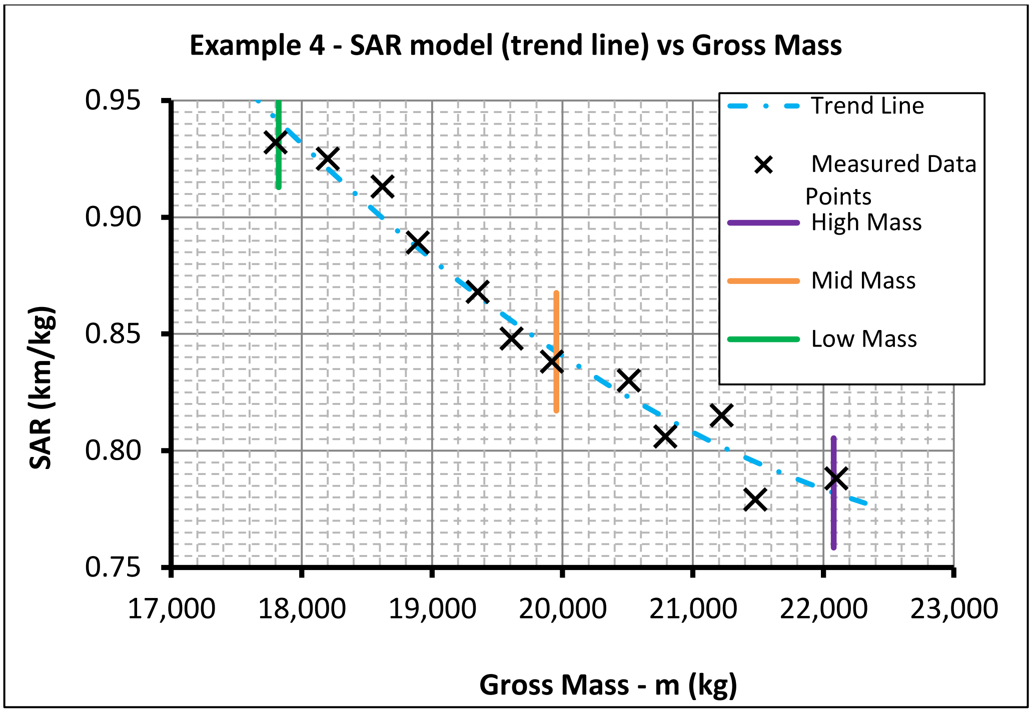

Figure 3.3-5 – SAR model (trend line) vs Gross Mass – Example 4

The mean SAR values at each of the three reference gross masses of the CO2 emission evaluation metric are as follows:

Reference mass	*Mass value (kg)*	*Mean SAR value (km/kg)*
Low Mass	17825	0.94100
Mid Mass	19953	0.84238
High Mass	22080	0.78198

Table 3.3-10 – Mean SAR value – Example 4

Estimate of the standard deviation (s)

$$s = \sqrt{\frac{\sum_{i=1}^{i=n}(SAR_i - SARav(i))^2}{n-K-1}} = 0.01050\ km/kg$$

Where
- The number of data points (n) = 12
- K = 2 for a second order polynomial regression (See §3.3.3)
- The degrees of freedom (n-K-1) = 9

Confidence Interval determination

The 90 per cent confidence interval (CI_{90}) at an aeroplane gross mass m_0 is calculated as follows (see §3.3.3):

$$\boxed{CI90 = SARav(m0) \pm t_{(.95\,,n-K-1)}\, s \sqrt{\underline{m0}\ \underline{A-1}\ \underline{m0'}}}$$

Where:

- The Student's t-distribution for 90 per cent confidence and 9 degrees of freedom $t_{(.95,\ 9)} = 1.833$ (see Table 3.3-1).

- $\underline{m_0} = (1 \ \ m_0 \ \ m_0^2)$ and $\underline{m_0'} = \begin{pmatrix} 1 \\ m0 \\ m0^2 \end{pmatrix}$

- $\underline{A}^{-1} = (\underline{M'}\ \underline{M})^{-1}$ = Inverse of $(\underline{M'}\ \underline{M})$

The following figure 3.3-6 provides a representation of the 90% confidence interval as a function of aeroplane gross mass:

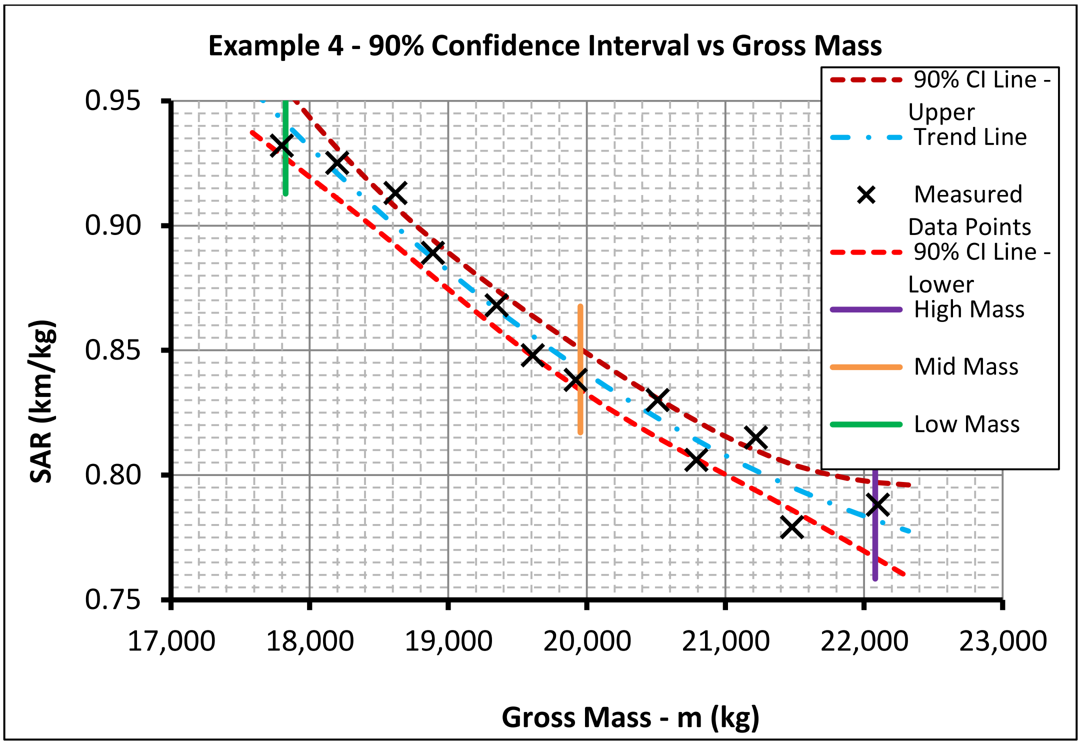

Figure 3.3-6 – 90% Confidence Interval vs Gross Mass – Example 4

The 90% confidence intervals at each of the three reference gross masses of the CO2 emissions evaluation metric are as follows:

Reference mass	*Mass value (kg)*	*90% Confidence Interval (kg/km)*
Low Mass	17825	$CI_{90} = 0.94100 \pm 0.01399$
Mid Mass	19953	$CI_{90} = 0.84238 \pm 0.00823$
High Mass	22080	$CI_{90} = 0.78198 \pm 0.01505$

Table 3.3-11 – Confidence intervals – Example 4

Check of confidence interval limits

For each of the three reference gross masses of the CO2 emissions evaluation metric, the confidence interval extends around the mean SAR value to an amount provided in below table.

Reference mass	*Mass value (kg)*	*90% Confidence Interval (percentage of mean SAR)*
Low Mass	17825	(0.01399/0.94100) x 100 = 1.52%
Mid Mass	19953	(0.00823/0.84238) x 100 = 0.98%
High Mass	22080	(0.01505/0.78198) x 100 = 1.93%

Table 3.3-12 – Check of confidence intervals – Example 4

The 90 per cent Confidence Intervals at the low and high reference gross masses of the CO2 emissions evaluation metric are above the confidence interval limit of 1.5 per cent defined in Annex 16 Volume 3 Appendix 1 §6.4.

In such a case, a penalty equal to the amount that the 90 per cent confidence interval exceeds ±1.5 per cent shall be applied to the mean SAR values as follows:

Reference mass	*Mass value (kg)*	*Corrected SAR value (km/kg)*
Low Mass	17825	0.94100 x [1 - (1.52-1.5)/100] = 0.94081
High Mass	22080	0.78198 x [1 - (1.93-1.5)/100] = 0.77862

Table 3.3-13 – Corrected SAR values – Example 4

As a result, the following mean SAR values associated to each of the three reference masses of the CO2 emissions evaluation metric can be used for the metric determination.

Reference mass	*Mass value (kg)*	*Mean SAR value (km/kg)*
Low Mass	17825	0.94081
Mid Mass	19953	0.84238
High Mass	22080	0.77862

Table 3.3-14 – Mean SAR values – Example 4

3.4 EQUIVALENT PROCEDURES

3.4.1 APPROVAL BASED ON EXISTING DATA

3.4.1.1 The use of existing data as an equivalent procedure may be requested by applicants, and it can be utilized in the below approach of equivalent procedures or other approaches approved by the certificating authority according to their technical judgement.

a) Develop a regression curve approach for SAR values across the gross weight (MTOM) range using existing data.

3.4.1.2 The information typically needed to use existing data for demonstrating compliance as an equivalent procedure is as follows:

a) The existing model used company test data that was not witnessed by an authority and/or the aeroplane configuration was not conformed by an authority, but the data obtained is deemed acceptable by the certificating authority.
b) The accuracy of the instrumentation and the data reduction processes may not have been documented to the quality standard desired for certification, or the original documentation may not have been retained, but the data available is deemed acceptable by the certificating authority.

3.4.2 APPROVAL BASED ON BACK-TO-BACK TESTING

3.4.2.1 The use of back-to-back test data may be requested by applicants as an equivalent procedure for determining the CO_2 evaluation metric value for relatively small configuration changes that can be made based on test data obtained on the same aeroplane with the same engines (e.g. antenna installations or other simple drag changes). This approach will typically not be appropriate for engine changes where the SFC of the engine may change due to internal changes. This compliance approach will likely be especially useful for STC modifiers who do not have access to the original flight test data from the aeroplane manufacturer.

a) Back-to-back testing should be accomplished on the same aeroplane and engines with the modification installed and not installed.
b) Instrumentation adequate to provide data meeting the accuracy requirements of the standard is installed in the test aeroplane.
c) The data reduction and comparison processes are acceptable to the certificating authority.

3.4.3 APPROVAL OF CHANGES BASED ON ANALYSIS

3.4.3.1 The use of analytical processes to establish compliance with the CO_2 evaluation metric value criteria for changes to the CO_2 evaluation metric value of a previously approved aeroplane configuration may be requested by applicants, provided those processes are approved by the certificating authority according to their technical judgement.

a) The data on which the analysis is based was derived from flight test data.
b) Use of CFD and wind tunnel analyses may be acceptable if agreed to by the certificating authority.

Appendix 1 - REFERENCES

[1] ASTM International D1655-15 entitled “Standard Specification for Aviation Turbine Fuels”. This ASTM International publication may be obtained from the ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959 USA, www.astm.org.

[2] Defence Standard 91-91, Issue 7, Amendment 3, entitled “Turbine Fuel, Kerosene Type, Jet A-1”. This Ministry of Defence Standard may be obtained from Defence Equipment and Support, UK Defence Standardization, Kentigern House, 65 Brown Street, Glasgow G2 8EX, UK.

[3] ASTM International D4809-13 entitled “Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)”. This ASTM International publication may be obtained from the ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959 USA, www.astm.org.

[4] ASTM International D4052-11 entitled “Standard Test Method for Density and Relative Density of Liquids by Digital Density Meter”. This ASTM International publication may be obtained from the ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959 USA, www.astm.org.

[5] ASTM International D445-15 entitled “Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)” This ASTM International publication may be obtained from the ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959 USA, www.astm.org.

Appendix 2 - BIBLIOGRAPHY

1. Kendall, M.G. and A. Stuart. *The Advanced Theory of Statistics.* Volumes 1, 2 and 3. New York: Hafner, 1971.
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4. Walpole, R.E. and R.H. Myers. *Probability and Statistics for Engineers and Scientists*. New York: MacMillan, 1972.
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6.3.4. Information on the methodology and data used to develop the new aeroplane CO2 emissions Standard

1. INTRODUCTION

1.1 The International Civil Aviation Organization (ICAO) is a United Nations (UN) specialized agency, established by States in 1944 to manage the administration and governance of the *Convention on International Civil Aviation* (referred to as the Chicago Convention). ICAO works with the Convention's 191 Member States and industry groups to reach consensus on international civil aviation Standards and Recommended Practices (SARPs) and policies in support of a safe, efficient, secure, economically sustainable and environmentally responsible civil aviation sector. Presently, there are over 10,000 such Standards and provisions contained in ICAO Annexes to the Chicago Convention. ICAO's ongoing mission is to support a global air transport network that meets or surpasses the social and economic development and broader connectivity needs of global businesses and passengers. While acknowledging the clear need to anticipate and manage the projected doubling of global air transport capacity by 2030 without unnecessary adverse impacts on system safety, efficiency, convenience or environmental performance, ICAO has established five comprehensive Strategic Objectives, namely: Safety, Air Navigation Capacity and Efficiency, Security and Facilitation, Economic Development of Air Transport, and Environmental Protection.

1.2 Improving the environmental performance of aviation is a challenge ICAO takes very seriously. In fulfilling its responsibilities, ICAO has three major environmental goals, which are to limit or reduce: 1) the number of people affected by significant aircraft noise, 2) the impact of aviation emissions on local air quality, and 3) the impact of aviation greenhouse gas emissions on the global climate. To limit or reduce the impact of aviation greenhouse gas emissions on the global climate, ICAO has identified a Basket of Measures with the aim of reducing carbon dioxide (CO_2) emissions from international aviation. The Basket of Measures includes solutions focused on technological improvements, operational improvements, sustainable alternative fuels and market-based measures (MBMs). Each measure will individually contribute to the overall effort to reduce CO_2 emissions from the air transport system.

1.3 The ICAO Committee on Aviation Environmental Protection (CAEP) is a technical committee of the ICAO Council established in 1983. CAEP assists the Council in formulating new policies and adopting new SARPs related to aircraft noise and emissions, and more generally to aviation environmental impacts. CAEP undertakes specific studies, as requested by the Council. Its scope of activities encompasses noise, air quality and the Basket of Measures considered for reducing international aviation CO_2 emissions. CAEP is structured into Working Groups in order to progress tasks under the various environmental areas (noise, emissions, modelling etc.).

1.4 Since 2010, CAEP has been developing an Aeroplane CO_2 Emissions Certification Standard, following the plan approved by the ICAO Council and the request from the 37th Session of the Assembly (Resolution A37-19[19]). This new Standard will be formed into a new Volume (Volume III) to Annex 16 to the *Convention on International Civil Aviation*, where Annex 16 Volume I covers aircraft noise and Volume II addresses aircraft engine emissions. The Aeroplane CO_2 Emission Certification Standard, which is part of the Basket of Measures identified by the ICAO Assembly, focuses on reducing CO_2 emissions through the integration of fuel efficiency technologies into aeroplane type designs. In a

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[19] Doc 9958, Assembly Resolutions in Force (as of 8 October 2010), ISBN 978-92-9231-773-7, ICAO, 2011. The current Assembly resolutions in force are: Doc 10022, Assembly Resolutions in Force (as of 4 October 2013), ISBN 978-92-9249-419-3, ICAO, 2014

similar way to the Annex 16, Volume I noise Standards, the CO_2 Standard is a technology standard focussed at the aeroplane level. The Standard is not aimed at reducing CO_2 emissions through operational measures, as these will be addressed by a different aspect of the Basket of Measures; however, it is underpinned by a certification requirement that is relevant to day-to-day operations, permits transport capability neutrality at a system level, and allows for equitable recognition of fuel efficiency improvement technologies in an aeroplane type design. Finally, the scope of applicability for a CO_2 standard should not include out-of-production nor in-service aeroplanes.

