Notice of Proposed Amendment 2020-06

Implementation of the latest CAEP amendments to ICAO Annex 16 Volumes I, II and III

RMT.0514

EXECUTIVE SUMMARY

The objective of this Notice of Proposed Amendment (NPA) is to align the European Union (EU) regulations and the associated acceptable means of compliance (AMC) and guidance material (GM) with the International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPs) and guidance on environmental protection.

The ICAO Committee on Aviation Environmental Protection (CAEP) agreed in February 2019 on a new non-volatile particulate matter (nvPM) emissions standard, and proposed improvements to the existing noise, aircraft engine emissions, and aeroplane CO_2 emissions standards.

Thus, this NPA proposes to amend accordingly Article 9 'Essential requirements' of Regulation (EU) 2018/1139, Annex I (Part 21) to Commission Regulation (EU) No 748/2012 as well as the AMC and GM to Annex I (Part 21), CS-34, CS-36, and CS-CO_2.

The proposed amendments are expected to ensure a high uniform level of environmental protection and to provide a level playing field for all actors in the aviation market.

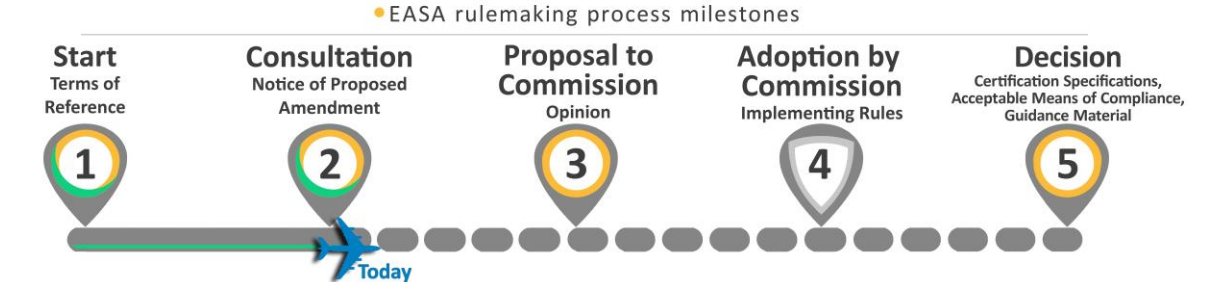
Action area: Noise, local air quality and climate change standards

Affected rules:
- Article 9 of Regulation (EU) 2018/1139;
- Annex I (Part 21) to Commission Regulation (EU) No 748/2012 and AMC and GM to Annex I (Part 21);
- CS-34;
- CS-36;
- CS-CO_2

Affected stakeholders: Design organisation approval (DOA) and production organisation approval (POA) holders

Driver: Environmental protection | **Rulemaking group:** No

Impact assessment: Full (by ICAO CAEP) | **Rulemaking Procedure:** Standard



10.12.2019 (Issue 2)	16.3.2020	2020/Q4	2022/Q1	2022/Q1

An agency of the European Union

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

Table of contents

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

1. About this NPA

1.1. How this NPA was developed

The European Union Aviation Safety Agency (EASA) developed this NPA in line with Regulation (EU) 2018/1139[1] (the 'Basic Regulation') and the Rulemaking Procedure[2]. This rulemaking activity is included in the European Plan for Aviation Safety (EPAS) for 2020–2024[3] under rulemaking task (RMT).0514. The text of this NPA has been developed by EASA. It is hereby submitted to all interested parties[4] for consultation.

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 **16 June 2020**.

1.3. The next steps

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

Based on the comments received, EASA will work on proposed amendments to the Basic Regulation and to Annex I (Part 21) to Commission Regulation (EU) No 748/2012[6], and will issue an opinion. A summary of the comments received will be provided in the opinion.

The opinion will be submitted to the European Commission, which will use it as a technical basis in order to take a decision on whether or not to amend the Regulations.

If the European Commission decides that the Regulations should be amended, EASA will issue a decision to amend the certification specifications (CSs) and AMC or GM to comply with the amendments introduced into the Regulations.

The comments received on this NPA and the EASA responses to them will be reflected in a comment-response document (CRD). The CRD will be published together with the opinion on the EASA website[7].

---

1 Regulation (EU) 2018/1139 of the European Parliament and of the Council of 4 July 2018 on common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency, and amending Regulations (EC) No 2111/2005, (EC) No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/30/EU and 2014/53/EU of the European Parliament and of the Council, and repealing Regulations (EC) No 552/2004 and (EC) No 216/2008 of the European Parliament and of the Council and Council Regulation (EEC) No 3922/91 (OJ L 212, 22.8.2018, p. 1) (https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1535612134845&uri=CELEX:32018R1139).

2 EASA is bound to follow a structured rulemaking process as required by Article 115(1) of Regulation (EU) 2018/1139. 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 EASA 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 https://www.easa.europa.eu/sites/default/files/dfu/EPAS_2020-2024.pdf

4 In accordance with Article 115 of Regulation (EU) 2018/1139 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).

6 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 (OJ L 224, 21.8.2012, p. 1) (https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1582902070300&uri=CELEX:32012R0748).

7 https://www.easa.europa.eu/document-library/comment-response-documents

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

2. In summary — why and what

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

Following its 11th formal meeting (CAEP/11) from 4 to 15 February 2019, the ICAO CAEP agreed amendments to ICAO Annex 16 Volume I 'Aircraft Noise', Volume II 'Aircraft Engine Emissions', and Volume III 'Aeroplane CO_2 Emissions'. The recommendations are the outcome of the work conducted during the 3 years preceding the meeting in accordance with the CAEP/11 Work Programme. It is envisaged that these proposed amendments will be adopted, after consultation, by the ICAO Council in 2020/Q1.

The proposed amendments to ICAO Annex 16 Volume I include updates to the existing aircraft noise Standards and Recommended Practices (SARPs). No new standard on aircraft noise was discussed at CAEP/11.

The proposed amendments to ICAO Annex 16 Volume II include updates to the existing aircraft engine emissions SARPs, new non-volatile particulate matter (nvPM) mass and number Landing–Take-off (LTO) standards, and the introduction of an applicability end date for the Smoke Number (SN) standard.

The proposed amendments to ICAO Annex 16 Volume III include updates to the existing aeroplane CO_2 emissions SARPs. No new standard on aeroplane CO_2 emissions was discussed at CAEP/11.
In addition to the amendments to ICAO Annex 16, CAEP/11 approved ICAO Doc 9501 'Environmental Technical Manual' (ETM), Volume I 'Procedures for the Noise Certification of Aircraft', Volume II 'Procedures for the Emissions Certification of Aircraft Engines', and Volume III 'Aeroplane CO_2 Emissions'. These updated ETM volumes provide clarifications and additional guidance material to facilitate a harmonised implementation of ICAO Annex 16.

Regulations (EU) 2018/1139 and (EU) No 748/2012 make a direct reference to specific amendments to ICAO Annex 16 Volumes I, II and III, and to specific editions of the ETM Volumes I, II and III. These Regulations need therefore to be amended to ensure that they, in the field of aviation environmental protection, are aligned with the latest amendment of the ICAO SARPs.

The latest amendments to the ICAO SARPs considered in this RMT are:

— ICAO Annex 16 Volume I, latest edition including Amendment 13,

— ICAO Annex 16 Volume II, latest edition including Amendment 10,

— ICAO Annex 16 Volume III, latest edition including Amendment 1,

— ICAO Doc 9501 Volume I, latest edition,

— ICAO Doc 9501 Volume II, latest edition, and

— ICAO Doc 9501 Volume III, latest edition.

2.2. What we want to achieve — objectives

The overall objectives of the EASA system are defined in Article 1 of the Basic Regulation. This proposal will contribute to the achievement of the overall objectives by addressing the issues outlined in Section 2.1.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

The specific objective of this proposal is to contribute to a high, uniform level of environmental protection by aligning environmental protection requirements uniformly with the ICAO SARPs contained in Annex 16 Volumes I, II and III, and in the respective ETM volumes.

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

In order to align with the latest amendments to the ICAO SARPs and guidance material, this NPA proposes amendments to:

— Article 9 of Regulation (EU) 2018/1139,

— Annex I (Part 21) to Commission Regulation (EU) No 748/2012,

— AMC and GM to Annex I (Part 21),

— CS-34,

— CS-36, and

— CS-CO_2.

The latest amendments to the ICAO SARPs and guidance material are described hereafter.

- ICAO Annex 16 Volume I amendments (see details in Chapter 7)

These amendments address technical issues and editorial corrections:

— updates of the previous references to the International Electrotechnical Commission (IEC) Standards IEC61260 to IEC61260-1 and IEC61260-3, as appropriate, and revisions that improve the description of these references; and

— corrections to general technical, nomenclature and typographical issues and revision of the definitions that use the word ‘abeam’, a definition for ‘reference ground track’, revision of the specified tolerance for slow exponential time averaging to better characterise actual exponential time response with a one-second time constant, and revisions related to the proper use of modal verbs ‘must’, ‘shall’ and ‘should’.

- ICAO Doc 9501 Volume I amendments

These amendments address new guidance, updates and editorial corrections including:

— updates related to nomenclature and the use of digital photography; and

— new guidance material on determining SLOW ‘timestamps’.

- ICAO Annex 16 Volume II amendments (see details in Chapter 7)

These amendments address new standards, new nvPM mass and number regulatory levels, technical issues and editorial corrections:

— introduction of the new text on CAEP/11 nvPM mass and number engine emissions standards; description of limit lines for nvPM mass and number that would be applied to new engine types from 1 January 2023, accompanied by an in-production standard for nvPM mass and number with an applicability date on or after 1 January 2023;

— introduction of an applicability end date on 1 January 2023 for the Smoke Number (SN) standard for engines with a maximum rated thrust greater than 26.7 kN (the SN standard is still applicable to engines with a maximum rated thrust less than or equal to 26.7 kN);

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

— an update to the applicability language for new engine types; this update will have no impact on the current NOx standard for in-production engines, nor will it impact the existing production standards for Smoke Number (SN), hydrocarbons (HC), carbon monoxide (CO) and current non-volatile particulate matter (nvPM) mass standard;

— corrections to flow rate specifications and conditions due to the application of standard temperature and pressure (STP) conditions for measurement equipment and sampling system operation specifications;

— introduction of generic language for production engines exemptions after the dates of applicability of the smoke, NOx, HC and CO, nvPM mass and number emission standards, clarification on the 'competent authority' references, introduction of 'State of Design' definition, and update of the text on exemptions;

— introduction of consequential changes across Annex 16 Volume II for consistency with the new nvPM mass and number standards including: definition of procedures for measurement and computation of nvPM mass and number emission levels, definition of procedures for nvPM assessment for inventory and modelling purposes, update of compliance procedure for particulate matter emissions, introduction of instrumentation and measurement techniques for nvPM emissions, updates to corrections for dilution and thermophoretic losses in the nvPM sampling system, definition of penetration fractions of individual components of the nvPM sampling and measurement system, replacement of units for the fuel sulphur content reporting, and the introduction of the end applicability date set on 1 January 2023 for the Smoke Number (SN) standard for engines of rated thrust greater than 26.7 kN; and

— corrections to general technical and typographical issues, including introduction of the Note on Type Certificate and revisions of reference humidity.

- ICAO Doc 9501 Volume II amendments

These amendments address new guidance related to the new requirements in Annex 16 Volume II, updates and editorial corrections including:

  — guidance material on how to consider applications for engines for a type or model, the change in applicability language and on engines which are designed as an integrated propulsive power plant;

  — guidance material resulting from the new requirements on nvPM mass and number (e.g. characteristic levels reporting, emission indices correction, sulphur unit, instruments hardware or software changes and certificates, instruments calibration, calculations, consideration of mixed flow engines, correlation with Smoke Number, fuel composition correction); and

  — updates on exemption procedures.

- ICAO Annex 16 Volume III amendments (see details in Chapter 7)

These amendments address technical issues and editorial corrections:

  — introduction of the definition for 'type design' and various definition improvements; clarification of the applicability of standards for CO_2-certified derived versions of non-CO_2-certified aeroplanes;

  — clarification of the exemption issuing authority and of the exemption recording process;

  — various editorial improvements, including the deletion of superfluous text; and

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

— correction of minor typographical issues.

- ICAO Doc 9501 Volume III amendments

These amendments address new guidance, updates and editorial corrections including:

— guidance material on the applicability of standards regarding changes to CO_2-certified derived aeroplanes and to non-CO_2-certified type designs;

— guidance material on the certification process and on the approval of first principle performance models used to determine specific air range; and

— updates on exemption procedures, corrections to reference conditions and on the approval of a change.

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 (IA) of the alternative options, please refer to Chapter 4.

The IA has highlighted the expected benefits and drawbacks of the two policy options identified, namely:

Option 0 ‘No policy change’: leave current rules unchanged; or

Option 1 ‘CAEP/11 implementation’: implement the CAEP/11 amendments, as proposed for adoption by the relevant ICAO State Letters.

Out of the two options, only Option 1 has positive impacts in all identified aspects, while Option 0 has negative impacts in these aspects. It is therefore proposed to select Option 1 and proceed with the implementation of the CAEP/11 amendments.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

3. Proposed amendments and rationale in detail

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

— deleted text is ~~struck through~~;

— new or amended text is highlighted in blue;

— an ellipsis '[…]' indicates that the rest of the text is unchanged.

3.1. Draft regulation (draft EASA opinion)

3.1.1. Draft amendment to Regulation (EU) 2018/1139

[…]

CHAPTER III

SUBSTANTIVE REQUIREMENTS

SECTION I

Airworthiness and environmental protection

'*Article 9*

Essential requirements

1. Aircraft referred to in points (a) and (b) of Article 2(1), other than unmanned aircraft, and their engines, propellers, parts and non-installed equipment shall comply with the essential requirements for airworthiness set out in Annex II to this Regulation.

2. As regards noise and emissions, those aircraft and their engines, propellers, parts and non-installed equipment shall comply with the environmental protection requirements contained in Amendment ~~12~~ 13 of Volume I, in Amendment ~~9~~ 10 of Volume II, and in ~~the initial issue~~ Amendment 1 of Volume III, all as applicable on 1 January ~~2018~~ 2021, of Annex 16 to the Chicago Convention.'

[…]

3.1.2. Rationale for amending Article 9 of Regulation (EU) 2018/1139

This amendment updates the essential requirements for environmental protection such that aircraft referred to in points (a) and (b) of Article 2(1) of the Basic Regulation and their engines, propellers, parts and non-installed equipment comply with the latest requirements of Annex 16 Volumes I, II and III.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

3.1.3. Draft amendment to Commission Regulation (EU) No 748/2012 and to the related AMC and GM

Article 9 Production organisations

[…]

‘4. By way of derogation from paragraph 1, the production organisation may apply to the competent authority for exemptions from the environmental protection requirements referred to in the first subparagraph of Article 9(2) of Regulation (EU) 2018/1139.’

[…]

21.A.21 Requirements for the issuance of a type certificate or restricted type certificate

Regulation (EU) 2019/897

‘(a) In order to be issued a product type certificate or, when the aircraft does not meet the essential requirements of Annex II to Regulation (EU) 2018/1139 an aircraft restricted type certificate, the applicant shall:

1. demonstrate its capability in accordance with point 21.A.14;
2. comply with point 21.A.20;
3. demonstrate that the engine and propeller, if installed in the aircraft:

   ~~(A)~~ (i) have a type-certificate issued or determined in accordance with this Regulation; or

   ~~(B)~~ (ii) have been demonstrated to be in compliance with the aircraft type-certification basis established and the environmental protection requirements designated and notified by the Agency as necessary to ensure ~~the~~ safe and environmentally compatible flight of the aircraft.’

   […]

21.A.130 Statement of conformity

[…]

‘(b) A statement of conformity shall include all of the below:

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

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

4. additionally, in the case of environmental protection requirements:

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

   (ii) a statement that the completed aeroplane is in compliance with the applicable CO_2 emissions requirements on the date its first certificate of airworthiness is issued.'

[…]

AMC No 2 to 21.A.130(b) Statement of Conformity for Products (other than complete aircraft), parts, appliances and materials — The Authorised Release Certificate (EASA Form 1)

'A. INTRODUCTION

[…]

5. COMPLETION OF THE CERTIFICATE BY THE ORIGINATOR

[…]

Block 12 – Remarks

[…]

d) In case of an engine, when the ~~C~~competent ~~A~~authority has granted an ~~emissions production cut-off~~ exemption from the environmental protection requirements, the following statement must be entered in block 12:

~~["NEW" OR "SPARE"] ENGINE EXEMPTED FROM NOx EMISSIONS PRODUCTION CUT-OFF REQUIREMENT'.~~ 'ENGINE EXEMPTED FROM [*REFERENCE TO THE TYPE OF EMISSION*] EMISSIONS ENVIRONMENTAL PROTECTION REQUIREMENT.'

[…]'

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

'1. General

This determination is made according to the data provided by the engine type-certificate holder. This data should allow the determination of whether the engine complies with the emissions production cut-off requirements ~~of paragraph (d)~~ of Volume II, Part III, Chapter 2 and Chapter 4~~, paragraph 2.3.2~~ of Annex 16 to the Chicago Convention.

It should be noted that ~~in the case of engines for which~~ the ~~C~~competent ~~A~~authority has the possibility to grant~~ed an~~ exemptions from these requirements as noted in Volume II, Part III, Chapter 2, paragraph 2.1.1 and Chapter 4, paragraph 4.1.1 of Annex 16 to the Chicago Convention. In the case the competent authority has granted an exemption, the emissions requirements applicable are the regulatory levels from the previous corresponding standard.

~~defined in Volume II, Part III, Chapter 2, paragraph 2.3.2 c) of Annex 16 to the Chicago Convention.~~

When such an exemption is granted, the competent authority:

— takes into account the number of exempted engines that will be produced and their impact on the environment;

— considers imposing a time limit on the production of such engines; and

— issues an exemption document.

The Agency establishes and maintains a register, containing at least the engine serial number, and makes it publicly available.

The ICAO Doc 9501 'Environmental Technical Manual' Volume II provides guidance on the issuing of exemptions.

~~2. Process and criteria for exemptions against a NOx emissions production cut-off requirement~~

~~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) Administration~~

~~— Name, address and contact details of the organisation.~~

~~b) Scope of the request~~

~~— Engine type (model designation, type-certificate (TC) number, TC date, emission TC basis, ICAO Engine Emissions Databank Unique Identification (UID) Number);~~

~~— Number of individual engine exemptions requested;~~

~~— Duration (end date) of continued production of the affected engines.~~

~~— Whether the proposed affected engines are 'spares' or 'new' and whom the engines will be originally delivered to.~~

~~Note: In the case where the engines are 'new' (new engines installed on new aircraft), and if this would result in a larger negative environmental impact as compared to exemptions only for spare engines, more detailed justification could be required to approve this application.~~

~~c) Justification for exemptions~~

~~When requesting an exemption for a 'new' engine, the organisation should, to the extent possible, address the following factors, with quantification, in order to support the merits of the exemption request:~~

~~— Technical issues, from an environmental and airworthiness perspective, which may have delayed compliance with the production cut-off requirement;~~

~~— Economic impacts on the manufacturer, operator(s) and aviation industry at large;~~

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

- Environmental effects. This should consider the amount of additional NOx emissions that will be emitted as a result of the exemption. This could include consideration of items such as:
  - the amount that the engine model exceeds the NOx emissions standard, taking into account any other engine models in the engine family covered by the same type-certificate and their relation to the standard;
  - the amount of NOx emissions that would be emitted by an alternative engine for the same application; and
  - the impact of changes to reduce NOx on other environmental factors, including community noise and CO_2 emissions;
- Impact of unforeseen circumstances and hardship due to business circumstances beyond the manufacturer's control (e.g. employee strike, supplier disruption or calamitous events);
- Projected future production volumes and plans for producing a compliant version of the engine model seeking exemption;
- Equity issues in administering the production cut-off among economically competing parties (e.g. provide rationale for granting this exemption when another manufacturer has a compliant engine and does not need an exemption, taking into account the implications for operator fleet composition, commonality and related issues in the absence of the engine for which exemptions are sought);
- 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.

2.2.2 The evaluation of an exemption request should be based on the justification provided by the organisation and on the following definitions and criteria:

a) Use of engines

- 'Spare engines' are defined as complete new engine units which are to be installed on in-service aircraft for maintenance and replacement. It can be presumed that exemption applications associated with engines for this purpose would be granted as long as the emissions were equal to or lower than those engines they are replacing. The application should include the other items described in points (a) and (b) of paragraph 2.1 above, but it would not need to include the items specified in point (c). For spare engines, the evaluation of the exemption application would be conducted for record keeping and reporting purposes, but it would not be done for approval of an exemption.
- 'New engines' are defined as complete new engine units which are to be installed on new aircraft. They can only be exempted from a NOx production cut-off requirement if they already meet the

~~previous standard (e.g. exemption from the CAEP/6 NOx production cut-off requirement of paragraph (d) of Volume II, Part III, Chapter 2, paragraph 2.3.2 of Annex 16 to the Chicago Convention is only possible if an engine type already meets the regulatory levels defined in Volume II, Part III, Chapter 2, paragraph 2.3.2 c) of Annex 16 to the Chicago Convention). Also, in order for and exemption to be granted for this type of engine the applicant must clearly demonstrate that they meet the criteria for an exemption by including items described in points (a), (b) and (c) of paragraph 2.1 above. The Competent Authority may require additional information regarding the appropriateness of the potential exemption.~~

~~b) Number of new engine exemptions~~

~~Exemptions should be based on a total number of engines and time period for delivery of these engines, which would be agreed at the time the application is approved and based on the considerations explained in point (c) of paragraph 2.1 above. The number of engines exempted should not exceed 75 per engine type-certificate, and the end date of continued production of the affected engines should not exceed 31.12.2016. The number of exemptions is related to individual non-compliant engines covered under the same type-certificate.~~

~~Exemptions for new engines should be processed and approved by the Competent Authority, in agreement with the Agency, for both the manufacture of the exempted engines and the initial operator of the aircraft to which they are to be fitted. Given the international nature of aviation, the Agency should attempt to collaborate and consult on the details of exemptions. In the case where engine type certification is done through a reciprocity agreement between the Agency and Third Countries, the Agency should coordinate on the processing of exemptions and concur before approval is granted.~~

~~c) Other engines~~

~~Unlimited exemptions may be granted for continued production of spare engines having emissions equivalent to or lower than the engines they are replacing.~~

~~Engines for use on aircraft excluded from the scope of the Basic Regulation – i.e. aircraft specified in Annex II to the Basic Regulation and aircraft involved in activities referred to in Article 1(2) of the Basic Regulation (e.g. military, customs, police, search and rescue, fire fighting, coastguard or similar activities or services) – are excluded from civil aircraft NOx production cut-off requirements.~~

~~2.3 Rejection of request~~

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

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

GM 21.A.130(b)(4)(i) Definitions of engine type-certification date and production date

'Volume II of Annex 16 to the Chicago Convention contains ~~two~~ three different references to applicability dates:

1. the 'Date of manufacture for the first individual production model' which refers to the engine type-certification date; ~~and~~

2. the 'date of application for a type certificate' which refers to the engine type certification; and

~~2.~~3. the 'Date of manufacture for the individual engine' which refers to the production date of a specific engine serial number (date of EASA Form 1).

The third reference refers to the date of the first engine EASA Form 1 issued after the completion of the engine production pass-off test.

The ~~second~~ third reference is used in the application of the engine ~~NOx~~ emissions production cut-off requirement, which specifies a date after which all in-production engine models must meet a certain ~~NOx~~ emissions standard.

21.A.130(b)(4)(i) includes the production requirements for engine exhaust emissions. ~~and refers to paragraphs (b) and (d) of Volume II, Part III, Chapter 2, paragraph 2.3 of Annex 16 to the Chicago Convention.~~'

AMC 21.A.130(b)(4)(ii) 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 ~~C~~competent ~~A~~authority has the possibility to grant exemptions as noted in Volume III, Part II, Chapter 1, paragraph 1.11 and Chapter 2, paragraph 2.1.3.

When such an exemption is granted, the competent authority:

— takes into account the number of exempted aeroplanes that will be produced and their impact on the environment; and

— issues an exemption document.

The Agency establishes and maintains a register, containing at least the aeroplane serial number, and makes it publicly available.

ICAO Doc 9501 'Environmental Technical Manual' Volume III provides guidance on the issuing of exemptions.'

[…]

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 protection 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~~ environmental protection requirements, to determine conformity with the applicable design data;'

[…]

'AMC-ELA No 1 to 21.A.145(b) Approval requirements — Airworthiness ~~noise fuel venting and exhaust emissions~~ and environmental protection data

For applicants whose design and production entities operate in one consolidated team, and for which the applicable design data is provided as part of the approved type design data, the availability of all the necessary airworthiness~~, noise, fuel venting and exhaust emissions~~ and environmental protection data is considered to be met.

In all other cases, in accordance with the practised methods and procedures that were established as part of the quality system, the PO can demonstrate that the production data contains all the necessary data to determine that there is conformity with the applicable design data, and that this data is kept up to date and is available to the relevant personnel.'

GM 21.A.145(b)(2) Approval requirements — Airworthiness and environmental protection, 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 protection 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 a condition for safe operation and issuing a Statement of Conformity or EASA Form 1.'

An agency of the European Union

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

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 protection characteristics 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 implementing the change, that it complies with this Subpart.

(b) The competent authority shall establish the conditions under which a production organisation approved under this Subpart may operate during such changes unless the competent authority determines that the approval should be suspended.’

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

[…]

‘EASA Form 1 Block 12 ‘Remarks’

Examples of conditions which would necessitate statements in Block 12 are:
[…]

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 reassembly after delivery.

— References to aid traceability, such as batch numbers.

— In the case of an engine, if the competent authority has granted an exemption from the engine ~~exhaust emissions production cut-off~~ environmental protection requirements ~~exemption~~, the record: ~~‘[New or Spare] engine exempted from NOx emissions production cut-off requirements’~~ ‘Engine exempted from [*reference to the type of emission*] emissions environmental protection requirement’.’

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

'1. General

This determination is made according to the data provided by the engine type-certificate holder. This data should allow the determination of whether the engine complies with the emissions production cut-off requirements of paragraph (d) of Volume II, Part III, Chapter 2 and Chapter 4, paragraph 2.3.2 of Annex 16 to the Chicago Convention.

It should be noted that in the case of engines for which the competent authority has the possibility to granted an exemptions from these requirements as noted in Volume II, Part III, Chapter 2, paragraph 2.1.1 and Chapter 4, paragraph 4.1.1 of Annex 16 to the Chicago Convention. In the case the competent authority has granted an exemption, the emissions requirements applicable are the regulatory levels from the previous corresponding standard. defined in Volume II, Part III, Chapter 2, paragraph 2.3.2 c) of Annex 16 to the Chicago Convention.

When such an exemption is granted, the competent authority:

— takes into account the number of exempted engines that will be produced and their impact on the environment;

— considers imposing a time limit on the production of such engines; and

— issues an exemption document.

The Agency establishes and maintains a register, containing at least the engine serial number, and makes it publicly available.

ICAO Doc 9501 'Environmental Technical Manual' Volume II provides guidance on the issuing of exemptions.

2. Process and criteria for applying for exemptions against a NOx emissions production cut-of requirement.

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) Administration

— Name, address and contact details of the organisation.

b) Scope of the request

— Engine type (model designation, type-certificate (TC) number, TC date, emission TC basis, ICAO Engine Emissions Databank Unique Identification (UID) Number);

— Number of individual engine exemptions requested;

— Duration (end date) of continued production of the affected engines.

— Designate whether the proposed exempted engines are 'spares' or 'new' and whom the engines will be originally delivered to.

~~Note: In the case where the engines are 'new' (new engines installed on new aircraft), and if this would result in a larger negative environmental impact as compared to exemptions only for spare engines, more detailed justification could be required to approve this application.~~

~~c) Justification for exemptions~~

~~When requesting an exemption for a 'new' engine, the organisation should, to the extent possible, address the following factors, with quantification, in order to support the merits of the exemption request:~~

- ~~Technical issues, from an environmental and airworthiness perspective, which may have delayed compliance with the production cut-off requirement;~~
- ~~Economic impacts on the manufacturer, operator(s) and aviation industry at large;~~
- ~~Environmental effects. This should consider the amount of additional NOx emissions that will be emitted as a result of the exemption. This could include consideration of items such as:~~
  - ~~the amount that the engine model exceeds the NOx emissions standard, taking into account any other engine models in the engine family covered by the same type-certificate and their relation to the standard;~~
  - ~~the amount of NOx emissions that would be emitted by an alternative engine for the same application; and~~
  - ~~the impact of changes to reduce NOx on other environmental factors, including community noise and CO_2 emissions;~~
- ~~Impact of unforeseen circumstances and hardship due to business circumstances beyond the manufacturer's control (e.g. employee strike, supplier disruption or calamitous events);~~
- ~~Projected future production volumes and plans for producing a compliant version of the engine model seeking exemption;~~
- ~~Equity issues in administering the production cut-off among economically competing parties (e.g. provide rationale for granting this exemption when another manufacturer has a compliant engine and does not need an exemption taking into account the implications for operator fleet composition, commonality and related issues in the absence of the engine for which exemptions are sought);~~
- ~~Any other relevant factors.~~

~~2.2 Evaluation process.~~

~~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.~~

~~2.2.2 The evaluation of an exemption request should be based on the justification provided by the organisation and on the following definitions and criteria:~~

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

a) Use of engines

— 'Spare engines' are defined as complete new engine units which are to be installed on in-service aircraft for maintenance and replacement. It can be presumed that exemption applications associated with engines for this purpose would be granted as long as the emissions were equal to or lower than those engines they are replacing. The application should include the other items described in points (a) and (b) of paragraph 2.1 above, but it would not need to include the items specified in point (c). For spare engines, the evaluation of the exemption application would be conducted for record keeping and reporting purposes, but it would not be done for approval of an exemption.

— 'New engines' are defined as complete new engine units which are to be installed on new aircraft. They can only be exempted from a NOx production cut-off requirement if they already meet the previous standard (e.g. exemption from the CAEP/6 NOx production cut-off requirement of paragraph (d) of Volume II, Part III, Chapter 2, paragraph 2.3.2 of Annex 16 to the Chicago Convention is only possible if an engine type already meets the regulatory levels defined in Volume II, Part III, Chapter 2, paragraph 2.3.2 c) of Annex 16 to the Chicago Convention). Also, in order for and exemption to be granted for this type of engine the applicant must clearly demonstrate that they meet the criteria for an exemption by including items described in points (a), (b) and (c) of paragraph 2.1 above. The Competent Authority may require additional information regarding the appropriateness of the potential exemption.

b) Number of new engine exemptions

Exemptions should be based on a total number of engines and time period for delivery of these engines, which would be agreed at the time the application is approved and based on the considerations explained in point (c) of paragraph 2.1 above. The number of engines exempted should not exceed 75 per engine type-certificate, and the end date of continued production of the affected engines should not exceed 31.12.2016. The number of exemptions is related to individual non-compliant engines covered under the same type-certificate.

Exemptions for new engines should be processed and approved by the Competent Authority, in agreement with the Agency, for both the manufacture of the exempted engines and the initial operator of the aircraft to which they are to be fitted. Given the international nature of aviation, the Agency should attempt to collaborate and consult on the details of exemptions. In the case where engine type certification is done through a reciprocity agreement between the Agency and Third Countries, the Agency should coordinate on the processing of exemptions and concur before approval is granted.

c) Other engines

Unlimited exemptions may be granted for continued production of spare engines having emissions equivalent to or lower than the engines they are replacing.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

~~Engines for use on aircraft excluded from the scope of the Basic Regulation – i.e. aircraft specified in Annex II to the Basic Regulation and aircraft involved in activities referred to in Article 1(2) of the Basic Regulation (e.g. military, customs, police, search and rescue, fire fighting, coastguard or similar activities or services) – are excluded from civil aircraft NOx production cut-off requirements.~~

~~2.3 Rejection of request~~

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

GM 21.A.165(c)(3) Definitions of engine type-certification date and production date

'Volume II of Annex 16 to the Chicago Convention contains ~~two~~ three different references to applicability dates:

1. the 'Date of manufacture for the first individual production model' which refers to the engine type-certification date;~~ and~~

2. the 'Date of application for a type certificate' which refers to the engine type certification; and

~~2.~~3. the 'Date of manufacture for the individual engine' which refers to the production date of a specific engine serial number (date of EASA Form 1).

The third reference refers to the date of the first engine EASA Form 1 issued after the completion of the engine production pass-off test.

The ~~second~~ third reference is used in the application of engine ~~NOx~~ emissions production cut-off requirement which specifies a date after which all in-production engine models must meet a certain ~~NOx~~ emissions standard.

21.A.165(c)(3) includes the production requirements for engine exhaust emissions. ~~and refers to paragraphs (b) and (d) of Volume II, Part III, Chapter 2, paragraph 2.3 of Annex 16 to the Chicago Convention.~~'

AMC 21.A.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 and Chapter 2, paragraph 2.1.3.

When such an exemption is granted, the competent authority:

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

— takes into account the number of exempted aeroplanes that will be produced and their impact on the environment; and

— issues an exemption document.

The Agency establishes and maintains a register, containing at least the aeroplane serial number, and makes it publicly available.

ICAO Doc 9501 'Environmental Technical Manual' Volume III provides guidance on the issuing of exemptions.'

21.A.801 Identification of products

'(a) The identification of products shall include the following information:

1. manufacturer’'s name;
2. product designation;
3. manufacturer’'s Sserial number;
4. 'EXEMPT' mark in case of an engine, when the competent authority has granted an exemption from the environmental protection requirements;

~~4.~~ 5. any other information the Agency finds appropriate.'

[…]

21.B.45 Reporting/coordination

'(a) The competent authority of the Member State shall ensure coordination as applicable with other related certification, investigation, approval or authorisation teams of that authority, other Member States and the Agency to ensure efficient exchange of information relevant for safety and environmental protection compatibility of the products, parts and appliances.

(b) The competent authority of the Member State shall notify the Agency of any difficulty in the implementation of ~~this~~ Annex I (Part~~-~~ 21) ~~to the Agency~~.'

21.B.85 Designation of applicable environmental protection requirements ~~and certification specifications~~ for a type-certificate or restricted type-certificate

'(a) The Agency shall designate and notify to the applicant the applicable environmental protection requirements for a type-certificate or restricted type-certificate for an aircraft or an engine. The environmental protection requirements shall consist of:~~, for a supplemental type-certificate or for a major change to a type-certificate or to a supplemental type-certificate, the applicable noise requirements established in Annex 16 to the Chicago Convention, Volume I, Part II, Chapter 1 and:~~

1. the applicable noise requirements established in:

   (i) Annex 16 to the Chicago Convention, Volume I, Part II, Chapter 1 and:

      ~~1.~~(A) for subsonic jet aeroplanes, in Chapters 2, 3, 4 and 14;

      ~~2.~~(B) for propeller-driven aeroplanes, in Chapters 3, 4, 5, 6, 10~~,~~ and 14;

      ~~3.~~(C) for helicopters, in Chapters 8 and 11;

      ~~4.~~(D) for supersonic aeroplanes, in Chapter 12; and

      ~~5.~~(E) for tilt rotors, in Chapter 13~~.~~; and

   (ii) Annex 16 to the Chicago Convention, Volume I:

      (A) Appendix 1 for aeroplanes for which Chapters 2 and 12 of Annex 16 to the Chicago Convention, Volume I, Part II are applicable;

      (B) Appendix 2 for aeroplanes for which Chapters 3, 4, 5, 8, 13 and 14 of Annex 16 to the Chicago Convention, Volume I, Part II are applicable;

      (C) Appendix 3 for aeroplanes for which Chapter 6 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable;

      (D) Appendix 4 for aeroplanes for which Chapter 11 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable; and

      (E) Appendix 6 for aeroplanes for which Chapter 10 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable.

~~(b)~~ 2. ~~The Agency shall designate and notify to the applicant referred to in point (a)~~ the applicable emissions requirements for preventions of intentional fuel venting for aircraft established in Annex 16 to the Chicago Convention, Volume II, Part II, Chapters 1 and 2.