1.5 The CO_2 Standard has been developed considering the four core CAEP tenets, which are technical feasibility, environmental effectiveness, economic reasonableness, and the consideration of interdependencies (e.g. with noise and local air quality emissions). This has involved two phases of work which have focussed on the development of a certification requirement and options for a regulatory limit line. Figure 1 shows a representative framework of an ICAO Environmental Standard.

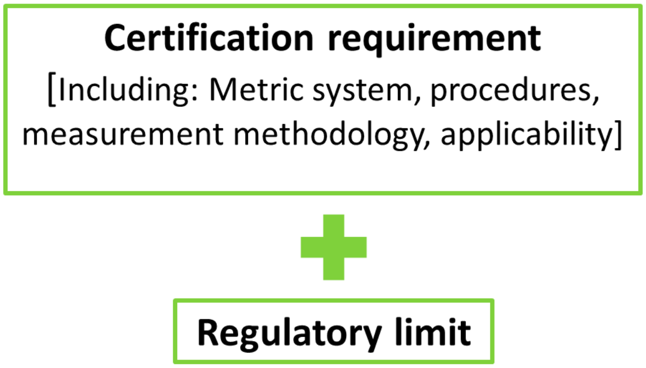

Figure 1: The basic framework of an ICAO Environmental Standard

1.6 Phase 1 involved tasks associated with the forming of a certification requirement for the CO_2 Standard, including the development of a CO_2 emissions evaluation metric system (i.e. metric/correlating parameter/test points), certification procedures, measurement methodologies, applicability to new aeroplane types, and initial inputs to the cost effectiveness assessment. Phase 2 included the development of ten regulatory limit stringency options (SOs), technology responses from the manufacturers when aeroplanes do not meet the SOs, a group of cost effectiveness analyses of the options available for the CO_2 Standard, interdependencies with noise and local air quality emissions, and an investigation of potential applicability to in-production aeroplanes. The text that follows provides a summary of the CO_2 Standard development work that has been conducted through a period of six years (i.e. two CAEP work cycles).

2. CAEVEATS

2.1 The data and information provided in this document were provided to support the selection of a CO_2 standard by ICAO CAEP in the context of the current ICAO Standard setting process. In particular, the assumptions on which the analysis is based uses current in-production and current project aircraft types (i.e. aeroplanes in development at the time of the analysis) as a baseline throughout the full analysis period (i.e. 2010-2040). They are not intended to be used for other purposes and should not be used as the basis to speculate on the introduction of potential future types. In addition, available feasible technology is used as the basis for potential technology improvements resulting from the standard. The analysis does not speculate on potential future technology developments.

2.2 Assumptions of aeroplane technology responses to regulatory levels were based on input from both manufacturers and other expert sources. These responses were meant for CO_2 cost effectiveness modelling purposes, and do not imply a commitment from manufacturers to develop actual individual products.

2.3 As a consequence, the environmental benefits and the costs are comparable between analysis cases but cannot be represented as absolute benefits and costs. Hence the data and information are not suitable for application to any other purpose of any kind, and any attempt at such application would be in error.

3. ANNEX 16, VOLUME III AND THE ENVIRONMENTAL TECHNICAL MANUAL, VOLUME III

3.1 Overview of the CO_2 emissions evaluation metric

3.1.1 The provisions contained in the draft First Edition of Annex 16, Vol. III represent the SARPs for the certification of aeroplane CO_2 emissions based on the consumption of fuel. The certification requirements are underpinned by a CO_2 emissions evaluation metric, which is a measure of the aeroplane fuel burn performance and therefore the CO_2 emissions produced. The CO_2 emissions evaluation metric is made up of a metric, a correlating parameter and test points and it is shown in Table 1.

Metric[20]	**Correlating Parameter**	**Test Points**
$= \frac{\left(1/\mathrm{SAR}\right)_{\mathrm{AVG}}}{(\mathrm{RGF})^{0.24}}$	MTOM	Three test points with equal weighting at optimum conditions: i) High gross mass = 0.92 * MTOM ii) Mid gross mass = Average of high gross mass and low gross mass iii) Low gross mass = (0.45 × MTOM) + (0.63 × ($\mathrm{MTOM}^{0.924}$))

where:

SAR – Specific Air Range is the distance an aeroplane travels in the cruise flight phase per unit of fuel consumed.

RGF – Reference Geometric Factor is an adjustment factor based on a measurement of aeroplane fuselage size derived from a two-dimensional projection of the fuselage**.**

MTOM – Maximum Take-Off Mass is the highest of all take-off masses for the type design configuration.

Table 1: The CO_2 evaluation metric used within the CO_2 Standard

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[20] More details can be found in: ICAO Circular 337, CAEP/9 Agreed Certification Requirement for the Aeroplane CO_2 Emissions Standard, ISBN 978-92-9249-351-6

3.1.2 To establish the fuel efficiency of the aeroplane, the CO_2 emissions evaluation metric uses multiple test points to represent the fuel burn performance during cruise. Three equally weighted points represent aeroplane weights at high, middle and low percentages of MTOM, as specified in Table 1 and illustrated in Figure 2. Each of these points represents an aeroplane cruise gross weight which could be seen in service. The objective of using three gross weight cruise points is to make the evaluation of fuel burn performance more relevant to day-to-day aeroplane operations. The fuel efficiency performance of an aeroplane is represented by Specific Air Range (SAR), which represents the distance an aeroplane travels in the cruise flight phase per unit of fuel consumed. Within the CO_2 emissions evaluation metric, 1/SAR is used. Further details on its measurement and calculation can be found in the certification requirement contained within the proposed First Edition of Annex 16, Vol. III.

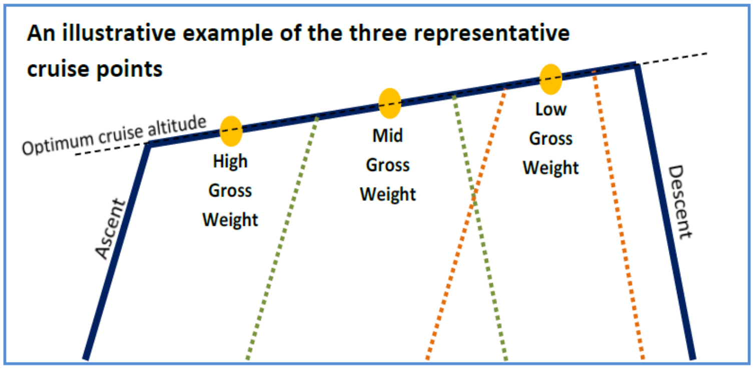

Figure 2: An illustrative example of the three representative certification test points

3.1.3 In some aeroplane designs, there are instances where changes in aeroplane size may not reflect changes in aeroplane weight, such as when an aeroplane is a stretched version of an existing aeroplane design. To better account for such instances, as well as the wide variety of aeroplane types and the technologies they employ, an adjustment factor was used to represent aeroplane size. This is defined as the Reference Geometric Factor (RGF) which is a measure of aeroplane fuselage size based on a two-dimensional projection of the fuselage. This improved the performance of the CO_2 emissions evaluation metric, making it better able to account for different aeroplane designs. The definition of RGF can be found in the certification requirement contained within the proposed First Edition of Annex 16, Vol. III.

3.1.4 The overall design of the aircraft is represented in the CO_2 emissions evaluation metric by the certified MTOM (the correlating parameter). This accounts for the majority of aircraft design features which allow an aircraft type to meet market demand.

3.1.5 The intent of the CO_2 emissions evaluation metric shown in Table 1 is to equitably reward advances in aeroplane technologies (i.e. structural, propulsion and aerodynamic) that contribute to reductions in aeroplane CO_2 emissions, and to differentiate between aeroplanes with different generations of these technologies. As well as accommodating the full range of technologies and designs which manufacturers can employ to reduce CO_2 emissions, the metric has been designed to be common across different aeroplane categories, regardless of aeroplane purpose or capability. The CO_2 emissions evaluation metric was developed based on data for in-production and out of production aeroplane types. A set of key criteria was followed during the development of the CO_2 emissions evaluation metric:

- General. The certification standard must not compromise safety levels. The CO_2 certification requirement should be aeroplane performance-based, should reflect CO_2 emissions at the aeroplane level. It should also allow for the differentiation of products with different generations of CO_2 reduction technologies and should aim to be independent of aeroplane purpose or utilization. The certification requirement should decouple effects of fuel performance from aeroplane performance;

- Effective. Improvements observed via the CO_2 certification requirement should correlate with reduction of CO_2 emissions at the aeroplane level as demonstrated by procedures which are relevant to day-to-day operations. It should also take into account fundamental aeroplane design elements and capabilities (such as distance travelled and what is transported);
- Objective. The certification requirement should be objective and therefore needs to be based on certified aeroplane parameters and/or currently non-certified parameters as long as the parameters that compose the metric are easily measurable at the certification stage, or derived from engineering data. The certification requirement should consider the industry standard practices of measurement and adjustment;
- Robust. The metric should be robust in order to minimise the potential for unintended system and aeroplane design consequences, to limit interdependencies and to limit any influence on other standards. To the extent practicable, the certification requirement should be fair across the set of stakeholders, such as manufacturers and operators;
- Reasonable. The certification requirement should not require an inappropriate level of resources on the part of National Airworthiness Authorities and manufacturers to implement. If the certification requirement requires the certification of additional parameter(s) compared to existing practices, the implications (such as technical feasibility and economic reasonableness) should be evaluated; and
- Open. The output should be explainable to the general public.

3.1.6 The discussions on an appropriate CO_2 emissions evaluation metric were also guided by a set of high level principles, namely:

1) Within the Basket of Measures, an aircraft CO_2 standard should focus on reducing CO_2 emissions through integration of fuel efficiency technologies into aeroplane type designs.
2) Aim to design a metric system (metric/correlating parameter/test points) which could permit transport capability neutrality at a system level when stringency is applied based on this metric system.
3) Aim for equitable recognition of fuel efficiency improvement technologies in an aircraft type design.

3.2 The Certification Requirement

3.2.1 Based on the agreed CO_2 emissions evaluation metric, CAEP developed procedures for the certification requirement including, *inter alia*, SAR flight test and measurement conditions; the measurement of SAR and corrections to reference conditions; and the definition of the RGF used in the CO_2 emissions metric. CAEP established and utilized a Certification Experts (CE) group to support the discussions on the certification requirement and to facilitate oversight of commercially sensitive information. The CE group identified the manufacturers' existing practices in measuring aircraft fuel burn and high speed performance in order to understand how current practices could be used and built upon. Based on this information, a draft proposed ICAO Annex 16, Volume III CO_2 Standard certification requirement was developed, and this was approved by the CAEP/9 meeting in February 2013 as documented in ICAO Circular 337. Following this, the certification procedures were further developed to reinforce the requirements within the proposed Volume III and ensure a smooth implementation in Type

Certification projects once adopted by ICAO and Member States. The topics covered during the development of the CO_2 Standard certification requirement included: stability criteria and confidence intervals; methodologies to correct test data to reference conditions; extrapolation of data; fuel used in SAR flight tests; verifying test aeroplane mass determination; demonstrating nominal operating values for power extraction; RGF for unpressurized aeroplanes; numerical model confidence intervals; and correction of engine fuel efficiency performance.

3.3 The Environmental Technical Manual (ETM), Volume III

3.3.1 An Environmental Technical Manual, Vol. III (ETM, Vol. III) has also been developed with the aim of promoting uniformity of implementation of the technical procedures of Annex 16, Volume III by providing: (1) guidance to certificating authorities, applicants and other interested parties regarding the intended meaning and stringency of the Standards in the current edition of the Annex; (2) guidance on specific methods that are deemed acceptable in demonstrating compliance with those Standards; and (3) equivalent procedures resulting in effectively the same CO_2 emissions evaluation metric that may be used in lieu of the procedures specified in those Standards.

4. STRINGENCY OPTIONS (SOs)

4.1 An important part of the Standard-setting process was the definition of a set of SOs, which could be chosen to represent the eventual limit line for the CO_2 Standard. Each SO aimed to maintain the intended behaviour of the CO_2 emissions metric, i.e. to equitably reward advances in aeroplane technologies that contribute to reductions in aeroplane CO_2 emissions, and to differentiate between aeroplanes with different generations of these technologies.

4.2 Unlike other recent CAEP Standard-setting processes that led to more stringent regulatory levels to an existing standard, the CO_2 Standard work had no baseline in the form of an existing regulatory level or a proposed range of stringency options to assess. In addition, applicability scenarios for new aeroplane types (NT) and new deliveries of in-production (InP[21]) aeroplane types were also considered and so the underlying production assumptions to be used in the cost-effectiveness assessment were also uncertain. As a consequence, a preliminary analysis framework was developed, and this helped to form an initial wide analytical space that included all InP and in-development project aeroplane types. The analytical work to define the wide analytical space, and the set of SOs across contained within it, necessarily considered the impact of SOs on the InP and in-development project aeroplane types. The selection of the SOs formed a fundamental part of the cost-effectiveness analysis and as such the set of ten SOs were carefully selected so as not to pre-judge the outcome of this analysis.

4.3 As with other ICAO environmental standards, the shape of the limit line is important to capture the differences in technology across the spread of aeroplane types. Discussions on appropriate SO curve shapes within the wide analytical space involved assessing equivalent levels of fuel efficient technology between aeroplane types at different MTOMs. Technical and economic limitations in adopting fuel efficiency technologies within different aeroplane categories were also recognised.

4.4 The analysis to develop the ten CO_2 SOs was based on several extensive CO_2 metric value databases. The Metric Value database (MVdb) contained uncertified data provided directly from manufacturers on in-production aeroplane types, and the Project Aircraft Metric Value database

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[21] InP refers to those aeroplane types which have already applied for a Type Certificate before the applicability date of the new type CO_2 Standard, and for which manufacturers either have existing undelivered sales orders or would be willing and able to accept new sales orders.

(PAMVdb) contained performance estimates for in-development project aeroplane types provided directly by either the manufacturers or other entities. The CO_2 SOs were generated as percentage offsets at 60 tonnes (t) maximum take-off mass (MTOM) to an Adapted Reference Line (ARL) datum that passed through the worst performing (in terms of CO_2 emissions metric) of the in-production aeroplanes. The percentage offsets were made at 60t MTOM because this represents a "kink point" in the SO lines between the largest of the "smaller" aeroplanes and the smallest of the "larger" aeroplanes.

4.5 Locating the kink point at 60t MTOM acknowledges observed differences in behaviour between the "smaller" aeroplanes and the "larger" aeroplanes, and takes into account the latest single aisle and regional jet data which has become available since the end of the CAEP/9 meeting in February 2013. The 60t kink point was found to be the optimal place to split the new small aeroplane entries from Bombardier, Embraer, and Mitsubishi from the larger aeroplanes built by Boeing, Airbus, and other manufacturers. It falls below the large aeroplane weight variants and above all but one of the small aeroplane variants. The 60t kink in the CO_2 SOs is designed to produce a continuous stringency line that minimizes market distortions.

4.6 In order to accommodate potential future Type Certificate applications above the highest MTOM within the current fleet of InP and in-development aeroplanes (i.e. the highest MTOM was 600t in the CO_2 MVdb and PAMVdb), the CO_2 SO curve shape has been extrapolated above the 60t kink towards infinity. This aims to avoid potential ambiguity and delays in future type certification projects by ensuring there is an associated regulatory CO_2 limit line for aeroplanes with an MTOM above 600t. The lack of data above 600t MTOM on which to base the curve extrapolation is certainly a concern, and it is envisaged that this issue will be considered during future CAEP work programmes if the industry aims to manufacture aeroplanes above 600t MTOM.

4.7 The choice to have ten SOs was based on an analysis of impact rates across the fleet of aeroplane types, and this is shown in Table 2 across all the seat classes, along with margins to the ARL for all InP and project aircraft types. This means that the percentage differences between SOs is not constant because the analysis was conducted so that the SOs would impact the full scope of InP and project aeroplanes as the SOs become more stringent. For project aeroplanes, the data used included a level of uncertainty over a range of metric values that represented the type design under development. For the purposes of the analysis, the upper point (i.e. the worst case combination of highest metric value with lowest MTOM) was used for determining pass/fail compliance and therefore the impact rate of the SOs. The ten SOs provided a convenient analytical space within which to conduct a full cost effectiveness analysis, but had no particular meaning with regards to the stringency ultimately chosen as the regulatory limit line.

CO_2 Stringency Option	% to ARL at 60t MTOM	MV at 60t MTOM	Impact Rate
1	- 20.0%	0.8734	7%
2	- 24.0%	0.8297	13%
3	- 27.0%	0.7970	24%
4	- 28.5%	0.7806	32%
5	- 30.0%	0.7642	41%
6	- 31.5%	0.7479	50%
7	- 33.0%	0.7315	57%
8	- 34.3%	0.7173	60%
9	- 37.5%	0.6823	79%
10	- 40.4%	0.6507	99%

Table 2: The ten SOs and the impact rate across the fleet of aeroplane types

4.8 Figures 3 and 4 show the ten SOs resulting from the CAEP analysis. The ten SOs provide a data driven measurement of fuel efficiency performance from aeroplane technology and design within the full range of MTOM, seeking as far as practicable to apply approximately equal pressure across aeroplane categories.

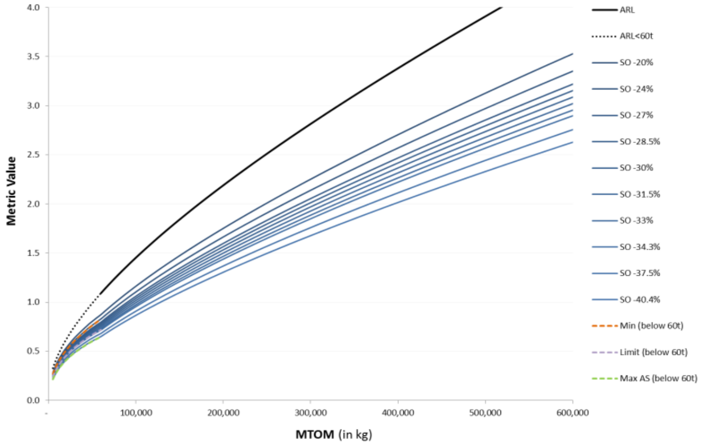

Figure 3: CO2 stringency options analysed within the cost effectiveness analysis (0-600t MTOM)

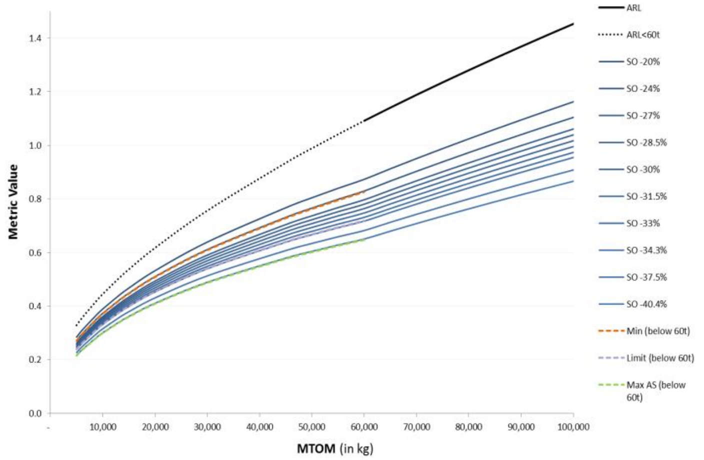

Figure 4: CO_2 stringency options analysed within the cost effectiveness analysis (0-100t MTOM)

5. MODELLING APPROACH FOR THE COST EFFECTIVENESS ANALYSIS

5.1 In order to address the CAEP tenets of environmental effectiveness and economic reasonableness, CAEP has conducted a full cost effectiveness analysis. This involved the definition of an analysis framework and analytical tools, including fleet evolution modelling, environmental modelling, recurring costs, non-recurring costs, costs per metric tonne of CO_2 avoided, certification costs, hybrid applicability and sensitivity tests. The analysis framework has allowed CAEP to conduct the CO_2 main analysis (CO2ma), with the aim of providing a reasonable assessment of the economic costs and environmental benefits for a potential CO_2 standard in comparison with a “No ICAO action” baseline. A high level overview of the CO2ma process is provided in Figure 5. An overview of the models used is contained in Table 3.

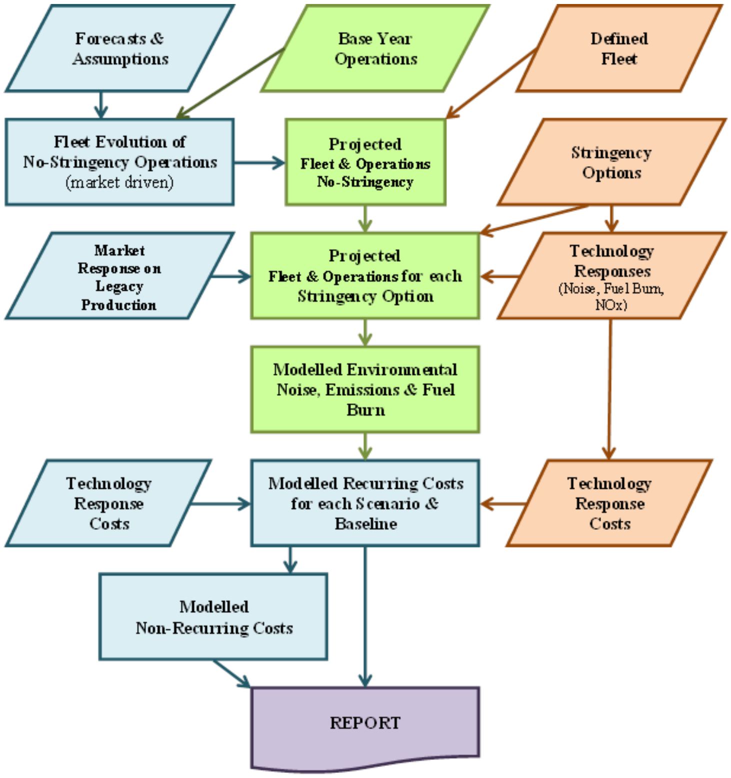

Figure 5: An overview of the CO_2 Main Analysis Framework and Processes

Model		Area	Sponsor
AAT	Aircraft Assignment Tool	Fleet Evolution	EUROCONTROL, EC and EASA
APMT-E	Aviation environmental Portfolio Management Tool for Economics[22]	Fleet Evolution & Cost-Effectiveness	US
FCM	FESG Cost Model for the CO2ma	Cost-Effectiveness	ICAO/CAEP FESG[23]
FAST	Future Civil Aviation Scenario Software Tool[24]	GHG	UK
IMPACT	Multi-airport environmental impact assessments tool for noise, gaseous and particulate emissions, and local air quality modelling[25]	GHG	EUROCONTROL
AEDT	Aviation Environmental Design Tool[26]	GHG and Noise	US
ANCON	Aircraft Noise Contour Model[27]	Noise	UK
STAPES	SysTem for AirPort noise Exposure Studies[28]	Noise	EUROCONTROL, EC and EASA

Table 3: An overview of the models used in the CO_2 Main Analysis (CO2ma)

5.2 Defining the global aeroplane fleet

5.2.1 The modelling process relies on aeroplanes available for entry into the global aeroplane fleet during forecast years up to 2040, for both the baseline and each of the ten SOs. The aeroplane data are collated into what is known as the Growth and Replacement (G&R) database. This database documents all of the information required by the modelling community regarding each aeroplane and engine type in the analysis, both in their base configuration and as defined for each SO. The G&R database also includes references to other data sources such as the ICAO Aircraft Engine Emissions Databank and the ICAO noise certification database (NoisedB).

5.2.2 The CO2ma G&R database fleet includes project aeroplanes that enter the fleet from 2014 to 2020. Some aeroplanes are described as having a “transition pair” where project aeroplanes are paired with current InP aeroplanes that transition out of the fleet as the project aeroplanes transition into the fleet. These Transition Pairs (TP) approximate a “ramp up/ramp down” of production for the two aeroplane types of a period of 6 years (this is described further in Section 6). If transitioning-out types are still available for growth and replacement after the implementation date of a CO_2 Standard, then their technology relationship to the SOs is taken into account. In other words, if an InP aeroplane with a TP passes a given SO then it continues to transition as it would have. However, if it were to not pass a given SO then the current InP aeroplane would go out of production earlier and the transition to the project aircraft could happen immediately upon implementation of the CO_2 Standard if that aeroplane were available for deployment.

5.3 Fleet evolution modelling

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[22] https://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/apmt/
[23] ICAO/CAEP Forecast and Economic Analysis Support Group (FESG)
[24] http://www.cate.mmu.ac.uk/about-us/how-we-do-it/climate-models-and-tools/emissions-models/
[25] http://www.eurocontrol.int/services/impact
[26] https://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/aedt/
[27] http://publicapps.caa.co.uk/modalapplication.aspx?catid=1&pagetype=65&appid=11&mode=detail&id=784
[28] https://www.eurocontrol.int/eec/public/standard_page/proj_STAPES.html

5.3.1 Using the G&R database fleet, the fleet evolution models use air traffic forecasts to project a schedule of operations by specific aircraft types, and generate required inputs for the environmental models. The EUROCONTROL, European Commission (EC) and European Aviation Safety Agency (EASA) Aircraft Assignment Tool (AAT) and the U.S. Federal Aviation Administration (FAA) Aviation environmental Portfolio Management Tool for Economics (APMT-E) modelled the fleet evolution for the CO2ma.

5.3.2 The underlying forecast targets input into the fleet evolution models, and their relative allotment to the Competition Bins (Cbin) [29], have an important influence on the CO2ma results. CBins are a method to describe different segments of the fleet without the need to specify demand for specific aeroplane types. Table 5 describes how these bins are divided across the fleet.

	Seat Range and Aircraft Type	**MTOM (tonne)**
CBin-1	Business Jets (BJ): <20seats, Cabin 300-700cft & Range 1700 to 3100 nm	6.3 to 13.9
CBin-2	BJ: <20seats, Cabin 700-1500cft & Range 3100 to 5000 nm	16.4 to 24.3
CBin-3	BJ: <20seats, Cabin 1500-3000cft & Range over 5000 nm	31.8 to 45.2
CBin-4	BJ: <20seats, Large Corporate Jets	68.0 to 80.6
CBin-5	20-70 seat Turboprops	18.6 to 28.4
CBin-6	71-100 seat Turboprops	29.6
CBin-7	20-70 seat Regional Jets	20.0 to 43.7
CBin-8	71-100 seat Regional Jets	38.3 to 56.2
CBin-9	101-150 seats	52.3 to 107.5
CBin-10	151-210 seats	74.3 to 110.8
CBin-11	211-300 seats	186.9 to 347.8
CBin-12	301-400 seats	248.4 to 351.5
CBin-13	401-600 seats	447.7 to 575.0
CBin-14	New Purpose-Built Freighters equivalent to 211-300 seats	107.5 to 233.0
CBin-15	New Purpose-Built Freighters equivalent to 301 seats and up	347.8 to 447.7

Table 4: Aeroplane Competition Bins (Cbins), Seat Ranges, and MTOMs

5.3.3 The left side of Table 5 shows the distribution of baseline operations by CBin; and, combined CBin-9 and CBin-10 represent approximately 50% of total operations. The right side of Table 5 shows the distribution of available seat kilometres (ASKs) by CBin. Around 93% of ASKs (and around 69% of operations) in 2040 are from five CBins (9, 10, 11, 12 & 13), which means that these CBins will have a more pronounced effect on the CO2ma results.

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[29] A Competition Bin or CBin is aligned to the forecasted seat classes, either one-to-one or in combination (e.g., seat classes for aircraft above 401 seats were combined into CBin-13).

	2020 Ops	2030 Ops	2040 Ops	Avg. Seats	2020 ASK	2030 ASK	2040 ASK
CBin-1	4.3%	4.0%	4.0%	13	0.3%	0.3%	0.2%
CBin-2	2.3%	2.4%	2.6%	13	0.3%	0.3%	0.2%
CBin-3	0.9%	1.2%	1.6%	13	0.2%	0.2%	0.3%
CBin-4	0.0%	0.0%	0.0%	13	0.0%	0.0%	0.0%
CBin-5	10.9%	10.5%	10.0%	55	0.9%	0.9%	0.8%
CBin-6	1.2%	1.2%	1.2%	74	0.2%	0.1%	0.1%
CBin-7	8.1%	6.7%	5.8%	55	1.4%	1.2%	1.0%
CBin-8	6.2%	5.9%	5.9%	86	2.0%	1.8%	1.6%
CBin-9	26.8%	25.1%	22.8%	126	16.7%	14.5%	12.3%
CBin-10	28.8%	28.1%	26.8%	171	28.2%	25.8%	23.2%
CBin-11	6.4%	9.3%	10.6%	261	25.1%	26.2%	24.2%
CBin-12	2.5%	3.1%	4.4%	332	13.9%	13.7%	15.3%
CBin-13	1.1%	2.2%	4.0%	484	8.6%	13.2%	18.9%
CBin-14	0.2%	0.1%	0.2%	220	0.3%	0.2%	0.3%
CBin-15	0.3%	0.3%	0.3%	368	1.9%	1.6%	1.6%

Table 5: Baseline Operations (Ops) and ASK Distribution by Competition Bin (Cbins) and Forecast Year

5.3.4 The CO2ma fleet evolution modelled by APMT-E was used to generate the Fleet Evolution Output Database (FEOD) that was provided as input for all GHG and noise modellers. In addition, GHG results associated with the fleet evolution modelled by AAT were calculated using the EUROCONTROL IMPACT tool. Overall, the fleet evolution models produced consistent aggregate output metrics for the CO2ma baseline run and consistent interpretation of the CO2ma stringency option responses. While there are differences between the models when calculating market shares and deploying aircraft that result in some variation in operations, flight kilometres and aircraft deliveries[30] at the CBin level, there is good alignment between the models in terms of the direction and magnitude of the CBin level changes between the baseline and SO scenarios.