~~(c)~~ 3. ~~The Agency shall designate and notify to the applicant referred to in point (a)~~ the applicable smoke, gaseous and particulate matter engine emissions requirements established in:

   (i) Annex 16 to the Chicago Convention, Volume II, Part III, Chapter 1 and:

      ~~1.~~(A) for smoke and gaseous emissions of turbojet and turbofan engines intended for propulsion only at subsonic speeds, in Chapter 2;

      ~~2.~~(B) for smoke and gaseous emissions of turbojet and turbofan engines intended for propulsion at supersonic speeds, in Chapter 3; and

      ~~3.~~(C) for particulate matter emissions of turbojet and turbofan engines intended for propulsion only at subsonic speeds, in Chapter 4~~.~~; and

   (ii) Annex 16 to the Chicago Convention, Volume II:

      (A) Appendix 1 for the measurement of reference pressure ratio;

      (B) Appendix 2 for smoke emissions evaluation;

      (C) Appendix 3 for instrumentation and measurement techniques for gaseous emissions;

      (D) Appendix 4 for specifications for fuel to be used in aircraft turbine engine emissions testing;

      (E) Appendix 5 for instrumentation and measurement techniques for gaseous emissions from afterburning gas turbine engines;

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

(F) Appendix 6 for compliance procedure for gaseous, smoke and particulate matter emissions; and

(G) Appendix 7 for compliance procedure for particulate matter emissions;

~~(d)~~ 4. ~~The Agency shall designate and notify to the applicant referred to in point (a)~~ the applicable aeroplane CO_2 emissions requirements established in:

(i) Annex 16 to the Chicago Convention, Volume III, Part II, Chapter 1, and

~~1.~~(A) for subsonic jet aeroplanes, in Chapter 2; and

~~2.~~(B) for subsonic propeller-driven aeroplanes, in Chapter 2~~.~~; and

(ii) Annex 16 to the Chicago Convention, Volume III, Appendices 1 and 2 for aeroplanes for which Chapter 2 of Annex 16 to the Chicago Convention, Volume III, Part II is applicable; and

5. for engines, the applicable requirements in Annex 16 to the Chicago Convention, Volume II, Part IV and Appendix 8 for non-volatile particulate matter assessment for inventory and modelling purposes.'

'GM 21.B.85(a)(5) Designation of applicable environmental protection requirements for inventory and modelling purposes

These requirements are for inventory and modelling purposes. Aircraft engine manufacturers are required to calculate the nvPM mass and nvPM number loss correction factors as per ICAO Annex 16 Volume II Appendix 8 and to report them to the competent authority. The nvPM mass and number system loss correction factors permit an estimation of the nvPM mass and number emissions at the exhaust of the aircraft engine from the nvPM mass and number concentration obtained in accordance with the procedures laid down in Annex 16 Volume II Appendix 7.'

3.1.4. Rationale for amending Commission Regulation (EU) No 748/2012 and the related AMC and GM

Amendment to:	Rationale
Article 9	Editorial corrections
21.A.21(3)	— Editorial corrections (change of numbering) — Addition of compatibility of flight with environmental protection requirements
21.A.130(b)(4)	Editorial corrections
AMC No 2 to 21.A.130(b)	Update of the exemption statement according to ICAO ETM Volume II
GM 21.A.130(b)(4)	— Update of the reference in the title (addition of (i)) — Update of the applicability date according to ICAO Annex 16 Volume II — Addition of clarification — Moved after AMC 21.A.130(b)(4)(i)
AMC 21.A.130(b)(4)(i)	— Update of the general information on the exemption process according to ICAO Annex 16 Volume II — Addition of provisions related to exemptions according to ICAO

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

	Annex 16 Volume II — Deletion of the ‘evaluation’ section since it can be found in the ICAO ETM Volume II
AMC 21.A.130(b)(4)(ii)	Addition of provisions related to exemptions according to ICAO Annex 16 Volume III
21.A.145	Introduction of the exemption concept according to Annex 16 Volume II
AMC-ELA No 1 to 21.A.145(b)	Editorial corrections
GM 21.A.145(b)(2)	Editorial corrections
21.A.147	Editorial corrections
AMC No 2 to 21.A.163(c)	Update of the exemption statement according to ICAO ETM Volume II
AMC 21.A.165(c)(3)	— Update of the general information on the exemption process according to ICAO Annex 16 Volume II — Addition of provisions related to exemptions according to ICAO Annex 16 Volume II — Deletion of the ‘evaluation’ section since it can be found in the ICAO ETM Volume II
GM 21.A.165(c)(3)	— Update of the applicability date according to ICAO Annex 16 Volume II — Addition of clarification
AMC 21.A.165(c)(4)	Addition of provisions related to exemptions according to ICAO Annex 16 Volume III
21.A.801	Introduction of the exemption marking according to Annex 16 Volume II
21.B.45(a)	Addition of a coordination requirement for environmental compatibility
21.B.85(a)	— Deletion of ‘and certification specifications’ from the title since it is included in 21.B.70 — Deletion of ‘for a supplemental type-certificate or for a major change to a type-certificate or to a supplemental type-certificate’ for consistency with 21.B.80 and 21.B.82 (21.A.95, 21.A.97, 21.A.101, 21.A.113 and 21.A.115 refer to Environmental Protection Requirements (EPR)) — Addition of the references to the appendices to ICAO Annex 16 since they contain requirements for the certification of aircraft and engines — Addition of a new requirement for inventory and modelling purposes
GM 21.B.85(a)(5)	Explanation for the new requirement for inventory and modelling purposes

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

3.2. Draft Certification Specifications, Acceptable Means of Compliance and Guidance Material for Aircraft Engine Emissions and Fuel Venting — CS-34

3.2.1. Draft amendment to CS-34

CS 34.1 Fuel venting

'The aircraft must be designed to comply with the applicable fuel venting requirements ~~defined under 21.B.85(b)~~ as specified in point 21.A.21 of Annex I (Part 21) to Commission Regulation (EU) No 748/2012.

[Amdt 34/2]
[Amdt 34/3]
[Amdt 34/4]'

GM 34.1 Fuel venting

Point 21.A.21 of Annex I (Part 21) does not list the applicable requirements, but refers to the requirements designated by the Agency in accordance with point 21.B.85. Therefore, the environmental protection requirements which need to be complied with according to point 21.A.21 are listed in point 21.B.85 of Annex I (Part 21) to Commission Regulation (EU) No 748/2012.

The guidance material for the application of the certification procedures for aircraft engine emissions is presented in ICAO Doc 9501 'Environmental Technical Manual' Volume II 'Procedures for the Emissions Certification of Aircraft Engines', XXX Edition, 20XX.

[Amdt 34/4]'

CS 34.2 Aircraft engine emissions

'The aircraft engine must be designed to comply with the applicable emissions requirements ~~defined under 21.B.85(c)~~ as specified in point 21.A.21 of Annex I (Part 21) to Commission Regulation (EU) No 748/2012.

[Amdt 34/2]
[Amdt 34/3]
[Amdt 34/4]'

'~~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 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;~~

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

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

~~(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.~~

[Amdt 34/2]
[Amdt 34/3]
[Amdt 34/4]'

GM 34.2 Aircraft engine emissions

'Point 21.A.21 of Annex I (Part 21) does not list the applicable requirements, but refers to the requirements designated by the Agency in accordance with point 21.B.85. Therefore, the environmental protection requirements which need to be complied with according to point 21.A.21 are listed in point 21.B.85 of Annex I (Part 21) to Commission Regulation (EU) No 748/2012.

The ~~G~~guidance material for the application of the certification ~~specifications~~ procedures for aircraft engine emissions is presented in:

(a) Annex 16 to the Chicago Convention, Volume II:

(1) Recommendations; and

(2) Attachment E to Appendix 3 for the calculation of the emissions parameters; and

(b) ICAO Doc 9501 'Environmental Technical Manual'~~,~~ Volume II 'Procedures for the Emissions Certification of Aircraft Engines', ~~Third~~ XXX Edition, ~~2018~~20XX.~~, except for the exemption process from the NOx emissions production cut-off requirements.~~

[Amdt 34/1]
[Amdt 34/2]
[Amdt 34/3]
[Amdt 34/4]'

3.2.2. Rationale for amending CS-34

Amendment to:	Rationale
CS 34.1	— Addition of the link (point 21.A.21) to the applicant requirements for the issuance of a TC or RTC (point 21.A.21)
GM 34.1	— Point 21.B.85 mirrors point 21.A.21 on the competent authority side and lists the applicable requirements of ICAO Annex 16 Volumes I, II and III. This reference permits to point out the environmental protection requirements — Reference to ETM Volume II added for guidance material
CS 34.2	— Addition of the link (point 21.A.21) to the applicant requirements for the issuance of a TC or RTC
AMC 34.2	— The references to the ICAO Annex 16 appendices are moved in point 21.B.85(a)
GM 34.2	— Point 21.B.85 mirrors point 21.A.21 on the competent authority side and lists the applicable requirements of ICAO Annex 16 Volumes I, II and III. This reference permits to point out the environmental protection requirements — Attachment E to Appendix 3 is guidance

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

	— Recommendations included into ICAO Annex 16 are included as guidance

3.3. Draft Certification Specifications, Acceptable Means of Compliance and Guidance Material for Aircraft Noise — CS-36

3.3.1. Draft amendments to CS-36

CS 36.1 Aircraft noise

'The aircraft must be designed to comply with the applicable noise requirements ~~defined under 21.B.85(a)~~ as specified in point 21.A.21 of Annex I (Part 21) to Commission Regulation (EU) No 748/2012.

[Amdt 36/4]
[Amdt 36/5]
[Amdt 36/6]'

'~~AMC 36.1 Aircraft noise~~

~~The acceptable means of compliance for aircraft noise are presented in:~~

~~(a) for aeroplanes for which Chapter 2 of Annex 16 to the Chicago Convention[8], Volume I, Part II is applicable, Appendix 1 to Annex 16, Volume I;~~

~~(b) for aeroplanes for which Chapter 3 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable, Appendix 2 to Annex 16, Volume I;~~

~~(c) for aeroplanes for which Chapter 4 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable, Appendix 2 to Annex 16, Volume I;~~

~~(d) for aeroplanes for which Chapter 5 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable, Appendix 2 to Annex 16, Volume I;~~

~~(e) for aeroplanes for which Chapter 6 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable, Appendix 3 to Annex 16, Volume I;~~

~~(f) for helicopters for which Chapter 8 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable, Appendix 2 to Annex 16, Volume I;~~

~~(g) for aeroplanes for which Chapter 10 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable, Appendix 6 to Annex 16, Volume I;~~

~~(h) for helicopters for which Chapter 11 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable, Appendix 4 to Annex 16, Volume I;~~

~~(i) for aeroplanes for which Chapter 12 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable, Appendix 1 to Annex 16, Volume I;~~

~~(j) for tilt-rotors for which Chapter 13 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable, Appendix 2 to Annex 16, Volume I; and~~

~~(k) for aeroplanes for which Chapter 14 of Annex 16 to the Chicago Convention, Volume I, Part II is applicable, Appendix 2 to Annex 16, Volume I.~~

[Amdt 36/1]
[Amdt 36/4]

~~[8] The Convention on International Civil Aviation on 7 December 1944.~~

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

[Amdt 36/6]'

GM 36.1 Aircraft noise

'Point 21.A.21 of Annex I (Part 21) does not list the applicable requirements, but refers to the requirements designated by the Agency in accordance with point 21.B.85. Therefore, the environmental protection requirements which need to be complied with according to point 21.A.21 are listed in point 21.B.85 of Annex I (Part 21) to Commission Regulation (EU) No 748/2012.

The ~~G~~guidance material for the application of the certification ~~specifications~~ procedures for aircraft noise is presented in:

(a) Annex 16 to the Chicago Convention, Volume I:

(1) Recommendations;

(2) Attachment 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)~~(3) Attachment D for evaluating an alternative method of measuring helicopter noise during approach~~, Attachment D to ICAO Annex 16, Volume I~~;

~~(c)~~(4) Attachment E for applicability of noise certification standards for propeller-driven aeroplanes~~, Attachment E to ICAO Annex 16, Volume I~~; and

~~(d)~~(5) Attachment F for guidelines for noise certification of tilt rotors~~, Attachment F to ICAO Annex 16, Volume I~~; and

~~(e)~~(b) ICAO Doc 9501 'Environmental Technical Manual'~~,~~ Volume I 'Procedures for the Noise Certification of Aircraft', ~~Third~~ XXX Edition, ~~2018~~20XX, except Chapters 1 and 8.

[Amdt 36/1]
[Amdt 36/2]
[Amdt 36/3]
[Amdt 36/4]
[Amdt 36/5]
[Amdt 36/6]'

3.3.2. Rationale for amending CS-36

Amendment to:	Rationale
CS 36.1	— Addition of the link (point 21.A.21) to the applicant requirements for the issuance of a TC or RTC
AMC 36.1	— The references to the ICAO Annex 16 appendices are moved in 21.B.85(a)
GM 36.1	— Point 21.B.85 mirrors point 21.A.21 on the competent authority side and lists the applicable requirements of ICAO Annex 16 Volumes I, II and III. This reference permits to point out the environmental protection requirements — Recommendations included into ICAO Annex 16 are included as guidance

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

3.4. Draft Certification Specifications, Acceptable Means of Compliance and Guidance Material for Aeroplane CO_2 Emissions — CS-CO_2

3.4.1. Draft amendments to CS-CO_2

CS CO_2.1 Aeroplane CO_2 emissions

'The aeroplane must be designed to comply with the applicable CO_2 emissions requirements ~~defined under point 21.B.85(d)~~ as specified in point 21.A.21 of Annex I (Part 21) to Commission Regulation (EU) No 748/2012.

[Amdt CO_2/1]'

'~~AMC CO_2.1 Aeroplane CO_2 emissions~~

~~For aeroplanes for which Annex 16 to the Chicago Convention[1], 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.~~

~~------~~

~~[1] The Convention on International Civil Aviation of 7 December 1944.~~

[Amdt CO_2/1]'

GM CO_2.1 Aeroplane CO_2 emissions

'Point 21.A.21 does not list the applicable requirements, but refers to the requirements designated by the Agency in accordance with point 21.B.85. Therefore, the environmental protection requirements which need to be complied with according to point 21.A.21 are listed in point 21.B.85 of Annex I (Part 21) to Commission Regulation (EU) No 748/2012.

The ~~G~~guidance material for the application of the certification ~~specifications~~ procedures for aeroplane CO_2 emissions is contained in:

(a) Annex 16 to the Chicago Convention, Volume III, Recommendations; and

(b) ICAO Doc 9501 'Environmental Technical Manual'~~,~~ Volume III 'Procedures for the CO_2 Emissions Certification of Aeroplanes', ~~First~~ XXX Edition, ~~2018~~20XX.

[Amdt CO_2/1]'

3.4.2. Rationale for amending CS-CO_2

Amendment to:	Rationale
CS CO_2.1	— Addition of the link (point 21.A.21)to the applicant requirements for the issuance of a TC or RTC
AMC CO_2.1	The references to the ICAO Annex 16 appendices are moved in 21.B.85
GM CO_2.1	— Point 21.B.85 mirrors point 21.A.21 on the competent authority side and lists the applicable requirements of ICAO Annex 16 Volumes I, II and III. This reference permits to point out the environmental protection requirements — Recommendations included into ICAO Annex 16 are included as guidance

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

4. Impact assessment (IA)

4.1. What is the issue

At its 11th formal meeting (CAEP/11) from 4 to 15 February 2019, the ICAO CAEP agreed amendments to ICAO Annex 16 Volume I 'Aircraft Noise', Volume II 'Aircraft Engine Emissions', and Volume III 'Aeroplane CO_2 emissions'.

Chapter 2 provides details on these amendments and the need for amending the regulations and the rules.

There are no exemptions in accordance with Article 70 'Safeguard provisions', Article 71 'Flexibility provisions' or Article 76 'Agency measures' of the Basic Regulation pertinent to the scope of this rulemaking task (RMT).

There are no alternative means of compliance (AltMoC) relevant to the content of this RMT.

4.1.1. Who is affected

The present RMT affects:

— design organisation approval (DOA) and production organisation approval (POA) holders;

— national aviation authorities (NAAs) and EASA;

— people impacted by aircraft noise and emissions.

4.1.2. How could the issue/problem evolve

Aircraft noise and emissions are expected to increase over the next decades as the forecasted improvement of aircraft and aircraft engines' environmental performance may be insufficient to compensate for the negative effect of air 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).

Furthermore, it is anticipated that the 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 regulations and rules unchanged would lead to an uneven playing field among the actors that operate in the international aviation market, and would create major loopholes in the field of environmental protection certification.

4.2. What we want to achieve — objectives

See Section 2.2.

4.3. How it could be achieved — options

Table 1: Selected policy options

Option No	*Short title*	**Description**
0	No policy change	No policy change (no change to the rules; risks remain as outlined in the issue analysis)
1	CAEP/11 implementation	Implementation of the CAEP/11 amendments, as proposed for adoption by the relevant ICAO State Letters

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

4.4. Methodology and data

4.4.1. Methodology applied

The methodology applied for this IA is the multi-criteria analysis (MCA) which allows comparing all options by scoring them against a set of criteria.

4.5. What are the impacts

4.5.1. Safety impact

There is no expected impact on safety.

4.5.2. Environmental impact

Out of the two options considered, only Option 1 has a positive environmental impact. The introduction of new nvPM mass and number standards in ICAO Annex 16 Volume II ensures that aircraft engine designs meet the latest environmental standards that mitigate the impact of aviation emissions on local air quality and have a positive environmental impact.

Therefore, negative environmental impacts are expected with Option 0 considering the dynamic baseline scenario with an increase in air traffic. Option 1 has a positive environmental impact since it reduces the nvPM burden compared to the baseline scenario.

4.5.3. Social impact

No social impacts are expected from the two options considered other than the indirect social effect through the mitigation of the environmental impacts (positive environmental impact of Option 1). The improvement of local air quality will reduce the health risks for the population.

4.5.4. Economic impact

Both options have an economic impact.

Engine manufacturers should make major investments in the development of compliant technologies and the manufacture of compliant engines. Secondary cost item is the asset value loss for those air operators which own aircraft with non-compliant engines.

Costs for stakeholders for designing, producing and operating aircraft compliant with the new CAEP/11 environmental requirements will also incur if EASA decides to opt for Option 0, as these requirements will likely be applicable in world regions other than Europe, and as aircraft designed to operate there will have to be compliant with the local regulations. 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 the environmental protection certification requirements worldwide, it reduces the administrative burden for industry and, therefore, has a positive economic impact.

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

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

Therefore, an overall negative economic impact is expected with Option 0 (considering the potential negative consequences on the level playing field) and a neutral economic impact for Option 1 (negative considering the investment needed but positive by ensuring better harmonisation and a level playing field).

4.6. Conclusion

4.6.1. Comparison of options

Out of the two options, only Option 1 has positive impacts in terms of environmental protection compared to Option 0 and it also ensures harmonisation and a level playing field. It is, therefore, proposed to select Option 1 and proceed with the implementation of the CAEP/11 amendments.

During a 3-year work cycle (March 2016 – February 2019), the proposed amendments to ICAO Annex 16 and the ETM, and, more specifically, the new nvPM 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. For further reference on the impact assessment developed at CAEP, please see Chapter 7.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

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

Impacts	Safety	Environment	Social	Economic	Total
Option 0	None **0**	Negative impact due to the forecasted increase in air traffic **–**	Indirect (health risks for the population) **–**	Risk of European products not being accepted outside Europe **–**	**negative**
Option 1	None **0**	— Engines will meet latest standards — Reduces nvPM burden compared to Option 0 **+**	— Indirect (improvement of local air quality reduces health risks for the population) **+**	— Harmonisation of certification worldwide reduces administrative burden — Cost for compliant technologies **+/–**	**positive**

Based on the above, it is recommended to select Option 1, that is, to implement the amendments agreed at CAEP/11 and proposed for adoption in the ICAO State Letters.

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

4.7. Monitoring

The related regulations and rules will be monitored every 3 years through the update of the European Aviation Environmental Report (EAER)[9]. The EAER provides information on the environmental performance of the aviation sector at European Union level. It supports the development of performance-based regulations focusing on measurable outcomes, informs strategic discussions on the prioritisation of future work, and facilitates coordination across different initiatives. More specifically, the 'Overview of Aviation Sector' and 'Technology and Design' chapters present the progress in the implementation of the latest CAEP amendments to ICAO Annex 16 Volumes I, II and III.

Among others, the EAER uses the following indicators:

— number of people inside L_{den} 55 dB noise contours;

— average noise energy per flight;

— full-flight CO_2 emissions;

— full-flight NO_x emissions;

— full-flight volatile and non-volatile particulate matter (nvPM) emissions;

— average fuel consumption of commercial flights.

In addition, the EAER shows advancements in technology linked to the implementation of the ICAO environmental standards.

The development of the EAER is coordinated by EASA with the support from the European Environment Agency (EEA), EUROCONTROL, and other European organisations.

[9] European Aviation Environmental Report for 2019, available at www.easa.europa.eu/eaer and at https://www.easa.europa.eu/eaer/downloads.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

5. Proposed actions to support implementation

n/a

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

6. References

6.1. Affected regulations

— Regulation (EU) 2018/1139 of the European Parliament and of the Council of 4 July 2018 on common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency, and amending Regulations (EC) No 2111/2005, (EC) No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/30/EU and 2014/53/EU of the European Parliament and of the Council, and repealing Regulations (EC) No 552/2004 and (EC) No 216/2008 of the European Parliament and of the Council and Council Regulation (EEC) No 3922/91 (OJ L 212, 22.8.2018, 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)

6.2. 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 No. 2019/016/R of the Executive Director of the Agency of 1 August 2019 on certification specifications, acceptable means of compliance and guidance material for aeroplane CO_2 emissions ('CS-CO_2')

— 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')

6.3. Other reference documents

— ICAO Doc 10126 'Committee on Aviation Environmental Protection Report – 11th meeting', February 2019

— ICAO State Letter AN 1/17.14 – 19/42, 'Proposals for the amendment of Annex 16, Volume I concerning Standards and Recommended Practices relating to environmental protection — Aircraft noise', 19 July 2019

— ICAO State Letter AN 1/17.14 – 19/43, 'Proposals for the amendment of Annex 16, Volume II concerning Standards and Recommended Practices relating to environmental protection — Aircraft engine emissions', 19 July 2019

— ICAO State Letter AN 1/17.14 – 19/44, 'Proposals for the amendment of Annex 16, Volume III, concerning Standards and Recommended Practices relating to environmental protection — Aeroplane CO_2 emissions', 19 July 2019

— Annex 16 'Environmental Protection' to the Convention on International Civil Aviation

— ICAO Doc 9501 'Environmental Technical Manual', Volumes I, II and III

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

7. Appendices

7.1. Appendix 1 — ICAO Annex 16 Volume I amendments

7.1.1. Summary of presentations, discussions, conclusions, recommendations and proposed general changes to ICAO Annex 16 Volume I and ETM Volume I (extract from the CAEP/11 Report (ICAO Doc 10126) — Agenda Item 4 'Aircraft noise')

Agenda Item 4: Aircraft noise

4.1 **REPORT OF WORKING GROUP 1 – NOISE TECHNICAL**

4.1.1 The co-Rapporteurs of Working Group 1 (WG1 – Noise Technical) presented the group's work since CAEP/10. The main aim of WG1 is to keep ICAO aircraft noise SARPs up to date and effective, whilst ensuring that the certification procedures are as simple and inexpensive as possible. The report provided an overview of progress on each of the work items as related to these objectives.

4.1.2 WG1 presented proposals (under N.02) to revise Annex 16, Volume I and ICAO Doc 9501, *Environmental Technical Manual* (ETM), Volume I – *Procedures for the Noise Certification of Aircraft*, which had previously been endorsed by the 2018 CAEP Steering Group meeting. These amendments include the caretaking of the Annex and ETM, monitoring the progress and status of IEC Standards referenced within the Annex and ETM, and the development of guidance material for flight path measurement.

4.1.3 During CAEP/11, the ICAO NoisedB was updated and extended several times. In September 2018, WG1 agreed to publish Version 2.26 of the ICAO NoisedB. Compared to the previous version (v2.25), changes were incorporated for 272 aeroplanes and Version 2.26 of the NoisedB was published on 4 October 2018.

4.1.4 WG1 has also continued to monitor the various national and international research programme goals and milestones (Task N.04.01) and a report on this activity was given, which provided a perspective on the strong government and industry commitment to address the technology aspects of the Balanced Approach.

4.1.5 WG1 reviewed the progress on the four supersonic aeroplane noise-related work items (Tasks N.05.01 to N.05.04). A presentation on the current status of supersonic aeroplane Standards and Recommended Practices (SARPs) development, industry projects, and the latest research was provided to the Air Navigation Commission (ANC) on 9 June 2016.

4.1.6 Concerning helicopter noise, WG1 reported on the feasibility of correlating certification noise levels with operational noise levels. This report is provided in Appendix B to the report on this agenda item. WG1 also assessed whether the current helicopter noise certification scheme is applicable for assessing hover noise, including the sufficiency of a correlation with one or more of the existing reference conditions. This report is provided in Appendix C to the report on this agenda item.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

Discussion and Conclusions

4.1.7 The meeting thanked WG1 for keeping Annex 16, Volume I up to date and relevant and the meeting approved the amendments as presented in Appendix A to the report on this agenda item. The meeting also approved the amendments to the ETM, Volume I as previously endorsed by the 2018 CAEP Steering Group meeting, as contained in the report from the working group.

4.1.8 The meeting approved the report on the feasibility of correlating helicopter certification noise levels with operational noise levels, and the report on helicopter hover noise. An Observer expressed appreciation for WG1's work on the CAEP/11 N.08 helicopter tasks, and underlined that helicopter noise is a major noise issue in her country. The Observer stressed the need for WG1 to continue these tasks when new data is available.

4.1.9 **Recommendations**

4.1.9.1 In light of the foregoing discussion, the meeting developed the following recommendations:

RSPP **Recommendation 4/1 — 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 4/2 — Amendments to the *Environmental Technical Manual*, Volume I — *Procedures for the Noise Certification of Aircraft*

That the *Environmental Technical Manual*, Volume I be amended, and that revised versions approved by subsequent CAEP Steering Group Meetings be made available, free of charge on the ICAO website.

4.2 **PROGRESS ON THE DEVELOPMENT OF A SUPERSONIC EN ROUTE (SONIC BOOM) NOISE STANDARD**

4.2.1 The co-Rapporteurs of WG1 reported on progress in the development of an en route (sonic boom) noise certification Standard for supersonic aeroplanes. This effort has focused on: the identification of viable sonic boom data processing scheme options; candidate reference atmosphere and humidity standards; updated sonic boom metric(s) analyses; and sonic boom reference flight conditions. An overview of recent supersonic noise technology research was also presented.

4.2.2 The WG1 Supersonic Research Focal Points (RFPs) presented an update on the state-of-the-art in sonic boom technology, with an overview of many of the developments in supersonic technology made by various organizations from the United States, Japan, Europe and industry. Each organization devoted a portion of their resources to efforts to develop understanding of, and models for, the effects of atmospheric turbulence on the propagated acoustic signature from a supersonic aircraft, and significant progress has been made in this important area of research. Atmospheric turbulence can distort the propagating waveform and result in a ground signature that is louder or quieter than the predicted level in a quiescent atmosphere. These new models will play a vital role in understanding the potential variation in the noise levels from quiet supersonic aircraft in daily operations. An additional conclusion was that there remain many unknowns related to overland supersonic flight, and continued careful monitoring of the developments in supersonics would be in the best interest of CAEP.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.
An agency of the European Union

4.2.3 Several Members and Observers considered that perception of sonic boom over land would constitute a new form of nuisance, therefore any supersonic civil aeroplanes should be subject to en route noise certification in order to establish its sonic boom noise level.

4.2.4 An Observer, on behalf of WG1, presented the industry efforts in the area of supersonics, including aeroplane development projects related to supersonic flight over water only, and enabling technologies to support low boom aeroplanes capable of supersonic operation over land. During the CAEP/11 cycle, six major developments had occurred, making it clear that sustained investments are being made by various international industry members and national research agencies.

Discussion And Conclusions

4.2.5 A Member congratulated WG1 on the work on the sonic boom noise Standard, and noted the challenging timeline proposed by WG1, which foresees the conclusion of this work at CAEP/13. The Member encouraged further research on the effects of sonic boom, especially on rattle, vibration and sleep disturbance.

4.2.6 Responding to a question by a Member, a WG1 RFP informed that, based on currently available results from NASA community testing, a level of 75 PLdB was identified as the threshold where sonic boom noise is potentially indistinguishable from background noise. On a related subject, the WG1 co-Rapporteurs clarified that WG1 had not yet investigated the data needed to support a future stringency definition on sonic boom levels.

4.2.7 A Member welcomed the initiatives of NASA on sonic boom community testing, and expressed the view that an eventual sonic boom certification scheme should only be applicable to designs interested in a “low boom” certification. An Observer highlighted how the present research constitutes only the beginning of the understanding of the issue as other factors should be considered such as culture, type of boom and location. The meeting encouraged the continuation of State supported supersonic noise research. The CAEP Secretary thanked WG1 RFPs for their presentation and highlighted the importance of the information provided in support of the work of CAEP.

4.2.8 The meeting acknowledged the supersonic standards work to date, and noted the logical staging of the basic technical activities timed by data availability, as outlined by WG1.

4.2.9 The meeting endorsed the six finalist sonic boom metrics (Stevens Mark VII Perceived Level (PL); Indoor sonic boom annoyance predictor (ISBAP); A-weighted Sound Exposure Level (ASEL); B-weighted Sound Exposure Level (BSEL); E-weighted Sound Exposure Level (ESEL); and D-weighted Sound Exposure Level (DSEL)), following the reassessment to include new laboratory subjective data pertaining to low-boom response.

4.2.10 The meeting agreed that WG1 should address the sonic boom data processing scheme, reference atmosphere-humidity standards, en route reference flight conditions and measurement locations, low boom SARPs applicability for non-low boom designs, continue to explore the management of Mach cut-off operations, and continue to gather data on which “other factors” need to be considered for SARP development. These may include boom at “off design” Mach numbers, boom from accelerations and turns, secondary sonic booms, restricting N-wave booms over water, sleep and booms at night, effects on animals, and avalanches.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

4.3 PROGRESS ON THE DEVELOPMENT OF A LANDING AND TAKE-OFF LTO NOISE STANDARD FOR SUPERSONIC AEROPLANES

4.3.1 The co-Rapporteurs of WG1 reported on progress in the development of a landing and take-off noise certification Standard for supersonic aeroplanes. WG1 started by gaining a common understanding of the current relevant regulations, reviewing historical data on civil supersonic aircraft, reviewing the details of programme lapse rate (PLR), and reviewing design differences between subsonic and supersonic aeroplanes. Additionally, take-off and landing differences were highlighted in terms of speeds and configurations.

4.3.2 In the absence of manufacturers' data, WG1 started working with a 55-tonne Supersonic Technology Concept Aeroplane (STCA) developed by NASA with manufacturers' oversight and cross-checking. JAXA and TsAGI also contributed by independently predicting noise levels of this STCA with the same publicly available input.

4.3.3 With a non-disclosure agreement finalized, manufacturers' data from three project aeroplanes was presented to WG1 members, including noise level estimates, weight information, range, balance field length, Mach number, engine information, operating procedures, etc.

4.3.4 At the 2017 CAEP Steering Group meeting, CAEP acknowledged that the basic design characteristics T/W (Thrust-to-weight-ratio), W/S (Wing loading) and CLMax (Maximum Usable Lift Coefficient) are, in general terms, fundamentally different between supersonic and subsonic aircraft, and that the evaluation of these differences in more precise terms will only be possible with a specific design in hand. The project aeroplanes data provided to WG1 supported some of the key differences between subsonic and supersonic aeroplanes. Data from the 55-tonne STCA also supported these differences.

4.3.5 WG1 assessed the suitability of the current LTO noise certification Standards and the ETM, developed for subsonic aeroplanes, for aircraft designed to fly at supersonic speeds. Based on this assessment, WG1 identified some categories that need, or may need, further investigation to determine their suitability. All the subsonic Standards that do not fit into these categories will require minor wording changes, or no changes at all, to become suitable for supersonic aircraft.

4.3.6 The metric Effective Perceived Noise Level (EPNL) was adopted as the single noise metric and agreed to during the 2017 CAEP Steering Group meeting, and is expected to be used without modification. While applicability definitions are needed, these will be completed at a later stage. A majority of WG1 members agreed that the Chapter 14 noise limit for each individual reference point should be used, but some felt that it was premature to make this decision before additional discussions on procedures took place. WG1 had not reached any agreement on whether the cumulative noise level would be an item for further review. The group had also not reached any consensus on whether a correlating parameter was an item for further review with the current knowledge in WG1. However, WG1 agreed to consider the use of an additional correlating parameter, to accommodate a range of design Mach numbers, provided that OEMs data and computational analysis data are made available to the group. Concerning procedures, WG1 agreed that test and reference day speeds for take-off needed further review. VNRS is already allowed for subsonics in the ETM, but some additional guidance may be needed for supersonics in the SARPs. PLR is expected to be a feature of supersonic products, and this is considered to be incorporated under VNRS provisions. At this point, there is insufficient data to decide whether a change is needed in Chapter 14 (being used as a starting point) in several other sections, including approach procedures.

4.3.7 One Observer supported that a supersonic fleet forecast is needed rapidly, including how and where this fleet will operate, which would allow fruitful discussions about regulatory impacts. The Observer offered resources to this effort, and supported the creation of a coordination group for SST SARPs development.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

4.3.8 Responding to a question, the WG1 co-Rapporteurs clarified that Chapter 14 presents noise limits in terms of each of the three measurement points, but also presents a limit in terms of the cumulative margin to these points. This makes it possible for a design to comply with the three individual limits, but not comply with the cumulative noise limit, thus not meeting Chapter 14.

4.3.9 A Member highlighted, and the WG1 co-Rapporteurs concurred, that the current WG1 analyses regarding supersonics compliance with Chapter 14 requirements were not yet conclusive, as they were supported by data from only two project aircraft, not including data from the third project aircraft with a higher design cruise Mach number.

4.3.10 Several Members and Observers presented their views related to the development of supersonic aeroplane LTO noise Standards. They reiterated their view that the development of noise SARPs for supersonic aeroplanes (both LTO and sonic boom) must be based on ICAO Assembly Resolution A39-1, ensuring no unacceptable situation is created for the public. Regarding LTO noise, they considered that civil supersonic aeroplanes should not be noisier than current and future subsonic aeroplanes in LTO operations. Also, they considered that civil supersonic aeroplanes should be certified according to Chapter 14 with some technical adaptations if need be, therefore they did not see the need to consider a set of new stringency options or to conduct a relative cost-effectiveness analysis of candidate options.

4.3.11 A Member proposed a CAEP future work item covering a scoping study for updating the Chapter 14 noise requirements for subsonic aeroplanes. This will be considered under Agenda Item 12 on future work.

4.3.12 A Member expressed the view that the unacceptable situations referred to in Resolution A39-1 can be interpreted in different ways by each State, and supported that the language could be clarified by including the word “inhabited land” when referring to sonic boom impact. A Member noted that this aspect could be addressed by proper operational rules.

4.3.13 Some Members and Observers supported the view that supersonic aircraft should comply with the current and future noise Standards for subsonics, while others supported gathering more data and analysis, as recommended by WG1, before reaching any decision.

4.3.14 A Member presented views on the supersonic noise work within CAEP. The Member recommended that CAEP develop a SARP and conduct an associated stringency assessment for civil supersonic aircraft landing and take-off noise for consideration at CAEP/12, in 2022. The Member recognized that there are fundamental technological differences between subsonic and supersonic aircraft types, which may lead to different approaches to Standard-setting, and at the very least, warrant a technical review and analysis prior to drawing policy conclusions. The Member reminded that Assembly Resolution A39-1, paragraph 1.1 “reaffirms the importance” that the Assembly attaches “to ensuring that no unacceptable situation for the public is created by sonic boom.” The Member interprets this language as specific to the issue of sonic boom and ensuring that sonic boom does not result in “unacceptable situations.” The Member did not support creating a new concept of “public acceptability” based on Resolution A39-1, as he considered this term to be subjective, imprecise, and inconsistent with the long-standing CAEP Terms of Reference that are premised on technological feasibility, environmental benefit and cost effectiveness.