5.4 Environmental modelling tools

5.4.1 Full-flight fuel burn and NO_X emissions were modelled using AEDT (USA), FAST (UK) and IMPACT (EUROCONTOL) for analysis years 2010, 2020, 2030 and 2040. It is important to understand that the tools model fuel burn and performance differently.

5.4.2 AEDT models all aircraft performance using a total of 111 unique aircraft from ICAO/ Aircraft Noise and Performance (ANP)[31] Version 3.0 database (up to 10,000 feet for fuel burn and 15,000 feet for noise) and 62 unique aircraft from the “Base of Aircraft Data” (BADA) version 4.1 and 37 unique aircrafts from version 3.12 (above 10,000 feet for fuel burn). Fuel burn computations are based on the output of the performance model and, nominally, the BADA fuel flow coefficients[32].

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[30] For example; when deploying aeroplanes AAT uses an equal distribution across forecast distance bands while APMT-E deploys aeroplanes according to the base year distribution; and, when calculating SO market shares in the aeroplane choice model, APMT-E adjusts fuel burn rates and costs to reflect the aircraft-specific TR for each SO.

[31] ANP – Aircraft Noise and Performance database

[32] BADA is a database developed by EUROCONTROL to estimate aeroplane fuel usage and was used by AEDT and IMPACT.

5.4.3 FAST is a global three-dimension (longitude, latitude and altitude) aviation inventory and scenario modelling platform that uses aircraft movement inputs and PIANO[33] fuel usage to generate fuel, CO_2, NOx, CO, particles, soot and distance flown.

5.4.4 The IMPACT model is a successor to the CAEP-approved Advanced Emissions Model (AEM) for the assessment of fuel burn and CO_2 emissions. IMPACT is a web-based environmental modelling system developed by EUROCONTROL in the context of the Single European Sky Air Traffic Management Research (SESAR) collaborative project. It allows the consistent assessment of trade-offs between noise and gaseous emissions owing to a common aircraft performance model based on a combination of the ICAO/ANP database and the latest release of BADA 4. IMPACT has successfully contributed to the GHG assessments of the CO2ma.

5.5 Environmental Modelling Framework

5.5.1 The CO2ma framework was initially defined as a series of four cases that could consider CO_2 standard application to new types (NT) and new deliveries of InP types[34]. The framework also provided for the assessment of something other than implementation of all technically feasible responses or assuming that aeroplanes go out of production at the implementation date(s) if they cannot be made compliant to an SO level. The “Case” terminology remains since it reflects terminology used during the work of CAEP on the development of the CO_2 Standard; however, there are no longer a full sequence of Cases. Rather, the three following cases were taken forward to support the standard setting process.

5.5.2 **NT and InP aeroplane applicability case - Full Technology Response (TR) / Out of Production Case (Case-1):** This involved the analysis of the ten SOs at the agreed implementation dates[35], using all technology responses[36] defined by CAEP, and with aeroplanes that are assumed to go out of production (OoP) at the implementation dates if they cannot be made compliant to a stringency option level[37].

5.5.3 **NT-Only applicability case - Alternative Response / Production Case (Case-4):** This involved the analysis of the ten SOs at agreed implementation dates for NT-only applicability using responses informed by market considerations since manufacturers would not have a legal deadline to bring InP types to levels required under a NT-only standard. This case, called Case 4, can be thought of as a range of response scenarios from a voluntary response similar to Case-1 down to an absence of any response by growth and replacement aircraft; and, within that range, Case-4 was summarized in the following sub-cases as follows:

- Case-4-A: Top 33% most likely families respond and non-compliant families go out of production, unless no aircraft types remain to meet distance band demand;
- Case-4-B: Repeat Case-4-A with the B767 family remaining in production without a TR; and
- Case-4-C: Top 33% most likely families respond and non-compliant families remain in production.

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[33] PIANO is a commercially available software program that allows for the calculation of full flight fuel estimates from a variety of aircraft and was used by FAST.

[34] It was agreed at the CAEP/9 meeting, that the scope of applicability for a CO_2 standard should include new aeroplane types, but not out-of-production, and that applicability to InP types should not be ruled out; applicability to in-service aeroplanes was ruled out.

[35] As agreed at CAEP/9, the implementation dates for the CO_2 Standard Stringency assessment are 2020 and 2023; and, subsequently additional sensitivity analyses were performed for 2025 and 2028 applicability dates.

[36] described below in Section 6

[37] The OoP assumption was referred to as the “Market Driven Production Cut-off” when used in previous CAEP analyses.

5.5.4 It was agreed by CAEP members that modelling should proceed for Case 1 and Case-4c; and, Cases 4a and b could be analysed if time and resources permit. The technology response to these cases is described in Section 6.

5.5.5 A **Hybrid Applicability case** was also investigated. This involved the application of the CO_2 standard to NT aeroplanes prior to new deliveries of InP types that allows for potentially combining a higher SO for NT applicability with a lower SO for InP applicability.

5.6 Cost modelling

5.6.1 The recurring direct operating costs (DOC) include: (a) capital costs (including finance and depreciation), (b) other-DOC (including crew, maintenance landing and route costs) and (c) fuel costs. The primary model used for modelling other-DOC and capital costs was APMT-E; and fuel costs were based on AEDT fuel burn data. The ICAO/CAEP FESG Cost Model (FCM) was used to confirm the results using both AAT and APMT-E fleet evolution data along with AEDT fuel burn data.

5.6.2 As there is no existing CO_2 Standard, there is no historic data on fleet valuation impacts on aircraft owner/operators or on how manufacturers will determine the technology response given changes in market demand associated with CO_2 regulatory levels. Consistent with standard principles of economic analysis, all relevant recurring and non-recurring cost (NRC) items should be accounted for in the cost analysis of the CO_2 Standard SOs. Among these cost items, non-recurring (N-R) aircraft owner/operator (AO/O) costs may include a loss in fleet value that could be incurred by aircraft owners and operators for fleet assets that would not meet the stringency options; referred to as asset value loss (AVL). This is based on the premise that the introduction of a new standard would reduce the market value of existing fleets that do not meet the standard, even if the standard does not apply to the in-service aircraft. Further details on the NRC assumptions can be found in Section 6.

5.6.3 It should be noted that CAEP has not definitively stated whether AVL costs should be included and therefore the results of the CO2ma were considered with and without AVL.

5.6.4 The CO2ma uses NRC to represent the cost of applying TRs to aircraft. It is understood, however, that while NRC capture the fixed cost associated with developing TRs applied to aircraft types so that they pass the standard, they do not reflect additional production cost of implementing these responses, i.e., material, labour and other recurring costs. The CO2ma assumes that the cost of manufacturing aeroplanes remains unchanged after they have been modified to meet an SO, whereas the additional technology contained in a technology response may be expected to cost more to manufacture. To fill this potential gap in the analysis, CAEP investigated methodologies for quantifying these additional manufacturing costs. One methodology, based on price after technology response (PATR) computations, estimates these costs as the increase in aircraft price resulting from the application of TRs. There were divergent views within CAEP on the use of PATR, and therefore it was agreed that PATR would only be incorporated as a sensitivity analysis into the CO2ma for TR-related costs.

6. TECHNOLOGY ASSUMPTIONS FOR THE COST EFFECTIVENESS ANALYSIS

6.1 The technology-related assumptions developed to be used in the CO2ma dealt with issues of technical feasibility, CO_2 Technology Responses, costs, interdependencies with noise and engine emissions, and other aeroplane technology related issues such as transition pairs and the technology applied across aeroplane families.

6.2 Technical Feasibility

6.2.1 Building on past NOx and noise definitions of technical feasibility and in the context of technology for improved emissions environmental performance to be used as part of the basis for the ICAO CO_2 certification Standard setting, technical feasibility refers to any technology expected to be demonstrated to be safe and airworthy proven to Technology Readiness Level 8 (TRL) 8 by 2016 or shortly thereafter[38], and expected to be available for application in the short term[39] over a sufficient range of newly certificated aircraft.

6.3 CO_2 Technology Responses

6.3.1 A CO_2 technology response refers to the manufacturer’s action when an InP aeroplane does not meet the level of a SO. Manufacturers have provided technology response information, which was supplemented with additional technology response input from within CAEP. These were in the form of percentage metric value improvements, are only for CO_2 cost effectiveness modelling purposes, and do not imply a commitment for actual individual products. As part of this input, some aeroplane families included in-production configurations which were considered to be transition pairs and due to be gradually replaced with similar in-development project aeroplane types. There were also configurations in the same family which were not considered part of a transition pair, and which were allocated a “no technology response” due to market considerations that were based on historical business decisions (e.g. A318-122, A319CJ, B737-600, B737-700IGW).

6.3.2 A key assumption is that aeroplane technology will be assumed to remain at its current state, that is, current aeroplane types will have the same CO_2 metric values in 2040 as they do today unless they are changed to meet an SO. As a result, costs and benefits values aim to reflect the effects of the CO_2 SOs alone. Aeroplane types with technology responses will be certified on the date of applicability (e.g. 1-1-2020 and 1-1-2023) and will then be available in the CO2ma. The proposed technology responses to the CO_2 SOs were compiled within a Stringency Options database (SOdb), which was used to create the necessary data and information needed for CAEP to conduct the CO2ma.

6.3.3 As part of wider discussions on technology responses, input on improvements made after Entry into Service (EIS) was considered for some project aeroplanes equipped with Pratt Whitney Geared Turbofan (GTF) engines. It was recognised that the MVs for the GTF-powered A320-family types delivered in/after 2019 are expected to be better than for initial deliveries. However, because the SO Pass/Fail status will not change, and the CO2ma is a comparative analysis, any effect on the overall results would be small. Consequently no change was made to the CO_2 Metric Values (MV) or MTOM for GTF-powered aircraft types.

6.4 Non-recurring costs and recurring production costs

6.4.1 A methodology has been developed to estimate non–recurring costs, based on a Continuous Modification Status (CMS) approach. Given inputs on the aeroplane MTOM, and required CO_2 metric value improvement, the CMS methodology yields non-recurring costs associated with the technology response as well as noise and NOx trade-offs. All technology responses will start from the

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[38] Per CAEP member guidance; approximately 2017

[39] Approximately 2020

zero position in terms of metric value improvement and NRC. Due to the difficulties in obtaining proprietary cost data, the validation of the methodology relied on expert engineering judgment and publicly available aeroplane development cost information with restricted insight into what costs were incorporated within these data, and the starting TRL. Because of the use of publicly available aeroplane development cost information, in many cases multiple enhancements were inextricably linked (e.g. in-flight entertainment, noise and fuel efficiency from high bypass ratio engines), making the incremental cost of CO_2 technology difficult to directly assess. In addition to publicly available information, data was used to estimate the cost for small CO_2 Metric Value improvements from the incorporation of single technology CO_2 responses. As such, the accuracy of the costs generated by the NRC methodology is categorised as only representative but considered fit for purpose.

6.4.2 The NRC method was based on the functional form of the NRC surface as shown in Equation 1, where NRC is measured in billions of US Dollars with a 2010 reference year. The development of the method was based on data from stakeholders within CAEP. This NRC method results in a surface that represents low and high ΔMVs. This is of particular importance in the low ΔMV portion of the NRC surface, where validation points were lacking. The cost-surface has been calibrated to yield NRC estimates across a wide range of aeroplane sizes and metric value improvements. The method consists of a single cost surface that is a function of metric value improvement and aircraft MTOW.

$$NRC\,(10^{9}\,\$) = \left(\underbrace{\left(A\cdot e^{(B\cdot x)}+C\right)}_{\substack{\text{Reference}\\ \text{Airframe NRC}}} + \underbrace{\left(A\cdot e^{(B\cdot 0.9)}+C\right)\cdot f(\Delta MV)\cdot \frac{2}{\#\,Engines}}_{\substack{\text{Reference}\\ \text{Engine NRC}}} \right)\cdot \underbrace{\left(\frac{MTOW}{MTOW_{ref}}\right)^{D}}_{\substack{\text{Aircraft}\\ \text{Size Scaling}}}$$

Equation 1: Function to describe the NRC cost surface

Where coefficients and functions; A, B, C, D and f(ΔMV) are defined as follows:

NRC Surface Coefficients

A	B	C
0.188902	3.247077	-0.142274

6.4.3 All coefficients are regressed based on MV improvement data, except for D, which along with f(ΔMV), is represented as a sigmoid function, as illustrated in Figure 6. Due to the boundaries of metric value improvements varying with MTOW, the cost surface is driven by a normalized metric value improvement. The normalized metric value improvement is given by:

$$\text{Normalized MV Improvement} = x = \frac{(\text{Abs.MV Impr.} - \text{MV Impr. Lower Bound})}{(\text{MV Impr.Upper Bound} - \text{MV Impr. Lower Bound})}$$

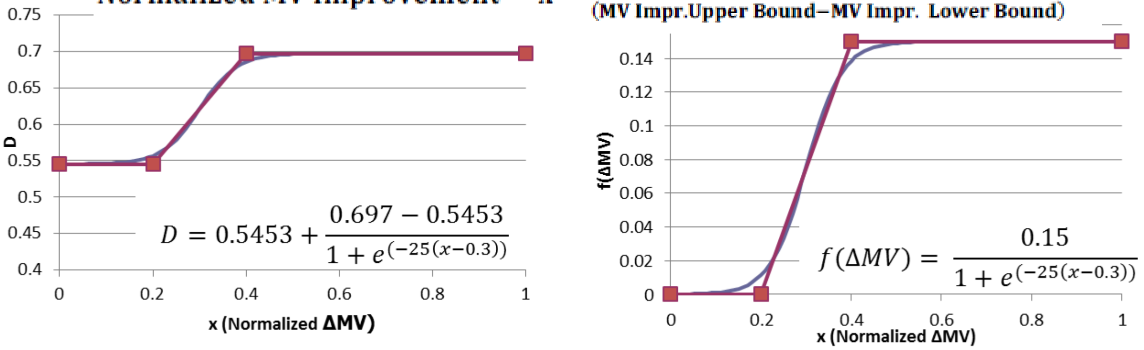

Figure 6: Coefficient D (left) and f (ΔMV) (right) Formulation

6.4.4 Information on changes to production costs after a technology response (i.e. recurring production costs) was not available to CAEP.

6.5 Recurring Direct Operation Cost Modelling

6.5.1 The recurring direct operating costs (DOC) include: (a) capital costs (including finance and depreciation), (b) other-DOC (including crew, maintenance landing and route costs) and (c) fuel costs. The primary model used for modelling other-DOC and capital costs was APMT-E; and, fuel costs were derived from AEDT fuel burn data. The FCM was used to confirm the results using both AAT and APMT-E fleet evolution data along with AEDT fuel burn data. The following is a full list of FCM inputs.

- Operations: The number of departures by scenario (for the baseline and each stringency option) by competition bin and analysis year. Operations are used in the estimation of crew and maintenance costs and airport charges;
- Flight kilometres: Distance flown in kilometres by scenario, competition bin and analysis year. This variable is used, in conjunction with the average cruise speed, in the estimation of flight hours;
- Fuel burn: Fuel in mega-tonnes by scenario, competition bin and analysis year. This variable is used in the estimation of fuel costs and CO_2 emissions;
- Average taxi time: 26 minutes;
- Fuel price: The assumed fuel price for the analysis is $3.00 per US gallon (2010 US Dollars);
- Depreciation rate: The depreciation rate for this analysis is 6.53%;
- Financing rate: The financing rate for this analysis is 5%;
- Block hours: are used in the estimation of crew and maintenance costs and airport charges;
- Average unit crew cost and unit maintenance cost: computed per block hour by competition bin;
- Average unit route charge: computed per kilometre flow by competition bin; and
- Average unit airport charge: computed per operation by competition bin.

6.6 The FCM aggregates projected annual costs over the forecast period at the global level, combining non-recurring and recurring costs. It computes the present value of the discounted cash flows for each stringency option compared against the no stringency base case using a range of discount rates. Specifically, costs were estimated for the baseline and each stringency option as follows:

- Crew costs: Block hours x average unit crew cost (by competition bin).
- Maintenance costs: Block hours x average unit maintenance cost (by competition bin)
- Route charges: Distance flown x average unit route charge
- Airport charges: Operations x average unit airport charge
- Fuel costs: Fuel burn (mega-tonnes) x fuel price ($/gallon) x conversion factor (gallon/mega-tonne)
- Depreciation cost: For the first year, depreciation cost = investment (in that year) x depreciation rate. For subsequent years, depreciation cost = [cumulative investment – cumulative depreciation] x depreciation rate.
- Financing costs: For the first year, financing cost = investment (in that year) x financing rate. For subsequent years, financing cost = [cumulative investment – cumulative depreciation] x financing rate.

6.7 Project aeroplane types

6.7.1 Since Project aeroplanes types are still in development, final performance is not specifically known. To accommodate this, data on project aeroplanes was provided with the PAMVdb as a range of CO_2 metric values and MTOM to represent the uncertainty associated with the final certified values. Table 6 below lists the Project Aeroplane types that were included in the analysis.

A350-800	A350-900	A350-1000
A319NEO	A320NEO	A321NEO
Boeing 737-7	Boeing 737-8	Boeing 737-9
Bombardier CS-100	Bombardier CS-300	
Cessna Model 680		
Cessna Model 750		
Irkut MS-21-300	Irkut MS-21-200	
Mitsubishi MRJ70	Mitsubishi MRJ90	
Illushyn IL-114-300		
Embraer E175-E2	Embraer E190-E2	Embraer E195-E2
Boeing 787-10		
Boeing 777-9X		
Comac C919ER		
A330-800NEO	A330-900NEO	

Table 6: Project Aeroplane Types

6.7.2 Since data was provided as a range of MTOM and metric value, this created a rectangular space defining a potential range of performance of each project aeroplane. The most conservative “upper left corner” point (highest metric value and lowest MTOM) was used as a simplification of this uncertainty. A similar conservative approach was taken for having no technology responses to CO_2 SOs due to the uncertainty in the project aeroplane performance.

6.7.3 A number of project aeroplanes were not included within the CO2ma and these are shown in Table 7.

Manufacturer	Aeroplane Type	Est.Type Certification Date	Notes	Rationale
Airbus	A330 Regional	2015	Reduced A330 MTOM variant optimised for shorter haul missions with high seat count and new de-rated version of Trent 700 engine with latest performance upgrades.	Covered by existing A330-200 and -300 configurations.
Boeing	B777-8X	2023	Derivative version of the B777 twin-aisle airplanes.	Outside the scope of technical feasibility as per CAEP Members guidance.
Bombardier	350	2014	Derivative version of the existing Bombardier 300 with 4.5% higher MTOM, upgraded engine and revised winglet design.	Covered by existing Bombardier 300 configuration.
	7000/8000	2016/2017	Ultra long-range corporate jet aircraft	No data provided due to commercial sensitivity.
COMAC	ARJ21	2014	New single aisle, short-range twin engine turbojet aircraft.	No data provided as in a critical phase of certification.
Dassault	5X	2017	New twin engine business jet.	No data provided due to commercial sensitivity.
Embraer	Embraer L1000E	2014	Ultra long range business jet based on Embraer E190 with enhanced range capability.	Covered by existing Embraer L1000 configuration.
	Legacy 450/500	2014	New small and mid size business jets.	No data provided due to commercial sensitivity.
Pilatus	PC-24	2017	New twin engine business jet.	No data provided.

Table 7: In-development (project) aeroplane types not included in the CO_2 Standard-setting process

6.8 Aeroplane transition pairs

6.8.1 Considering the definition of technical feasibility, the transition between in-production and project aeroplane pairs occurs over a six-year span beginning with the year the project (transitioning in) aeroplane is listed as entering into service (e.g. A320neo replaced A320ceo, B737MAX replaced B737NG). The process is implemented in a step manner where the project aircraft is limited to 15% of the combined demand for the transition pair in the first year. By the sixth year of the transition the project aircraft will take 90% of the purchase share, relative to its in- production transitioning out partner, and it will gain 100% of the share in the seventh year. Details on the aeroplane transition pairs are provided in Table 8.

Transition Pair
Project E175-E2 replaced E175
Project E190-E2 replaced E190
Project E195-E2 replaced E195
Project A319-NEO replaced A319-1 Project B737-7MAX replaced B737-7 and -7W
Project A320-NEO PW replaced A320-2 Project A320-NEO CFM replaced A320-2 Project B737-8MAX replaced B737-8 and -8W
Project A321-NEO PW replaced A321-2 Project A321-NEO CFM replaced A321-2 Project B737-9MAX replaced B737-9ER and -9ERW
Project B777-9X replaced B777-300ER
Project C680 post SN500 replaced C680 Project C750 post SN500 replaced C750 Project Learjet 70 post SN133 replaced Learjet 40 Project Learjet 75 post SN455 replaced Learjet 45
Project B737-8MAX BJ replaced B737-7 IGW BJ
Project A330-800neo replaced A330-200 Project A330-900neo replaced A330-300

Table 8: Transition pairings between in-production and project aeroplane.

6.9 Technology changes applied across aeroplane family

6.9.1 In-Production and in-development (project) aeroplane models, having a common build standard (i.e. certified on the same Type Certificate (TC)), are grouped into aeroplane families. If any model within a given aeroplane family fails a given stringency option and responds via technology insertion, then all the aeroplane models within the family will receive the same level of technology insertion. Family members that pass a stringency line are assumed to receive this family technology response by default. NRC will be based on the MTOM of the heaviest member of the family receiving a technology response, even if the heaviest member of the family is not the one that triggered the response for the family. The NRC is attributed to the whole family and not split over individual family members. This assumption is based on the need for fleet commonality amongst aeroplane design in order to minimize manufacturer and operator costs, and has been demonstrated in practice. For reference, the aeroplane families used in the CO2ma are shown in Table 9.

Aircraft Family	Aircraft Types	Aircraft Family	Aircraft Types
A320ceo	A318-100, A319-100, A320-200, A321-200	Lear 60	Learjet 60XR
A320neo	A319neo, A320neo, A321neo	Lear 75	Learjet 70, Learjet 75
A330	A330-200, -300, -200F	Q400	Q400
A330neo	A330-800neo, A330-900neo	CNA525B	CJ3 Model 525B CitationJet
A350 XWB	A350-800, -900, -1000	CNA525C	CJ4 Model 525C Citation
A380	A380-800	CNA560-XLS	XLS+ Model 560XL Citation
AN140	AN-140-100	CNA680	Sovereign CNA680, CNA680-S
AN148/158	AN-148-100E, AN-158	CNA750	CX Model 750 Citation, CNA750-X
AN32	AN32P	F2000	F2000 LX
AN72	AN74TK-300D	F7X	F7X
ATR42/72	ATR42-500, ATR72-212A	F900	F900 LX
B737MAX	B737-7, -8, -8 (BBJ), -9	E-Jets 2	E175-E2, E190-E2, E195-E2
B737NG	B737-700, -800, -900ER	ERJ170/175	ERJ175
B737NG (Winglet)	B737-700W, -700IGW(BBJ), -800W, -900ERW	ERJ190/195	ERJ190, ERJ195
B747	B747-8i; B747-8F	ERJ135/145	ERJ135-LR, ERJ145
B767	B767, -300ER, -300F	L650	L650
B777	B777-200, -200ER	Phenom	P300
B777LR	B777-200LR, -300ER; B777-2LRF	G280	G280
B777X	B777-9X	GULF150	GULF150
B787	B787-8, -9, -10	GULF4	GULF450
Challenger 300	Challenger 300	GULF5	GULF550
Challenger 600	Challenger 605	GVI	GVI
Challenger 850	Challenger 850	IL114	IL114-100
C919ER	C919ER	MS-21	MS-21-200, -300
CRJ	CRJ-700, -900, -1000	MRJ	MRJ-70, -90
CSeries	CS100, CS300	RRJ	RRJ-95, -95LR
Global	G5000, G6000	TU-204	TU-214, TU-204-300, TU-204SM
Lear 45	Learjet 40XR, Learjet 45XR	TU-334	TU-334

Table 9: Aeroplane families used in the CO2ma

6.9.2 Any aeroplane which fails an SO, and is explicitly identified as not receiving a technology response, is not included in the family response for that stringency option. No aeroplane in that situation will be used as the basis of calculating MV impact or NRC.

6.10 Margin to Stringency Option

6.11 Technology responses are required to meet an SO by an additional one percent margin to the SO in order to take into account manufacturer and policymaking risks, and facilitate subsequent modelling efforts in performing the CO2ma. This simplified margin assumption was not used to judge whether an aircraft passes or fails a given SO, in other words, it is not used to define the “yes/no” technology response input. The margin was used to establish what the metric value impact will be to achieve the SO level. This was then used to establish the NRC data and the fuel burn changes.

6.12 CO_2 scaling methodology

6.12.1 A 1:1 ratio was used between delta CO_2 metric value and mission fuel burn for Technology Response because it is expected that, on the whole for a comparative analysis, the net change in fleet fuel burn between SOs should be reasonable. It is recognized that this is not a correct assumption at the aircraft level and should be looked at again for future stringencies.

6.13 NOx trade-offs

6.13.1 Considering the definition of technical feasibility, it is assumed to be a 1:1 ratio where a 1% improvement in aeroplane fuel burn would thus result in a 1% improvement in LTO and cruise NOx emissions. This is on the basis that engine changes are neutral between temperature increases and improved combustion technology and that the same per cent improvement in engine NOx performance at all the four emissions certification thrust settings of 100, 85, 30 and 7%.

6.14 Annex 16, Volume I, Chapter 14 noise production assumptions

6.14.1 The baseline fleet evolution allows Annex 16, Vol. I, Chapter 14 noise technology responses for all modelled aeroplane types at the CO_2 applicability dates for new types. This does not mean that all aeroplanes which are non-Chapter 14 compliant will respond, but that they may respond based on the technical discussions within CAEP. Aeroplane types which would not respond to Chapter 14 will not be available for the CO2ma, except for those which are part of “transition pairs” with separately agreed timescales. No costs or benefits from the baseline fleet evolution Chapter 14 responses will be attributed to the CO_2 Standard-setting process. This includes fuel burn trade-offs which was recognised as a conservative approach for some proposed Chapter 14 responses (e.g. re-engining) which would be expected to lead to significant fuel burn improvements.

6.15 Noise trade-offs

6.15.1 Detailed information on specific CO_2 technology responses could not be provided given their proprietary nature. Consequently it was concluded that it was not feasible to devise a generic noise-CO_2 interdependency function which is generally applicable to all aircraft in all scenarios. Instead some general high level input was provided by CAEP experts on noise and fuel burn trade-offs.

6.15.2 As the validation points in the NRC methodology included noise improvement costs which could be considered to mitigate any adverse noise trade-offs, it was considered reasonable to assume that the noise performance following a CO_2 technology response would remain neutral. However, it was noted that CO_2 technology responses may have beneficial noise trade-offs, which would not be captured.

6.15.3 Given the schedule for the CAEP/10 CO_2 stringency cost-effectiveness analyses, a simplified assumption compatible with other modelling assumptions would be appropriate. Therefore, noise trade-offs have not formed part of the CAEP/10 CO_2 Standard-setting process for CO_2 technology responses.

6.16 Particulate Matter trade-offs

6.16.1 Particulate matter (PM) emissions from aircraft engines are not regulated nor measured in a consistent manner. As a result, CAEP did not have sufficient confidence to assess the trade-offs on aeroplane engine PM emissions and, as such, it has not formed part of the CAEP/10 CO_2 Standard-setting process.

6.17 Aeroplanes Impacted by the Combined Assumptions

6.18 When combined together in the CO2ma, the technology related assumptions allow for modelling of how the global fleet of aeroplanes responds to the ten SOs. To illustrate this, Figure 7 shows the percentage of impacted aeroplanes which (1) are “transition pairs”, (2) meet the SOs, (3) are fixed due to a technology response, and (4) do not meet the SOs.

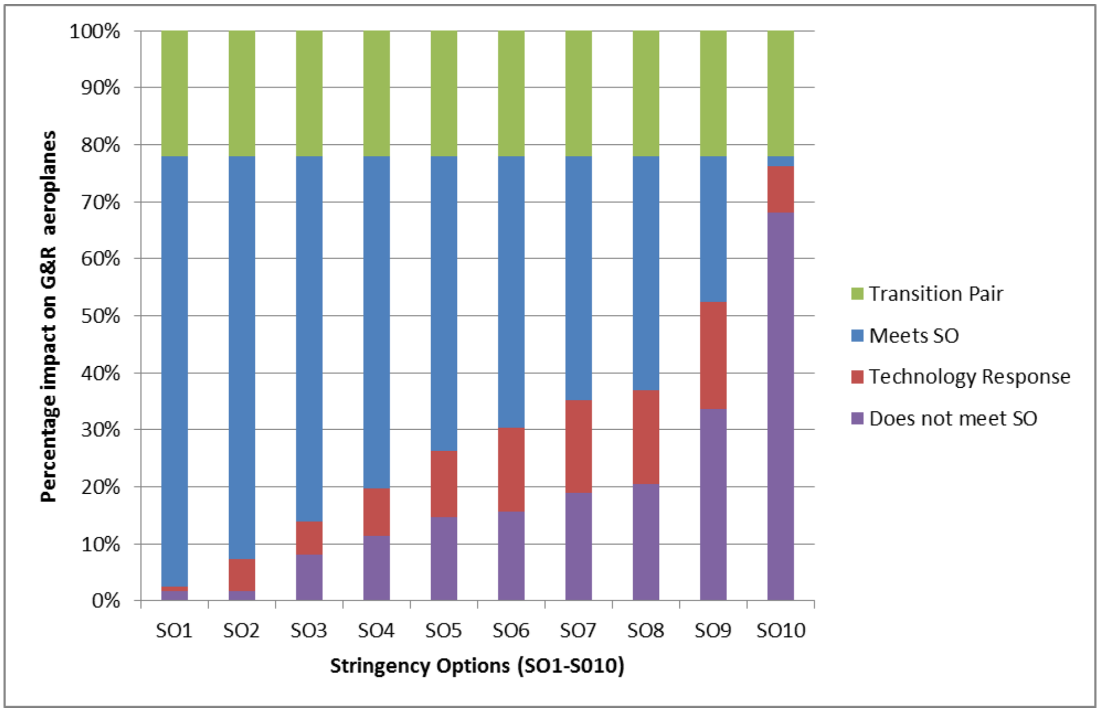

Figure 7: Illustrates the percentage of impacted aeroplane types due to the ten SOs.

7. APPLICABILITY OPTIONS - SCOPE/TRIGGER/DATE

7.1 The scope of applicability for the CO_2 Standard work shall include new aeroplane types in the form of subsonic jets with Maximum Take-Off Mass (MTOM)>5700kg (12566lb) and propeller driven multi-engine aeroplanes (turboprops) with MTOM>8618kg (19000lb). These mass categories correspond to those used in Annex 16 Volume I for the certification of aircraft noise and the Annex 8 large aeroplane airworthiness requirements, and thereby capture aeroplane types which represent >99% global fuel burn, flight distance and operations. For the NT standard the CO_2 Standard applicability dates which were considered included 1 January 2020 or 1 January 2023. Proposals have also been developed for InP aeroplane type applicability requirements and dates proposed for evaluation within the CO2ma.