4.3.15 Responding to a question, the Member affirmed that it would be possible to consider noise limits for supersonics more stringent than Chapter 14 limits, after the proper technical analysis was completed. The Member was also of the view that CAEP will have to adapt its Standard-setting process to address the unique situation caused by the lack of certified noise data for supersonics, and noted that such adaptations should not set a precedent for future analyses, due to their exceptional characteristics.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

4.3.16 One Member supported innovations in air transport, provided they do not come with unacceptable environmental impacts, and expressed the view that supersonics have potentially serious environmental impacts, which could be avoided only by applying existing subsonic Standards in their certification. The Member also noted that supersonics and subsonics will compete in the same markets, and therefore different noise limits for supersonics would incur a competitive advantage for them.

4.3.17 An Observer shared concerns regarding the development of supersonics LTO SARPs, and expressed that in order to be acceptable to communities around airports, supersonic aircraft cannot be noisier than their subsonic counterparts (same level of MTOM) under subsonic operations and must also comply with current and future noise and emissions subsonic SARPs. The Observer proposed work on further analysis of community noise impact of supersonic operations around airports using other noise indicators, in addition to the EPNL, and expressed views on the application of the ICAO Assembly Resolution A39-1 to the SST LTO noise.

4.3.18 Members and Observers questioned how the results of the proposed analysis of community noise would be used by CAEP. The Observer clarified that such results would be used to support policy decisions on supersonics but would not question the choice of EPNL as the metric for noise certification. The meeting agreed to discuss the proposal under the future work agenda item.

4.3.19 Two Observers summarized the significant technical progress on the development of LTO noise Standards for supersonics, as well as the contributions provided by the industry. They highlighted that OEMs are working hard to bring supersonic aeroplanes into service by the mid-2020s, and therefore OEMs need definitive LTO noise requirements in order to finalize project designs. The Observers supported the initiation of elements of SARPs development and identification of resources to meet the proposed CAEP/12 date for supersonic LTO noise SARPs.

4.3.20 An Observer questioned the consistency between the traditional SARPs development approach of CAEP, namely the setting of SARPs based on measurement and certification data, and the new approach suggested by industry to solely rely on project aircraft and modelling data of lower TRL. He then asked if the TRL of the project aeroplanes could be clearly identified. Another Observer replied that this was not possible due to the variety of technologies involved.

4.3.21 An Observer presented the view that future certification of supersonic aeroplanes must be handled carefully to ensure no net increase in airport noise and community disturbance. The Observer proposed that, until a robust data set of SST noise performance is available to develop supersonic noise Standards, new SST aircraft should comply with the current subsonic Chapter 14 noise Standards.

4.3.22 The meeting noted the information provided by a Member regarding the potential noise reduction for supersonics from using take-off thrust management, as well as on the interdependencies of noise, emissions and flight range for supersonics. According to the information, taking into account main engine noise sources, the noise level predictions show that SST would fail Chapter 14 even with the use of take-off thrust control.

Discussion And Conclusions

4.3.23 The meeting considered the interpretation that CAEP work is aimed at maintaining at least the existing level of environmental protection, referred to as “environmental benefit” in the CAEP Terms of Reference. Responding to a question regarding the term “existing level of environmental protection”, a Member expressed the opinion that this term means to not deteriorate the existing noise levels around airports. An Observer questioned whether CAEP work should aim at a specific element of the Terms of Reference, or on a balance amongst the four elements, to which a Member responded that the industry efforts on technology development may still allow this balance to be achieved. An Observer was of the opinion that the term “anti-backsliding” should be a non-controversial interpretation of the environmental benefit aspect under CAEP Standard-setting. A Member expressed concerns that the “environmental benefit” aspect of the CAEP Terms of Reference is being interpreted by some Members and Observers as a “net environmental benefit to the overall system”, which is not in line with past CAEP practices. The meeting noted the different interpretations on this element of the CAEP Terms of Reference.

4.3.24 Some Members supported the view that the language in Resolution A39-1 is specific to the issue of sonic boom and ensuring that sonic boom does not result in “unacceptable situations”. Other Members noted that Resolution A39-1 refers to the “problems which the operation of supersonic aircraft may create for the public”, and supported that these problems include LTO noise and its public acceptability. A Member commented that the concept of public acceptability is not new to CAEP, since the CAEP/10 meeting noted that the CAEP 2015 Steering Group meeting “acknowledged public acceptability of booms is a pre-requisite of a standard for supersonic aircraft”, while another Member supported that CAEP should refrain from referencing Steering Group decisions instead of the Assembly resolution language, which refers to “unacceptable situations for the public due to sonic boom”.

4.3.25 Given the different views expressed, the meeting noted the view of a Member that the language of Resolution A39-1 is specific to the issue of sonic boom and ensuring that sonic boom does not result in “unacceptable situations”.

4.3.26 The meeting agreed that both subsonic and supersonic civil aeroplanes are jet aeroplanes with fixed wings intended for passenger transport and that certain basic design characteristics are fundamentally different between supersonic and subsonic aeroplanes.

4.3.27 Several Members and Observers objected to performing a noise stringency assessment for supersonics under the CAEP/12 work programme, as there was no clarity on how such a stringency assessment would be performed and which data would be used. These Members and Observers supported the adoption of Chapter 14 as the LTO noise Standard, with some technical adaptations if needed. A Member noted that the use of current subsonic Standards as a reference for supersonics would provide regulatory certainty to the industry, which is also important, besides the environmental benefit aspects.

4.3.28 A Member stated that in the absence of certification data, the current data can be used to carry out a stringency analysis. Other Members and Observers supported that there is still insufficient data and analysis available to decide on Chapter 14 adoption for supersonics, and requested further work from WG1 during the CAEP/12 cycle. A Member highlighted the fundamental design differences between supersonic and subsonic aeroplanes, and considered it simplistic to equate subsonics and supersonic aeroplanes. Another Member reminded that Chapter 14 currently covers both turbojets and turboprops, which are also fundamentally different.

4.3.29 From the ensuing discussion, the meeting agreed with the elements of an exploratory study for supersonic aircraft during the CAEP/12 work programme, detailed as follows:

4.3.30 Recognizing that there is no consensus on the necessity to conduct a stringency option analysis on LTO noise for supersonic aircraft, CAEP recommended that an exploratory study using currently available data be undertaken during the CAEP/12 cycle. The results of the study are intended to provide CAEP with a better understanding of airport noise impacts resulting from the introduction of supersonic aircraft, and do not prejudge the need to conduct a stringency options analysis. This work consists of a fleet and operations forecast and an LTO noise impact assessment for a selection of airports based on the noise performance information currently available. It will also include an assessment of the project aircraft used, with regards to Annex 16, Volume I, Chapter 14 noise levels and margin requirements.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

4.3.31 The study is to contain the various elements below:

1) **Procedures**
   - Working Group 1 to make recommendations by the 2019 CAEP Steering Group (SG2019) meeting on procedures for LTO noise certification, taking into account the need for additional data from industry.
2) **Forecast Scenarios**
   - FESG to develop multiple demand scenarios for supersonic transport markets, based on data provided by the industry and by Working Groups of CAEP.
3) **Aircraft Data**
   - CAEP expressly recognizes the uncertainty associated with the available aircraft data.
   - WG1 to use STCA and OEM data to develop an environmental and performance modelling data, which would represent a range of concept and project aircraft, as a proxy for future supersonic aircraft types.
   - WG1 to develop noise-power-distance and spectral data based on certification procedures, subject to a feasibility assessment. As appropriate, new aircraft data is to be considered for inclusion as it becomes available.
   - WG3 to provide corresponding estimates on LTO engine emissions as well as aeroplane fuel burn and CO_2 emissions data (cruise and full-flight) for the purposes of an exploratory analysis, subject to feasibility assessment.
   - ISG, with input from WG1 and WG3 if needed, to provide information regarding environmental impacts originating from SST noise and emissions.
   - WG1 and WG3 to provide information regarding trades among noise, emissions, fuel burn, and Mach number.
4) **Study**
   - MDG to develop environmental modelling scenarios, acknowledging that this will require additional resources to update existing models and databases, and run the exploratory study.
   - Include regional representation of business jet and mixed-use large airports, and consider the feasibility of taking into account airport capacity constraints, as needed, to ensure a realistic representation of subsonic operations. As part of the regionally based airport selection for LTO noise analysis, sample origin-destination pairs will also be included so that full-flight fuel burn and emissions can be computed.
   - Noise metric would be DNL, and single event metrics (LA max, SEL).
   - Considering the uncertainty of the project aircraft data used in the study, an assessment of the corresponding uncertainty of the output results will be conducted.
   - Consider trades such as noise and full-flight fuel burn.
5) **Results**
   - Results of the analysis to be presented for initial consideration by the 2021 CAEP Steering Group (SG2021) meeting, and final results to CAEP/12.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.
An agency of the European Union

— — — — — — — —

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

7.1.2. Proposed amendments to Annex 16 Volume I (extract from CAEP/11 Report (ICAO Doc 10126) — Agenda Item 4 — Appendix A)

APPENDIX A

1. **PROPOSED AMENDMENTS TO ANNEX 16, VOLUME I**

2.

1. 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:

2.

3. 1. ~~Text to be deleted is shown with a line through it.~~	4. text to be deleted
5. 2. New text to be inserted is highlighted with grey shading	6. new text to be inserted
7. 3. ~~Text to be deleted is shown with a line through it~~ followed by the replacement text which is highlighted with grey shading.	8. new text to replace existing text

9.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

10. **TEXT OF PROPOSED AMENDMENT TO THE**
11.
12. **INTERNATIONAL STANDARDS AND RECOMMENDED PRACTICES**
13.
14. **ENVIRONMENTAL PROTECTION**
15.
16. **ANNEX 16**
17. **TO THE CONVENTION ON INTERNATIONAL CIVIL AVIATION**
18.
19. **VOLUME I**
20. **AIRCRAFT NOISE**
21.
22. …
23.

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.
c_{HR}	m/s	*Reference speed of sound*. The reference speed of sound corresponding to the ambient temperature – assuming a lapse rate of 0.65°C per 100 m – for a standard day at the aeroplane reference height above mean sea level.
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~~ m/s	*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~~ m/s	*Maximum airspeed in conversion mode*. The never-exceed airspeed of a tilt-rotor when in conversion mode.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

V_G	~~km/h~~ m/s	*Ground speed*. The aircraft velocity relative to the ground.
V_{GR}	~~km/h~~ m/s	*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~~ m/s	*Maximum airspeed in level flight*. The maximum airspeed of a helicopter in level flight when operating at maximum continuous power.
V_{MCP}	~~km/h~~ m/s	*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~~ m/s	*Maximum operating airspeed*. The maximum operating limit airspeed of a tilt-rotor that may not be deliberately exceeded.
V_{NE}	~~km/h~~ m/s	*Never-exceed airspeed*. The maximum operating limit airspeed that may not be deliberately exceeded.
V_R	~~km/h~~ m/s	*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~~ m/s	*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~~ m/s	*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~~ m/s	*Speed for best rate of climb*. The test airspeed for best take-off rate of climb.
V_2	~~km/h~~ m/s	*Take-off safety speed*. The minimum airspeed for a safe take-off.

…

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

1.4 Noise metrics

Symbol	*Unit*	*Meaning*
…		
L_{AE}	dB SEL(A)	*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 (dB(A), normalized to a reference duration of 1 second. (See Appendix 4, Section 3 for specifications.)
Δ_1	TPNdB	*PNLTM adjustment* for Appendix 2 or Attachment F. 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)	Under Appendix 4. The adjustments to be added to the measured L_{AE} to account for noise level changes for spherical spreading and duration due to the difference between test and reference helicopter height.
	dB(A)	Under Appendix 6. For propeller-driven aeroplanes not exceeding 8 618 kg, the adjustment to be added to the measured L_{ASmax} to account for noise level changes due to the difference between test and reference aeroplane heights.
Δ_2	TPNdB	*Duration adjustment* for Appendix 2 or Attachment F. 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)	Under Appendix 4. The adjustments to be added to the measured L_{AE} to account for noise level changes due to difference between reference and adjusted airspeed.
	dB(A)	Under Appendix 6. For propeller-driven aeroplanes not exceeding 8 618 kg, the adjustment to be added to the measured L_{ASmax} to account for the noise level changes due to the difference between test and reference propeller helical tip Mach number.
Δ_3	TPNdB	*Source noise adjustment* for Appendix 2. 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)	Under Appendix 6. For propeller-driven aeroplanes not exceeding 8 618 kg, the adjustment to be added to the measured L_{ASmax} to account for noise level changes due to the difference between test and reference engine power.

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

Symbol	*Unit*	*Meaning*
Δ_4	dB(A)	*Atmospheric absorption adjustment* for Appendix 6. For propeller-driven aeroplanes not exceeding 8 618 kg, 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.

…

1.6 Flight path geometry

Symbol	*Unit*	*Meaning*
H	m	*Height*. The aircraft height ~~when overhead or abeam of the centre microphone~~ at the point where the flight path intercepts the vertical geometrical plane perpendicular to the reference ground track at the centre microphone.
H_R	m	*Reference height*. The reference aircraft height ~~when overhead or abeam of the centre microphone~~ at the point where the reference flight path intercepts the vertical geometrical plane perpendicular to the reference ground track at the centre microphone.

[…]

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

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

…

11.2 Noise evaluation measure

The noise evaluation measure shall be the sound exposure level ~~(SEL)~~L_{AE} as described in Appendix 4.

...

11.4 Maximum noise level

11.4.1 For helicopters specified in 11.1.2 and 11.1.3, the maximum noise levels, when determined in accordance with the noise evaluation method of Appendix 4, shall not exceed 82 ~~decibels~~ dB(A) ~~SEL~~ for helicopters with maximum certificated take-off mass, at which the noise certification is requested, of up to 788 kg and increasing linearly with the logarithm of the helicopter mass at a rate of 3 decibels per doubling of mass thereafter.

11.4.2 For helicopters specified in 11.1.4, the maximum noise levels, when determined in accordance with the noise evaluation method of Appendix 4, shall not exceed 82 ~~decibels~~ dB(A) ~~SEL~~ for helicopters with maximum certificated take-off mass, at which the noise certification is requested, of up to 1 417 kg and increasing linearly with the logarithm of the helicopter mass at a rate of 3 decibels per doubling of mass thereafter.

Note.— See Attachment A for equations for the calculation of maximum permitted noise levels as a function of take-off mass.

…

11.6 Test procedures

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

11.6.2 The test procedure and noise measurements shall be conducted and processed in an approved manner to yield the noise evaluation measure designated as sound exposure level (~~SEL~~L_{AE}), in A-weighted decibels integrated over the duration time, as described in Appendix 4.

11.6.3 Test conditions and procedures shall be closely similar to reference conditions and procedures or the acoustic data shall be adjusted, by the methods outlined in Appendix 4, to the reference conditions and procedures specified in this chapter.

11.6.4 During the test, flights shall be made in equal numbers with tailwind and headwind components.

11.6.5 Adjustments for differences between test and reference flight procedures shall not exceed 2.0 dB(A).

11.6.6 During the test, the average rotor rpm shall not vary from the normal maximum operating rpm by more than ±1.0 per cent during the 10 dB-down period.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

11.6.7 The helicopter airspeed shall not vary from the reference airspeed appropriate to the flight demonstration as described in Appendix 4 by more than ±5.5 km/h (±3 kt) throughout the 10 dB-down period.

11.6.8 The helicopter shall fly within ±10° from the vertical above the reference track through the reference noise measurement position.

11.6.9 Tests shall be conducted at a helicopter mass not less than 90 per cent of the relevant maximum certificated mass and may be conducted at a mass not exceeding 105 per cent of the relevant maximum certificated mass.

Note.— Guidance material on the use of equivalent procedures is provided in the Environmental Technical Manual *(Doc 9501), Volume I —* Procedures for the Noise Certification of Aircraft.

…

CHAPTER 13. TILT-ROTORS

…

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

…

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

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. NOISE CERTIFICATION TEST AND MEASUREMENT CONDITIONS

…

2.2 Test environment

…

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" (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~~ flight path intercepts the vertical geometrical plane perpendicular to the reference ground track at the centre microphone.

Note.— The reference ground track is defined in 8.1.3.5.

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" (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~~ flight path intercepts the vertical geometrical plane perpendicular to the reference ground track at the centre microphone. The

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

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)”.

…

3. MEASUREMENT OF AIRCRAFT NOISE RECEIVED ON THE GROUND

…

3.7 Analysis systems

…

3.7.3 The one-third octave band analysis system shall conform to the class 1 electrical performance requirements of IEC 61260-1[2] as amended, over the range of one-third octave filters having nominal midband frequencies from 50 Hz to 10 kHz inclusive.

Note 1.— The certificating authority may allow the substitution of an analysis system that complies with class 2 as an alternative to class 1 electrical performance requirements of IEC 61260-1[2] or with class 1 or class 2 of an earlier version of IEC 61260.

Note 2.—Tests of the one-third octave band analysis system should be made according to the methods described in IEC 61260-3[x10] or by an equivalent procedure approved by the certificating authority, for relative attenuation, anti-aliasing filters, real-time operation, level linearity, and filter integrated response (effective bandwidth).

3.7.4 When SLOW-time-averaging is performed in the analyser, the response of the one-third octave band analysis system to a sudden onset or interruption of a constant sinusoidal signal at the respective one-third octave nominal midband frequency shall be measured at sampling instants 0.5, 1, 1.5 and 2 seconds after both the onset and 0.5 and 1 seconds after the interruption. The rising response shall be –4 ± 1 dB at 0.5 seconds, –1.75 ± 0.75 dB at 1 second, –1 ± 0.5 dB at 1.5 seconds and –0.5 ± 0.5 dB at 2 seconds relative to the steady-state level. The falling response shall be such that the sum of the output signal levels, relative to the initial steady-state level, and the corresponding rising response reading is The sum of the rising and corresponding falling response shall be –6.5 ± 1 dB, at both 0.5 and 1 seconds. At subsequent times the The sum of the rising and falling responses shall be –7.5 –6.5 dB or less at 1.5 seconds and –7.5 dB or less at 2 seconds and subsequent times relative to the steady-state levels. This equates to an exponential averaging process (SLOW weighting) with a nominal 1-second time constant (i.e. 2 seconds averaging time).

…

4. CALCULATION OF EFFECTIVE PERCEIVED NOISE LEVEL FROM MEASURED NOISE DATA

…

4.7 Mathematical formulation of noy tables

4.7.1 The relationship between sound pressure level (SPL) and the logarithm of perceived noisiness is illustrated in Table A2-3 and Figure A2-3.

…

Table A2-3. Constants for mathematically formulated noy values

10. IEC 61260-1:19952014 entitled “Electroacoustics — Octave-band and fractional-octave-band filters - Part 1: Specifications”. This IEC publication may be obtained from the Central Office of the International Electrotechnical Commission, 3 rue de Varembé, Geneva, Switzerland.

x2. IEC 61260-3:2016 entitled “Electroacoustics — Octave-band and fractional-octave-band filters - Part 3: Periodic tests”. This IEC publication may be obtained from the Central Office of the International Electrotechnical Commission, 3 rue de Varembé, Geneva, Switzerland

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

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~~9	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		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	NOT APPLICABLE	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

…

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

8. ADJUSTMENT OF AIRCRAFT FLIGHT TEST RESULTS

8.1 Flight profiles and noise geometry

…

8.1.1 Aeroplane flight profiles

8.1.1.1 *Reference lateral full-power profile characteristics*

Figure A2-4 illustrates the profile characteristics for the aeroplane take-off procedure for noise measurements made at the lateral full-power noise measurement points:

a) the aeroplane begins the take-off roll at point A and lifts off at point B at full take-off power. The climb angle increases between points B and C. From point C the climb angle is constant up to point F, the end of the noise flight path; and

b) positions K_{2L} and K_{2R} are the left and right lateral noise measurement points for jet aeroplanes, located on a line parallel to and at the specified distance ~~abeam~~ from the runway centre line, where the noise level during take-off is greatest. Position K_4 is the “lateral” full-power noise measurement point for propeller-driven aeroplanes located on the extended centre line of the runway vertically below the point on the climb-out flight path where the aeroplane is at the specified height.

…

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

…

8.1.3.5 The reference ground track is defined as the vertical projection of the reference flight path onto the ground.

…

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

…

2. NOISE CERTIFICATION TEST AND MEASUREMENT CONDITIONS

…

2.4 Flight test conditions

…

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

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

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

3. NOISE UNIT DEFINITION

…

3.4 The integration time ($t_2 - t_1$) in practice shall not be less than the 10 dB-down period during which $L_{AS}(t)$ first rises to 10 dB(A) below its maximum value and last falls below 10 dB(A) of its maximum value.

…

4. MEASUREMENT OF HELICOPTER NOISE RECEIVED ON THE GROUND

…

4.3 Sensing, recording and reproducing equipment

…

4.3.2 The ~~SEL~~ L_{AE} may be directly determined from an integrating sound level meter. Alternatively, with the approval of the certificating authority the sound pressure signal produced by the helicopter may be stored on an analogue magnetic tape recorder or a digital audio recorder for later evaluation using an integrating sound level meter. The ~~SEL~~ L_{AE} may also be calculated from one-third octave band data obtained from measurements made in conformity with Section 3 of Appendix 2 and using the equation given in 3.3. In this case each one-third octave band sound pressure level shall be weighted in accordance with the A-weighting values given in IEC Publication 61672-1.[11]

4.3.3 The characteristics of the complete system with regard to directional response, frequency weighting A, time weighting S (slow), level linearity, and response to short-duration signals shall comply with the class 1 specifications given in IEC 61672-1.[1] The complete system may include tape recorders or digital audio recorders according to IEC 61672-1.[1]

Note.— The certificating authority may approve the use of equipment compliant with class 2 of the current IEC standard, or the use of equipment compliant with class 1 or Type 1 specifications of an earlier standard, if the applicant can show that the equipment had previously been approved for noise certification use by a certificating authority. This includes the use of a sound level meter and graphic level recorder to approximate ~~SEL~~ L_{AE} using the equation given in 3.3. The certificating authority may also approve the use of magnetic tape recorders that comply with the specifications of the older IEC 561 standard if the applicant can show that such use had previously been approved for noise certification use by a certificating authority.

…

4.3.5 When the sound pressure signals from the helicopter are recorded, the ~~SEL~~ L_{AE} may be determined by playback of the recorded signals into the electrical input facility of an approved sound level meter that conforms to the class 1 performance requirements of IEC 61672-1.[12] The

11. IEC 61672-1: 2002 entitled "Electroacoustics — Sound level meters — Part I: Specifications". This IEC publication may be obtained from the Bureau central de la Commission électrotechnique internationale, 3 rue de Varembé, Geneva, Switzerland.
12. IEC 61672-1: 2002 entitled "Electroacoustics — Sound level meters — Part I: Specifications". This IEC publication may be obtained from the Bureau central de la Commission électrotechnique internationale, 3 rue de Varembé, Geneva, Switzerland.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

acoustical sensitivity of the sound level meter shall be established from playback of the associated recording of the signal from the sound calibrator and knowledge of the sound pressure level produced in the coupler of the sound calibrator under the environmental conditions prevailing at the time of the recording of the sound from the helicopter.

4.3.6 A windscreen should be employed with the microphone during all measurements of helicopter sound levels. Its characteristics should be such that when it is used, the complete system including the windscreen will meet the specifications in 4.3.3.

…

5. ADJUSTMENT TO TEST RESULTS

…

5.2 Corrections and adjustments

…

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

$$\Delta_1 = 12.5 \log (H/150\ \underline{m})$$

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:

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

where Δ_2 is the quantity in decibels that must be algebraically added to the measured ~~SEL~~ L_{AE} 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 is the reference airspeed as prescribed under Part II, Chapter 11, 11.5.2, and V_{AR} is the adjusted reference airspeed as prescribed in 2.4.2 of this appendix.

6. REPORTING OF DATA TO THE CERTIFICATING AUTHORITY AND VALIDITY OF RESULTS

6.3 Validity of results

6.3.1 The measuring point shall be overflown at least six times. The test results shall produce an average ~~SEL~~ L_{AE} 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 for the reference procedure.

6.3.2 The sample shall be large enough to establish statistically a 90 per cent confidence limit not exceeding ±1.5 dB(A). No test results shall be omitted from the averaging process unless approved by the certificating authority.

Note.— Methods for calculating the 90 per cent confidence interval are given 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.*

…

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

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

…

5. ADJUSTMENT TO TEST RESULTS

…

5.2 Corrections and adjustments

…

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

$$L_{ASmaxR} = L_{ASmax} + \Delta_1 + \Delta_2 + \Delta_3 + \Delta_4$$

where

Δ_1 is the adjustment for sound propagation path lengths;
Δ_2 is the adjustment for helical tip Mach number;
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.

….

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

$$\Delta_3 = k_3 \log (P_{\theta R}/P)$$

where $P_{\theta R}$ and P are the test and reference engine powers respectively obtained from the manifold pressure/torque gauges and engine rpm. The value of 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 = 17 may be used. The reference power $P_{\theta R}$ shall be that obtained at the reference height temperature and pressure assuming temperature and pressure lapse rates with height defined by the ICAO Standard Atmosphere.

…

ATTACHMENTS TO ANNEX 16, VOLUME I

ATTACHMENT A. EQUATIONS FOR THE CALCULATION OF MAXIMUM PERMITTED NOISE LEVELS AS A FUNCTION OF TAKE-OFF MASS

…

10. CONDITIONS DESCRIBED IN CHAPTER 11, 11.4.1

M = Maximum take-off mass in 1 000 kg	0	0.788	3.175
Noise level in dB(A) ~~SEL~~	82	83.03 + 9.97 log M	

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

11. CONDITIONS DESCRIBED IN CHAPTER 11, 11.4.2

M = Maximum take-off mass in 1 000 kg	0	1.417	3.175
Noise level in dB(A) ~~SEL~~	82	80.49 + 9.97 log M	

…

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

…

— — — — — — — —

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

7.2. Appendix 2 — ICAO Annex 16 Volume II amendments

7.2.1. Summary of presentations, discussions, conclusions, recommendations and proposed general changes to ICAO Annex 16 Volume II and ETM Volume II (extract from the CAEP/11 Report (ICAO Doc 10126) — Agenda Item 3 'Aircraft engine emissions')

Agenda Item 3: Aircraft engine emissions

3.1 **REPORT OF WG3**

3.1.1 The co-Rapporteurs of WG3 provided an overview of the work carried out by WG3 during the CAEP/11 cycle. The majority of the work items were dealt with by three Task Groups (Particulate Matter (PMTG); Certification (CTG); and Technology and Goals (TGTG)). The work on the non-volatile Particulate Matter (nvPM) mass and number SARPs, and the associated Annex 16, Volume II and ETM, Volume II amendments, were provided in a separate report under this agenda item.

3.1.2 The meeting thanked WG3 for its dedication, efforts and high quality work during this CAEP cycle.

3.2 **PARTICULATE MATTER STANDARD DEVELOPMENT**

3.2.1 Prior to the presentation of the work of WG3 and MDG on the nvPM stringency assessment, a Member presented information that outlined a proposal to shift the nvPM mass regulatory limit line for in-production engines to accommodate the Russian engine PS-90A, which is planned to be in-production after 2023. The Member commented that, due to scheduling issues, the nvPM
certification-like measurements for these engines were conducted after the final CAEP/11 WG3 meeting and therefore, the data were submitted to the CAEP/11 meeting for consideration during the nvPM
Standard-setting process.

3.2.2 The meeting noted the nvPM mass metric value of the PS-90A engine, relative to the WG3 proposed in-production regulatory limit, and agreed to shift the proposed nvPM mass regulatory limit for in-production engines to accommodate the Russian engine PS-90A.

3.2.3 The WG3 co-Rapporteurs reported on the completion of the CAEP/11 tasks pertaining to nvPM emissions, including on the proposed Landing and Take-Off (LTO)-based nvPM mass and number SARPs and associated guidance material.

3.2.4 The WG3 co-Rapporteurs noted that additional work is required to finalize ambient conditions corrections during the CAEP/12 cycle. Additional new data from combustor rig tests and multiple engine tests could be used to validate and improve the cruise nvPM methodology. The WG3 co-Rapporteurs highlighted that more work would also be needed to address nvPM losses in the measurement system and proposed to include the above mentioned work items in the CAEP/12 work programme.

3.2.5 The WG3 co-Rapporteurs proposed to end the Smoke Number (SN) Standard applicability for engines of rated thrust >26.7 kN from 1 January 2023, given that the agreed CAEP/10 limit line will give the visibility constraint provided by the SN Standard.

3.2.6 The MDG co-Rapporteurs provided an overview of the work on the nvPM stringency analysis carried out under the CAEP/11 work programme including caveats, limitations and the

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

context of the information; summaries of key tools, methods, data and assumptions; and environmental costs and cost-effectiveness results.

3.2.7 The meeting accepted the results presented and acknowledged the corresponding caveats related to modelling, business jet market uncertainties and nvPM measurement uncertainties.

3.2.8 The WG3 co-Rapporteurs provided material to support the public rulemaking processes of a number of ICAO Member States and to assist in the development of States' nvPM Regulatory Impact Assessments (RIAs) for the implementation of the proposed CAEP/11 nvPM LTO mass and number emissions SARPs. Additionally, since WG3 had recommended ending the applicability of the SN Standard for engines of rated thrust >26.7 kN on 1 January 2023, the material provided the background technical information that was used to develop this recommendation.

3.2.9 A Member acknowledged the importance of supporting the public rulemaking processes of ICAO Member States and assisting the development of States' nvPM RIAs for implementation of the proposed CAEP/11 nvPM LTO mass and number emissions Standard. The meeting agreed that the RIA would be updated based on the CAEP/11 decisions and included in Appendix C to the report on this agenda item.

3.2.10 Several Members and Observers supported setting the new aircraft engine LTO-based nvPM mass and number SARPs for turbofan and turbojet engines >26.7 kN, but also acknowledged specific technology issues associated with nvPM mass and number emissions control, and that different manufacturers are at different stages of the development cycle of potential technological solutions for in-production and new type engine designs. The Members and an Observer supported only stringency options 1-3 for consideration in setting the new technology nvPM SARPs.

3.2.11 Referring to the statements made by several Members and Observers, a Member asked about additional information on the rationale for the applicability date proposals and which stringency options these Members and Observers would consider appropriate. The Members and Observers clarified that the decision should be data-driven and from this standpoint, the new Standards should be sufficiently challenging, but not extreme for the stakeholders.

3.2.12 The meeting acknowledged the specific technology issues associated with nvPM mass and number emissions control, and noted that different manufacturers have in-production engines which are at very different positions relative to the new technology stringency options. The meeting further recognized that different manufacturers are at different stages of the development cycle of potential technological solutions for new technology designs.

3.2.13 A Member supported the work on the nvPM mass and number Standards, expressing the view that stringency options (SOs) 6, 9, 10-12 should not be considered for a new type Standard. The Member also shared concerns that scaling challenges for small engines require consideration of their particular issues in the selection of the stringencies, to ensure technical feasibility. The Member proposed that selecting a stringency level for the new type nvPM mass and number Standard should take into account interdependencies, and should be technologically feasible, economically reasonable and environmentally beneficial across a full range of engine rated thrusts. The meeting acknowledged the concerns raised by the Member regarding scaling challenges for small engines.

3.2.14 A Member suggested that for new type engines the limit lines should be selected in accordance with the CAEP Terms of Reference based on the results of the analysis. The Member supported the anti-backsliding in-production limit lines for nvPM mass and number with an applicability date of 1 January 2023. The Member noted that the preferable stringencies for mass would be 3 and 4, and the number stringencies would be 1 and 2. The Member supported ending the

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

applicability of the SN SARPs for engines with rated thrust > 26.7 kN to reflect the new in-production nvPM emissions Standard.

3.2.15 An Observer commented that the stringency options 4 and beyond were not cost effective and were highly likely to result in additional costs of USD 5 to 10 billion to the industry.

3.2.16 An Observer supported the adoption of LTO-based nvPM mass and number emissions SARPs for in-production and new type aircraft engines. The Observer supported the proposed limit lines for nvPM mass and number for in-production engines, with an applicability date of 1 January 2023, and supported ending the applicability of the existing SN SARPs from 1 January 2023.

3.2.17 A Member and an Observer underlined the proposed new nvPM emissions SARPs should not be used as a basis to restrict the growth of civil aviation, such as imposing operating restrictions or levying emission charges. The Observer also noted that the most challenging stringency options, 10 to 12 for the new technology aircraft, do not meet the technological feasibility requirement.

3.2.18 Another Observer objected and clarified that although the observer agrees that in principle the objective of developing SARPs is not to impose operation restrictions or levy charges, the observer's view is that both charges and operation restrictions may be necessary to address constraints from airports in terms of their ability to continue operating and meeting the required demand of air transport, in accordance with policies established by ICAO Doc 9082, particularly regarding Section II, paragraph 9.

3.2.19 Two Observers shared their views on the nvPM mass and number stringencies, underlining that for the SOs 10 to 12 analysis results, market forces overwhelm the technology responses, thus giving unreliable results. The Observers expressed concerns on technological feasibility of NI3 and that as a result, selection of a limit line beyond SO3 would represent high risks for manufacturers.

3.2.20 Following the comments from the two Observers, one Member asked why other stringency options were considered as not technologically feasible or economically reasonable, given that they had been agreed by WG3 to be part of the stringency analysis. The Observers clarified that due to variability and uncertainty in the analysis, initially they had requested to exclude several stringency options during the WG3 process, while commenting that the manufacturers require time to reach the higher stringency options from a technical perspective. The WG3 co-Rapporteurs clarified that additional uncertainty had been added to the analysis lines to preserve variability. The Observers noted that the cost-effectiveness results should not be reviewed in isolation – cumulative costs and trade-offs with other emissions and fuel burn/CO_2 must also be considered and this would be the challenge for the industry.

3.2.21 An Observer acknowledged and appreciated the work completed by all stakeholders in support of a CAEP/11 decision, and supported the development of ICAO's nvPM Standard and the "anti-backsliding" limit line for in-production aircraft as proposed by WG3 with an applicability date of
1 January 2023. The Observer proposed that SO12 should be selected for the CAEP/11 new type nvPM Standard with an applicability date of 1 January 2023.

Discussion and Conclusions

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

3.2.22 Several Members and Observers highlighted their support of the approval of the LTO-based nvPM mass and number SARPs and associated guidance material.

3.2.23 Several Members and an Observer noted that, according to the previous experience with the NOx Standard, industry requires a reasonable time in order to meet the new requirements. A Member and an Observer acknowledged that even minimal SOs would have a positive effect, while giving industry time for adaptation. One Member supported SOs 1 to 9, proposing that it would initially be reasonable to accept a lower option with a possibility to switch to a higher option at a later date.

3.2.24 The meeting agreed on 1 January 2023 as the end date for the applicability of the SN SARPs for engines of a rated thrust > 26.7 kN, as proposed by WG3. The meeting also agreed to the WG3 proposal for an anti-backsliding in-production nvPM emissions Standard, which included recently submitted measurement data.

3.2.25 An Observer noted that the process of inclusion of the late data from the Russian Federation and subsequent revision of the in-production limit line endorsed by the CAEP 2017 Steering Group meeting, was inconsistent with the procedure used to analyse all other submitted nvPM data. It was clarified that following the data submission to CAEP, the CAEP Members were consulted, WG3 performed an analysis and agreed on a revision to the proposed in-production limit line. The purpose was to preserve consistency and transparency in CAEP, and the meeting noted that while this practice was unusual, the process was adapted due to time constraints.

3.2.26 An Observer urged CAEP to exercise caution in the evaluation of stringency options for new type engines and expressed concerns related to potential trade-offs with fuel efficiency and NOx emissions, as well as the importance of not undermining the adaptability and flexibility in fleet choices. Several Observers also expressed concerns on trade-offs risks with NOx, CO and HC as well as CO_2, when setting the nvPM mass and number Standards, and noted the lack of ambient condition corrections and the differences in nvPM number measurement equipment when setting the nvPM number Standards.

3.2.27 The meeting agreed to exercise caution in the selection of the stringency option for the new type nvPM SARPs, and further agreed that new type nvPM SARPs should be based on a stringency level which takes into account interdependencies, is technologically feasible, economically reasonable and environmentally beneficial across a full range of engine rated thrusts. The meeting also agreed to consider the risk of trade-offs with NOx, CO and HC, as well as CO_2, the lack of ambient condition corrections and the differences in nvPM number measurement equipment, in evaluating stringency options as part of the nvPM mass and number Standard-setting process.