7.2 In-production applicability options development

7.2.1 A set of broad options were defined to implement applicability requirements for InP aeroplane types. It was recognised that the elements of an applicability option (e.g. applicability date, process, InP/NT regulatory level, trigger) could be used to identify an appropriate balance between the costs and administrative burden with the utility and data robustness, thereby taking into account the specific concerns expressed by stakeholders (e.g. manufacturers and regulatory authorities). A full range of options were considered, as described in Figure 8.

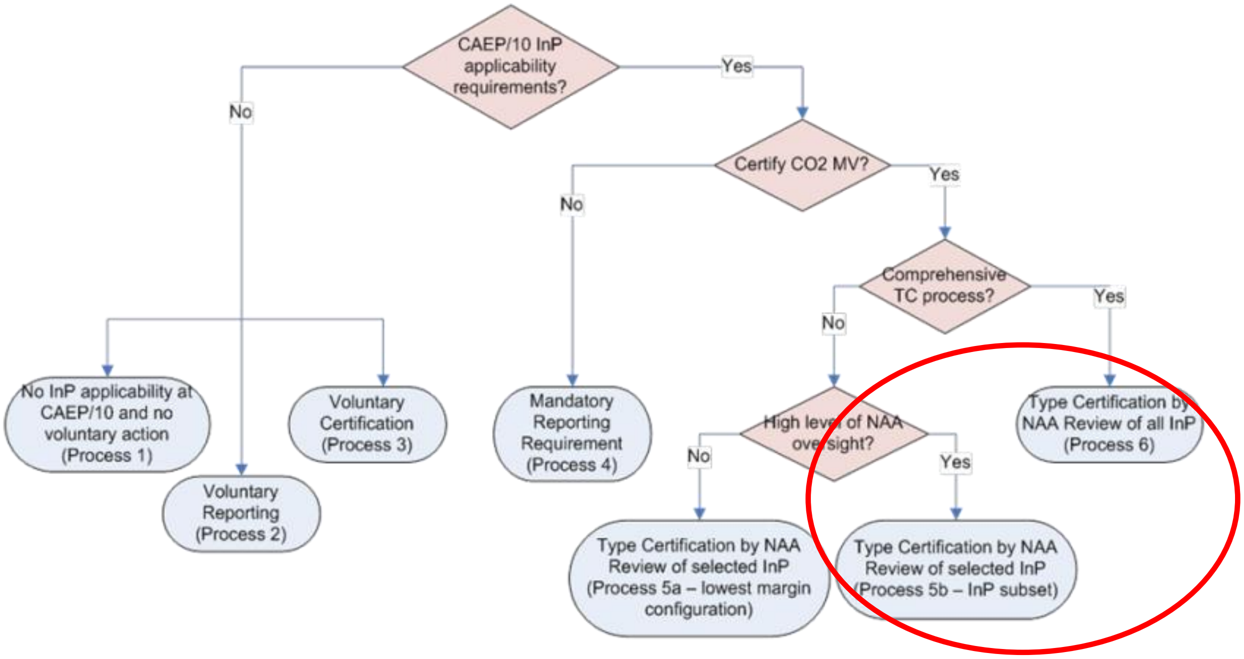

Figure 8: Potential mandatory processes which were investigated as possible InP applicability options

7.2.2 With reference to Figure 8, the details behind the options for potential processes, hybrid approaches and triggers for an InP CO_2 Standard are as follows:

<u>POTENTIAL IMPLEMENTATION PROCESSES</u>[40]

1. **No InP applicability and no voluntary action –** There will be no InP requirements, and focus will be on applicability requirements for new aeroplane types only. (Process 1)

2. **Voluntary Reporting -** Aeroplane CO_2 MVs would be voluntarily provided by manufacturers directly to CAEP for inclusion in the ICAO CO2DB. There would be no NAA review of the data, no regulatory level, and all data would be marked as “uncertified”. (Process 2)

3. **Voluntary Certification –** Would be the same as Voluntary Reporting, but would be reviewed by an NAA according to ICAO Annex 16 Volume III and marked as “certified”. (Process 3)

4. **Mandatory Reporting -** Aeroplane CO_2 MVs would be provided by manufacturers to NAAs for provision to CAEP and inclusion in the ICAO CO2DB. There would be no NAA review of the data, no regulatory level, and all data would be marked as “uncertified”. (Process 4)

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[40] Processes 2 and 4 are purely Reporting Requirements with uncertified CO_2 MV data, and are therefore considered unsuitable for applying a regulatory level. Processes 3, 5, and 6 include Type Certification elements which result in the determination of certified CO_2 MV data, and could thus be considered with or without a regulatory level.

5. **Type Certification by NAA Review of selected InP -** The NAA would review some, but potentially not all, of the aeroplane type configurations according to ICAO Annex 16 Volume III and on that basis develop certified CO_2 MVs to all configurations. (Process 5a & 5b)

6. **Type Certification by NAA Review of all InP -** The CO_2 MVs for all InP aeroplane type configurations would be certified by an NAA according to ICAO Annex 16 Volume III. (Process 6)

POTENTIAL HYBRID APPROACHES

Hybrid approaches aim to balance the data credibility and resource concerns highlighted with pure Reporting or TC processes, while not undermining the original objective of Annex 16 Volume III, which is to act as a robust standard that provides a fair and comparative measure of fuel efficiency technology integrated into a range of aeroplane type design.

1. **Type Certification by NAA Review of selected InP aeroplanes (Process 5) -** The NAA would review some, but potentially not all, of the configurations according to ICAO Annex 16 Volume III and on that basis allocate certified CO_2 MVs to all configurations. This has two sub-processes:

   a) Process 5a (lowest margin) - The NAA would review in detail and certify the configuration in each family with the lowest margin to the regulatory level, and the same margin would be used to develop initial conservative CO_2 MVs for all configurations in that family. All aircraft would be marked as “certified” within the CO2DB. Once all InP aeroplane types have an initial certified CO_2 MV, then each InP type would be subsequently treated individually within the TC process and not as a family.
   b) Process 5b (InP subset) - The NAA would certify some, but potentially not all, of the configurations in a type certification application to provide sufficient confidence that all configurations could be classified as “certified”. The number of configurations to be certified, and the appropriate selection criteria, would need to be defined.

2. **Mid gross mass SAR certification test point only (Processes 2 to 6) -** This would require a manufacturer to only perform flight tests to measure one certification test point (the mid gross mass SAR value) where existing flight test data is insufficient to meet Annex 16 Vol. III, Chapter 2 requirements of three certification test points (low, mid and high gross mass SAR values.

POTENTIAL TRIGGERS FOR IN-PRODUCTION CERTIFICATION[41]

It was recognized that there could be a range of options that could be used to trigger an InP certification.

1. **Voluntary (Applicable to processes 2 and 3) -** Manufacturers would initiate the process to provide CO_2 MV data on their InP aeroplane types at a time of their choosing.

2. **Certificate of airworthiness for the individual aeroplane first issued on or after a future date (Applicable to processes 4 to 6) -** As per other existing Annex 16 requirements[42], the

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[41] The use of additional criteria in the applicability trigger, such an MTOM threshold or type certification date, have been identified to potentially further refine the applicability scope of Annex 16 Vol. III to a selected subset of InP aeroplane types.

CO_2 applicability process would be initiated for InP aeroplane types based on the date of issuance of a Certificate of Airworthiness for a new InP aeroplane[43]. The associated text, similar to that used in Volume I, could take the form of "…for which the application for a Type Certificate was submitted before XX-XX-20XX and a certificate of airworthiness for the individual aeroplane was first issued on or after XX-XX-20XX".

3. Change criteria (Applicable to processes 4 to 6) - The CO_2 applicability process would be initiated when an application is submitted to the NAA by a manufacturer to modify an InP aeroplane type design, and that modification meets an specific change criteria.

7.3 Proposed InP options to CAEP

7.3.1 Overall, while all of the processes shown are possible options for a CAEP/10 decision, including no InP applicability, it was agreed to build on mandatory processes 5b and 6 which included type certification elements that accurately derived the CO_2 metric value performance of aeroplane type configurations (see red circle in Figure 8).

7.3.2 Regarding the possible InP applicability dates, a sensitivity analysis was performed using the dates of 1 January 2025 and 1 January 2028. However, 1 January 2028 was considered an upper boundary condition in terms of InP applicability dates, as anything beyond that date is too far-reaching for a decision at the CAEP/10 meeting 2016. It was also agreed that an InP applicability date of 1-1-2020 could be considered if the trigger was based on a criteria that would only be triggered by a technical change to an existing aeroplane type design. This is referred to as a CO_2 change criteria and more information can be found in the draft First Edition of Annex 16, Volume III.

7.3.3 It was recognised that implementation of a mandatory InP applicability option would probably involve a combination of both Process 5b and 6 (Figure 8 refers). A certificating authority will discuss an appropriate level of involvement with the applicant during each TC process. This is likely to include a more detailed review during an initial TC programme, while subsequent applications from the same applicant would require less involvement as the certificating authority gains confidence in the applicant's processes and capabilities.

7.3.4 Taking into account all of the above, three potential mandatory, type certification based options were subsequently developed and are summarised in Table 10. They are presented as a framework which aims to inform the decision on certain details (e.g. choice of date, regulatory level).

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[42] Annex 16, Volume I, Chapter 2 (Subsonic jet aeroplanes — Application for Type Certificate submitted before 6 October 1977), Chapter 5 (Propeller-driven aeroplanes over 8 618 kg — Application for Type Certificate submitted before 1 January 1985), Chapter 6 (Propeller-driven aeroplanes not exceeding 8 618 kg — Application for Type Certificate submitted before 17 November 1988) and Chapter 12 (Supersonic aeroplanes).

[43] New in-production aeroplane: An individual aeroplane that receives a certificate of airworthiness first issued after the date when the in-production standard becomes applicable, and which is not certified against the new type standard.

	Option 1	**Option 2**	**Option 3**
Scope	As per New Types		
Date (change criteria)	▨	1-1-2020 or 1-1-2023 or 1-1-2025	1-1-2020 or 1-1-2023 or 1-1-2025
Date (production cut-off)	1-1-2023 or 1-1-2025 or 1-1-2028	▨	1-1-2023 or 1-1-2025 or 1-1-2028
Trigger	Applicability date based on initial certificate of airworthiness for the individual aeroplane.	Application for a design change that meets a specific change criteria.	Application for a design change that meets a specific criteria. If not triggered by a change, then will be default triggered by an applicability date based on the initial CofA for an individual aeroplane on or after a date[44] later than the change criteria applicability date.
Regulatory Level	Separate InP and NT regulatory levels or a single InP/NT regulatory level		
Process	Full type certification as per Annex 16 Vol. III Chapter 2, allowing for equivalent procedures[45] and discussions between the certificating authority and the applicant on an appropriate level of involvement in a particular type certification programme		

Table 10: Potential mandatory, type certification based InP applicability options

- Option 1 represents a requirement for all aeroplanes to certify to the standard by the date. A production cut-off for all InP aeroplane types if they have not been certified to the CO_2 Standard by this date.

- Option 2 represents applicability being triggered only if an application for a design change for new in-production aeroplanes exceeds a specific CO_2 change criteria. This change criteria was defined as an increase in CO_2 emissions MV of greater than 1.5% or a significant CO_2 change (e.g. new wing or engine option). There would be no production cut-off that would require aeroplanes to certify by the dates above.

- Option 3 represents a hybrid approach, where Option 2 is active for a period of time and is subsequently followed by Option 1.

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[44] In terms of Option 3, it is noted that the applicability of a production cut-off could reasonably lie in the range of 3 to 5 years after the applicability of a change criteria.

[45] ETM Vol. III guidance should be developed over time to identify equivalent procedures that are a more cost-effective means of compliance compared to the requirements in Annex 16 Vol. III.

7.3.5 Options 1 and 3 have triggers with an applicability date based on the issuance of the initial certificate of airworthiness for an individual aeroplane. It is recognised that aeroplanes released into service before a type configuration is certified to meet the InP requirement, may have the same type configuration as those entering service after the type configuration was certified. In this situation, those aeroplanes that entered in to service before the identical configuration was certified, could volunteer to be CO_2 certified as well. Once CO_2 certified, these aeroplanes would be required to continue to demonstrate compliance with the Annex 16 Vol. III Standard via the CO_2 certification change process.

7.3.6 In considering the potential future effect of the proposed three options, it was recognised that these could potentially vary significantly. Options 1 and 3 end in a production cut-off date by which all InP aeroplane types are expected to be CO_2 certified.

7.3.7 Options 2 and 3 include specific change criteria which would trigger the applicability of the CO_2 standard. The proposed criteria are an adverse 1.5% change in the CO_2 metric value of the aeroplane type configuration or a significant change (e.g. new wing or engine option[46]). It is difficult to predict what, and when, future changes will be demanded by the market, and whether they would trigger these applicability criteria. However, historical data suggests that the adverse 1.5% change criterion would be primarily triggered by increases in the highest MTOM mass for the specific aeroplane type configuration. It should also be highlighted that applicants historically have voluntarily sought certification of significantly beneficial changes to the latest environmental standards. Finally, it is noted that this trigger would result in the post-change derived InP type configuration being certified, but no mandatory certification requirement would apply to the pre-change InP type configuration.

7.4 The possible timeline for mandatory NT and InP type applicability options

7.4.1 To understand further the implementation of the mandatory NT and InP type applicability options detailed in Table 7 there were several issues to comprehend regarding the timeline.

7.4.2 An applicability date should take into account that integrating the CAEP/10 agreement into Member State legislative frameworks will take approximately three years (e.g. end of 2018). Schedule risks have been identified, for example if Member States do not integrate Annex 16 Vol. III into their legislative frameworks in a timely manner such that industry can meet its mandatory obligations (e.g. tech response and certification).

7.4.3 The certification basis for New Types is valid for five years from the date of application for type certification. If the TC process goes beyond five years, then the certification basis is reviewed and, if necessary, updated.

7.4.4 For the InP applicability trigger, an applicability date based on an aeroplane’s initial certificate of airworthiness represents a production cut-off requirement if the aeroplane type has not been certified before the applicability date. For example, a 2025 InP date would provide approximately six years for InP aeroplane types within the applicability scope to be made compliant. A CO_2 change criteria based trigger would require the approval of a design change application for an aeroplane type after the applicability date, when exceeding some agreed CO_2 change criteria. This would include the need to demonstrate compliance with the CO_2 Standard.

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[46] These criteria are intended to be triggered by generational changes made to in-production aeroplane types. Recently announced examples of generational changes which would have been triggered by these criteria if the application for type certification had been submitted after the CO_2 standard comes into effect include the E2 jets, 737MAX, A330NEO and B777X.

7.4.5 An applicability date will be influenced by what is considered pragmatic and implementable in terms of time needed for industry to respond to the final agreed CO_2 Standard (e.g. combination of a certification requirement and a regulatory level). A later applicability date may have been necessary for more stringent regulatory levels and vice versa.

7.4.6 Annex 16, Volume I precedents have had an InP applicability date based on the initial certificate of airworthiness, and these InP applicability dates were typically four to five years after a NT applicability date.

8. RESULTS FROM THE COST EFFECTIVENESS ANALYSIS CO_2 MAIN ANALYSIS (CO2MA)

8.1 The CO2ma has been conducted in accordance with the framework described in Section 5.5 that considered CO_2 Standard application to both NT aeroplanes and new deliveries of InP aeroplane types. This section provides an overview of the important results from the CO2ma.

8.1.1 Full flight performance-based CO_2 emissions results, presented in Figure 9, exhibit the expected trend of increasing benefits with increasing stringency. Noise results for areas and population counts within a 55dB Day-Night Average Sound Level (DNL) contour, as presented in Figure 10, show increasing benefit with the increasing SO modelled. NO_X emissions results, presented in Figure 11, are influenced by the relative NOx performance of the aircraft available for growth and replacement (G&R) as they change with SO. Specifically, there is a greater NO_X benefit at SO5 when aircraft with relatively higher NOx emissions drop out of the fleet mix. Conversely, SO6 aircraft with relatively lower NOx emissions drop out of the fleet mix and are replaced by aircraft with relatively higher NOx emissions, causing an overall increase in NOx emissions.

8.2 Based on past CAEP practice, all of the Case 1 results represent a situation where a NT SO would be chosen and there would be no legal deadline to bring InP types to levels required under an NT-only standard. However, the CO2ma assumptions are that aeroplanes not meeting a particular SO would be have a technology response informed by market considerations on the implementation dates for NT-only applicability, thus the modelled results represent a pseudo InP applicability. The results consistently reflect their relative time spans from the implementation year through 2040, including the change in costs results presented in Figures 12 through to 15. The CO2ma Case 1 costs reported herein are influenced primarily by the reduction in fuel costs with increasing stringency, resulting in negative overall costs for all SOs. Thus, both the CO2ma Case 1 costs and environmental benefits are driven by the same data (CO_2 saving/ fuel cost saving), leading to a flatter cost effectiveness profile than for previous environmental standard analyses.

8.3 The Case 4 results can be considered as a range of response scenarios from a voluntary response similar to Case 1 (section 8.2), down to an absence of any response by growth and replacement aeroplanes. The results were prepared for sub-case c, Section 5.5, which was the most limited in the range of voluntary NT-Only Applicability response scenarios considered. Because no types are required to go out of production under NT-only applicability, NO_X emissions only go down with increasing stringency levels; noise benefits are negligible; and, while CO_2 and cost savings increase progressively through SO10 without Price After Technology Response (PATR), and through SO9 with PATR, the amplitude of the savings is less than under NT and InP aeroplane Applicability case. These results are reflected in Figures 9 to 11 and Figures 16 through to 19.

8.4 Hybrid Applicability: It is recognized that there could be a range of possible combinations of standards adopted by CAEP. These responses would be influenced by both the NT-only SO level and the INP SO level since voluntary responses for INP types could occur both prior to the INP applicability date and/or beyond the INP SO level. As such, the assumptions from Case 1 and Case 4 were used to model a number of hybrid applicability scenarios where both NT and INP standards are adopted. These results are included in Figures 16 and 17, and provide an indication of potential responses but represent only part of a possible range of outcomes.

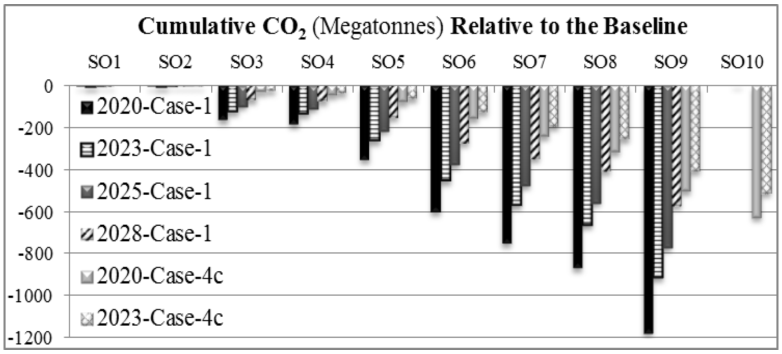

Figure 9: Cumulative CO2 (Megatonnes[47]) Results[48] Relative to the No Stringency Baseline from the Implementation Year to 2040

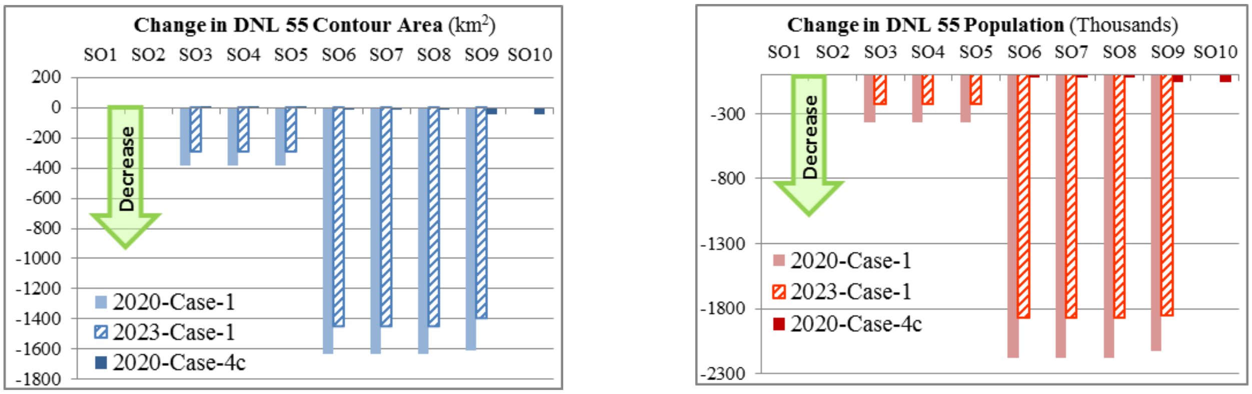

Figure 10: 2040 Noise Results Relative to the No Stringency Baseline at DNL 55dB

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[47] Megatonne (Mt) a unit of mass equal to one million tonnes

[48] The results depicted were modelled by AEDT from APMT-E fleet evolution.

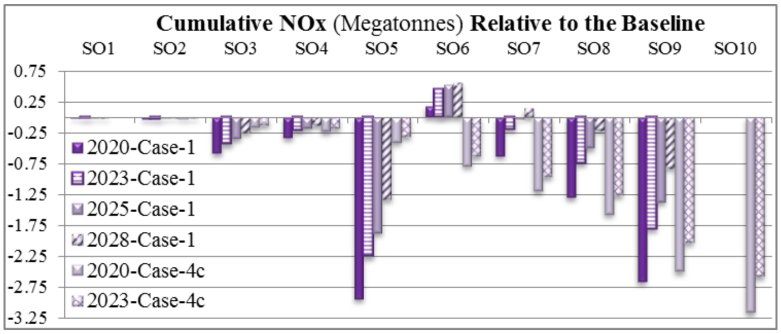

Figure 11: Cumulative NOx (Megatonnes) Results[49] Relative to the No Stringency Baseline from the Implementation Year to 2040

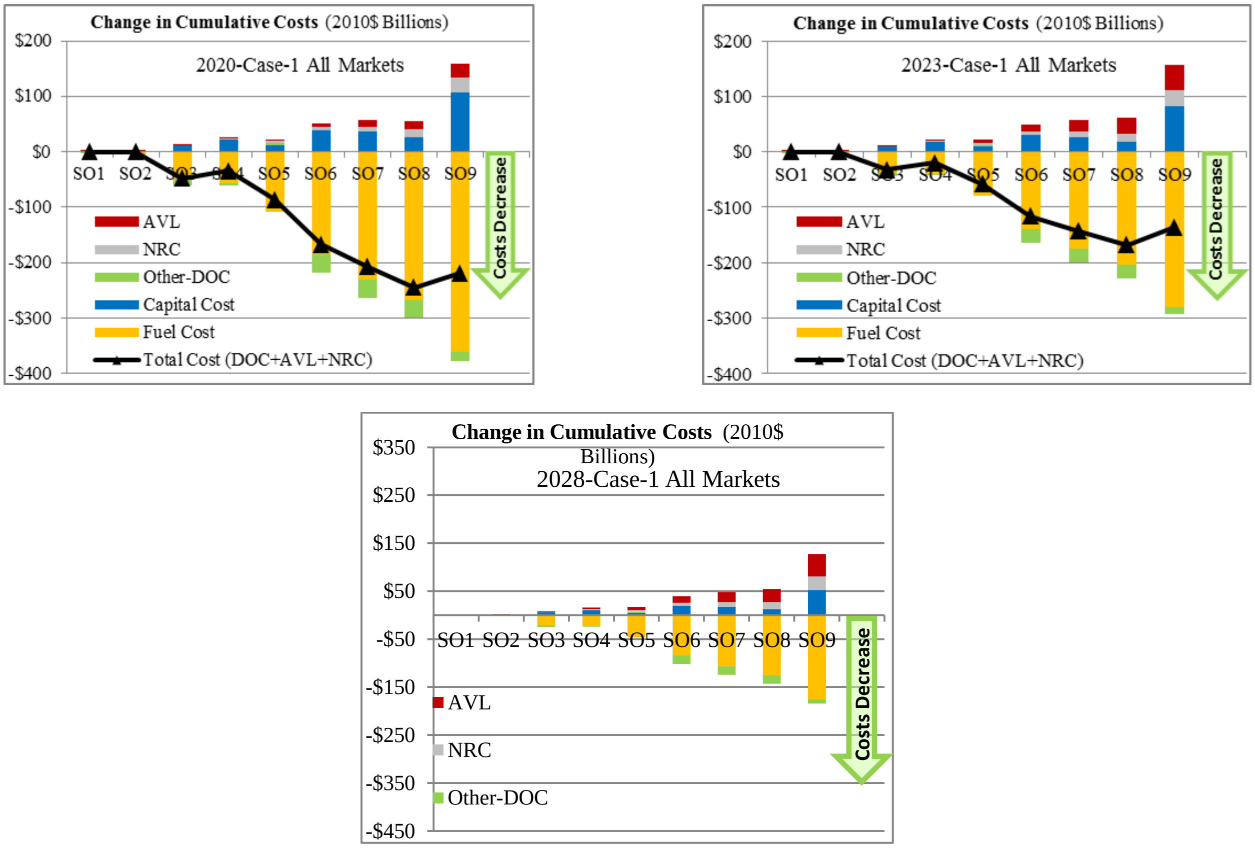

Figure 12: Change in Cumulative Costs for 2020, 2023 and 2028 Case-1 (US2010$ Billions) Total Recurring Direct Operating Costs (DOC), Manufacturer Non-Recurring Costs (NRC) for Technology Response (TR) and Owner /Operator Asset Value Loss (AVL) from the Implementation Year to 2040

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[49] The results depicted were modelled by AEDT from APMT-E fleet evolution.

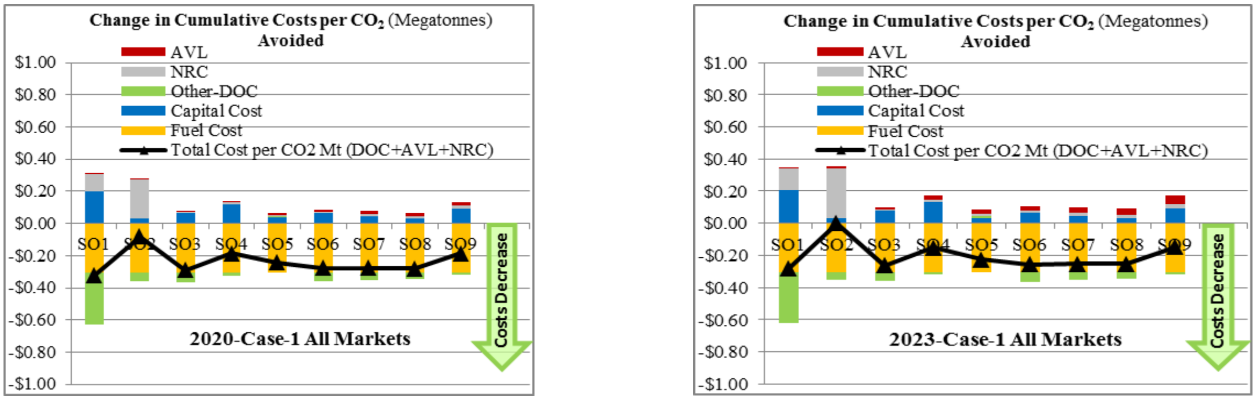

Figure 13: Change in Cumulative Costs per Megatonne CO_2 Avoided Total Recurring Direct Operating Costs (DOC), Manufacturer Non-Recurring Costs (NRC) for Technology Response (TR) and Owner /Operator Asset Value Loss (AVL) from the Implementation Year to 2040

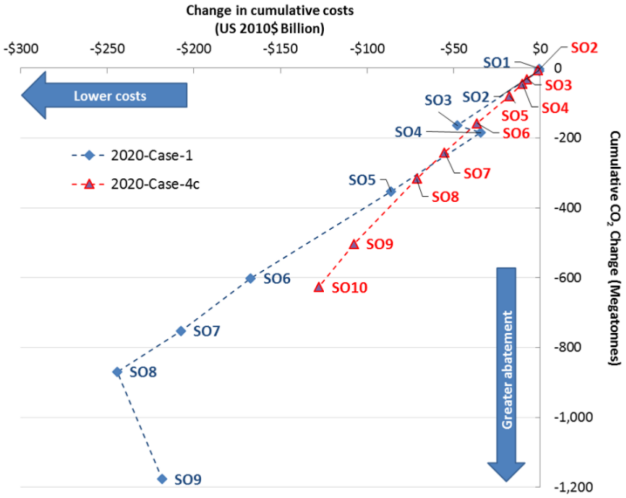

Figure 14 : 2020 Cases 1 and 4c Change in Cumulative Costs (DOC+AVL+NRC) versus Cumulative CO_2 Change from the Implementation Year to 2040

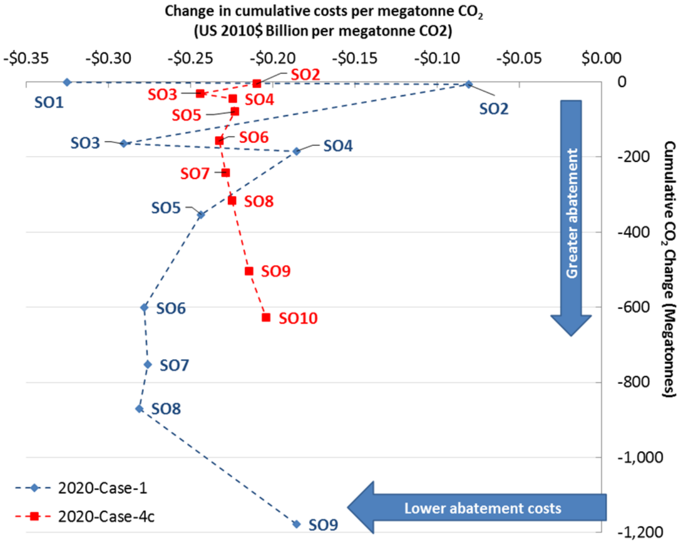

Figure 15: 2020 Cases 1 and 4c Change in Total Cumulative Costs (DOC+AVL+NRC) per Megatonne CO_2 (0% Discount Rate) against Cumulative CO_2 Change (Megatonne) from the Implementation Year to 2040