3.2.28 Following a discussion on the possible use of the new nvPM SARPs for operating restrictions, an Observer proposed that CAEP reiterate the principle that ICAO’s environmental Standards are not intended to introduce or serve as the basis for operating restrictions or levies, but have been adopted for certification purposes only. One Observer reiterated their objection as described in section 3.2.18. The Observer also urged consistency between ICAO policies and highlighted that previous recommendations from CAEP/10 on the intention of the CO_2 Standard was not based on a local air quality emissions Standard. The Observer replied that the wording was not intended to contradict or question the policies in Doc 9082 and explained that the recognition of the principle would ensure continued support for the adoption of ICAO certification Standards. The meeting agreed that the operating restrictions and charges would be discussed further at a later point during the meeting.

3.2.29 The meeting acknowledged the large body of work carried out by WG3 in the development of nvPM SARPs, and noted the technical contributions of SAE E-31 in this work.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

3.3 AGREEMENT ON NEW nvPM MASS AND NUMBER SARPs

3.3.1 The Members and Observers shared their views on the acceptable stringency options (SOs) related to the new type nvPM mass and number SARPs.

3.3.2 Several Members and Observers stated that in their papers they had suggested the exclusion of SOs from consideration and not necessarily the preferred SOs. The meeting then discussed and agreed to eliminate SOs 10 to 12 from consideration. A Member commented that only SOs 2 to 9 should be considered.

3.3.3 A Member stated a preference for some alleviation for small engines with less than 50 kN thrust and that SO2 would represent an appropriate level.

3.3.4 Several Members considered as the optimum nvPM number stringency 2 and nvPM mass stringencies 2 to 3 that would yield a result between SO3 and SO5, highlighting that should a lower stringency option be chosen, then an earlier applicability of 2023 would be appropriate. This would give a result close to SO5, with costs only slightly higher than those of SO3. Should these options be chosen, then the Members supported an earlier review of the new type Standard in 2025. Another Member suggested that if lower SOs were selected, then CAEP should commit to reviewing the nvPM SARPs no later than 2028 for substantially higher mass and number SOs.

3.3.5 Several Members commented that engines with thrust below 150kN should be granted some alleviation due to scaling constraints that affect the implementation of the low emission technologies for these sizes of engines.

3.3.6 Several Members asked to remove from consideration SOs associated with the number stringency 3 (i.e. SO6 and SO9). One Member supported SO8, which would remain the most stringent of the options left, noting that some alleviation in stringency may be possible for engines with rated thrust less than 150 kN. Another Member commented that, in his opinion, SO8 and SO9 did not fulfil the CAEP Terms of Reference.

3.3.7 Several Members shared concerns on whether an earlier applicability date would be feasible (i.e. 2023 instead of 2025), since sufficient time would still be required for inclusion of the new nvPM SARPs into the legislative frameworks of ICAO Member States.

3.3.8 A Member further commented that the nvPM limit line should be set at an SO beyond SO3, and preferably SO5. Another Member added their preference to consider only SOs 1 to 5 in the standard-setting process.

3.3.9 One Member proposed SO3, with an applicability date of 2025.

Discussion and Conclusions

3.3.10 The meeting discussed the available options for a new type nvPM mass and number Standard and following consideration of all the various viewpoints on SOs and applicability dates, the meeting agreed on new type nvPM mass and number SARPs. This included limit lines for nvPM mass

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

and number[13], that would be applied to new engine types from 1 January 2023, providing some alleviation for engines with rated thrusts below 150 kN. As agreed earlier in the meeting, these new type SARPs would be accompanied by an in-production Standard for nvPM mass and number, with an applicability date of 1 January 2023. The meeting agreed to the amendments to Annex 16, Volume II as presented in Appendix A to this agenda item. The meeting also agreed to amendments to the ETM, Volume II, as contained in the report from the working group, in order to include elements that would facilitate the implementation of the new nvPM mass and number SARPs. The recommendations on the new nvPM mass and number SARPs for Annex 16, Volume II and associated guidance in the ETM, Volume II, along with the collation of all other Annex 16, Volume II and ETM, Volume II amendments agreed at CAEP/11, are contained in section 3.5 of this report.

3.3.11 This agreement on a new nvPM mass and number Standard was accompanied with the agreement for an early review of the regulatory levels. The meeting agreed that this will involve the collation and analysis of the certified and certification-like nvPM mass and number emissions data that becomes available for all in-production engines during the period 2019 to 2022. The meeting also agreed to review the margins to the agreed CAEP/11 new type nvPM mass and number Standards and to assess possible technological advancements to reduce nvPM emissions. It was agreed that a recommendation will be provided from WG3 to CAEP/12 to inform the need to update nvPM engine emissions Standards. If agreed at CAEP/12, a Standard-setting process will be performed during CAEP/13 to consider revised nvPM mass and number SARPs.

3.3.12 While agreeing to the new nvPM mass and number SARPs, two Members expressed reservations regarding the early applicability date (of 2023) as this would require significant efforts to update the States' regulatory frameworks in a timely manner.

3.3.13 A Member, reflecting the sentiment of the meeting, congratulated CAEP Members on successfully agreeing these new nvPM mass and number SARPs. In commending these new SARPs and ground breaking achievement, the Member highlighted that this now meant that the final component of aircraft environmental certification had been agreed, closing the full circle on noise, local air quality and CO_2 Standards for subsonic aeroplanes. This new Standard would lead to nvPM emissions reductions from international aviation in the coming years.

3.4 SUPERSONIC ENGINE EMISSIONS STANDARD

3.4.1 The co-Rapporteurs of WG3 presented an overview of the work on supersonic transport (SST) engine emissions SARPs. As a result of this work, WG3 concluded that there was insufficient technical information currently available to recommend changes to Annex 16, Volume II, Chapter 3. In addition, there was also no consensus in WG3 to repeal the current applicability requirements. However, WG3 did conclude that the subsonic LTO cycle as currently defined in Chapters 2 and 4 was considered a reasonable starting point for future work. WG3 recognized that additional SST engine emissions data would be useful to guide potential updates to the SARPs in the near-term and WG3 proposed amendments to the ETM, Volume II in order to highlight that engine manufacturers may voluntarily collect a broader set of emissions data spanning Chapters 2, 3, and 4, which could be made available to ICAO/CAEP WG3 to inform potential updates to SST engine emissions SARPs. It was highlighted that data on gaseous, nvPM, and smoke emissions, for SST engines without afterburners, would only be collected.

3.4.2 Several Members thanked WG3 and supported the important progress made towards the update of the SST emission SARPs. A Member and an Observer asked which data would be required to further progress the work, and when this data was expected to be received. The WG3 co-Rapporteurs clarified that WG3 requires manufacturers' data from mature SST engine projects, based on real measurements, as early as possible. One Member expressed support for the report of WG3 and

[13] For information only, in the context of the proposed SOs, the agreed limit lines are equivalent to nvPM mass stringency 2.8 and nvPM number stringency 2 for engines with rated thrust greater than 150kN.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

shared the view that further assessment on data correction is needed to develop SST emission SARPs, taking into account technology advancements.

3.4.3 Several Members and an Observer shared their views on SST emission Standards supporting the approach proposed by WG3, noting their view on the need for a CO_2 Standard for new SST aeroplane types, and proposed that this item be included in the work programme for the next CAEP cycle. The Members and the Observer proposed approaching the SST Standards under consideration as a package, and to add a Note to Annex 16, Volume II, Chapter 3, to clarify that the chapter is considered outdated.

3.4.4 An Observer supported the views expressed by the Members and the Observer. Another Observer inquired whether there was an interim process to start gathering data, given that the proposal on the CO_2 Standard for new SST aeroplane types would require sufficient time. The Member replied that more time is needed, as well as the manufacturer data, and that there was no approved schedule for the work. Another Observer noted that due to lack of data, it was premature to make a decision on a CO_2 Standard for new SST aeroplane types.

3.4.5 Several Members objected to considering SST SARPs as a package, as such an approach would not facilitate the process of Standard development.

3.4.6 A Member expressed a concern regarding the proposal to include an additional Note in Annex 16, Volume II, Chapter 3, due to inconsistency with the State's legislation. Several Members supported this view, sharing their concerns that an additional Note would neither provide clarity to the aviation authorities, nor would it have any regulatory effect.

3.4.7 The meeting recognized that new SST aeroplane engine projects were not yet sufficiently mature to yield the necessary data to inform amendments of Annex 16, Volume II, Chapter 3 at CAEP/11. However, the meeting noted the need to continue to work on updating the SST engine emissions requirements in Annex 16, Volume II by CAEP/12.

3.4.8 A Member shared views on supersonic engine emissions and emphasized the need for technical data from sufficiently mature civil supersonic engine programmes in order to update supersonic engine emissions SARPs, with the highest confidence. The Member also noted that the work to create the existing Annex 16, Volume II, Chapter 3, specifically in regard to afterburning engine applicability, should not be discarded as WG3 endeavours to revise the Standards for the anticipated non-afterburning supersonic engines. Another Member supported these views on supersonic engine emissions.

3.4.9 Responding to a question regarding the differences between the noise and emissions SARPs development, a Member clarified that, differently for engine emissions certification, there is not currently a noise certification Standard applicable to new supersonic aircraft in his State.

3.4.10 An Observer shared views on the introduction of supersonic aircraft into the global fleet, and proposed that this must not lead to a net increase in total noise, air pollution, or CO_2 emissions from aviation, compared to a baseline of subsonic aircraft only. The Observer proposed that CAEP should develop new SARPs for supersonic aircraft and engines in a deliberate, data-driven manner, and that until sufficient data was available, the latest subsonic Standards should apply to new supersonic designs.

3.4.11 One Member noted that the concept of "no net increase" in environmental parameters was never used in CAEP processes, and asked how this would be applied in other CAEP Standard-setting processes. The Observer acknowledged that, even if supersonics were to comply with current subsonic aircraft Standards, there remained a possibility of a net increase of environmental parameters

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

at a global level. Over and above the Standard-setting process the Observer argued that ICAO's environmental activities should aim to avoid the possibility of such a net increase.

3.4.12 One Observer noted that given the fundamental technical differences between supersonics and subsonic aeroplanes, applying the same Standards for subsonic and supersonic engines would not be in line with the CAEP Terms of Reference. The Observer supported further work to assess the noise and emission impact of supersonics, but cautioned that this assessment could differ from traditional CAEP cost-effectiveness analyses, due to the specificities of the supersonic aircraft market.

3.4.13 The CAEP Secretary noted that the traditional CAEP Standard-setting processes were typically supported by measured data, gathered from real operating fleets, and questioned whether this approach should be adjusted for future SARP-development processes to consider other types of data, keeping in mind the new aircraft designs under development, such as hybrid and electric aircraft. The Observer noted that CAEP should consider possible ways to develop Standards for these new designs in a manner that is not selective with respect to aircraft type or pollutants, so that the same principles in terms of technological feasibility are applied uniformly.

Discussion and conclusions

3.4.14 The meeting agreed to retain and revise Annex 16, Volume II, Chapter 3 as part of the CAEP/12 work programme. The meeting also noted the concerns raised on the consideration of the existing Annex 16, Volume II, Chapter 3, with respect to afterburning engine applicability.

3.4.15 In order to highlight that engine manufacturers may voluntarily collect a broader set of emissions data spanning Chapters 2, 3, and 4, which could be made available to ICAO/CAEP WG3 to inform potential updates to SST engine emissions SARPs, the meeting agreed to amend the ETM, Volume II to include the following text: *"Based on work in ICAO, it is recognized that additional supersonic engine emissions data would be helpful to inform potential updates to the supersonic engine emissions Standards in Annex 16, Volume II, Part III, Chapter 3. It is highlighted that engine manufacturers may voluntarily measure and report engine emissions according to the Chapters 2 and 4 subsonic LTO cycle. The engine manufacturer is encouraged to offer the broader set of emissions data spanning Chapters 2, 3 and 4 to support discussions in ICAO/CAEP for the purpose of updating the supersonic engine emissions Standards in Annex 16, Volume II, Part III, Chapter 3."*

3.4.16 The meeting noted an Observer's position that the introduction of supersonic aircraft into the global fleet must not lead to a net increase in total noise, air pollution, or CO_2 emissions from aviation, compared to a baseline for subsonic aircraft only.

3.4.17 The meeting agreed that the development of SST environmental Standards should be pursued in parallel by CAEP, but did not agree that SST environmental Standards should be considered as a package.

3.4.18 Responding to a question, the WG3 co-Rapporteurs clarified that the WG3 proposal for further work on supersonic engine Standards is generic, as it is unclear what data would be available. The meeting agreed to discuss this further under Agenda Item 12 on future work.

3.4.19 Regarding a question for clarification that the CAEP Terms of Reference did not contain any specific reference to a type of aircraft, the CAEP Secretary replied that at present, although there were no mature supersonic projects with full data available, as new aircraft types with novel technologies on-board came to fruition, work on an appropriate and applicable process for Standard-setting could be developed for them, highlighting that CAEP may need to be flexible in the future to deal with the high pace of technology development.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

3.4.20 Several Members and an Observer noted that SST operating modes were expected to be significantly different from their subsonic counterparts. The meeting considered whether it would be reasonable to apply current subsonic SARPs to new SST engine types.

3.4.21 One Member raised a proposal for future work on CO_2-related subsonic aeroplane SARPs and the meeting agreed that this would be considered under Agenda Item 12 on future work.

3.5 PROPOSED AMENDMENTS TO ANNEX 16, VOLUME II AND ETM (DOC 9501), VOLUME II

3.5.1 The WG3 co-Rapporteurs presented the report on the proposed amendment to Annex 16, Volume II and the proposed amendment to ICAO Doc 9501, *Environmental Technical Manual*, Volume II – *Procedures for Emissions Certification of Aircraft Engines*. These changes include, amongst others, applicability date language for new engines, flow rate specifications and conditions, and exemptions for production engines.

3.5.2 The meeting thanked WG3 for the hard work in keeping the ICAO SARPs on engine emissions up to date and approved the amendments as contained in Appendix A to this agenda item.

3.5.3 The meeting also approved the amendments to the ETM, Volume II as contained in the reports of the Working Group.

3.5.4 The meeting developed the following recommendation to reflect the agreed amendments for Annex 16, Volume II in sections 3.3.10 (the new nvPM mass and number emissions SARPs) and 3.5.2 (other amendments) of the meeting report:

RSPP **Recommendation 3/1 — 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.

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

Recommendation 3/2 — Use of the nvPM Standard

Recognize that the nvPM emissions certification Standards are a technical comparison of aviation technologies designed for use in nvPM emissions certification processes, and are not designed to serve as a basis for operating restrictions or emissions levies.

3.5.5 The meeting also developed the following recommendation to reflect the agreed amendments for the ETM, Volume II in sections 3.3.10 (the new nvPM mass and number emissions SARPs), 3.4.15 (supersonics) and 3.5.3 (other amendments):

Recommendation 3/3 — Amendments to the *Environmental Technical Manual*, Volume II — *Procedures for the Emissions Certification of Aircraft Engines*

That the Environmental Technical Manual, Volume II be amended and published, and that revised versions approved by subsequent CAEP Steering Groups be made available, free of charge, on the CAEP website.

— — — — — — — —

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

Proposed amendments to Annex 16 Volume II (extract from CAEP/11 Report (ICAO Doc 10126) – Agenda Item 3 – Appendix A)

APPENDIX A

PROPOSED AMENDMENTS TO ANNEX 16, VOLUME II

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

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

TEXT OF PROPOSED AMENDMENTS TO THE

INTERNATIONAL STANDARDS AND RECOMMENDED PRACTICES

ENVIRONMENTAL PROTECTION

ANNEX 16
TO THE CONVENTION ON INTERNATIONAL CIVIL AVIATION

VOLUME II
AIRCRAFT ENGINE EMISSIONS

...

PART I. DEFINITIONS AND SYMBOLS

CHAPTER 1. DEFINITIONS

...

Smoke Number. The dimensionless term quantifying smoke emissions (*see* 3 of Appendix 2).

State of Design. The State having jurisdiction over the organization responsible for the type design.

Take-off phase. The operating phase defined by the time during which the engine is operated at the rated thrust.

Taxi/ground idle. The operating phases involving taxi and idle between the initial starting of the ***propulsion*** engine(s) and the initiation of the take-off roll and between the time of runway turn-off and final shutdown of all propulsion engine(s).

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 1.— In some Contracting States a document equivalent to a Type Certificate may be issued for an engine or propeller type.

Note 2.— In some Contracting States the Type Certificate may also certify that the design meets the appropriate aircraft engine emissions requirements of that State.

Unburned hydrocarbons. The ***total*** of hydrocarbon compounds of all classes and molecular weights contained in a gas sample, calculated as if they were in the form of methane.

…

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

PART III. EMISSIONS CERTIFICATION

CHAPTER 1. ADMINISTRATION

…

1.3 The document attesting emissions certification for each individual engine shall include at least the following information which is applicable to the engine type:

a) name of certificating authority;

b) manufacturers type and model designation;

c) statement of any additional modifications incorporated for the purpose of compliance with the applicable emissions certification requirements;

d) rated thrust;

e) reference pressure ratio;

f) a statement indicating compliance with Smoke Number requirements;

g) a statement indicating compliance with gaseous pollutant requirements~~.~~ ;

h) a statement indicating compliance with particulate matter requirements.

1.4 Contracting States shall recognize as valid emissions certification granted by the certificating authority of another Contracting State provided that the requirements under which such certification was granted are not less stringent than the provisions of Volume II of this Annex.

…

1.5 Contracting States shall recognize as valid engine exemptions ~~for an engine production cut-off requirement~~ granted by ~~a certificating~~ the competent authority of another Contracting State which is responsible for the production organisation of the engine provided that ~~the exemptions are granted in accordance with the process and criteria defined in the *Environmental Technical Manual* (Doc 9501),Volume II — *Procedures for the Emissions Certification of Aircraft Engines*~~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 II — Procedures for the Emissions Certification of Aircraft Engines.

1.6 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 when the application for a Type Certificate for engines of a type or model 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.

1.7 An application for a Type Certificate for engines of a type or model shall be effective for the period specified in the designation of the airworthiness regulations appropriate to the engine of a type or model, except in special cases where the certificating authority accepts an extension of this period. When this period of effectivity is exceeded and an extension is approved, the date to be used

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

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 the type design, or the date of issue of approval under an equivalent procedure prescribed by the State of Design, less the period of effectivity.

____

CHAPTER 2. TURBOJET AND TURBOFAN ENGINES INTENDED FOR PROPULSION ONLY AT SUBSONIC SPEEDS

2.1 General

2.1.1 Applicability

2.1.1.1 The provisions of this chapter shall apply to all turbojet and turbofan engines, as further specified in 2.2 and 2.3, intended for propulsion only at subsonic speeds, except when the certificating ~~authorities~~ authority or the competent authority responsible for the production organisation of the engines ~~make~~ grants exemptions for:

a) specific engine types and derivative versions of such engines for which the type certificate of the first basic type was issued or other equivalent prescribed procedure was carried out before 1 January 1965; ~~and~~

b) a limited number of engines over a specific period of time beyond the dates of applicability specified in 2.2 and 2.3 for the manufacture of the individual engine.

2.1.1.2 In such cases, an exemption document shall be issued by the certificating authority or the competent authority responsible for the production organisation of the engine, the identification plates on the engines shall be marked “EXEMPT ~~NEW” or “EXEMPT SPARE~~” and the grant of exemption shall be noted in the permanent engine record. The certificating authority or the competent authority responsible for the production organisation of the engines shall take into account the numbers of exempted engines that will be produced and their impact on the environment. Exemptions shall be reported by engine serial number and made available via an official public register.

Recommendation.- *When such an exemption is granted, the certificating authority or the competent authorities responsible for the production organisation of the engines should consider imposing a time limit on the production of such engines.*

~~2.1.1.3 The provisions of this chapter shall also apply to engines designed for applications that otherwise would have been fulfilled by turbojet and turbofan engines.~~

Note.— ~~*In considering exemptions, certificating authorities should take into account the probable numbers of such engines that will be produced and their impact on the environment. When such an exemption is granted, the certificating authority should consider imposing a time limit on the production of such engines for installation on new aircraft.*~~ *Further guidance on issuing exemptions is provided in the* Environmental Technical Manual *(Doc 9501), Volume II —* Procedures for the Emissions Certification of Aircraft Engines*.*

2.1.1.3 The provisions of this chapter shall also apply to engines designed for applications that otherwise would have been fulfilled by turbojet and turbofan engines and which are designed as an integrated propulsive power plant and certified with a rated thrust.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

Note.— Guidance material is provided in the Environmental Technical Manual (Doc 9501), Volume II — Procedures for the Emissions Certification of Aircraft Engines

...

2.1.4 Reference conditions

2.1.4.1 *Atmospheric conditions*

The reference atmospheric conditions shall be ISA at sea level except that the reference ~~absolute~~ humidity shall be 0.00634 kg water/kg dry air.

2.1.4.2 *Thrust settings*

…

2.2 Smoke

2.2.1 Applicability

The provisions of 2.2.2 shall apply:

a) to engines whose date of manufacture is on or after 1 January 1983 and before 1 January 2023; and

b) to engines with a maximum rated thrust of less than or equal to 26.7kN whose date of manufacture is on or after 1 January 2023.

2.2.2 Regulatory Smoke Number

The Smoke Number at any of the four LTO operating mode thrust settings when measured and computed in accordance with the procedures of Appendix 2, or equivalent procedures as agreed by the certificating authority, and converted to a characteristic level by the procedures of Appendix 6 shall not exceed the level determined from the following formula:

Regulatory Smoke Number = $83.6\ (F_{oo})^{-0.274}$
or a value of 50, whichever is lower

Note.— Guidance material on the definition and the use of equivalent procedures is provided in the Environmental Technical Manual *(Doc 9501), Volume II —* Procedures for the Emissions Certification of Aircraft Engines.

2.3 Gaseous emissions

…

2.3.2 Regulatory levels

…

e) for engines of a type or model for which the date of manufacture of the first individual production model was on or after 1 January 2014 and for which an application for a Type Certificate was submitted before 1 January 2023:

1) for engines with a pressure ratio of 30 or less:

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

i) for engines with a maximum rated thrust of more than 89.0 kN:

$D_p / F_{oo} = 7.88 + 1.4080\pi_{oo}$

ii) for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$D_p / F_{oo} = 40.052 + 1.5681\pi_{oo} - 0.3615F_{oo} - 0.0018\pi_{oo}F_{oo}$

2) for engines with a pressure ratio of more than 30 but less than 104.7:

i) for engines with a maximum rated thrust of more than 89.0 kN:

$D_p / F_{oo} = -9.88 + 2.0\pi_{oo}$

ii) for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$D_p / F_{oo} = 41.9435 + 1.505\pi_{oo} - 0.5823F_{oo} + 0.005562\pi_{oo} F_{oo}$

3) for engines with a pressure ratio of 104.7 or more:

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

f) for engines of a type or model for which an application for a Type Certificate was submitted on or after 1 January 2023:

1) for engines with a pressure ratio of 30 or less:

i) for engines with a maximum rated thrust of more than 89.0 kN:

$D_p / F_{oo} = 7.88 + 1.4080\pi_{oo}$

ii) for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$D_p / F_{oo} = 40.052 + 1.5681\pi_{oo} - 0.3615F_{oo} - 0.0018\pi_{oo}F_{oo}$

2) for engines with a pressure ratio of more than 30 but less than 104.7:

i) for engines with a maximum rated thrust of more than 89.0 kN:

$D_p / F_{oo} = -9.88 + 2.0\pi_{oo}$

ii) for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$D_p / F_{oo} = 41.9435 + 1.505\pi_{oo} - 0.5823F_{oo} + 0.005562\pi_{oo} F_{oo}$

3) for engines with a pressure ratio of 104.7 or more:

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

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

Note.— Guidance material on the definition and the use of equivalent procedures is provided in the Environmental Technical Manual *(Doc 9501), Volume II* — Procedures for the Emissions Certification of Aircraft Engines.

2.4 Information required

…

CHAPTER 4. PARTICULATE MATTER EMISSIONS

4.1 General

4.1.1 Applicability

4.1.1.1 The provisions of this chapter shall apply to all aircraft engines, as further specified in 4.2, intended for propulsion only at subsonic speeds~~, for which an application for type certification is submitted to the certificating authority~~.

4.1.1.2 Specific provisions for the relevant engine categories shall apply as detailed in section 4.2 except when the certificating authority or the competent authority responsible for the production organisation of the engines grants exemptions for a limited number of engines over a specific period of time beyond the dates of applicability specified in 4.2 for the manufacture of the individual engine.

4.1.1.3 In such cases, an exemption document shall be issued by the certificating authority or the competent authority responsible for the production organisation of the engine, the identification plates on the engines shall be marked “EXEMPT” and the grant of exemption shall be noted in the permanent engine record. The certificating authority or the competent authority responsible for the production organisation of the engines shall take into account the number of exempted engines that will be produced and their impact on the environment. Exemptions shall be reported by engine serial number and made available via an official public register.

Recommendation.— *When such an exemption is granted, the certificating authority or the competent authorities responsible for the production organisation of the engines should consider imposing a time limit on the production of such engines.*

Note.— Further guidance on issuing exemptions is provided in the Environmental Technical Manual (Doc 9501), Volume II — Procedures for the Emissions Certification of Aircraft Engines.

4.1.2 Emissions involved

The purpose of this section is to control non-volatile particulate matter (nvPM) emissions.

4.1.3 Units of measurement

4.1.3.1 The concentration of nvPM mass ~~($nvPM_{mass}$)~~ shall be measured and reported in ~~µg~~micrograms/m^3.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

4.1.3.2 The nvPM mass emitted during the reference emissions landing and take-off (LTO) cycle, defined in 4.1.4.2 (LTO_{mass}), shall be measured and reported in milligrams.

4.1.3.3 The nvPM number emitted during the reference emissions landing and take-off (LTO) cycle, defined in 4.1.4.2 (LTO_{num}), shall be measured and reported in number of particles.

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~~ the reference emissions LTO cycle thrust settings and at thrusts producing maximum nvPM~~mass~~ mass concentration, maximum EI_{mass} and maximum EI_{num} as agreed by the certificating authority~~:~~.

For the calculation and reporting of nvPM emissions the reference emissions LTO cycle shall be represented by the following thrust setting and time in each following operating mode:

LTO operating mode	*Thrust setting Per cent F_{oo}*	*Time in operating mode Minutes*
Take-off	100 ~~per cent Foo~~	0.7
Climb	85 ~~per cent Foo~~	2.2
Approach	30 ~~per cent Foo~~	4.0
	7 ~~per cent Foo~~	26.0

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 in accordance with the procedures of Appendix 7.

4.1.5.4 The maximum nvPM~~mass~~ mass concentration shall be corrected for dilution and thermophoretic losses in the Collection Part of the sampling system in accordance with the procedures of Appendix 7. The~~and~~ EI_{mass} and EI_{num} shall be corrected for thermophoretic losses in the ~~collection part~~Collection Part of the sampling system and fuel composition in accordance with the procedures of Appendix 7.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

4.2 Non-Volatile Particulate Matter Emissions

4.2.1 Applicability

4.2.1.1 The provisions 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~~.

4.2.1.2 The provisions of this chapter shall also apply to engines designed for applications that otherwise would have been fulfilled by turbojet and turbofan engines and which are designed as an integrated propulsive power plant and certified with a rated thrust.

4.2.2 Regulatory levels

4.2.2.1 *Maximum nvPM mass concentration*

For an engine whose date of manufacture of the individual engine is on or after 1 January 2020, t~~T~~he maximum nvPM~~mass~~ mass concentration ~~[μg/m³]~~ 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 regulatory level determined from the following formula:

$$\text{Regulatory limit } \sout{\text{concentration}} \text{ of nvPM}_{\sout{\text{mass}}} \text{mass concentration} = 10^{(3 + 2.9 F_{oo}^{-0.274})}$$

Note.— Since there is a correlation between nvPM mass concentration and Smoke Number, the regulatory level in §4.2.2.1 was derived from the Smoke Number regulatory level. Further information is provided in the Environmental Technical Manual (Doc 9501), Volume II – Procedure for the Emissions Certification of Aircraft Engines.

4.2.2.2 *nvPM mass and nvPM number emitted during the reference LTO cycle*

The nvPM mass and nvPM number emission levels when measured 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 regulatory levels determined from the following formulas:

a) LTO_{mass}:

1) for engines of a type or model for which the date of manufacture of the individual engine was on or after 1 January 2023:

i) for engines with a maximum rated thrust of more than 200kN:

$LTO_{mass}/F_{oo} = 347.5$

ii) for engines with a maximum rated thrust of more than 26.7kN but not more than 200kN

$LTO_{mass}/F_{oo} = 4646.9 – 21.497F_{oo}$

2) for engines of a type or model for which an application for a type certificate was submitted on or after 1 January 2023:

i) for engines with a maximum rated thrust of more than 150kN:

$LTO_{mass}/F_{oo} = 214.0$

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

ii) for engines with a maximum rated thrust of more than 26.7kN but not more than 150kN

$LTO_{mass}/F_{oo} = 1251.1 – 6.914F_{oo}$

b) LTO_{num}:

1) for engines of a type or model for which the date of manufacture of the individual engine was on or after 1 January 2023:

i) for engines with a maximum rated thrust of more than 200kN:

$LTO_{number}/F_{oo} = 4.170 \times 10^{15}$

ii) for engines with a maximum rated thrust of more than 26.7kN but not more than 200kN

$LTO_{number}/F_{oo} = 2.669 \times 10^{16} – 1.126 \times 10^{14} Foo$

2) for engines of a type or model for which an application for a type certificate was submitted on or after 1 January 2023:

i) for engines with a maximum rated thrust of more than 150kN:

$LTO_{number}/F_{oo} = 2.780 \times 10^{15}$

ii) for engines with a maximum rated thrust of more than 26.7kN but not more than 150kN

$LTO_{number}/F_{oo} = 1.490 \times 10^{16} – 8.080 \times 10^{13} F_{oo}$

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/m³);~~

~~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~~a) maximum EI_{mass} (~~mg~~milligrams/kg of fuel); and

~~f~~b) maximum EI_{num} (particles/kg of fuel).

4.3 Information required

Note.— The information required is divided into ~~two~~ three groups: 1) general information to identify the engine characteristics, the fuel used and the method of data analysis; ~~and~~ 2) the data obtained from the engine test(s); and 3) derived information.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

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 thrust (kN);

c) reference pressure ratio;

d) fuel specification reference;

e) fuel hydrogen/carbon ratio;

f) the methods of data acquisition; and

~~g) the method of making corrections for thermophoretic losses in the collection part of the sampling system; and~~

~~h)~~g) the method of data analysis.

4.3.2 Test information

4.3.2.1 The following information shall be provided for each engine tested for certification purposes~~For each test the following information shall be reported~~:

a) fuel net heat of combustion (MJ/kg);

b) fuel hydrogen content (mass %);

c) fuel total aromatics content (volume %);

d) fuel naphthalenes content (volume %); and

e) fuel sulphur content (ppm by mass ~~%~~).

4.3.2.2 The following information as measured and computed in accordance with the procedures of Appendix 7, or any equivalent procedures as agreed by the certificating authority, shall be provided for each engine tested for certification purposes:

a) fuel flow (kg/s) at each thrust setting of the LTO cycle;

b) EI_{mass} (milligrams/kg of fuel) at each thrust setting of the LTO cycle;

c) EI_{num} (particles/kg of fuel) at each thrust setting of the LTO cycle;

4.3.3 Derived Information

4.3.3.1 The following derived information shall be provided for each engine tested for certification purposes:

a) emission rate, i.e. emission index × fuel flow, (milligrams/s) for nvPM mass;

b) emissions rate, i.e. emission index × fuel flow, (particles/s) for nvPM number;

c) total gross emission of nvPM mass measured over the LTO cycle (milligrams);

d) total gross emission of nvPM number measured over the LTO cycle (particles);

e) values of LTO_{mass} / F_{oo} (milligrams/kN);

f) values of LTO_{num} / F_{oo} (particles/kN); and

g) maximum nvPM mass concentration (micrograms/m^3)

4.3.3.2 The characteristic levels shall be provided for the maximum nvPM mass concentration, the LTO_{mass}/F_{oo} and the LTO_{num}/F_{oo} for each engine type for which emissions certification is sought.

PART IV. NON-VOLATILE PARTICULATE MATTER ASSESSMENT
FOR INVENTORY AND MODELLING PURPOSES

Note 1.— The purpose of this part 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~~Collection Part thermophoretic losses. The nvPM sampling and measurement system, the ~~collection part~~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 nvPM mass and number emissions at the exhaust of the aircraft engine from the nvPM mass and number concentration obtained in accordance with the procedures of Appendix 7.

For engines of a type or model subject to Part III Chapter 4, and for which the date of manufacture of the individual engine was on or after 1 January 2023, the nvPM mass and nvPM number system loss correction factors (k_{SL_mass} and k_{SL_number}), and EI_{mass} and EI_{number} corrected for system losses shall be reported to the certificating authority in accordance with the procedures of Appendix 8, or equivalent procedures as agreed by the certificating authority.

~~**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 by Appendix 8 Band should report these factors to the appropriate authority.*~~

Recommendation ~~2~~.— *For inventory and modelling purposes, the nvPM mass and nvPM number ~~concentration~~emissions obtained in accordance with the procedures of Appendix 7 should be corrected for system losses using the methodology described in Appendix 8.*

…

APPENDIX 2. SMOKE EMISSION EVALUATION

…

2. MEASUREMENT OF SMOKE EMISSIONS

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

2.1 Sampling probe for smoke emissions

The sampling probe shall meet the following requirements:

a) The probe material with which the exhaust emission sample is in contact shall be stainless steel or any other non-reactive material.

b) If a sampling probe with multiple sampling orifices is used,:

1) all sampling orifices shall be of equal diameter. ; and

2) Tthe sampling probe design shall be such that at least 80 per cent of the pressure drop through the probe assembly is taken at the orifices.

c) The number of locations sampled shall not be less than 12.

…

2.3 Smoke analysis system

Note.— The method prescribed herein is based upon the measurement of the reduction in reflectance of a filter when stained by a given mass flow of exhaust sample.

The arrangement of the various components of the system for acquiring the necessary stained filter samples shall be as shown schematically in Figure A2-1. An optional bypass around the volume meter may be installed to facilitate meter reading. The major elements of the system shall meet the following requirements:

…

e) *vacuum pump:* this 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 2826 L/min at normalstandard temperature and pressure;

…

i) *leak performance:* the subsystem shall meet the requirements of the following test:

1) clamp clean filter material into holder,

2) shut off valve A, fully open valves B, C and D.

3) run vacuum pump for one minute to reach equilibrium conditions;

4) continue to pump and measure the volume flow rate through the meter over a period of five minutes. This volumeflow rate shall not exceed 51 L/min (referred to normalstandard temperature and pressure) and the system shall not be used until this standard has been achieved.

…

2.5 Smoke measurement procedures

…

2.5.2 Leakage and cleanliness checks

No measurements shall be made until all sample transfer lines and valves are warmed up and stable. Prior to a series of tests the system shall be checked for leakage and cleanliness as follows:

a) *leakage check:* isolate probe and close off end of sample line, perform leakage test as specified in 2.3 h) with the exceptions that valve A is opened and set to “bypass”, valve D is closed and that the leakage limit is 20.4 L/min at standard temperature and

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

pressure. Restore probe and line interconnection;

…

APPENDIX 3. INSTRUMENTATION AND MEASUREMENT TECHNIQUES FOR GASEOUS EMISSIONS

…

5.1 Sampling system

5.1.1 Sampling probe

The sampling probe shall meet the following requirements:

a) The probe material with which the exhaust emission sample is in contact shall be stainless steel or any other non-reactive material.

b) If a sampling probe with multiple sampling orifices is used~~,~~:

1) all sampling orifices shall be of equal diameter~~.~~ ; and

2) ~~T~~the sampling probe design shall be such that at least 80 per cent of the pressure drop through the probe assembly is taken at the orifices.

c) The number of locations sampled shall not be less than 12.

…

6.3 Operation

6.3.1 No measurements shall be made until all instruments and sample transfer lines are warmed up and stable and the following checks have been carried out:

a) leakage check: prior to a series of tests the system shall be checked for leakage by isolating the probe and the analysers, connecting and operating a vacuum pump ~~of equivalent performance to that used in the smoke measurement system~~ to verify that the system leakage flow rate is less than 0.4 L/min referred to ~~normal~~ standard temperature and pressure. 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 26 L/min at normal temperature and pressure;

b) cleanliness check: isolate the gas sampling system from the probe and connect the end of the sampling line to a source of zero gas. Warm the system up to the operational temperature needed to perform hydrocarbon measurements. Operate the sample flow pump and set the flow rate to that used during engine emission testing. Record the hydrocarbon analyser reading. The reading shall not exceed 1 per cent of the engine idle emission level or 1 ppm (both expressed as methane), whichever is the greater.

…

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

APPENDIX 4. SPECIFICATION FOR FUEL TO BE USED IN AIRCRAFT TURBINE ENGINE EMISSION TESTING

The fuel shall meet the specifications of this appendix, 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 %	0.0 – 3.0
Smoke point, mm	20 – 28
Hydrogen, mass %	13.4 – 14.3
Sulphur, ppm by mass ~~%~~	less than ~~0.~~3000
Kinematic viscosity at –20°C, mm^2/s	2.5 – 6.5

…

APPENDIX 6. COMPLIANCE PROCEDURE FOR GASEOUS EMISSIONS, SMOKE AND PARTICULATE MATTER EMISSIONS

1. GENERAL

…

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 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.

Table A6-1. Coefficients to determine characteristic levels

Number of engines tested (i)	*CO*	*HC*	*NOx*	*SN*	*nvPM mass concentration*	*nvPM LTO mass*	*nvPM LTO number*
1	0.814 7	0.649 3	0.862 7	0.776 9	0.776 9	0.719 4	0.719 4
2	0.877 7	0.768 5	0.909 4	0.852 7	0.852 7	0.814 8	0.814 8
3	0.924 6	0.857 2	0.944 1	0.909 1	0.909 1	0.885 8	0.885 8
4	0.934 7	0.876 4	0.951 6	0.921 3	0.921 3	0.901 1	0.901 1
5	0.941 6	0.889 4	0.956 7	0.929 6	0.929 6	0.911 6	0.911 6
6	0.946 7	0.899 0	0.960 5	0.935 8	0.935 8	0.919 3	0.919 3
7	0.950 6	0.906 5	0.963 4	0.940 5	0.940 5	0.925 2	0.925 2
8	0.953 8	0.912 6	0.965 8	0.944 4	0.944 4	0.930 1	0.930 1
9	0.956 5	0.917 6	0.967 7	0.947 6	0.947 6	0.934 1	0.934 1
10	0.958 7	0.921 8	0.969 4	0.950 2	0.950 2	0.937 5	0.937 5
more than 10	$1-\frac{0.130\,59}{\sqrt{i}}$	$1--\frac{0.247\,24}{\sqrt{i}}$	$1-\frac{0.096\,78}{\sqrt{i}}$	$1-\frac{0.157\,36}{\sqrt{i}}$	$1-\frac{0.157\,36}{\sqrt{i}}$	$1-\frac{0.197\,78}{\sqrt{i}}$	$1-\frac{0.197\,78}{\sqrt{i}}$

2.2 Particulate matter emissions

2.2.1 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~~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~~*Collection Part *of the sampling system, divided by the coefficient corresponding to the number of engines tested, as shown in Table A6-1.*

2.2.2 The certificating authority shall award a certificate of compliance if the mean of the values of the nvPM mass and the mean of the values of the nvPM number emissions measured and corrected for thermophoretic losses in the Collection Part of the sampling system and for fuel composition 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 nvPM mass and nvPM number emissions is the mean of the values of all the engines tested, and appropriately corrected for the thermophoretic losses in the Collection Part of the sampling system *and for fuel composition, divided by the coefficient corresponding to the number of engines tested, as shown in Table A6-1.*

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

2.3 Characteristic level

The coefficients needed to determine the characteristic levels of engine emissions are given in Table A6-1.

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.

…

APPENDIX 7. INSTRUMENTATION AND MEASUREMENT TECHNIQUES FOR NON-VOLATILE PARTICULATE MATTER EMISSIONS

1. INTRODUCTION

…

2.3 Symbols

…

EI_{mass}	nvPM mass emission index corrected for thermophoretic losses and for fuel composition, in mg/kg fuel
EI_{num}	nvPM number emission index corrected for thermophoretic losses and for fuel composition, in number/kg fuel
F	thrust for the given operating mode
H	fuel hydrogen content (mass percentage)
[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_{fuel_M}	fuel composition correction factor for nvPM mass emissions index
k_{fuel_N}	fuel composition correction factor for nvPM number emissions index
k_{thermo}	Collection ~~part~~Part thermophoretic loss correction factor

…

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

4. GENERAL ARRANGEMENT OF THE nvPM SAMPLING AND MEASUREMENT SYSTEM

4.1 nvPM sampling and measurement system

…

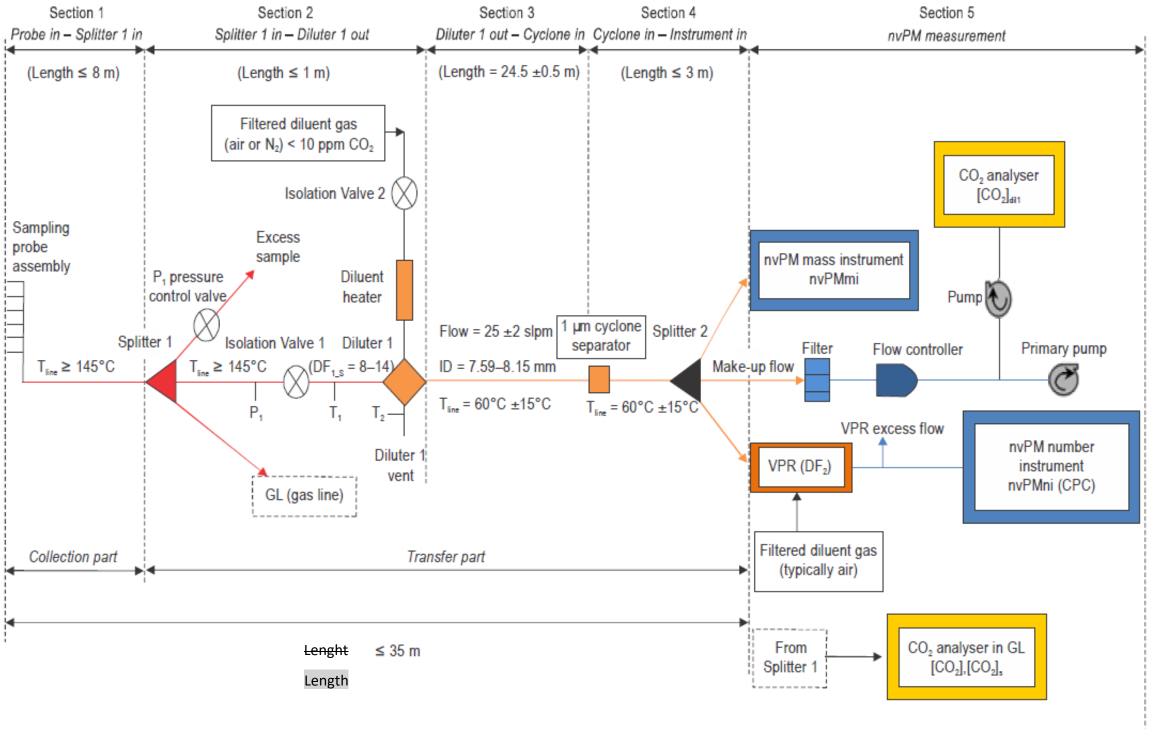


Figure A7-1. Overview schematic of an nvPM sampling and measurement system

…

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,:

1) all sampling orifices shall be of equal diameter.; and

2) Tthe 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.

…

6. CALCULATIONS

6.1 nvPM mass concentration and nvPM mass and number emission indices equations

…

6.1.1 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:

$$nvPM_{mass} = DF_1 \times nvPM_{mass\_STP} \times k_{thermo}$$

6.1.2 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 and their respective fuel composition correction factors. They are calculated using the following equations:

$$EI_{mass} = \frac{22.4 \times nvPM_{mass\_STP} \times 10^{-3}}{\left([CO_2]_{dil1} + \frac{1}{DF_1}([CO] - [CO_2]_b + [HC])\right)(M_C + \alpha M_H)} \times k_{thermo} \times k_{fuel\_M}$$

$$EI_{num} = \frac{22.4 \times DF_2 \times nvPM_{num\_STP} \times 10^{6}}{\left([CO_2]_{dil1} + \frac{1}{DF_1}([CO] - [CO_2]_b + [HC])\right)(M_C + \alpha M_H)} \times k_{thermo} \times k_{fuel\_N}$$

$[CO_2]$, $[CO]$ and $[HC]$ shall be calculated as shown in Attachment E to Appendix 3.

…

6.2 Correction factors for nvPM emissions

6.2.1 Correction for nvPM thermophoretic losses in the Collection Part

…

6.2.2 Correction for fuel composition

The correction for fuel composition shall be determined using:

$$k_{fuel\_M} = exp\left\{\left(1.08\frac{F}{F_{00}} - 1.31\right)(13.8 - H)\right\}$$

$$k_{fuel\_N} = exp\left\{\left(0.99\frac{F}{F_{00}} - 1.05\right)(13.8 - H)\right\}$$

…

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

ATTACHMENT A TO APPENDIX 7. REQUIREMENTS AND RECOMMENDATIONS FOR NVPM SAMPLING SYSTEM

…

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.

…

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 P1 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~~26 L/min at ~~normal~~standard temperature and pressure.

1.2 Leakage check requirement

…

2. COLLECTION PART AND GAS LINE CLEANLINESS CHECK

This check is only performed if using the full gaseous nvPM EI calculation method.

2.1 Cleanliness check procedure

The ~~collection part~~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 P1 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 HC measurements.

d) Operate the sample flow pump and set the flow rate to that used during engine emission testing.

e) Record the HC analyser reading.

2.2 Cleanliness check requirement

2.2.1 The HC reading shall not exceed 1 per cent of the engine idle emission level or 1 ppm (both expressed as C), whichever is the greater.

2.2.2 **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

…

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

APPENDIX 8. PROCEDURES FOR ESTIMATING NON-VOLATILE PARTICULATE MATTER SYSTEM LOSS CORRECTIONS

Note 1.— The procedures specified in this ~~appendix~~Appendix are concerned with the determination of non-volatile particulate matter (nvPM) sampling and measurement system loss correction factors, excluding the ~~collection part~~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 35 m and includes several sampling and measurement system components, which can result in significant particle loss on the order of 50 per cent for nvPM mass and 90 per cent 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~~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~~3.— The method proposed in this ~~appendix~~Appendix uses data and measurements as specified in Appendix 7 and ~~its attachments~~Attachments to Appendix 7. Symbols and definitions not defined in this ~~appendix~~Appendix are defined in Appendix 7 and ~~its attachments~~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~~Collection Part thermophoretic loss is specified in Appendix 7, 6.2.1.

1.2 The overall nvPM sampling and measurement system particle loss excluding the ~~collection part~~Collection Part thermophoretic loss is referred to as system loss.

1.3 The nvPM size distribution needs to be taken into consideration because the particle 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 and measurement 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:

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

Aerodynamic diameter of a particle. The diameter of an equivalent sphere of unit density (1g/cm^3) 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 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.

Non-volatile pParticulate mMatter (nvPM). Emitted particles that exist at a gas turbine engine exhaust nozzle exit plane that do not volatilize when heated to a temperature of 350°C.

Particle loss. The loss of particles during transport through a sampling or measurement system component or due to instrument performance. ~~This~~ Sampling and measurement system loss is due to various deposition mechanisms, some of which are particle 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. A 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
EENEP	Engine Exhaust Nozzle Exit Plane
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~~Litres per minute at STP)

STP Instrument condition at standard temperature 0°C and pressure 101.325 kPa

VPR Volatile ~~particle remover~~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

D $\frac{k_B\times(273.15+T_i)\times C_c}{3\times\pi\times\mu\times D_m}\times 10^7$, the particle diffusion coefficient, cm^2/s

DF_1 First stage dilution factor

DF_2 Second stage (VPR) dilution factor as per calibration

D_m nvPM ~~electrical mobility~~particle diameter, refers to the electrical mobility diameter except for the cyclone separator where the particle diameter is the aerodynamic diameter, ~~μm~~nm

D_{mg} Geometric mean diameter of nvPM size distribution, ~~μm~~nm

δ ~~The sum~~Sum of the square of relative differences between measured and calculated dilution corrected nvPM mass and number concentrations

EI_{mass} nvPM mass emission index corrected for Collection Part thermophoretic losses, in mg/kg fuel

EI_{num} nvPM number emission index corrected for Collection Part thermophoretic losses, in number/kg fuel

~~ε~~ ~~Convergence criterion (1×10^{-9})~~

$f_{lgn}(D_m)$ ~~The lognormal~~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~~EENEP particle number lognormal distribution function

ID_{ti} Inner diameter of the i^{th} segment of the sampling line, mm

k_B 1.3806×10^{-16}, Boltzmann constant, $(g\cdot cm^2)/(s^2\cdot K)$

k_{SL_mass} ~~EImass~~EI_{mass} correction factor for system losse~~s~~ without Collection Part thermophoretic loss correction~~, μg/m³~~

k_{SL_num}	~~EInum~~EI_{num} correction factor for system loss~~es~~ without Collection Part thermophoretic loss correction~~, number/cm³~~
k_{thermo}	Collection part thermophoretic loss correction factor, specified in Appendix 7, 6.2.1
λ	$67.3 \sout{\times 10^{-3}} \times \left(\frac{273.15+T_i}{296.15}\right)^2 \times \left(\frac{101.325}{P_i}\right) \times \left(\frac{406.55}{T_i+383.55}\right)$, the carrier gas mean free path, ~~μm~~nm
μ	Carrier gas viscosity, g/cm·s
~~$nvPM_{mass\_EST}$~~	~~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 section 4 of this appendix, not corrected for collection part thermophoretic losses.~~
~~$nvPM_{num\_EP}$~~	~~Estimated engine exhaust nozzle exit plane nvPM number concentration, specified in section 4 to this appendix, not corrected for collection part thermophoretic losses~~
$nvPM_{mass\_STP}$	Diluted nvPM mass concentration at instrument STP condition, μg/m³
$nvPM_{num\_STP}$	Diluted nvPM number concentration at instrument STP condition, number/cm³
$\eta_{mass}(D_m)$	~~The overall~~Overall sampling and measurement system penetration fraction for the nvPMmi without ~~collection part~~Collection Part thermophoretic losses at electrical mobility particle size Dm
$\eta_{num}(D_m)$	~~The overall~~Overall sampling and measurement system penetration fraction for the nvPMni without ~~collection part~~Collection Part thermophoretic losses at electrical mobility particle size Dm
$\eta i(D_m)$	Penetration fraction for the i^{th} component of the sampling and measurement system at electrical mobility particle size D_m
$\eta bi(D_m)$	Penetration fraction for the sampling line bend for i^{th} component of the sampling and measurement system at electrical mobility particle size D_m
P_i	Carrier gas pressure in the i^{th} segment of the sampling line, kPa
ρ	~~The assumed~~Assumed nvPM effective density, g/cm³
σ_g	~~The assumed~~Assumed geometric standard deviation of lognormal distribution
Q_i	~~The carrier~~Carrier gas flow in the i^{th} 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

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

$R_{MN}(D_m)$	Calculated ratio of the estimated nvPM mass concentration to the estimated nvPM number concentration
T_i	~~The carrier~~Carrier gas temperature in the i[th] segment of the sampling line, °C

~~3. CORRECTION FACTORS FOR nvPM MASS AND NUMBER EIs~~

~~3.1 **Recommendation.—** *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:*~~

$$k_{SL\_mass} = \frac{nvPM_{mass\_EP}}{DF_1 \times nvPM_{mass\_STP}}$$

~~3.2 **Recommendation.—** *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~~

~~4.1 **Recommendation.—** *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 0.02 µm should be assumed for the geometric mean diameter, D_{mg}, of the lognormal 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:*~~

$$nvPM_{mass\_EST} = \sum_{D_m=0.01\mu m}^{1\mu m} \eta_{mass}(D_m) \times \frac{\rho\pi D_m^3}{6} \times nvPM_{num\_EP} \times f_{lgn}(D_m) \times \Delta\, ln(D_m)$$

$$nvPM_{num\_EST} = \sum_{D_m=0.01\mu m}^{1\mu m} \eta_{num}(D_m) \times nvPM_{num\_EP} \times f_{lgn}(D_m) \times \Delta ln(D_m)$$

~~*where*~~

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

$$f_{lgn}(D_m) = \frac{1}{\sqrt{2\pi}\ ln(\sigma_g)} \times e^{-\frac{1}{2}\left(\frac{ln(D_m)-ln(D_{mg})}{ln(\sigma_g)}\right)^2}$$

~~*$\Delta ln(D_m) = \frac{1}{n} \times \frac{1}{log_{10}(e)}$ 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 minimized value of δ.*~~

~~*g) Using $nvPM_{num\_EP}$ and D_{mg} from step f), $nvPM_{mass\_EP}$ should be determined using the following expression:*~~

$$nvPM_{mass\_EP} = \sum_{D_m=0.01\mu m}^{1\mu m} \frac{\rho\pi D_m^3}{6} \times nvPM_{num\_EP} \times f_{lgn}(D_m) \times \Delta\, ln(D_m)$$

~~4.2 **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 $\Delta ln(D_m)$ above). The sums in the above equations start at 0.01 µm.*~~

~~4.3 **Recommendation.—** *The nvPM effective density should be a constant and equal to 1 g/cm³ across all particle sizes.*~~

~~4.4 **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.*~~

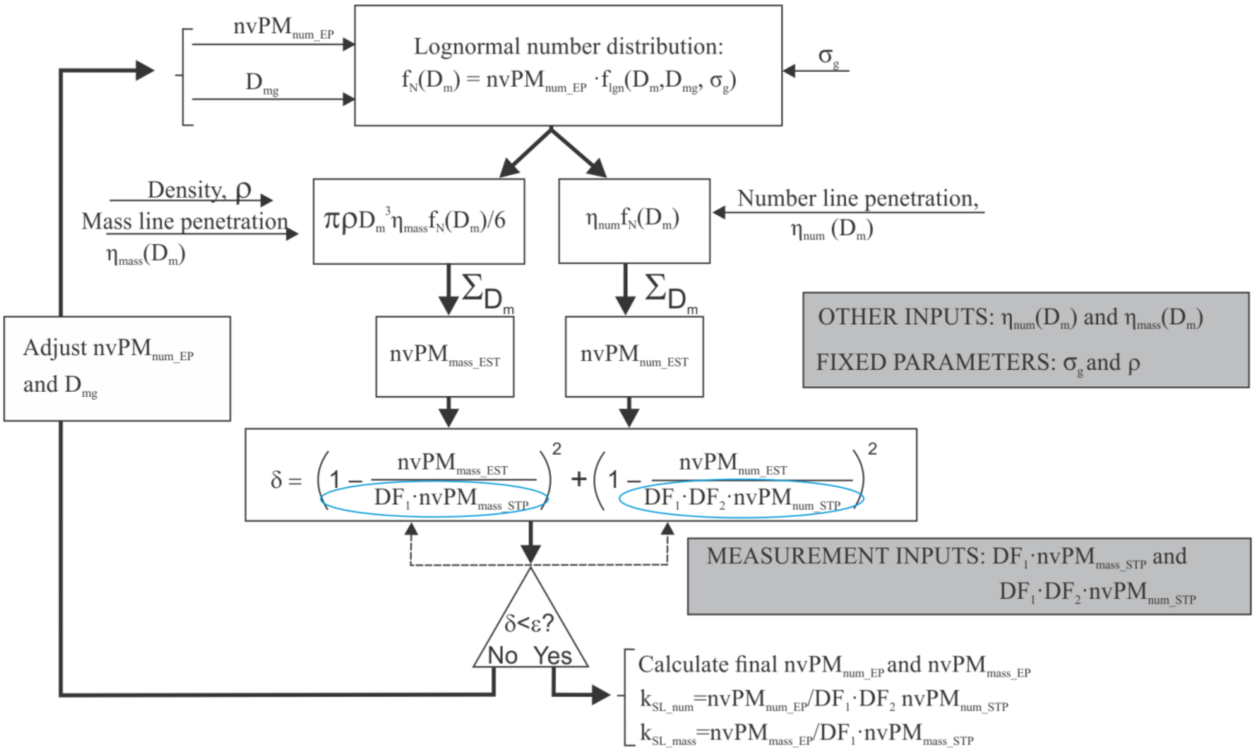
An agency of the European Union

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

~~*Note 2.— If $nvPM_{mass\_STP}$ is less than 1 µg/m³, a minimum value of 1 µg/m³ should be used for the procedure to converge.*~~

~~*Note 3.— The procedure outlined in section 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 Splitter 2.*~~

~~*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.*~~

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

Table A8-1. Required nvPM sampling and measurement system component penetration fractions

Parameter symbol	*Description*
$\eta_1(D_m)$	Section 1 — Probe inlet to Splitter 1
$\eta_{b1}(D_m)$	Section 1 — Probe inlet to Splitter 1 for bends
$\eta_2(D_m)$	Section 2 — Splitter 1 to Diluter 1 inlet
$\eta_{b2}(D_m)$	Section 2 — Splitter 1 to Diluter 1 inlet for sampling line bends
$\eta_{di1}(D_m)$	Section 2 — Diluter 1
$\eta_3(D_m)$	Section 3 — Diluter 1 outlet to cyclone separator inlet
$\eta_{b3}(D_m)$	Section 3 — Diluter 1 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 Splitter 2
$\eta_{b4}(D_m)$	Section 4 — Cyclone separator outlet to Splitter 2 for sampling line bends
$\eta_5(D_m)$	Section 4 — Splitter 2 to nvPMmi
$\eta_{b5}(D_m)$	Section 4 — Splitter 2 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 — Splitter 2 to VPR
$\eta_{b6}(D_m)$	Section 4 — Splitter 2 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

Recommendation.— *The overall penetration fraction for the nvPM mass, for 80 discrete particle sizes (D_m) from 0.003 µm to 1 µm, 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 section 6 of 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

~~**Recommendation.—** *The overall penetration fraction for the nvPM number, for 80 discrete particle sizes (D_m) from 0.003 µm to 1 µm, should be calculated by combining system component penetration fractions:*~~

$$\eta_{num}(D_m) = \eta_1 \times \eta_{b1} \times \eta_2 \times \eta_{b2} \times \eta_3 \times \eta_{b3} \times \eta_{cyc} \times \eta_4 \times \eta_{b4} \times \eta_6 \times \eta_{b6} \times \eta_{VPR} \times \eta_{CPC} \times \eta_{th\_n}$$

~~*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 section 6 of 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 THE 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, 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*~~	~~*Unit*~~
~~T_i~~	~~Temperature of the carrier gas at the entrance of i[th] 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 i[th] segment of the sampling line~~	~~°C~~
~~P_i~~	~~Pressure of the carrier gas in the i[th] segment of the sampling line, assumed constant throughout the i[th] section and equal to 101.325 kPa~~	~~kPa~~
~~Q_i~~	~~Flow rate of the carrier gas through the i[th] segment of the sampling line~~	~~slpm~~
~~ID_{ti}~~	~~Inside diameter of the i[th] segment of the sampling line~~	~~mm~~
~~L_i~~	~~Length of of the i[th] segment of the sampling line~~	~~m~~
~~θ_{bi}~~	~~Total angle of bends in the i[th] segment of the sampling line~~	~~degrees~~
~~$\eta_{VPR}(15)$, $\eta_{VPR}(30)$, $\eta_{VPR}(50)$, $\eta_{VPR}(100)$~~	~~VPR penetration fractions at four particle diameters~~	~~dimensionless~~
~~$\eta_{CPC}(10)$,~~	~~CPC counting efficiency at two particle diameters~~	~~dimensionless~~

~~$\eta_{CPC}(15)$~~		

~~6.2 Diffusional penetration fractions~~

~~6.2.1 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 i^th^ 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)~~

~~6.2.2 **Recommendation.—** *Penetration fractions at 80 discrete particle sizes (D_m) from 0.003 µm to 1 µm should be calculated for diffusional losses for each applicable line section.*~~

~~6.3 Thermophoresis~~

~~**Recommendation.—** *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~~

~~6.4.1 **Recommendation.—** *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 5 000, and laminar flow, Re less than or equal to 5 000 where Re is the Reynolds number. For laminar flow when Re less than or equal to 5 000, the penetration due to bends in the transport lines should be calculated as:*~~

$$\eta_{bi} = 1 - 0.01745 \times Stk \times \theta_{bi}$$

~~*For turbulent flow when Re greater than 5 000, the penetration due to bends in the transport lines should be calculated as:*~~

$$\eta_{bi} = e^{-0.04927\times Stk\times\theta_{bi}}$$

~~*where*~~

~~*Stk* = $\frac{Q_t \times C_c \times \rho \times D_m^2 \times 10^{-3}}{27 \times \pi \times \mu \times ID_{ti}^3}$, *the dimensionless Stokes number*~~

~~ϑ_{bi} = *total angle of bends in the of the* i^{th} *segment of the sampling line, degrees.*~~

~~6.4.2 **Recommendation.—** *Penetration fractions at 80 discrete particle sizes* (D_m) *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~~

~~6.5.1 **Recommendation.—** *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})$^{0.5}$~~

~~6.5.2 **Recommendation.—** *Penetration fractions at 80 discrete particle sizes* (D_m) *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; and*~~

~~*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.*~~

~~6.6.1 **Recommendation.—** *The total VPR penetration function should be estimated using the expression:*~~

$$\eta_{VPR} = \eta_{VPRth} \times \begin{cases} 1 - 5.5 \times \psi^{\frac{2}{3}} + 3.77 \times \psi & \psi < 0.007 \\ 0.819 \times e^{-11.5\psi} + 0.0975 \times e^{-70.1\psi} + 0.0325 \times e^{-179\psi} & \psi > 0.007 \end{cases}$$

~~*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*~~

~~6.6.2 **Recommendation.—** *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.*~~

~~6.6.3 **Recommendation.—** *Penetration fractions at 80 discrete particle sizes (D_m) 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 Diluter 1 penetration fraction~~

~~6.7.1 **Recommendation.—** *A constant Diluter 1 penetration, $\eta_{di1}(D_m) = 1$ should be used for all particle sizes.*~~

~~6.7.2 **Recommendation.—** *Penetration fractions at 80 discrete particle sizes (D_m) from 0.003 µm to 1 µm should be used for the diluter penetration function.*~~

~~6.8 CPC counting efficiency~~

~~6.8.1 **Recommendation.—** *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*~~

~~$\eta_{CPC,15}$ = *the counting efficiency at 0.015 µm.*~~

~~6.8.2 **Recommendation.—** *Penetration fractions at 80 discrete particle sizes (D_m) from 0.003 µm to 1 µm should be calculated from the CPC continuous function.*~~

3. DATA REQUIRED

3.1 nvPM Emissions

In order to calculate the system loss correction factors, the following concentrations as specified in Appendix 7 are needed:

a) nvPM mass concentration: $nvPM_{mass\_STP}$;

b) nvPM number concentration: $nvPM_{num\_STP}$.

3.2 Other Information

Additional information listed in Attachment D to Appendix 7 is required to perform the calculation procedure.

4. nvPM SYSTEM LOSS CORRECTION METHODOLOGY AND CALCULATION PROCEDURE

4.1 Overview

Note.— An overview diagram of the methodology for estimating the system loss correction factors is shown Figure A8-1.

4.1.1 The system loss correction factors shall be estimated based on the following assumptions: EENEP nvPM is represented by a constant value of nvPM effective density, a lognormal distribution, a fixed value of geometric standard deviation, no coagulation, limiting the nvPM mass and number concentrations as described in the calculation method limitations section, and a minimum summation particle size cut-off of 10 nm.

4.1.1.1 The system loss correction methodology shall use a particle effective density of 1 g/cm^3

4.1.1.2 A mono-modal lognormal distribution with a geometric standard deviation of 1.8 shall be used in the system loss correction methodology.

4.1.1.3 The system loss correction methodology does not consider reduction in nvPM number concentration due to coagulation.

4.1.1.4 The EENEP nvPM number concentration calculated using:

$$k_{SL\_num} \times k_{thermo} \times DF_1 \times DF_2 \times nvPM_{num\_STP}$$

is greater 10^8 particles/cm^3, coagulation may occur and shall be reported to the certificating authority.

Note 1.— The system loss correction methodology does not consider penetration drift. This is not considered significant for Appendix 7 compliant nvPM measurement systems.

Note 2.— An illustration of the iterative calculation procedure is shown in Figure A8-2.

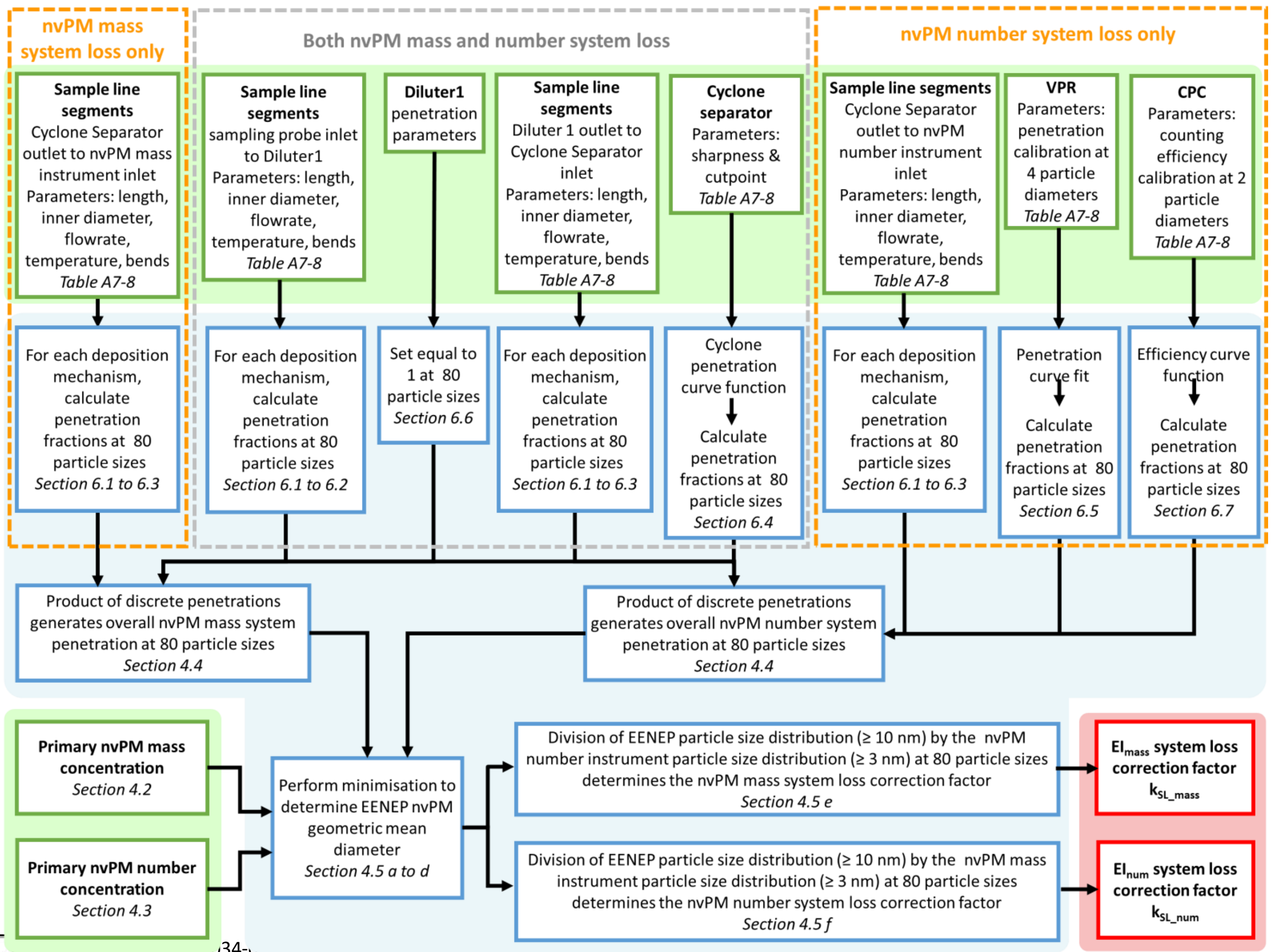


Figure A8-1: Flow block diagram of the nvPM system loss correction methodology. Green blocks show model input parameters, the blue blocks shows model calculations and the red outline blocks shows calculation output system loss correction factors.

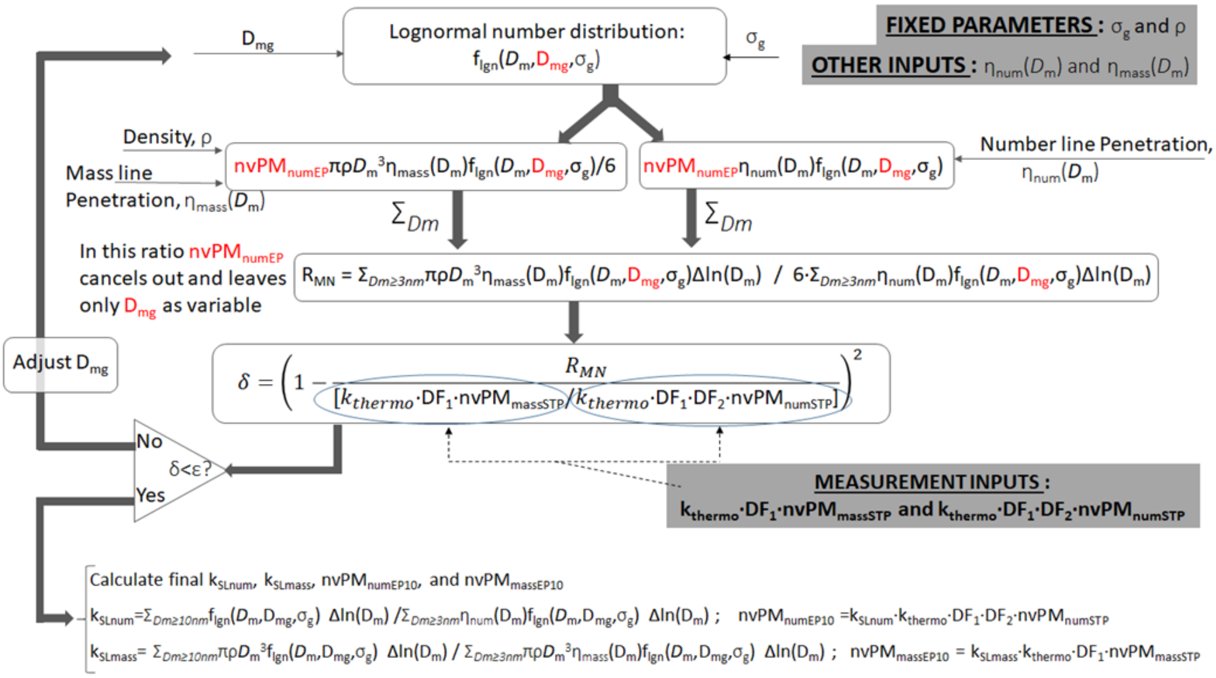


Figure A8-2: Iterative calculation procedure diagram for determination of system loss correction factors

4.2 Primary nvPM Mass Concentration

The primary nvPM mass concentration ($nvPM_{mass}$) is calculated using the following equation as defined in Appendix 7:

$$\mathbf{nvPM_{mass} = k_{thermo} \times DF_1 \times nvPM_{mass\_STP}}$$

4.3 Primary nvPM Number Concentration

The primary nvPM number concentration (nvPMnum) represents the number of particles per unit volume of engine exhaust sample corrected for the first stage dilution factor (DF1) and second stage dilution factor (DF2) and the Collection Part thermophoretic particle loss. It is calculated using the following equation:

$$\mathbf{nvPM_{num} = k_{thermo} \times DF_1 \times DF_2 \times nvPM_{num\_STP}}$$

4.4 nvPM Penetration Functions

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.
An agency of the European Union

4.4.1 The sampling system penetration fraction is a product of the individual penetration and counting efficiency functions. Table A8-1 provides the required nvPM penetration and counting efficiency functions and shall be calculated using the procedures described in Section 6.