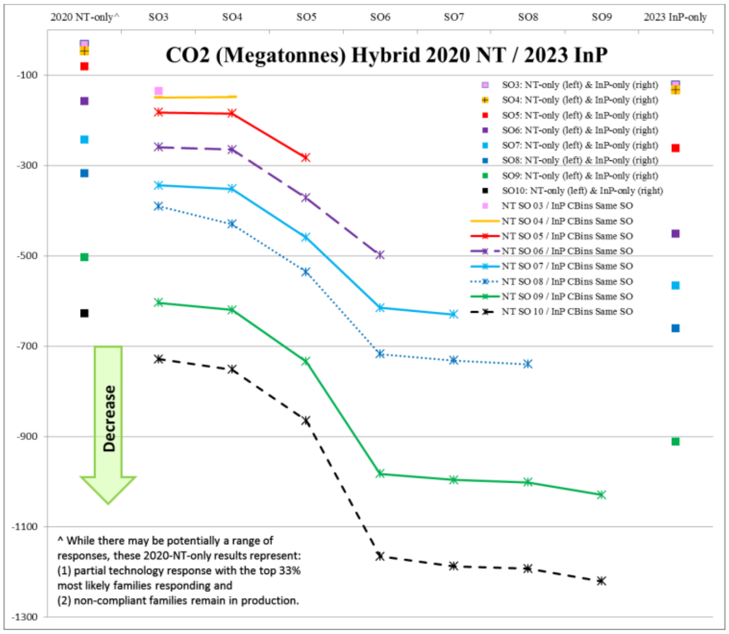

Figure 16: Modelled hybrid 2020-NT/2023-InP CO2 results are shown in the middle, along with 2020-NT-only (Case-4c) results to the left and 2023-InP-only (Case-1) results to the right

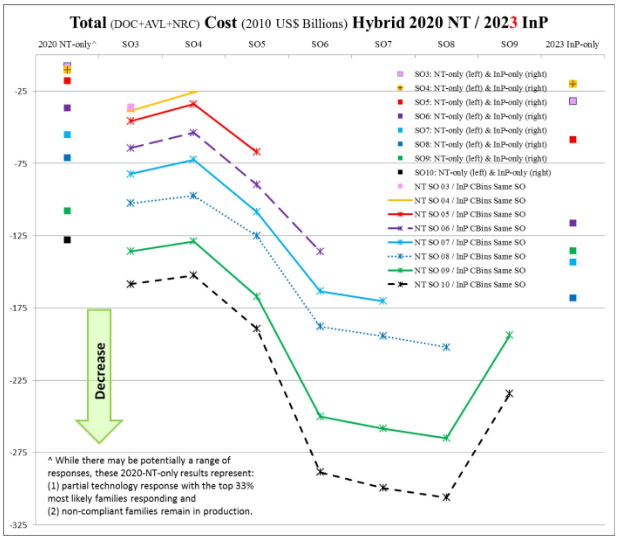

Figure 17: Modelled hybrid 2020-NT/2023-INP (DOC+AVL+NRC) Cost results are shown in the middle, with 2020-NT-only (Case-4c) results to the left and 2023-INP-only (Case-1) results to the right

8.5 The CO2ma results discussed above assumed that the cost of manufacturing aircraft remains unchanged after they have been modified to meet an SO, whereas the additional technology contained in a technology response may be expected to cost more to manufacture (i.e., material, labour and other recurring costs). Results from a sensitivity analysis to capture the additional technology costs of responding aircraft, based on a proxy using a PATR methodology[50], are shown against other individual cost elements in Figure 14a and for different groupings of total costs in Figure 18b. These results show that even though magnitude varies when costs are combined in different ways, there is a consistent cost trend. When any combination of costs includes the change in cumulative fuel costs against the baseline, there is a savings; and, the savings increase from SO4 through SO8. For all “NT and INP” Applicability (Case 1) and hybrid results, both of which consider InP applicability, the combined cost savings at SO9 is consistently less than SO8. However, under the NT-only Applicability (Case 4) assumptions, when no INP types go out of production, the savings increase through SO10 without PATR or to SO9 when PATR is included. The InP applicability SO9 behaviour is due demand shifting to smaller aircraft that require more operations and aircraft to meet the demand, increasing capital and operating costs.

8.6 Within the CO2ma, assumptions have been made regarding discount rates and fuel price. A sensitivity analysis on both of these aspects is shown in Figure 19 and Figure 20 respectively.

8.7 During the CO_2 Standard-setting process, much discussion was had over the contribution of aeroplanes above and below the 60t MTOM kink point. Figure 21 shows the CO_2 sensitivity results when above 60 tonne CBins are at SO5 through SO9 and combined with below 60t MTOM results at each SO. Much of this discussion was driven by unexpected results among business aeroplanes below 60t MTOM (CBins 1-3). These unexpected results were found to have been driven by initial assumptions that produced potentially unrealistic market behaviour that was not noticed until late in the analysis. This behaviour was qualitatively very different from that of the greater than 60t MTOM fleet, but due to the

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[50] The PATR methodology represents the missing costs by the increase in aircraft price as a result of the technology response. The price increase is calculated based on a proportion of the projected fuel savings over the life of the aircraft. Since a product may in some cases sell for a significantly higher price than it actually costs to develop and produce, the use of PATR as a proxy for the total TR-related costs may overestimate the costs borne at system level

small CO_2 contribution of CBins 1-3, it is nearly undetectable within the larger fleet results, despite its significance for the impacted CBins.

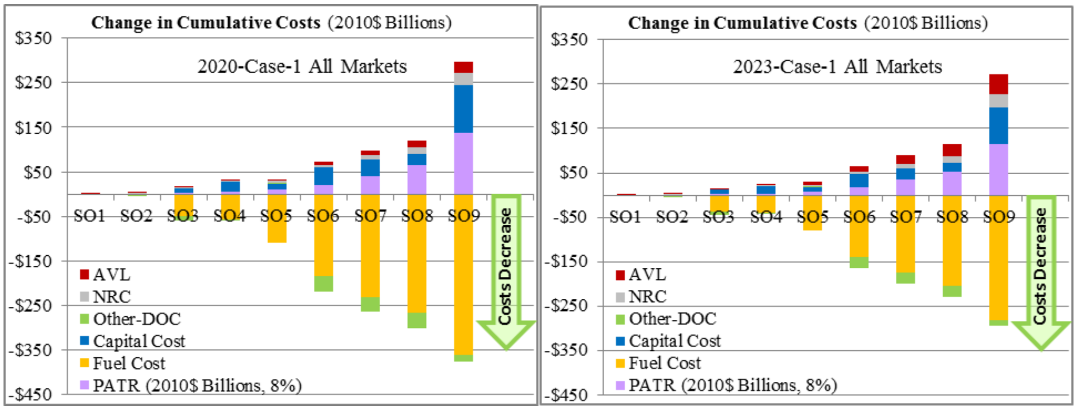

Figure 18a: Change in Cumulative Costs for 2020 and 2023 Case-1 (US2010$ Billions) Fuel Costs, Capital Costs, Other Direct Operating Costs (DOC), Manufacturer Non-Recurring Costs (NRC) for Technology Response (TR), Owner /Operator Asset Value Loss (AVL) and Price After Technology Response (PATR) from the Implementation Year to 2040

8.8 While PATR and NRC are both shown on the Figure 14a charts that is only to understand the magnitude of the different costs. Because PATR includes both recurring and non-recurring costs associated with an aeroplane receiving a technology response to pass a stringency option, PATR and NRC are never added together for any of the total cost combinations shown in the Figure 18b charts.

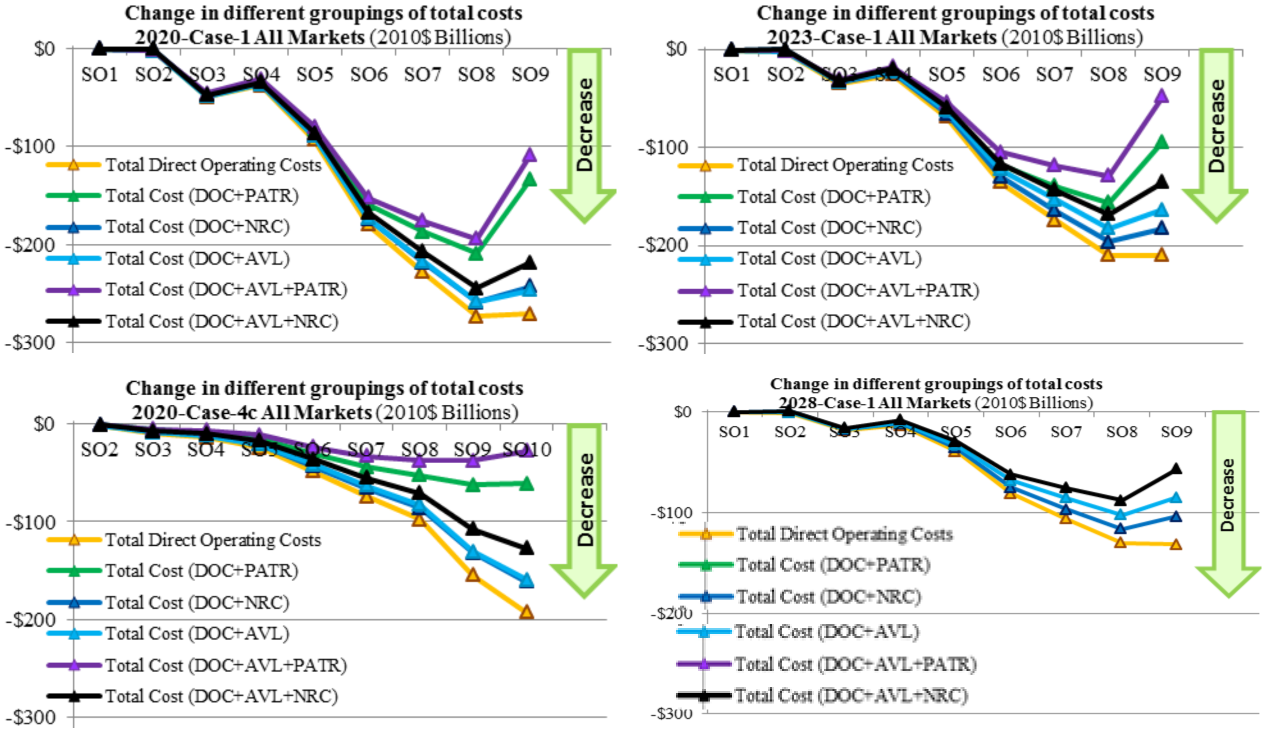

Figure 18b: Change in Different Groupings of Total Costs from the Implementation Year to 2040

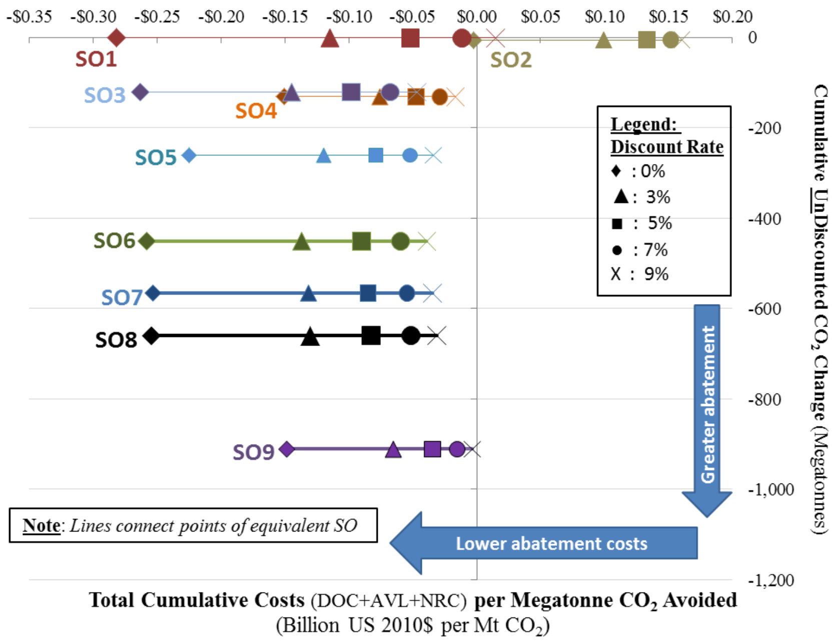

Figure 19: Sensitivity Analysis Results for 2023-Case-1 Change in Total Cumulative Costs (DOC+AVL+NRC) reported with _Discount Rate Variation_ per Un-Discounted Megatonne CO_2 Avoided against cumulative CO_2 Change (Mt) from the Implementation Year to 2040

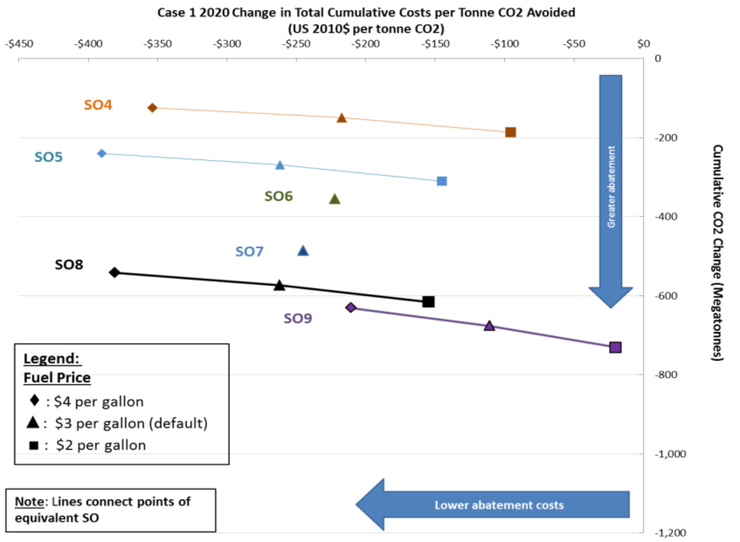

Figure 20: 2020-Case-1 Abatement Cost versus Cumulative CO_2 with \$3, \$2 and \$4 Fuel Prices from the Implementation Year to 2040[51]

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[51] Note that the fuel price sensitivity was conducted with APMT-Economics. While these values differ slightly from the final CO2ma results, the SO ranking and trends are the same. Because the final CO2ma changes did not impact the fleet selection algorithm or fuel price assumptions, which are the primary drivers of the observed changes in the fuel price sensitivity, the results would not be impacted by the final CO2ma model.

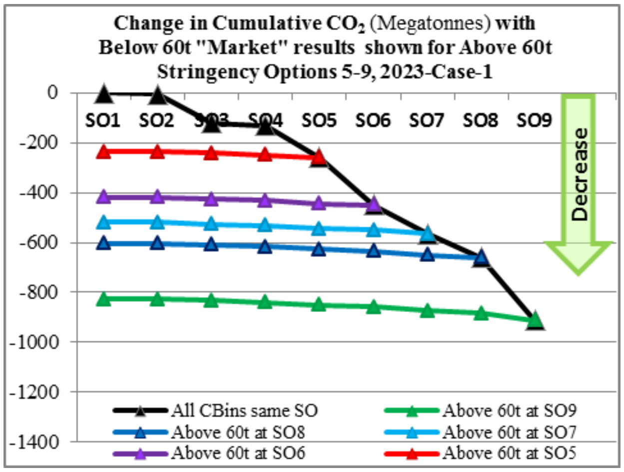

Figure 21: Change in Cumulative CO_2 when above 60 tonne aeroplanes are at SO5 through SO9 and combined with below 60 tonne CBin results at each SO

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