4.4.2 The sampling system penetration for nvPMmi for a particle of diameter D_m is:

$$\eta_{mass}(D_m) = \eta_1 \times \eta_{b1} \times \eta_2 \times \eta_{b2} \times \eta_3 \times \eta_{b3} \times \ldots \times \eta_{dil} \times \eta_{cyc}$$

4.4.3 The sampling system penetration for nvPMni for a particle of diameter D_m is:

$$\eta_{num}(D_m) = \eta_1 \times \eta_{b1} \times \eta_2 \times \eta_{b2} \times \eta_3 \times \eta_{b3} \times \ldots \times \eta_{dil} \times \eta_{cyc} \times \eta_{VPR} \times \eta_{CPC}$$

4.4.4 The size independent nvPM mass and number sampling system thermophoretic penetration is:

$$\eta_{thermo} = \eta_{th1} \times \eta_{th2} \times \eta_{th3} \times \ldots$$

Note.— The Collection Part thermophoretic loss, k_{thermo}, is specified in Appendix 7, paragraph 6.2.1 and shall not be included in this calculation.

Table A8-1. Required nvPM Sampling and Measurement system component penetration fractions

Symbol	Description of nvPM Sampling and Measurement system particle transport functions
$\eta_i(D_m)$	Diffusional penetration fraction of i^th segment of sampling system
$\eta_{bi}(\Theta_i)$	Penetration fraction due to bends in i^th segment of sampling system
η_{thi}	Penetration fraction due to thermophoresis in ith segment of sampling system
$\eta_{dil}(D_m)$	Diluter1 penetration fraction
$\eta_{cyc}(D_m)$	Cyclone separator penetration fraction
$\eta_{VPR}(D_m)$	VPR penetration fraction
$\eta_{CPC}(D_m)$	CPC counting efficiency

4.5 Calculation of System Loss Correction Factors

System loss correction factors for nvPM mass (k_{SL_mass}) and nvPM number (k_{SL_num}) shall be calculated using the iterative procedure:

a) Estimate an initial value of the geometric mean diameter using the equation:

$$\mathbf{D_{mg}} = \sqrt[3]{\frac{\mathbf{6 \times DF_1 \times nvPM_{mass\_STP}}}{\boldsymbol{\pi \times \rho} \mathbf{\times DF_1 \times DF_2 \times nvPM_{num\_STP}}}} \times \mathbf{10^3}$$

Note.— Using the units defined for the inputs, the calculated particle diameter will be in nm.

b) Using the value of D_{mg} from step a), calculate the estimated nvPM mass to nvPM number ratio, $R_{MN}(D_{mg})$, using the equation:

$$\mathbf{R_{MN}(D_{mg})} = \frac{\sum_{D_m>3nm}^{1000nm} \boldsymbol{\eta}_{\mathbf{mass}}(\mathbf{D_m}) \times \frac{\boldsymbol{\pi\rho}\mathbf{D_m^3}}{\mathbf{6}} \times \mathbf{e}^{-\frac{1}{2}\left\{\frac{\ln(D_m)-\ln(D_{mg})}{\ln(\sigma_g)}\right\}^2} \times \Delta\ln(\mathbf{D_m})}{\sum_{D_m>3nm}^{1000nm} \boldsymbol{\eta}_{\mathbf{num}}(\mathbf{D_m}) \times \mathbf{e}^{-\frac{1}{2}\left\{\frac{\ln(D_m)-\ln(D_{mg})}{\ln(\sigma_g)}\right\}^2} \times \Delta\ln(\mathbf{D_m})}$$

where the exponential functions come from the lognormal distribution function,

$$f_{lgn}(D_m) = \frac{1}{\sqrt{2\pi}\ \ln(\sigma_g)} \times e^{-\frac{1}{2}\left\{\frac{\ln(D_m)-\ln(D_{mg})}{\ln(\sigma_g)}\right\}^2}$$

$\Delta\ln(D_m) = \frac{1}{n} \times \frac{1}{log_{10}(e)}$, 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.

c) Determine the squared relative difference, δ, between the measured and estimated nvPM mass to number ratio using:

$$\boldsymbol{\delta} = \left\{\mathbf{1} - \frac{\mathbf{R_{MN}(D_{mg})} \times \mathbf{10^{-9}}}{\left[\left(\mathbf{k_{thermo}} \times \mathbf{DF_1} \times \mathbf{nvPM_{mass\_STP}}\right)/\left(\mathbf{k_{thermo}} \times \mathbf{DF_1} \times \mathbf{DF_2} \times \mathbf{nvPM_{num\_STP}}\right)\right]}\right\}^2$$

d) Repeat steps b) and c) until δ reduces to less than 1×10^{-9}. The D_{mg} associated with this minimised value of δ shall be used to calculate the system loss correction factors.

e) Calculate the nvPM mass system loss correction factor using the equation:

$$\mathbf{k_{SL\_mass}} = \frac{\sum_{D_m>10nm}^{1000nm} \mathbf{D_m^3} \times \mathbf{e}^{-\frac{1}{2}\left\{\frac{\ln(D_m)-\ln(D_{mg})}{\ln(\sigma_g)}\right\}^2} \times \Delta\ln(\mathbf{D_m})}{\sum_{D_m>3nm}^{1000nm} \boldsymbol{\eta}_{\mathbf{mass}}(\mathbf{D_m}) \times \mathbf{D_m^3} \times \mathbf{e}^{-\frac{1}{2}\left\{\frac{\ln(D_m)-\ln(D_{mg})}{\ln(\sigma_g)}\right\}^2} \times \Delta\ln(\mathbf{D_m})}$$

f) Calculate the nvPM number system loss correction factor using the equation:

$$\mathbf{k_{SL\_num}} = \frac{\sum_{D_m>10nm}^{1000nm} \mathbf{e}^{-\frac{1}{2}\left\{\frac{\ln(D_m)-\ln(D_{mg})}{\ln(\sigma_g)}\right\}^2} \times \Delta\ln(\mathbf{D_m})}{\sum_{D_m>3nm}^{1000nm} \boldsymbol{\eta}_{\mathbf{num}}(\mathbf{D_m}) \times \mathbf{e}^{-\frac{1}{2}\left\{\frac{\ln(D_m)-\ln(D_{mg})}{\ln(\sigma_g)}\right\}^2} \times \Delta\ln(\mathbf{D_m})}$$

g) A minimum of 80 discrete sizes in the particle size range from 3 nm to 1000 nm or a minimum number of bins that will produce equivalent results as agreed by the certificating authority shall be used in this calculation.

Note 1.— For 80 discrete sizes, the number of size bins per decade, n, is 32 (see the definition for $\Delta\ln(D_m)$ *above).*

Note 2.– The summations to compute the system loss correction factors start at 10 nm in the numerator and 3 nm in the denominator.

Note 3.– The calculation procedure can be implemented using commercially available software programmes.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

5. REPORTING AND LIMITATIONS

Note 1.— The system loss correction factor calculation method described in Appendix 8 Section 4 has been shown to give acceptable results over a wide range of nvPM mass and number concentrations observed in aircraft turbine engine nvPM emissions. There are, however, ranges of mass and number concentrations that have been identified where the inputs to the analysis may lack the fidelity for the calculation method to yield quality results.

Note 2.— Any variations from the assumptions used by the calculation method as required in section 4.1.1 can lead to variation in the system loss correction factors. Similarly, variations in the data supplied to the calculation method will result in variation in system loss correction factors. The variation in the data could be due to particle size distributions, sampling system, or instruments. In addition, sampling and measurement system artifacts such as possible shedding from the walls when concentrations are low may provide invalid system loss correction factor. Method limitations are due to variation within the input data rather than the calculation method.

5.1 Applicable Mass Concentration Ranges

Note.— When raw nvPM mass concentrations at the nvPMmi (not dilution corrected) are below 3 μg/m³, use of this method to estimate system loss correction factors is cautioned because of the possible uncertainties with the nvPM mass concentration determination at such low values.

If the nvPMmi raw mass concentrations are below 3 μg/m^3, the applicant shall confirm that the predicted EENEP D_{mg} falls within the applicable range in section 5.3.

Recommendation.— *For cases where calculations from this Appendix or other equivalent methods do not provide reasonable values as noted in section 5.3 (e.g. when the system loss methodology calculates EENEP geometric mean diameters less than 7nm or greater than 100nm), or when the system loss methodology does not converge, alternate means of estimating system loss correction factors for the LTO operating modes may be used, subject to the approval of the certificating authority.*

Note.— There are no currently known limitations regarding high nvPM mass concentrations as long as it is verified that the nvPM mass concentration readings are within the range of the nvPMmi used.

5.2 Applicable Number Concentration Ranges

If the nvPM number concentration measured at the nvPMni, corrected for dilution (both DF1 and DF2) and Collection Part thermophoretic loss, is found to be less than or equal to the measured ambient number concentration[14], the applicant shall confirm that the predicted EENEP D_{mg} falls within the applicable range in section 5.3.

[14] See Appendix 7, Attachment E

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

Recommendation.— *For cases where calculations from this Appendix or other equivalent methods do not provide reasonable values as noted in section 5.3 (e.g. when the system loss methodology calculates EENEP geometric mean diameters less than 7nm or greater than 100nm), or when the system loss methodology does not converge, alternate means of estimating system loss correction factors for the LTO operating modes may be used, subject to the approval of the certificating authority.*

Note.— For the nvPMni, there are no currently known limitations on low nvPM number concentrations. CPC manufacturers report the CPC LOD to be about 1 particle/cm^3. High number concentration measurements are limited by the requirement for the CPC to stay in the single count mode. If EENEP nvPM number concentrations are above 10^8 particles /cm^3, particle coagulation may be occurring. Coagulation is not considered in the system loss calculation method.

5.3 Applicable Predicted Geometric Mean Diameters

Note.— The geometric mean diameter of nvPM at EENEP from aircraft gas turbines is anticipated to be in the range of 7 to 100nm.

If the system loss calculation method predicts an EENEP geometric mean diameter that is smaller than 7nm or larger than 100nm, and/or if the system loss calculation method predicts an EENEP geometric mean diameter whereby the convergence criterion is not met (δ is greater than 1×10^{-9}), results for k_{SL_mass} and k_{SL_num} shall be reviewed with the certificating authority to determine if the recommendation below applies.

Recommendation.— *For cases where calculations from this Appendix or other equivalent methods do not provide reasonable values (e.g. when the system loss methodology calculates EENEP geometric mean diameters less than 7nm or greater than 100nm), or when the system loss methodology does not converge, alternate means of estimating system loss correction factors for the LTO operating modes may be used, subject to the approval of the certificating authority.*

Note.— Calculated EENEP geometric mean diameters <20 nm will result in underestimation of system loss factors due to the minimum summation particle size cut-off. The underestimation can be significant for k_{SL_num} when EENEP D_{mg} ≤10 nm.

6. PROCEDURE TO DETERMINE PENETRATION FRACTIONS OF INDIVIDUAL COMPONENTS OF THE nvPM SAMPLING AND MEASUREMENT SYSTEM

To estimate the nvPM transport efficiency for particles over a range of sizes, penetration fractions shall be calculated for each component of the nvPM sampling and measurement system, for a minimum of 80 discrete particle sizes or a minimum number of discrete particle sizes that will produce equivalent result as agreed by the certificating authority in the range from 3 nm to 1000 nm.

Note 1.— Where continuous functions are calculated to estimate penetration fractions, care should be taken such that they do not go below zero.

Note 2.— The nvPM measurement and sampling system parameters required to perform the penetration fraction calculations in this Attachment are contained in Appendix 7 Attachment D.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

6.1 Segment Diffusional Penetration Fractions

Penetration values, $\eta_i(D_m)$, for diffusional losses in sampling system segments at electrical mobility particle size D_m are calculated with the expression:

$$\eta_i(D_m) = e^{\frac{-\pi \times ID_{ti} \times L_i \times V_{d,diff}}{Q_i}}$$

where:

L_i	length of the ith segment of the sampling line, m
$V_{d,diff}$	$0.0118 \times Re^{\frac{7}{8}} \times Sc^{\frac{1}{3}} \times D/ID_{ti}$, the deposition speed, cm/s
Sc	$\frac{\mu}{\rho_{gas} D} \times 10^3$, the carrier gas Schmidt number
ID_{ti}	Inner diameter of the i^{th} segment of the sampling line, mm
Q_i	the carrier gas flow in the i^{th} segment of the sampling line, slpm

6.2 Segment Bend Penetration Fractions

The bend penetration fractions are distinguished for turbulent flow, Re is greater than 5000, and laminar flow, Re is less than or equal to 5000 where Re is the Reynolds number. For laminar flow (including the transition regime) the penetration due to bends in the sample transport lines for each segment at electrical mobility particle size D_m is calculated as:

$$\eta_{bi}(D_m) = 1 - 0.01745 \times Stk \times \theta_{bi}$$

For turbulent flow the penetration due to bends in the sample transport lines shall be calculated as

$$\eta_{bi}(D_m) = e^{-0.04927 \times Stk \times \theta_{bi}}$$

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 i^{th} segment of the sampling line, degrees

6.3 Segment Thermophoretic Losses

Thermal gradients ocurring because sample line wall temperatures are lower than gas temperatures cause additional particle deposition, thermophoretic losses, onto the sampling line surfaces. The thermophoretic losses, except for those in the Collection Part, are calculated using:

$$\eta_{thi} = \left[\frac{T_{linei} + 273.15}{T_{gasi} + 273.15}\right]^{Pr \times K_{th}} \times \left[1 + \left(\frac{T_{gasi} + 273.15}{T_{linei} + 273.15} - 1\right) \times e^{-\frac{\pi \times ID_i \times h_{gas} \times L_i}{\rho_{gas} \times Q_i \times C_p}}\right]^{Pr \times K_{th}}$$

where

T_{gasi}	sample gas temperature in °C

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

T_{linei}	line wall temperature in °C
h_{gas}	carrier gas convective heat transfer coefficient (W/(m^2 K))
C_p	constant pressure carrier gas specific heat (J/(kg K))
Pr	Prandtl number
K_{th}	$\frac{2\times C_s\times C_c}{1+3\times C_m\times K_n}\left[2+\frac{1}{\left(k_{gas}/k_p\right)+C_t\times K_n}\right]^{-1}$, the thermophoretic coefficient
C_s	1.17, slip coefficient
C_m	1.14, soot momentum
C_t	2.18, thermal coefficient
k_{gas}	thermal conductivity of the carrier gas (Wm^{-1}K^{-1})
K_n	$2\lambda/D_m$,Knudsen number
k_p	0.2 Wm^{-1}K^{-1}, particle thermal conductivity.

Note.— The Collection Part and VPR thermophoretic losses are taken in to account as specified in Appendix 7, paragraph 6.2.1 and paragraph 1.5 of this Attachment. A system compliant with specifications in Appendix 7 uses instruments and segments that currently don't need to be corrected for thermophoretic losses and therefore η_{thi} will effectively be equal to 1.0.

6.4 Cyclone Separator Penetration Function

The penetration function of the cyclone separator shall 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}	$\ln(D_{16}/D_{84})^{0.5}$

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 300 nm. *In such cases the Cyclone separator penetration function will be effectively equal to 1.0.*

6.5 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 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:

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

$$\eta_{VPR} = \eta_{VPRth} \times \begin{cases} 1 - 5.5 \times \psi^{\frac{2}{3}} + 3.77 \times \psi & \psi < 0.007 \\ 0.819 \times e^{-11.5\psi} + 0.0975 \times e^{-70.1\psi} + 0.0325 \times e^{-179\psi} & \psi > 0.007 \end{cases}$$

where

Ψ	$\frac{D \times L_{VPR} \times 100}{Q_{VPR}}$, deposition parameter
L_{VPR}	effective length of the VPR, m
Q_{VPR}	carrier gas flow in the VPR, slpm
T_{VPR}	VPR temperature, °C
η_{VPRth}	VPR thermophoretic loss

The VPR penetration function (η_{VPR}) shall be fitted to the four measured penetration points by varying the VPR effective length (L_{VPR}) and the thermophoretic loss factor (η_{VPRth}). The fit shall be calculated by minimising δ_{VPR}, the relative sum of squares difference between the measured VPR penetration, $\eta_{VPRmeas}$, and the calculated penetration function.

$$\delta_{VPR} = \sqrt{\sum_{D_m} \left(\frac{\eta_{VPRmeas}(D_m) - \eta_{VPR}(D_m)}{\eta_{VPRmeas}(D_m)} \right)^2}$$

A value of δ_{VPR} less than 0.08 has been shown to provide a good fit to the measured penetrations.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

6.6 Diluter1 Penetration Function

A constant diluter1 penetration, $\eta_{dil}(D_m) = 1$ shall be used for all particle sizes.

6.7 CPC Counting Efficiency

A continuous function for the CPC counting efficiency shall be determined using the two CPC counting efficiencies specified with a two-parameter sigmoid function using the expression:

$$\eta_{CPC} = 1 - e^{-\ln(2)\times\left[\frac{D_m - D_0}{D_{50} - D_0}\right]}$$

where

$$D_0 = \frac{\alpha_{10}D_{15} - \alpha_{15}D_{10}}{\alpha_{10} - \alpha_{15}}$$

$$D_{50} = \frac{(\alpha_{15}+1)D_{10} - (\alpha_{10}+1)D_{15}}{\alpha_{15} - \alpha_{10}}$$

$$\alpha_i = \frac{\ln(1 - \eta_{CPC,i})}{\ln(2)}, i = 10\ nm\ \ or\ 15\ nm$$

D_{10} 10 nm,
D_{15} 15 nm,
$\eta_{CPC,10}$ the counting efficiency at 10 nm, and
$\eta_{CPC,15}$ the counting efficiency at 15 nm.

— — — — — — — —

7.2.2. Information on the methodology data used to develop the new nvPM mass and number Standards (extract from CAEP/11 report (ICAO Doc 10126) Agenda Item 3 – Appendix C 'Regulatory Impact Assessment')

APPENDIX C
(English only)

REGULATORY IMPACT ASSESSMENT

INFORMATION TO SUPPORT THE RULEMAKING PROCESSES OF ICAO MEMBER STATES

Table of Contents

List of Figures

List of Tables

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.
An agency of the European Union

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 192 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 emissions on local air quality, ICAO takes actions on revising current and adopting new emission standards for international aviation. Following the development of a visibility based non-volatile Particulate Matter (nvPM) Standard, aircraft engine landing and take-off (LTO) nvPM mass and number emissions Standard is being adopted. The non-volatile particulate matter is defined as emitted particles that do not volatilize when heated to a temperature of 350° C. These particles are also known as "ultrafine soot" or "black carbon" particles. The new Standards regulate the mass and the number of such particles emitted during the landing and take-off cycle.

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 2013, CAEP has been developing Engine nvPM mass and number Emissions Certification Standards, following the plan approved by the ICAO Council and the request from the 38th Session of the Assembly (ResolutionA38-17[15]). These new Standards will be added to Chapter 4 (Volume II) to Annex 16 to the *Convention on International Civil Aviation*, where Annex 16, Volume I covers aircraft noise and Volume III addresses aircraft CO_2 emissions.

1.5 The nvPM mass and number Standards have 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 1.1 shows a representative framework of an ICAO Environmental Standard.

[15] Doc 10022, Assembly Resolutions in Force (as of 4 October 2013), ISBN 978-92-9249-419-3, ICAO, 2014

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

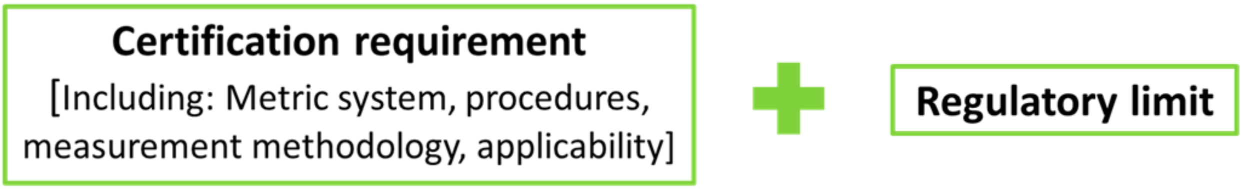


Figure 1.1: The basic framework of an ICAO Environmental Standard

1.6 Phase 1 involved tasks associated with the forming of a certification requirement for the nvPM mass and number Standards, including the development of nvPM emissions evaluation metric systems (i.e. metric/correlating parameter/test points), certification procedures, measurement methodologies, applicability to new engine types, and initial inputs to the cost effectiveness assessment. Phase 2 included the following. (1) Development of the regulatory limit stringency options for in-production and new engine types; (2) considering various combinations of mass and number limits; (3) technology responses from the manufacturers when engines do not meet the nvPM mass and number stringency option combinations (SO); and, (4) the cost effectiveness analyses. The subsequent material is a summary of the nvPM mass and number Standard development work that was conducted through a period of six years (i.e., two CAEP work cycles).

2. CAVEATS, LIMITATIONS AND CONTEXT

2.1 Context: The framework for this analysis does not necessarily represent what would occur in the real world. Specifically, (a) the real world does not ensure that all products of a similar capacity get used equally regardless of price or performance; and (b) the real world does not require in production aircraft or engines to go out of production if they do not perform to a level required of newly certificated types. This analysis uses aircraft and engines that are assumed to be in production at the implementation date to assess the technical feasibility, benefits and costs of the proposed stringency option combinations. When a product no longer responds, results are influenced by the fleet evolution analysis assumptions; and coincidently the remaining fleet tends to be more fuel-efficient.

2.2 Technological Feasibility: For the purposes of the nvPM Standard setting process, CAEP relied upon representative, certificated engines to measure nvPM performance as a basis for technological feasibility and economic reasonableness. In the larger context of technology for improved engine, emissions environmental performance to be used as part of the basis for ICAO certification Standard setting, technological feasibility refers to any technology demonstrated to be safe and airworthy proven to Technical Readiness Level (TRL) 8 and available for application over a sufficient range of newly certificated aircraft.

2.3 Limitations: The information used in the analysis included a mixture of public and non-public data that is subject to change. The data was informed by assumptions unique to this analysis, which limits the applicability of the data to only this work.

2.4 The data and information provided in this document were provided to support the selection of nvPM mass and number Standards by ICAO CAEP in the context of the current ICAO Standard setting process. The in-production fleet and known products scheduled for entry into the fleet by 2023 were used for growth and replacement throughout the full analysis period (i.e., 2012-2042). The analysis did not speculate on potential future technology developments.

2.5 Fleet evolution is an element of CAEP modelling that defines the future fleet and its' deployment on routes and schedules, under different policy options and assumptions regarding the future state of the air transport system. Many of the input assumptions for this modelling are forward-

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

looking and cannot be proven in advance. Thus, there is no certainty that any one baseline predicts what will actually happen in the future.

2.6 Assumptions of engine technology responses to regulatory levels were based on input from both manufacturers and other expert sources. These responses were meant for nvPM cost effectiveness modelling purposes, and do not imply a commitment from manufacturers to develop actual individual products.

2.7 Consequently, the environmental benefits and the costs are comparable relatively 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.

2.8 Recognizing the potential trade-offs between nvPM emissions and fuel efficiency and NOx, a range of trade-offs were modelled with the analysis submitted to CAEP. It should be noted however, regarding the proposed nvPM mass and number Standards for new engine type certificates, engines obtaining new type certificates are required to pass standards for all regulated pollutants. The anti-backsliding nvPM mass stringency proposed for in-production (InP) engines was not assessed.

2.9 Business Jets: Fleet evolution modelling for business jets (BJ) uses all types within a competition bin (CBin) equally without considering capacity, capital or operating costs, with the goal that CBins contain equivalent products in terms of costs and capabilities. However, after the analysis was run it was discovered that two BJ CBins had types with noticeably different capital costs. When some BJ types no longer respond, they were replaced by much less expensive types. This BJ CBin modelling is sufficiently influential that the combined market results are presented with and without the BJ market.

2.10 Two Paths: The analysis for the potential CAEP/11 nvPM mass and number Standards included a portion of the growth and replacement fleet modelled in two ways. Small and medium wide-bodied passenger aircraft were originally defined from the fleet forecast as CBin-9 (211 to 300 seats) and CBin-10 (301 to 400 seats). That fleet forecast-based approach was modelled as "**Path-B**" with CBin-9 and CBin-10 separated. An alternative "**Path-A**" approach modelled CBin-9/10 together. These different paths along with the equal product market share assumption resulted in a noticeable difference in the distribution of baseline operations. The original fleet forecast (Path-B) has an 82% to 18% distribution for the small and medium WB-PAX types; but 47% to 53% in the alternative (Path-A) modelling. The two paths have no noticeable consequence for the analysis until SO10 (mass5 #1) when some WB-PAX types no longer respond. Under Path-A, some small WB-PAX baseline operations are replaced by medium WB-PAX types at SO10 resulting in a noticeable capital cost increase. Results for the analysis are presented for all SO using the original fleet forecast (Path-B), as well as the alternative (Path-A) approach for SO10-12a.

3. ANNEX 16, VOLUME II AND THE ENVIRONMENTAL TECHNICAL MANUAL, VOLUME II

3.1 Overview of the nvPM Mass and Number Emissions Evaluation Metric

3.1.1 The provisions contained in the draft update to Part 3 Chapter 4 of Annex 16, Vol. II represent the SARPs for the certification of engine nvPM mass and number emissions for the standard ICAO LTO cycle: 1. The LTO nvPM mass emissions from the measured engines normalized by the given engine's rated thrust and plotted against the rated thrust; 2. The LTO nvPM number emissions from the measured engines normalized by the given engine's rated thrust and plotted against the rated thrust as follows:

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.
An agency of the European Union

3.1.1.1 nvPM Mass Metric Value:

$$\frac{LTO_{nvpm\_mass}}{F_\infty} = \frac{\sum_{LTO} t_m \times W_f \times EI_{nvpm\_mass}}{F_\infty}$$

3.1.1.2 nvPM number Metric Value:

$$\frac{LTO_{nvpm\_num}}{F_\infty} = \frac{\sum_{LTO} t_m \times W_f \times EI_{nvpm\_num}}{F_\infty}$$

Where: t_m time in mode [seconds s], W_f is the fuel flow [kg/s] and EI_{nvpm_mass} is the nvPM mass emissions index [mg/kg of fuel], EI_{nvpm_num} is nvPM number emissions index [particles/kg of fuel] and F_∞ is the rated thrust [kN].

3.2 **The Environmental Technical Manual (ETM), Volume II**

3.3 An update to Part 3, Chapter 4 of the Environmental Technical Manual, Volume II (ETM, Vol. II) has also been developed to promote implementation uniformity of the technical procedures of Annex 16, Volume II by providing the following: (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 nvPM emissions evaluation metric that may be used in lieu of the procedures specified in those Standards.

4. **STRINGENCY OPTIONS**

4.1 An important part of the Standard-setting process was the definition of the nvPM mass and number stringency options, which could be chosen to represent the eventual limit lines for the nvPM mass and number standards. Each stringency option for nvPM mass and number aimed to maintain the intended behaviour of the nvPM emissions metric; i.e., to equitably reward advances in engine technologies that contribute to reductions in engine nvPM emissions, and to differentiate between engines of different size and with different generations of technologies.

4.2 The development of the nvPM mass and number stringency options was based on the nvPM metric value database (nvPMVdb). The nvPMVdb contained engine test data provided directly from manufacturers and certification authorities on in-production engine types. Most of the measurements were targeted to comply with the CAEP/10 nvPM Standard (applicable from 1 January 2020), which contains the nvPM measurement system requirements, procedure and evaluation of LTO points and as such, the confidential nvPMVdb contained "certification-like" data. Overall, data from 23 engine types was used to develop the metric values and stringency options.

4.3 To correct nvPM emissions to standard day conditions, two proposed ambient conditions correction methodologies for nvPM mass and one for nvPM number were evaluated. Based on the results of the evaluation, it was concluded that additional tests may be needed and further analysis will be pursued in order to be able to propose satisfactory ambient corrections for nvPM mass and number emission indices (EIs), robust enough for inclusion into ICAO Annex 16, Volume II. For stringency options development, the nvPM emission EIs were not corrected for ambient conditions effects. The uncertainty on metric values for not correcting for ambient conditions have been taken into account, with an order of ± 10% for nvPM mass and ± 30% for nvPM number.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.
An agency of the European Union

4.4 Application of fuel corrections was recommended and used the following functions to correct measured nvPM mass and number EIs to a fuel hydrogen content reference of 13.8% mass, hence normalising the nvPM emission values to the reference fuel for the stringency options development:

$$\boldsymbol{k_{FUEL\_M}} = exp\left\{\left(0.95\frac{F}{F_{00}} - 1.12\right)(13.8 - H)\right\}$$

$$\boldsymbol{k_{FUEL\_N}} = exp\left\{\left(0.99\frac{F}{F_{00}} - 1.05\right)(13.8 - H)\right\}$$

where $\boldsymbol{k_{FUEL\_M}}$ is the fuel correction factor for the nvPM mass emission index, $\boldsymbol{k_{FUEL\_N}}$ fuel correction factor for the nvPM number emission index, exp the exponential function, F the thrust in mode [*kN*], F_{00} the rated thrust [*kN*] and H the fuel hydrogen content measured in %mass.

4.5 In contrast to gaseous emissions not being lost in a leak-tight system, any particle measurement system will have losses for particles in the sampling system resulting in nvPM values at instrument level that will always be lower than the values at engine exit plane. The dominant particle loss mechanisms are particle size dependent and are higher for nvPM number than for nvPM mass. Relatively bigger particles penetrate better compared to smaller particles; however, larger particles contribute more to nvPM mass. For example, an engine emitting generally larger particles than a competitor engine would report higher nvPM number levels at the instrument, although it may have similar nvPM number levels at the engine exit plane.

4.6 Based on the state of science informed by data analysis, it was concluded that the metric values could not be corrected for system losses with confidence while noting that not correcting for system losses may lead to some bias between engine metric values especially for number emissions, despite the use of standardised measurement systems. This potential bias was not taken into consideration in the stringency options development for the following additional reasons. (1) The certified metric value of an engine depends on its own performance, not on the relative performance of another engine; and (2) the unintended consequence of not addressing the potential bias could be an incentive to design engines to emit even smaller particles. However, the proposed CAEP/11 Standard makes use of two metric systems, for nvPM mass and nvPM number, which work together. If particle sizes are reduced and e.g. the particle number does increase, the particle mass is reduced but the particle number will be higher. The measurement system is less responsive to the smallest particles but it does not cut them off and is still measuring them. The metric values for nvPM mass and number in the nvPMVdb show that in general, engines with a lower number emit less mass.

4.7 **nvPM Mass Stringency Options**

4.7.1 A specific nvPM mass regulatory limit for in-production (INP) engines with a proposed applicability date of 1 January 2023 was derived based on the measured data. The INP regulatory limit is designed to be an anti-backsliding Standard. Given the fact that a number of small engine technologies had relatively higher metric values, the INP regulatory limit has a decreasing metric value as thrust increases until the 200 kN kink point. For engines with rated thrusts greater than 200 kN, the data indicates no trend in metric values and therefore a constant metric value is chosen to provide the INP regulatory limit.

4.7.2 The five New Type (NT) nvPM mass stringency options are chosen with a 150 kN kink point. The 150 kN is chosen because: a) it is the best mathematical fit to the clusters of data from different technologies; and b) this allows for reduction in severity of stringency for engines of rated thrust below 89 kN without being very lenient. Above a rated thrust of 150 kN, the five stringency options have been prescribed as per cent reductions from NT-1 (0%, 16%, 44%, 72% and 82%) for which the metric value is set at 250 mg/kN. Below a rated thrust of 150 kN, these five options

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

provide increasing margin to smaller engines due to associated technical challenges (200 per cent alleviation for NT-1 through NT-4 and 30 per cent for NT-5). Table 4.1 are the equations for the nvPM mass stringency lines are shown in Figure 4.1.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

Table 4.1: nvPM Mass Stringency Equations for In-Production (INP) and New Type (NT) Engines

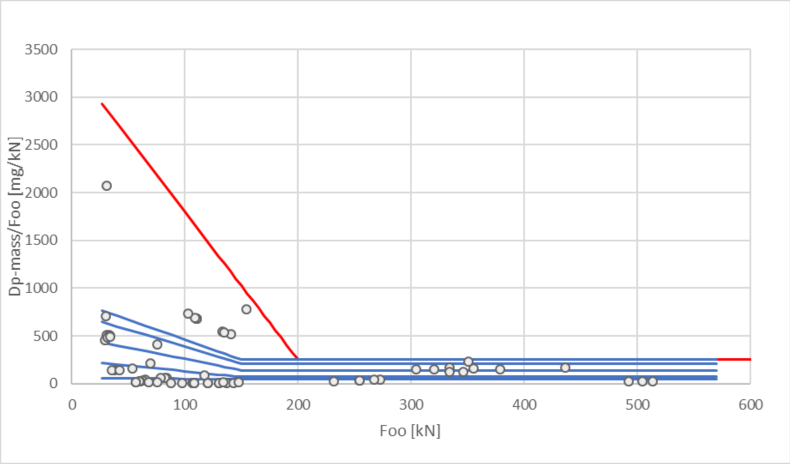
nvPM Mass Stringencies	Equations	Rated Output Range
INP	3343 – 15.465 F_{00}	26.7kN < F_{00} < 200 kN
	250	$F_{00} \geq$ 200 kN
NT-1	879.1 – 4.19 F_{00}	26.7kN < F_{00} < 150 kN
	250	$F_{00} \geq$ 150 kN
NT-2	738.4 – 3.52 F_{00}	26.7kN < F_{00} < 150 kN
	210	$F_{00} \geq$ 150 kN
NT-3	492.3 – 2.35 F_{00}	26.7kN < F_{00} < 150 kN
	140	$F_{00} \geq$ 150 kN
NT-4	246.1 – 1.17 F_{00}	26.7kN < F_{00} < 150 kN
	70	$F_{00} \geq$ 150 kN
NT-5	61.5 – 0.11 F_{00}	26.7kN < F_{00} < 150 kN
	45	$F_{00} \geq$ 150 kN

Figure 4.1: Proposed nvPM Mass Stringency Options.

The red line is the In-Production Regulatory Limit.

The blue lines represent the five proposed New Type nvPM Mass Stringency Options.

The circles are metric values obtained from the list of representative in-production engines in the nvPMVdb.



4.8 nvPM Number Stringency Options

4.8.1 One nvPM number stringency level for in-production engines with a proposed applicability date of 1 January 2023 was derived based on the cluster of data points across the thrust range. This necessitates a kink point at 200 kN. Given the trend of nvPM number metric values across the thrust range, use of one kink point is justified to represent this anti-backsliding stringency line.

4.8.2 The NT nvPM number stringency options are derived to be consistent with the mass stringency levels with a 150 kN kink point. The number of stringency options is limited to three, based on the analysis that reduction in nvPM mass does not translate to similar reductions in nvPM number metric values. Above a rated thrust of 150 kN, three stringency levels have been prescribed as per cent reductions from NT-1 (0%, 33% and 66%) for which the metric value is set at 3×1015 #/kN. The strictest stringency level for nvPM number has more margin to the best performing engines than for nvPM mass. Below a rated thrust of 150 kN, these three levels provide increasing margin to smaller engines due to associated technical challenges (200 percent alleviation for NT-1 through NT-3). The nvPM number stringency levels are shown in Figure 4.2. The equations for these lines are shown in Table 4.2.

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

Figure 4.2: Proposed nvPM Number Stringency Options.

The red line is the In-Production Regulatory Limit.

The blue lines represent the three proposed New Type Stringency Options.

The circles are metric values obtained from the list of representative in-production engines in the nvPMVdb.

There are two additional stringencies for nvPM mass as reducing mass emissions is better understood at this point of time.

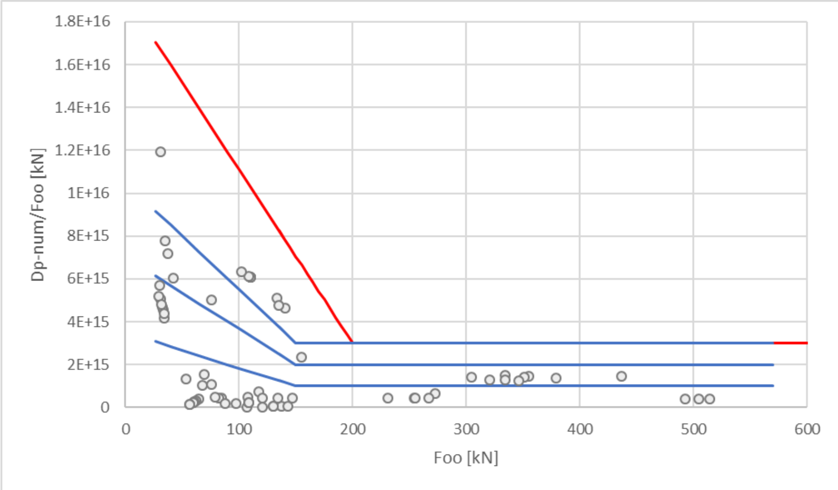


Table 4.2: nvPM Number Stringency Equations for In-Production (INP) and New Type (NT) Engines

nvPM Number Stringencies	Equations	Rated Output Range
INP	$1.92\times10^{16} - 8.1\times10^{13}\ F_{00}$	$26.7kN < F_{00} < 200$ kN
	3.0×10^{15}	$F_{00} \geq 200$ kN
NT-1	$1.05\times10^{16} - 5.0\times10^{13}\ F_{00}$	$26.7kN < F_{00} < 150$ kN
	3.0×10^{15}	$F_{00} \geq 150$ kN
NT-2	$7.03\times10^{15} - 3.36\times10^{13}\ F_{00}$	$26.7kN < F_{00} < 150$ kN
	2.0×10^{15}	$F_{00} \geq 150$ kN
NT-3	$3.52\times10^{15} - 1.68\times10^{13}\ F_{00}$	$26.7kN < F_{00} < 150$ kN
	1.0×10^{15}	$F_{00} \geq 150$ kN

4.9 nvPM Mass and Number Stringency Option Combinations (SO)

4.9.1 For the NT engines cost effectiveness analysis, the five nvPM mass and three nvPM number stringencies were combined to form the twelve stringency option combinations (SO) shown in Table 4.3. The colour differentiation is to indicate that the nvPM mass levels drive the responses for SO2, SO4, SO5 and SO7 to SO12, while the nvPM number levels drive the responses for SO1, SO3 and SO6.

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

. . . **Table 4.3:** nvPM Mass and Number Stringencies Modelled for New Types

	nvPM number Stringency 1	nvPM number Stringency 2	nvPM number Stringency 3
nvPM mass Stringency 1	SO-1		
nvPM mass Stringency 2	SO-2	SO-3	
nvPM mass Stringency 3	SO-4	SO-5	SO-6
nvPM mass Stringency 4	SO-7	SO-8	SO-9
nvPM mass Stringency 5	SO-10	SO-11	SO-12

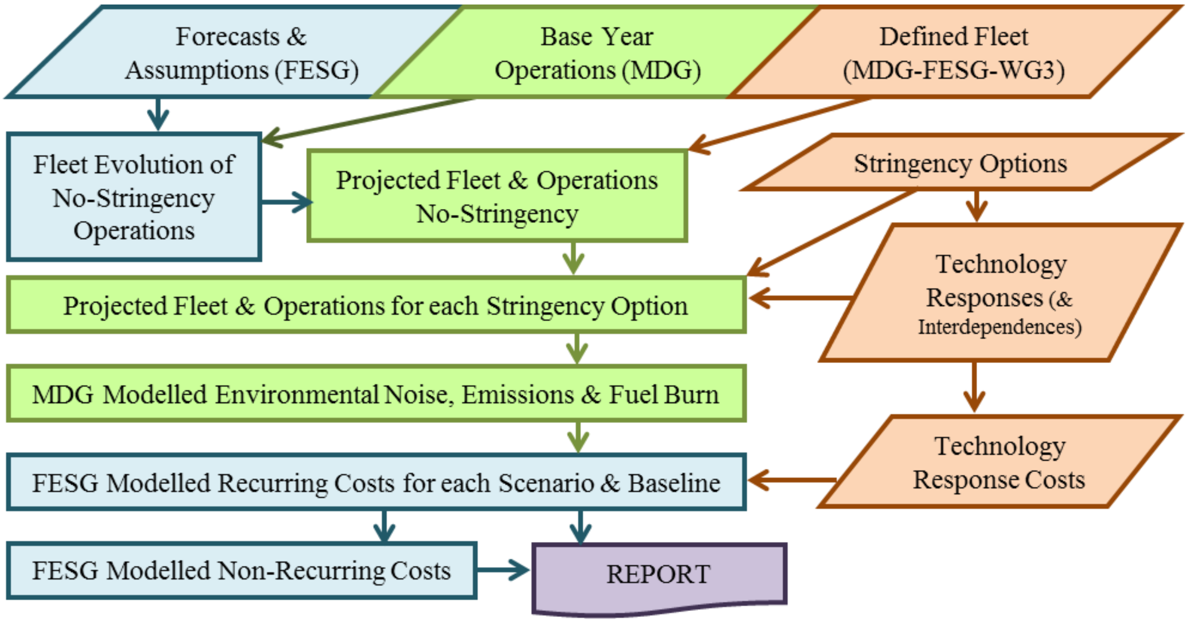
5. COST EFFECTIVENESS ANALYSIS APPROACH

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, and costs per nvPM mass and number emissions avoided. The analysis was conducted with the aim of providing a reasonable assessment of the economic costs and environmental benefits for a potential nvPM mass and number emissions Standard in comparison with a “No ICAO action” baseline. The models that contributed to the analysis are listed in Table 5.1 and a high-level overview of the modelling process is provided in Figure 5.1.

Table 5.1: Contributing Models

	Model	Area	Sponsor
AAT	Aircraft Assignment Tool	Fleet Evolution	EUROCONTROL, EC and EASA
APMT-E	Aviation Portfolio Management Tool for Economics	Fleet Evolution & Costs	US
FCM	FESG Cost Model for nvPM	Cost-Effectiveness	FESG
FAST	Future Civil Aviation Scenario Software Tool	GHG	UK
IMPACT		GHG	EUROCONTROL
AEDT	Aviation Environmental Design Tool	GHG and Noise	US
ANCON	Aircraft Noise Contour Model	Noise	UK
STAPES	SysTem for AirPort noise Exposure Studies	Noise	EUROCONTROL, EC and EASA
MDG Landing and Take-Off cycle (LTO) Consensus Model		LTO Emissions	MDG

Figure 5.2: Analysis Process Overview



5.2 **Defining the Global Fleet**

5.2.1 The analysis process requires defining aeroplane and engine types that enter into the global fleet during the forecast years up to 2042, for both the baseline and each SO. This information is collated into the Growth and Replacement database (GRdb). 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 GRdb 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 GRdb was defined with aeroplane and engine types that are both in-production (INP) and scheduled for entry into the fleet before 2023. For products that remain to be certified, the information required for modelling (project data) were provided by manufacturers. (The analysis did not speculate on potential future technology developments.) The baseline analysis scenario included some INP types going out of production and replaced by types entering the fleet prior to the 2023-implementation year. The transition between these paired types was immediate; i.e., there was no over-lapping "ramp up/ramp down" of production between transition pairs for this analysis. Because the transitioning process ended before the 2023 stringency applicability year, it had no effect on the results.

5.2.3 Another element defined in the GRdb are competition bins (CBins), which align to the fleet forecast seat classes. There can be a one-to-one relationship between the fleet forecast seat classes and CBins (as was the case for business jets); however, CBins have also been used to separate regional jets and turboprops[16] (which are not separated in the fleet forecast). While CBins are required for the modelling process, results are primarily reported with all markets combined or at a market-specific level. Table 5.2 shows the market shares of all baseline aviation markets combined versus only those subject to the proposed CAEP/11 nvPM mass and number Standards.

. . . Table 5.2: Comparison of All Baseline Path-B (2025-2042) **Operations vs. Those Subject to nvPM**

Market	All Operations	Operations Subject to nvPM	Operations Not Subject to nvPM

[16] Turboprops are not subject to the proposed nvPM mass and number standards

	Market Share	Market Share	Market Share
Narrow Body Passenger (NB-PAX)	55.6%	63.6%	0%
Wide Body Passenger (WB-PAX)	24.8%	28.4%	0%
Turboprops	9.2%	0.0%	73%
Business Jets (BJ)	7.6%	6.1%	18%
WB-Freighters	1.7%	1.5%	3%
NB-Freighters	1.1%	0.4%	6%
Total	100%	100%	100%

5.3 Two Paths

5.3.1 The analysis for the potential CAEP/11 nvPM mass and number Standards included a portion of the GRdb fleet modelled in two ways. Small and medium wide-bodied passenger aircraft were originally defined from the fleet forecast as CBin-9 (211 to 300 seats) and CBin-10 (301 to 400 seats). That fleet forecast-based approach was modelled as "**Path-B**" with CBin-9 and CBin-10 separated. An alternative "**Path-A**" approach modelled CBin-9/10 together. These different paths along with the equal product market share fleet evolution modelling assumption resulted in operations being distributed differently between the small and medium WB-PAX aircraft, as shown in Table 5.3.

Table 5.3: Operations distribution between CBin-9 and CBin-10 for Path-A and Path-B.

	ALTERNATE PATH-A BSL CBIN-9/10 COMBINED	PATH-A SO10 CBIN-9/10 COMBINED	FORECASTED PATH-B BSL CBIN-9 VS CBIN-10 SEPARATED	PATH-B SO10 CBIN-9 VS CBIN-10 SEPARATED
CBin-9 %	47%	46%	**82%**	**82%**
CBin-10 %	**53%**	**54%**	18%	18%

5.3.2 The "all-market" level results, presented later in the document, indicate whether the small and medium WB-PAX aircraft component is from Path-A or Path-B by the letter after the SO number; e.g., SO10a and SO10b. In most figures, all Path-B SO results are shown along with the Path-A SO10-12a on the right since SO10 through SO12 are where the two paths have the most notable differences in results, and because Path-B represents the original fleet forecast.

5.4 Fleet Evolution Modelling

5.4.1 Fleet evolution models use forecasted fleet and traffic demand as targets to project a scenario-compliant future fleet-specific schedule of operations and generate required inputs for the environmental models. The fleet evolution modelling process requires the following. (1) Base-year data, including a fleet-specific schedule of operations and the age profile for the base-year fleet. (2) The GRdb defined for the baseline (no stringency) and for each SO, and including seat/capacity assumptions for each aircraft/engine. (3) Fleet and traffic forecast targets along with compatible (4) aircraft retirement curves.

5.4.2 Depending on the "fleet choice" assumption used for particular analysis, costs can also be required for fleet evolution modelling. However, the fleet choice assumption for the CAEP/11 nvPM mass and number Standard analysis was "Equal Product Market Share" in which each available (scenario compliant) aircraft/engine within a competition bin is used equally (without considering operating costs).

5.4.3 The fleet-specific schedule of operations varies from the baseline when a GRdb entry does not respond to an SO, and is assumed to go out of production at the implementation date. The technology response nvPM Improvement (NI) levels do not impact fleet selection. Therefore, the fleet evolution modellers only needed to model four scenarios to represent the twelve SO defined for the cost-effectiveness analysis. This point is highlighted in Table 5.4; namely, a run where all engine

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

families remain in the analysis; a run where one drops out of the analysis; a run where two drop out of the analysis; and a run where eleven drop out of the analysis.

. . . Table 5.4: Summary of Engine Family nvPM Technology Responses

	BSL	SO1 m1n1	SO2 m2n1	SO3 m2n2	SO4 m3n1	SO5 m3n2	SO6 m3n3	SO7 m4n1	SO8 m4n2	SO9 m4n3	SO10 m5n1	SO11 m5n2	SO12 m5n3
Pass	33	31	28	26	23	22	21	18	18	18	13	13	13
NI1	0	0	1	1	1	1	0	1	1	1	0	0	0
NI2#	0	1	1	3	2	2	1	0	0	0	0	0	0
NI2M	0	0	2	1	2	2	0	2	2	2	1	1	1
NI3	0	1	1	1	5	5	9	10	10	10	8	8	8
No Response	0	0	0	1	0	1	2	2	2	2	11	11	11

5.4.4 When a growth and replacement fleet option (GRdb type) does not respond to an SO, the consequence varies by how much the remaining CBin growth and replacement options differ from the GRdb type(s) that do not respond. Apart from emissions improvements, the change from baseline stringency-results become more pronounced the more a stringency scenario fleet otherwise differs from the baseline fleet. Fuel burn and cost elements for individual GRdb types are part of the change; however, capacity differences magnify the change from the baseline because the levels of operations and deliveries change, which results in more (positive or negative) fuel burn, capital and direct operating cost changes.

5.5 nvPM Mass and Number Emissions Modelling

5.5.1 As much as possible, the 2012 base year and GRdb fleets were mapped to measured emission indices (EIs) from the nvPM metric value database (nvPMVdb) and provided directly from manufacturers. However, there were no measured nvPM emissions available for eleven of the thirty-three GRdb engine families represented in the analysis; so, the nvPM mass and number metric values for those engines had to be estimated. Those estimations were based on certified ICAO Smoke Numbers and correlation to nvPM derived-from-measurement comparisons between Smoke Numbers and nvPM.

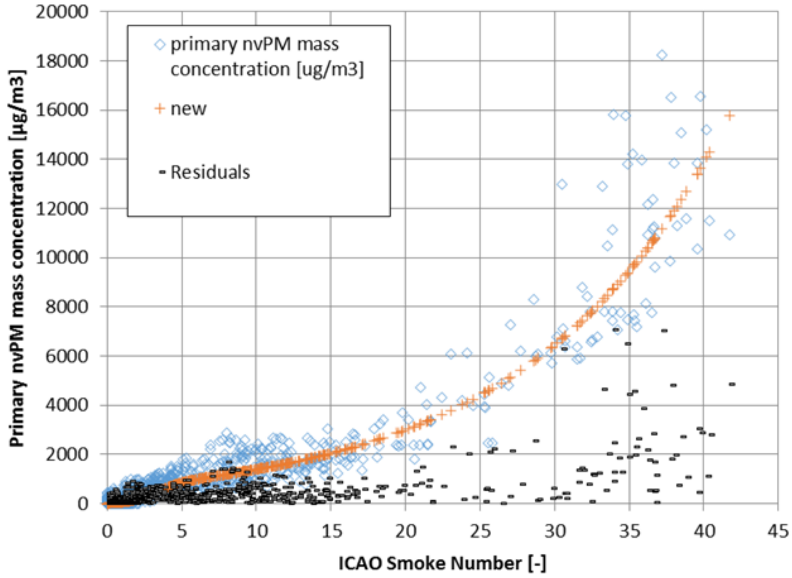
5.5.2 A large set of nvPM mass concentration to Smoke Number pairs was available as more engines were tested and a correlation database (Cdb) was updated using these measurements. With this larger set of data pairs, the Cdb correlation of nvPM mass concentration to SN could be more reliably determined. An improved correlation and the corresponding equations have been derived, based on this more extensive data set. The updated correlation can be expressed as:

$$nvPM\ mass\ concentration\ [\mu g/m3] = \frac{648.4\, e^{(0.0766\, SN)}}{1 + e^{-1.098(SN-3.064)}}$$

5.5.3 This correlation was recommended for use in estimating nvPM mass concentrations when measured nvPM mass data is not available and SN data is available. In particular, this correlation was used to calculate the nvPM mass Emission Index (EI) in conjunction with the Fuel to Air Ratio (FAR) estimation procedure previously developed for the published, so called FOA3 method used before, to estimate PM LTO mass emissions from aircraft engines.

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

Figure 5.2: Updated smoke number to mass concentration correlation



5.5.4 The new Smoke Number to nvPM mass correlation was named SCOPE11 and provides estimations of nvPM mass EIs corresponding to measured values at instrument level of an nvPM standard measurement system required for aircraft engine nvPM emission certification. An additional step was the estimation of nvPM number EIs, which is based on the nvPM mass EIs estimated from smoke number with SCOPE11 as provided by the equation below:

$$nvPM_{EI_{number,i}} = \frac{nvPM_{EI_{mass,i}}}{\left(\frac{\pi}{6}\right) \cdot GMD_i{}^3 \cdot \rho_i \cdot e^{(4.5\,(ln\,\sigma_i)^2)}}$$

Where $nvPM_{EI_{number,i}}$ is the nvPM number EI of LTO mode *i* (idle, approach, climb-out, take-off). $nvPM_{EI_{mass,i}}$ is the nvPM mass EI of LTO mode *i*. GMD_i is the geometric mean diameter of the particles in mode *i* (recommended values used in modelling provided in paragraphs below). ρ_i is the assumed particle effective density (proposed value for all modes 1 g/cm^3). σ_i is the dimensionless geometric standard deviation of an assumed one-mode lognormal distribution (proposed value for all modes 1.8).[17]

5.5.5 Two approaches were used in modelling nvPM number emissions from the mass EIs estimated from Smoke Number.

5.5.5.1 Approach 1: Use of a mode-specific set of GMDs with fixed values for the four LTO modes (GMD = 20 nm at idle and approach, 38 nm at climb-out and 41 nm at take-off thrust conditions).

5.5.5.2 Approach 2: Use a mass concentration-GMD relationship, which was given with the following formula:

$$GMD = 12.5 \cdot C^{0.15}$$

Where C is the nvPM mass concentration in µg/m^3 in the engine core, estimated using the SCOPE11 correlation and the GMD is the geometric mean diameter in nm.

5.5.6 The modellers estimated the nvPM number emissions using both approaches. While nvPM number metric values and emissions estimated using the two approaches were different, this did not adversely affect the technology response. This is because the engines for which the nvPM emissions had to be estimated using Smoke Number were driven by the mass components of the combined stringency options.

17 Note that unit conversion factors may be needed depending on the units used in the formula

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

5.6 **Environmental Modelling**

5.6.1 Landing and Take-Off cycle (LTO) Modelling – Time in mode-based LTO modelling was used with the ICAO/CAEP Modelling and Database Group (MDG) LTO Consensus Model for this analysis.

5.6.2 Project Data – The information required for modelling products that remain to be certified were provided by manufacturers. Modellers applied adjustments to fuel burn and emissions for all project types entering the fleet in the future years. A separate adjustment was also applied to the NOx results when specified. These results were applied as a scalar multiplier to each operation in the LTO dataset.

5.6.3 Trajectory Assumptions – Traditionally, CAEP full-flight greenhouse gas (GHG) emissions and fuel burn modelling has involved the use of great circle trajectory for the underlying origin-destination (OD) pairs as defined in the COD. For this analysis, however, all possible aircraft/engine types were modelled flying 18 representative tracks for the maximum possible range. In addition, each aircraft/engine type was modelled flying the type-specific minimum and maximum OD pair from the 2012 Common Operations Database (COD). Operations from each analysis year were then mapped to one of these tracks and all the parameters were interpolated (except for the minimum and maximum distance in which case the values were directly used) based on the actual and representative OD distances. In addition, AEDT modellers also processed base year 2012 using the traditional modelling method and compared the results with the representative tracks approach. Distance and fuel burn were within 0.5% and all other parameters were within 1% between the two approaches.

5.6.4 Other Environmental Modelling – Trade-off response modelling is the assessment of potential environmental disbenefits that may occur when technology improvements are focused on a single pollutant. While a range from zero to “full” noise and emissions trade-offs were modelled with the analysis submitted to CAEP, engines obtaining new type certificates are required to pass standards for all regulated pollutants; so, that data is not relevant for this document.

5.7 **Cost Modelling**

5.7.1 Recurring – Direct operating costs (DOC) include fuel costs, capital costs (depreciation and finance) and other-DOCs (crew, maintenance, landing and route costs).

5.7.2 Non-Recurring – Because there are no limiting nvPM mass and number standards, there is no historic data on fleet valuation impacts on owner/operators or on how manufacturers will determine the technology response given changes in market demand associated with potential 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 for a potential Standard. 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. However, it should be noted that CAEP has not definitively stated whether AVL costs should be included and therefore the results of the analysis were considered with and without AVL.

5.7.3 NRC was used to represent technology response (TR) costs. It is understood, however, that while NRC capture the fixed cost associated with developing TR to pass a standard level, they do not reflect additional production cost of implementing these responses, i.e., material, labour and other recurring costs. The analysis assumes that the cost of manufacturing remains

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

unchanged before and after TR, whereas the additional technology contained in a TR may cost more to manufacture.

5.7.4 Further details on the NRC assumptions are provided in Section 6.

6. TECHNOLOGY RESPONSE ASSUMPTIONS

6.1 Non-Recurring Manufacturer Technology Response Cost (NRC)

6.1.1 The need for considering the inclusion of manufacturer non-recurring cost (NRC) into the analysis arises from the stringency option combinations where one or more engine-family does not meet a stringency and receives a technology response (TR) to remain in the market. NRC captures the fixed costs associated with developing the TR applied to engine-families so that they pass the standard, but not any additional production costs associated with implementing TR. Thus, NRC does not include material, labour or other recurring costs. WG3 developed the technology responses and defined the non-recurring manufacturer costs. The agreed TR framework, as applied to the GRdb engine-families, is summarized in Table 6.1. The agreed TR framework included single, low and high NRC values. Table 6.2 shows the single NRC values applied for the respective NI levels by SO in the second through fourth columns; the last three columns show the total NRC by SO for the single, low and high NRC values respectively.

. . . Table 6.1: Summary of Engine Family nvPM Technology Responses

	Pass	NI1	NI2#	NI2M	NI3	No Response
Baseline	33	0	0	0	0	**0**
SO-1: NT SO mass1 #1	31	0	1	0	1	**0**
SO-2: NT SO mass2 #1	28	1	1	2	1	**0**
SO-3: NT SO mass2 #2	26	1	3	1	1	1
SO-4: NT SO mass3 #1	23	1	2	2	5	**0**
SO-5: NT SO mass3 #2	22	1	2	2	5	1
SO-6: NT SO mass3 #3	21	0	1	0	9	2
SO-7: NT SO mass4 #1	18	1	0	2	10	2
SO-8: NT SO mass4 #2	18	1	0	2	10	2
SO-9: NT SO mass4 #3	18	1	0	2	10	2
SO-10: NT SO mass5 #1	13	0	0	1	8	11
SO-11: NT SO mass5 #2	13	0	0	1	8	11
SO-12: NT SO mass5 #3	13	0	0	1	8	11

. . . Table 6.2: Manufacturer Non-Recurring Costs for Engine Family Responses

Single Value NRC ($M)	$15	$250	$150	$500	Single Value	Low NRC	High NRC
	NI1	NI2#	NI2M	NI3	NRC TOTAL	TOTAL	TOTAL
SO-1: NT SO mass1 #1	$-	$250	$-	$500	$750	$450	$1,050
SO-2: NT SO mass2 #1	$30	$250	$150	$500	$930	$560	$1,350
SO-3: NT SO mass2 #2	$15	$750	$150	$500	$1,415	$955	$1,900
SO-4: NT SO mass3 #1	$15	$250	$450	$2,500	$3,215	$1,755	$4,700
SO-5: NT SO mass3 #2	$15	$500	$300	$2,500	$3,315	$1,855	$4,800
SO-6: NT SO mass3 #3	$-	$250	$-	$4,500	$4,750	$2,450	$7,050
SO-7: NT SO mass4 #1	$-	$-	$150	$5,000	$5,150	$2,600	$7,700
SO-8: NT SO mass4 #2	$-	$-	$150	$5,000	$5,150	$2,600	$7,700
SO-9: NT SO mass4 #3	$-	$-	$150	$5,000	$5,150	$2,600	$7,700
SO-10: NT SO mass5 #1	$-	$-	$150	$3,500	$3,650	$1,850	$5,450
SO-11: NT SO mass5 #2	$-	$-	$150	$3,500	$3,650	$1,850	$5,450
SO-12: NT SO mass5 #3	$-	$-	$150	$3,500	$3,650	$1,850	$5,450

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

6.2 Non-recurring aircraft owner/operator Asset Value Loss (AVL)

6.2.1 Consistent with prior FESG practice and standard principles of economic analysis, all relevant recurring and non-recurring cost items should be accounted for in the cost analysis of the stringency option combinations. Among these, non-recurring (N-R) owner/operator (O/O) costs may include a loss in fleet value that could be incurred by owners and operators for fleet assets that would not meet a new standard (represented in the analysis by the stringency option combinations). This Asset Value Loss (AVL) is based on the following premises. (1) 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 fleet. (2) The introduction of a new Standard would cause a loss of fleet commonality between pre-Standard assets and new compliant-fleet assets.

6.2.2 The method used in this analysis uses much of the methodology developed for the CO_2 main analysis (CO2ma) that informed the CAEP/10 Standard.[18] As with the CO2ma, fleet assets subject to AVL are all those in the growth and replacement database that do not pass the nvPM stringency option combinations and enter the fleet between the announcement and implementation dates. For example, if the Standard is announced in 2019 and implemented in 2025, AVL would be assessed for aircraft that entered the fleet in 2020, 2021, 2022, 2023 and 2024.

6.2.2.1 How to recognize AVL: It is acknowledged that accounting practices allow for asset value losses and that they are recorded as impairment charges. When there is a change in the operating environment, such as the implementation of a new regulation, negative impacts on an asset's value are recorded in financial statements as an impairment loss.

6.2.2.2 When to recognize AVL: For the purposes of the modelling, an impairment charge is being used as a proxy for the actual realized market value loss, which would be recognized when an aircraft being assessed an AVL is sold. The idea is to consider the loss an operator would incur by selling an aircraft before the end of its economic life at a lower cost than initially estimated when the aircraft was purchased. For this purpose, it is assumed that asset values as projected through depreciation schedules are sensible proxies for resale prices.

6.2.2.3 It is also assumed that the impairment charge calculated at the implementation date will be equal to the loss in value when aircraft are sold when they near the end of the first third of their 25-year economic useful lives, that is, 8 years after their entry into service. This is due to the fact that, under the assumption of parallel depreciation curves, the impairment charge calculated at the Standard implementation date will be the same as the loss in market value observed when an aircraft is sold.

6.2.2.4 Estimating the AVL connected to the nvPM stringency analysis: Similar to the CAEP/8 NOx Standard analysis (NOx/8), the loss of asset value is tied to reduction in value to the engines that do not pass the Standard, whereas engines delivered from the Standard effective date will have technologies that allow them to pass the Standard. The magnitude of the value of the AVL or impairment charge for the current analysis was developed from the NOx/8 work.

6.2.2.5 One method for calculating lost value in engine fleets delivered before the stringency effective date that would not pass the Standard is to estimate the "upgrade" retrofit cost required to allow those same engines to pass the new Standard through engine improvements. For the NOx/8, the engine manufacturer experts had scaled the costs of existing emissions kits to develop cost estimates for hypothetical engine modification packages.

6.2.2.6 Table 6.3 shows the AVL values used for NOx/8 along with the values to use for the nvPM stringency analysis. The values for CAEP/8 were in 2009 US Dollars. The cost analysis for

[18] CAEP/10-IP/06 Appendix E, and to FESG-MDG in CAEP/11-FESG-MDG/6-WP/15, January 2018

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.
An agency of the European Union

nvPM is in 2012 US Dollars. The agreed approach is to use the CAEP/8 values by Modification Status (MS) level and escalate them to 2012 US Dollars. That requires a 1.07 escalation factor.

. . . Table 6.3 – CAEP/8 AVL

CAEP/8 Technology Response	AVL per Engine
MS1: Minor Changes	0
MS2: Scaled Proven Technology	$250,000
MS3: New Technology	$500,000

Table 6.4 – CAEP/11 AVL

Technology Response	AVL per Engine
NI1	0
NI2	$268,000
NI3	$535,000
No Response	$535,000

6.2.3 Table 6.4 presents the escalated values to use for the CAEP/11 nvPM stringency analysis. For CAEP/11, there are significantly more “no technical” responses at the higher stringency option combinations which wasn’t the case for the CAEP/8 NOX Standard analysis. Therefore, an additional impairment charge value is needed for the “no responses” in the CAEP/11 analysis. It has been agreed to use the highest technical response, NI3, value as a proxy. However, it should be acknowledged that with a “no response”, the aircraft goes out of production and the loss of asset value may be underestimated.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

6.3 **Spare Engine Costs**

6.3.1 Spare engines are required by operators to cover scheduled maintenance visits and unscheduled engine removals. By exchanging a ready-to-fly spare engine for an on-wing engine that requires repair, operators can keep their aircraft flying with minimum lost time on the ground while the removed engine is sent to a maintenance provider for servicing.

6.3.2 The introduction of a new Standard would cause a loss of fleet commonality between pre-Standard assets and new compliant-fleet assets. This would incur additional owner/ operator costs to maintain spare engines for the portion of the fleet acquired before the Standard effectiveness date and a separate set of spare engines for the subsequently acquired fleet.

6.3.3 A review and survey were conducted regarding the spare engine assumptions used for the CAEP/6 and CAEP/8 NOx stringency analyses because those were based on 15-year old data that did not consider the business jet market. In addition, there were concerns that assets may be managed differently with the rise of engine leasing.[19]

6.3.4 IATA 2018 inputs were assessed against the CAEP/6 and CAEP/8 assumptions with the conclusion that the requirement for spare engines has trended lower for the commercial passenger and freighter markets than previously calculated.[20]

6.3.5 The business jet segment's investment in spare engines is somewhat similar to the commercial segment, however the business jet operators rely ever more greatly on the engine manufacturers and maintenance repair organizations (MROs) to invest in a pool of engines and make them available to the operator on a rental basis to support scheduled and unscheduled maintenance and inspections. With input from two IBAC member companies, the conclusion was to use the agreed upon commercial fleet spare engine curve to also represent the business jet market. From a global perspective, a similar relationship of spare engines required, measured in terms of percent of in-service fleet, should hold for business jet and commercial operators. The engine manufacturers and MRO providers act effectively in bringing efficiencies to the market by bringing small fleets together to act like a large fleet in terms of spare asset management.

6.3.6 An investigation was made into the relationship between aircraft and engine prices; and the linear regression that is a function of airplane price was used to estimate spare engine prices for the families that require a NI3 technical response to meet certain stringency option combinations. Average engine price was calculated for the engines grouped by aircraft retirement code and the results are presented in Table 6.5.

[19] CAEP/6-IP/13, Economic Assessment of the NOx Stringency Options, and CAEP/8-IP/14, Economic Assessment of the NOx Stringency Scenarios
[20] CAEP/11-FESG-MDG/7-WP/08

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

. . . Table 6.5: Spare Engine Price Assumptions

Aircraft Retirement Code	Spare Engine Price (US2012$ Millions)
B_WB_PAX	$11.3
G_NB_FRT	$6.5
H_WB_FRT	$5.3
A_NB_PAX	$5.1
F_BJ	$3.4

6.3.7 Commonality Factor – The CAEP/8 NOx stringency analysis assumed that the requirements for extra spare engines would apply to 50% of the engines receiving a modification status level 3 (MS3) technology response. It was assumed that the other 50% of engines (receiving a MS3 technology response) could be mixed with the engines that they replaced and so did not require additional spare engines to be acquired. Lacking information to contradict the CAEP/8 assumption, the 50% commonality factor for engines receiving a NI3 response (equivalent to the CAEP/8 MS3 response) for the present analysis.

6.4 **Lost Revenue Assessment**

6.4.1 The cost impact for lost revenue is directly linked to engines receiving a NI3 tech response, where there is a 0% to 0.5% fuel burn penalty trade-off from technology to improve nvPM mass and number. The population of flights (operations) for which this cost impact is assessed is limited to those flights that are operated at long-range distances where the aircraft is operated at its maximum take-off mass (MTOM). For previous CAEP analyses, the percentage of an aircraft's total operations has been on the order of 0% to 2% for narrow body aircraft and 5% for wide body aircraft.

6.4.2 For the current CAEP/11 nvPM stringency analysis, forecast operations have been allocated into separate Competition Bins (CBins) that are organized by aircraft operating up to their MTOW and where the distance bands being operated on exceed the aircrafts' MTOW at full passengers; thus, the operations for these aircraft are at lower payloads to meet the long-range requirements.[21] It is this last set of CBins with long-range missions that would be impacted by an incremental fuel penalty from the NI3 tech response. An amount of payload has to be "off-loaded" so that additional fuel can be loaded to cover the incremental fuel penalty and still operate at a take-off mass that doesn't exceed the MTOM of the aircraft. Cargo is restricted first before blocking off seats to restrict revenue passengers. The reduction in payload to offset the incremental NI3 fuel penalty is approximated by a reduction in revenue belly cargo at a distance where aircraft is operated at MTOM.

6.4.3 To assess the cost impact for lost revenue the first step is to identify the aircraft models that would be impacted. For the CAEP/11 nvPM stringency analysis, the impacted aircraft are models belonging to the wide body segment that at a given level of stringency receive a NI3 tech response. The aircraft impacted for the nvPM stringency analysis are 787, A330neo, A350 and A380.

6.4.4 To simplify the analysis and to protect proprietary data, a single blended value was computed for the payload "off-loaded" at the long-range distances where the aircraft is operated at their respective MTOM.

Average cargo impact from off-loaded payload = 0.17 tonnes

6.4.5 The next step is to choose a representative cargo revenue yield. For the CAEP/8 NOx stringency analysis, cargo yields were determined from comparing IATA 2007 system average yields,

[21] Reduced capacity wide-bodied aircraft were used for operations above 999nmi in CBin-33 (85 seats); above 2499nmi in CBin-34 (100 seats) and CBin-35 (125 seats); above 3499nmi in CBin-36 (150 seats), CBin-37 (175 seats) and CBin-38 (210 seats); and above 6499nmi in CBin-39 (300 seats).

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

yield data collected by a manufacturer from the 2008 Association of European Airlines (AEA) Star Report and data obtained from public sources used as inputs in the APMT-Economics model. The values were reasonably close. The system wide values were adjusted to the 5000 NM distance using the yield - distance adjustment curve. The cargo revenue yield value for CAEP/8 was $$0.26/RTK, in 2009 US Dollars. This cargo revenue yield was inflated to 2012 US dollars using the US Consumer Price Index (CPI) and the resulting value was $0.28/RTK.

6.4.6 The final step is to perform a set of calculations to estimate the lost revenue for each impacted aircraft for the forecast years 2032 and 2042, then interpolate the intermediate years and calculate the cumulative and present value of the lost revenue. The following equation illustrates the approach.

Lost Revenue per year =
Off-loaded payload * C-Bin Distance * Cargo Yield ($0.28 / RTK) * number of operations at MTOM

6.4.7 The lost revenue for each impacted aircraft is then aggregated to report a global cost impact for each stringency option combination.

6.5 Other Costs

6.5.1 In subsequent sections, the label "Other Costs" represents the lost revenue, spare engine, maintenance and incremental build costs.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

7. COST EFFECTIVENESS ANALYSIS RESULTS

7.1.1 As shown in Table 5.4, the nvPM technology responses are slightly different for stringency option combinations SO1 to SO6; but they are the same for SO7 to SO9 and for SO10 to SO12. With these inputs, the cost and benefit consequences will be slightly different for the SO1 to SO6 stringency option combinations. Stringency option combinations SO7 to SO9 are defined by mass stringency 4 and number stringencies 1, 2, and 3, respectively. The same engine family technology responses were provided for SO7 to SO9 because mass stringency 4 is determined to be the driving force for these technology responses. Likewise, SO10 to SO12 are defined by mass stringency 5 and number stringencies 1, 2, and 3, respectively. The same engine family technology responses were provided for SO10 to SO12 because mass stringency 5 is determined to be the driving force for these technology responses. It is therefore understandable that there are identical cost and benefit results for SO7 to SO9, and for SO10 to SO12

7.2 The LTO nvPM mass and number emissions results are shown in Figures 7.1 and 7.2. Note that responding engines get their maximum nvPM Improvement (NI) level as soon as they respond. Thus, when an engine is defined to have an NI3 mass response to pass SO3 through SO9, the NI3 benefits are those achieved at SO9 for all NI3 responses. This response approach results in identical costs and benefits for combined SO7 to SO9, as well as combined SO10 to SO12.

Figure 7.1: LTO nvPM Mass (t) Change from Baseline, Cumulative 2025-2042

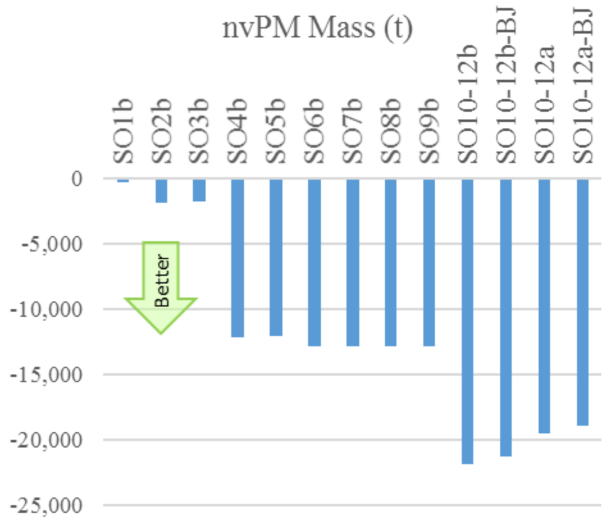
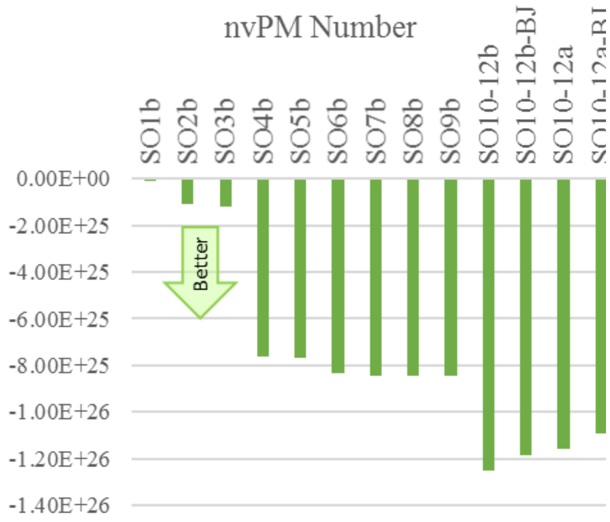


Figure 7.2: LTO nvPM Number Change from Baseline, Cumulative 2025-2042



7.3 The costs calculated included: fuel[22] costs, capital costs (depreciation and finance), other direct operating costs (crew, maintenance, landing and route costs), non-recurring aircraft owner/operator asset value loss (AVL), non-recurring manufacturer technology response cost (NRC), spare engine costs, incremental build costs, maintenance costs and lost revenue for long-range flights that are impacted by the fuel trade-off penalty. In subsequent figures, the label 'Other Costs' represents the lost revenue, spare engine, maintenance and incremental build costs.

7.4 Undiscounted change in cumulative (2025-2042) costs (Billions US2012$) is presented in Figure 7.3a for all markets combined. From left to right results are first shown using the original fleet forecast (Path-B), with SO10 to SO12 shown together (SO10-12b); followed by the Path-B SO10 to SO12 combined results minus the business jet market (SO10-12b-BJ). The last two columns on the right are the alternative (Path A) approach for SO10-12a, and those minus the

[22] Figures reflect the full fuel-burn trade-off penalty, which applied .25% to all operations performed by NI3 responding types.

business jet market (SO10-12a-BJ). Figure 7.3b is also provided to zoom in on the SO1 through SO9 results.

Figure 7.3a: Change in Cumulative Costs (2025-2042, 2012$ Billions)

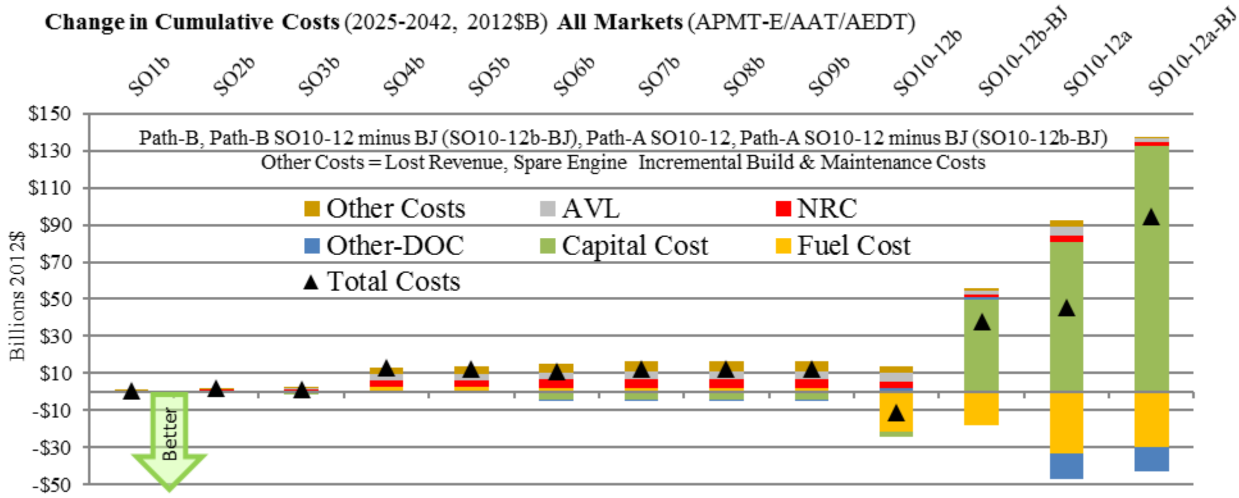
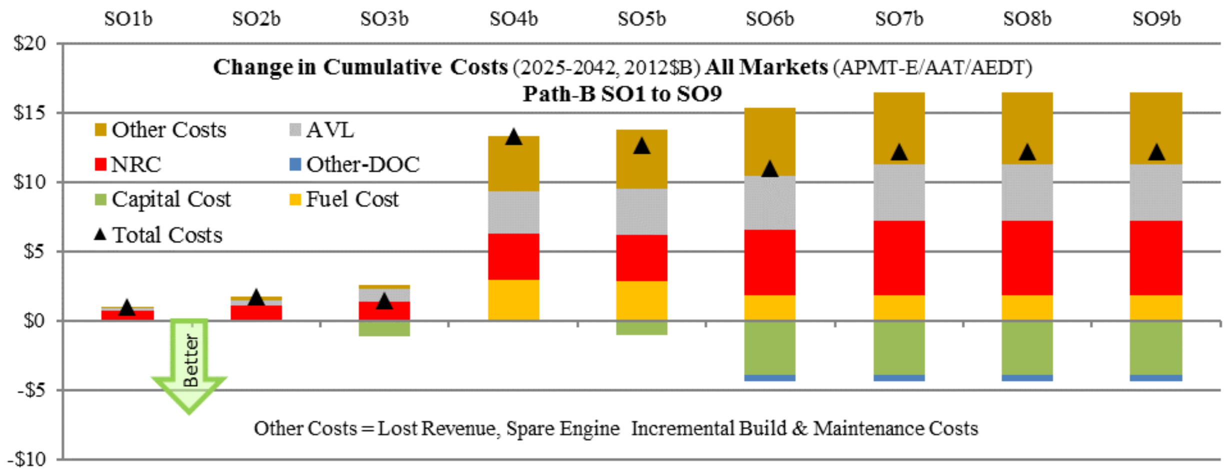


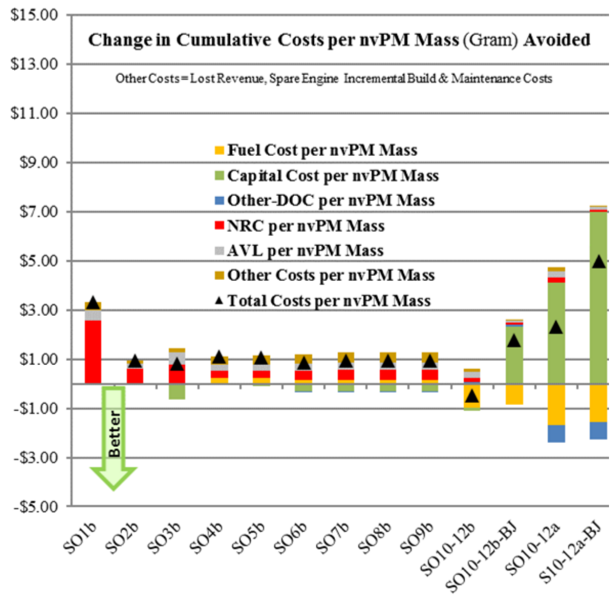
Figure 7.3b: Change in Cumulative Costs (2025-2042, 2012$ Billions) Path-B SO1 to SO9



7.5 Undiscounted change in cumulative costs per nvPM Mass avoided is presented for all markets combined in Figure 7.4. Results for nvPM Number avoided is presented Figure 7.5. The trend of the cost effectiveness ratios for both nvPM Mass and Number show the highest cost for emissions benefit at SO1, where only 7 of 119 GRdb types need to respond. The trend in total cost per emissions benefit is also relatively flat from SO2 through SO9 because the analysis framework required that responding engines meet the maximum stringency option combination defined for an nvPM Improvement (NI) level. Thus, when an engine is defined to have an NI3 mass response to pass SO3 through SO9, the NI3 benefits would be those achieved at SO9 for all NI3 responses.

Figure 7.4: Change in Cumulative Costs per nvPM Mass (Gram) Avoided

Figure 7.5: Change in Cumulative Costs per nvPM Number (10^{16}) Avoided



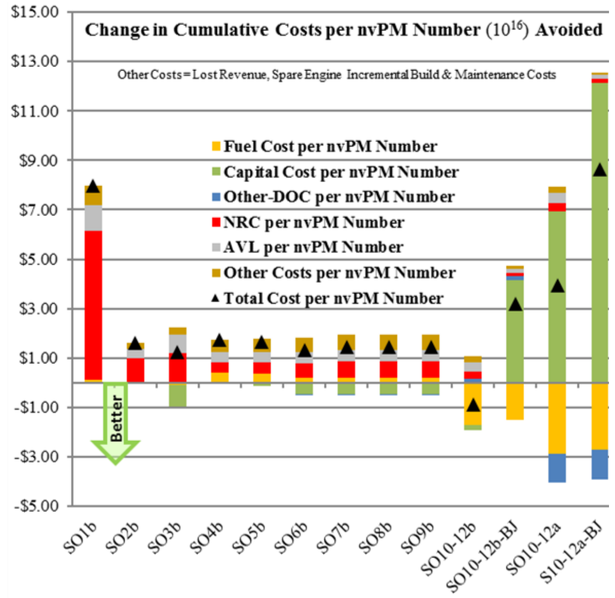
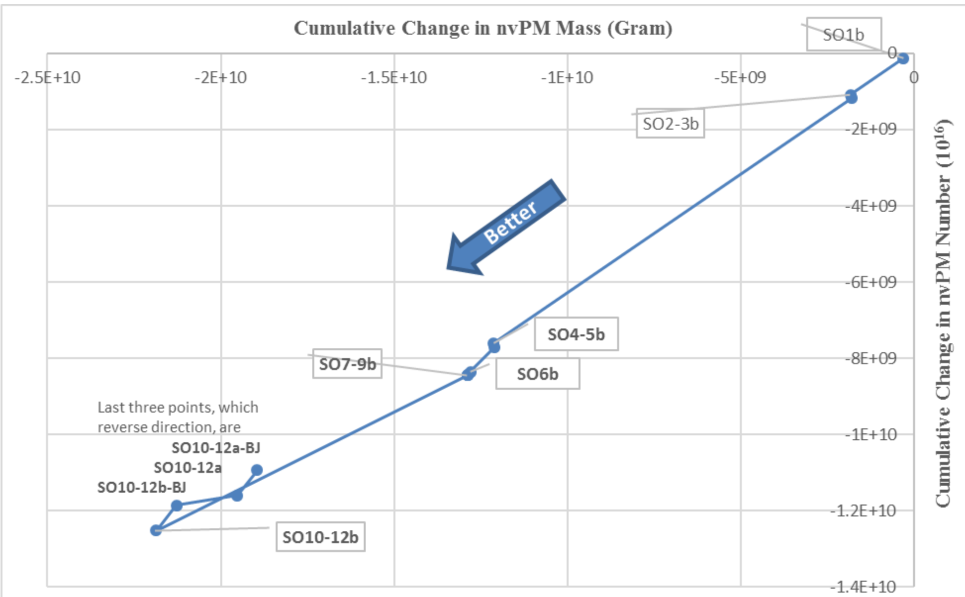


Table 8.1 **Total Costs per**	SO1b	SO2b	SO3b	SO4b	SO5b	SO6b	SO7b SO8b SO9b	SO10b SO11b SO12b	SO10/11/12b Minus BJ	SO10a SO11a SO12a	SO10/11/12a Minus BJ
nvPM Mass	$3.31	$0.96	$0.82	$1.10	$1.05	$0.86	$0.95	-$0.49	$1.79	$2.33	$4.98
nvPM Number	$7.96	$1.62	$1.25	$1.76	$1.65	$1.32	$1.44	-$0.86	$3.21	$3.93	$8.64

7.6 Figure 7.6 plots change in LTO nvPM mass versus nvPM number for all Path-B markets combined, with SO10 to SO12 shown together (SO10-12b); followed by the Path-B SO10 to SO12 combined results minus the business jet market (SO10-12b-BJ). The last points are the Path-A all markets combined for SO10 to SO12 (SO10-12b); and those minus the business jet market (SO10-12a-BJ).

Figure 7.6: Change in nvPM mass and number

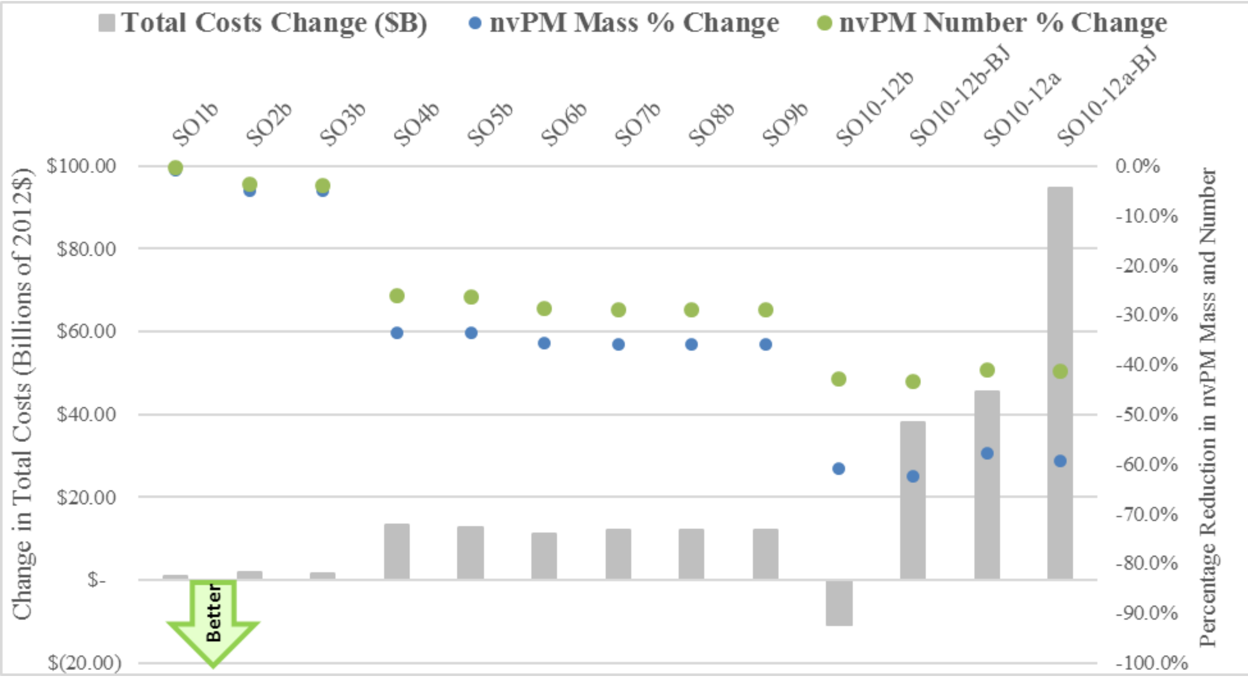


7.7 Figure 7.7 shows the same scenarios with per cent change in nvPM mass (blue dots) and nvPM number (green dots) against change in total cumulative costs (DOC + AVL + NRC + Other) from the 2025 implementation year to 2042.

Figure 7.7: Per cent nvPM Emissions Change and Change in Total Cumulative Costs

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union



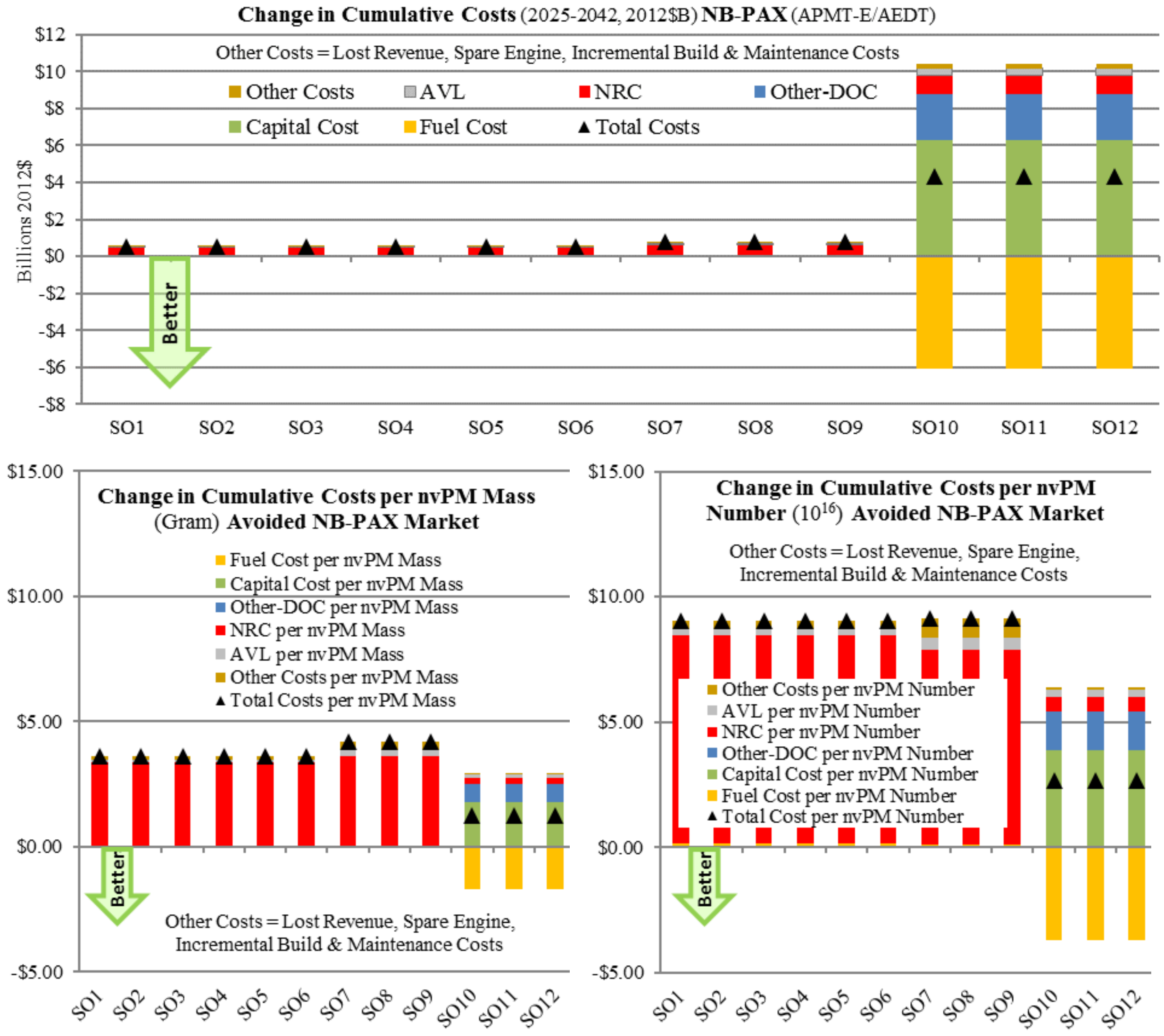
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

8. OTHER RESULT VIEWS

8.1 **Specific Markets:** In this section, undiscounted stringency change from the baseline results are presented for each market. Note that the scale used in the figures varies by market.

8.1.1 **Narrow Body Passenger Market**[23] (NB-PAX): All types remain available in this market through SO9; and for CBin-5 (101-125 seats) and CBin-7 (151-175 seats) all types remain available for all SO. For SO10-SO12 two engine families do not respond, which results in CBin-04 (86-100 seats) and CBin-06 (126-150 seats) capacities decreasing by 1%; operations, flight kilometres and aircraft deliveries increase to meet the forecasted demand. The other NB-PAX CBins maintain their average capacities.

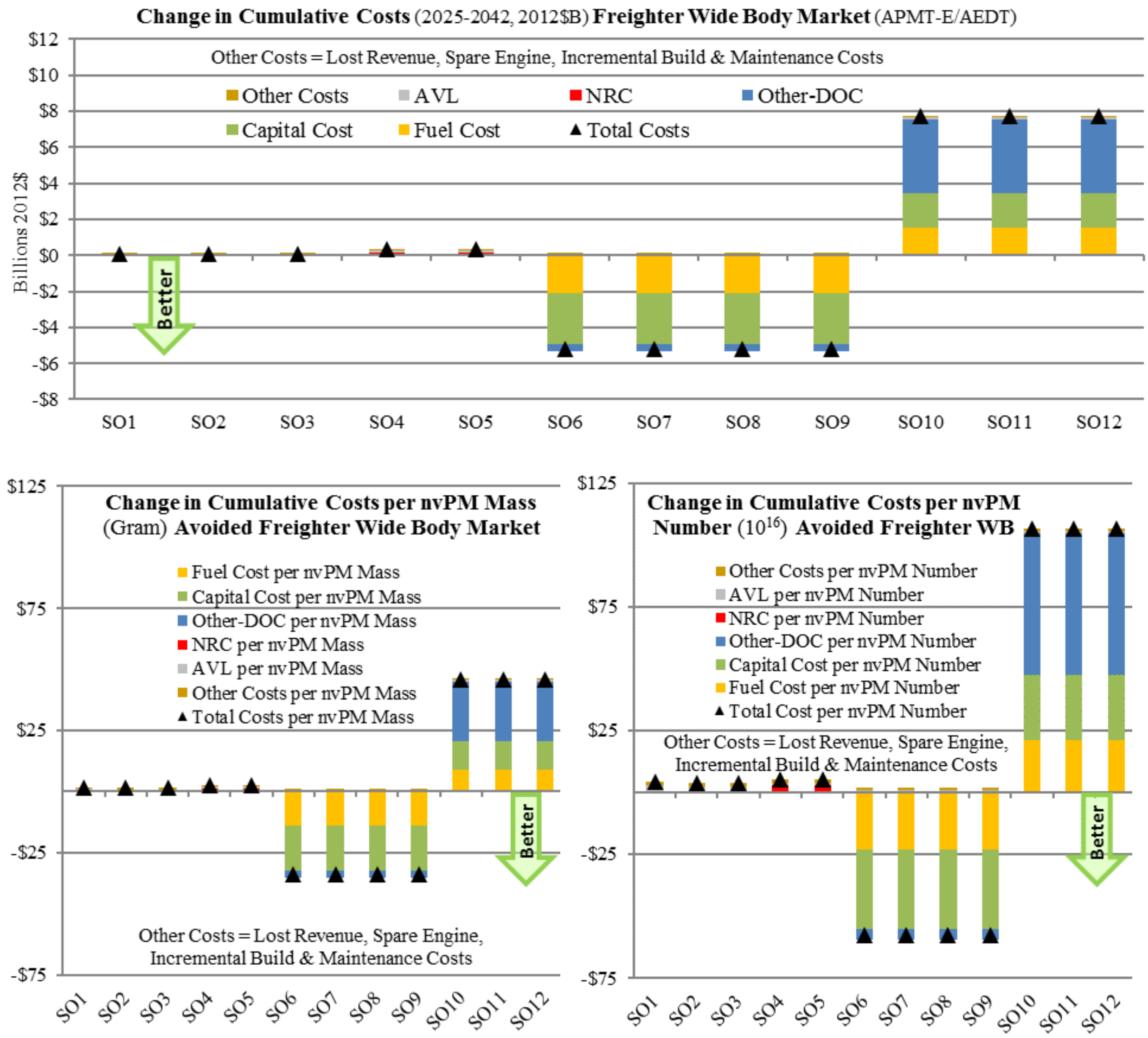
Figures 8.1a-c: Narrow Body Passenger Results



[23] For this analysis regional jets are included in the NB-PAX market.

8.1.2 **Freighter Markets:** The FESG fleet forecast for narrow-bodied freighters (NB-FR) defines all demand as being for passenger-to-freighter converted aircraft, which are not subject to the Standard. Russian and Ukrainian manufacturers are of a different opinion; so there are two NB-FR entries that are included in the modelling. Both of these remain available for all SO. All wide-bodied freighter (WB-FR) types subject to the Standard either pass or respond. Medium wide-bodied freighters (CBin-19) are impacted by engine families not responding at SO6, when average capacity increases by 1%, and at SO10, when average capacity decreases by 14%. For SO6-SO9 when average capacity increases it results in a decrease in operations, flight kilometres and fleet deliveries. For SO10-SO12 when average capacity decreases it leads to an increase in operations, flight kilometres and fleet deliveries.[24]

Figures 8.2a-c: Freighter Results



8.1.3 **Business Jet Market:** Since business jets are assumed to have equivalent capacity within a CBin, there are no capacity consequences such as operational changes or fleet deliveries. There are, however, cost consequences.

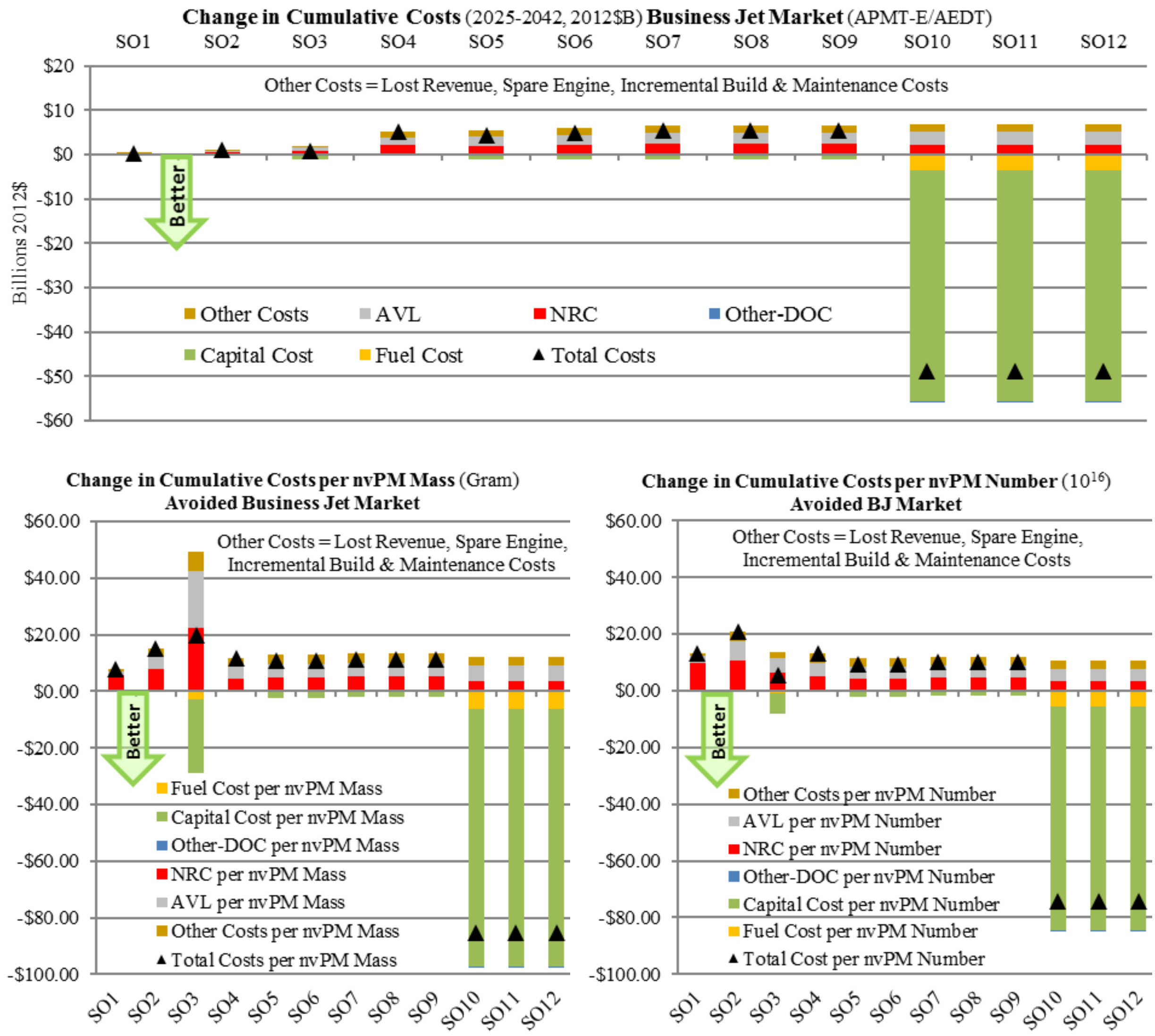
[24] The two fleet evolution models use different capacity metrics; AAT uses ATKs and APMT-E seats. To improve alignment between the two models, the freighter equivalent seat counts in APMT-E were adjusted to more closely reflect the change in payload capacity observed in AAT for the stringencies. The results presented in the Compendium files now show closer operational and fleet alignment between the two models.

8.1.3.1 Light-medium business jets (CBins 27&28) are impacted at SO3 and SO5 and above when one engine family does not respond. Average capital cost decreases 13% in CBin-27 and 3% in CBin-28.

8.1.3.2 Large business jets (CBins 29-31) are impacted at SO10 when 3 of 6 engine families do not respond. Average capital cost decreases 1% in CBin-29, 8% in CBin-30, and 3% in CBin-31.

8.1.3.3 Corporate business jets (CBin-32) are impacted at SO10 when two engine families do not respond. Unfortunately, given the wide range of aircraft prices in this CBin, it should have been subdivided between types above (3) and below (6) the $100M price. However, because they were modelled together the average capital cost drops by 26% when two types priced above $200M do not respond.

Figures 8.3a-c: Business Jet Market Results



8.1.3.4 Concerns: Some feel that it is counterintuitive to see less-expensive BJs replacing more expensive types, which no longer respond at SO10 through SO12. There is also concern that the business jet responses are producing a disproportionate impact on the overall fleet analysis, particularly in terms of capital costs. Figure 5.3b shows the sensitivity results where the corporate business jet market goes from a $29B capital cost saving to a $4B savings when the highest priced variants are no longer available and are replaced with only a similar type priced above $200M.

8.1.4 **Passenger Wide Body Market** (WB-PAX): This market has nine engine families; and all GRdb types remain available through SO9. For CBin-11 (≥401 seats) when one engine family does not respond at SO10, the average remaining capacity is 3% lower. Two engine families are used for CBin-9 (211-300 seats), when one does not respond at SO10 average capacity increases by 1% when CBin-9 is modelled alone (Path-B). Six engine families are used for CBin-10 (301-400 seats), when three do not respond at SO10 average capacity increases by 3% when CBin-10 is modelled alone (Path-B). These capacity increases reduce fleet deliveries, operations and the associated costs.

8.1.4.1 The reason this analysis had a Path-A and Path-B was covered in Section 1.3. The details regarding the Path-A and Path-B fleet evolution modelling results was covered in Section 3.2.6. The impact for capital costs is discussed in Section 5.4.6.

8.1.4.2 Per Table 3.1, the proportion of total baseline operations forecasted for CBin-9 (211-300 seats) is 14.5% and 3.5% for CBin-10 (301-400 seats). So, the assumptions for CBin-9 and how it is modelled have more influence on the analysis than those for CBin-10. Table 8.1 lists technology responses, seats and price assumptions for the wide-bodied passenger GRdb types up to 400 seats; and it shows a smaller price range for CBin-9 versus CBin-10.[25] So, when some GRdb types are no longer available at SO10, the similarity of prices within CBin-9 means the change from the baseline is small if demand is met with only CBin-9 types (Path-B). To break from the forecast and mix CBin-9/10 (Path-A) causes the wider range of CBin-10 prices to significantly influence capital costs.

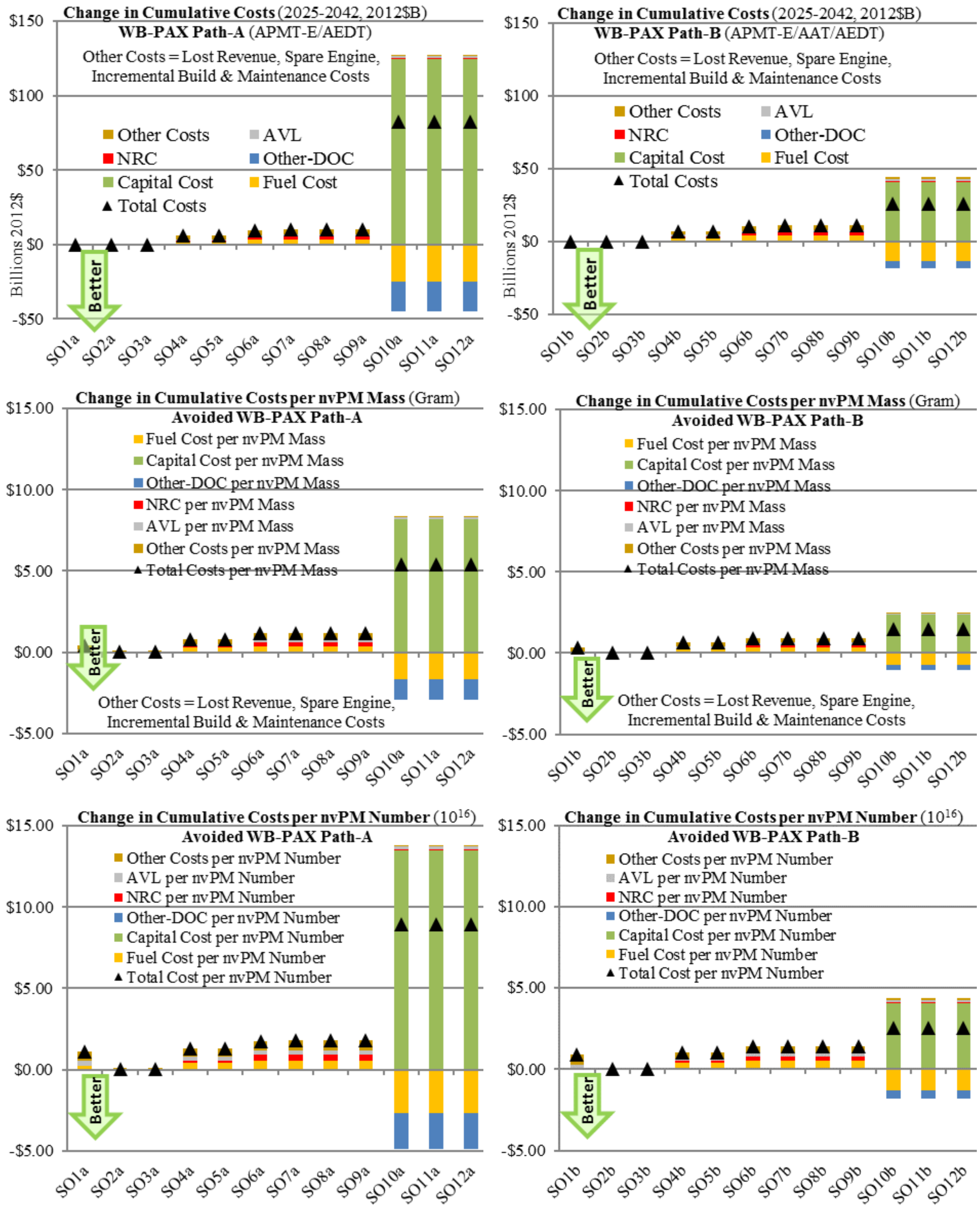
Table 8.1: GRdb wide-bodied passenger technology responses

CBin	SO-1	SO-2/3	SO-4/5	SO-6	SO7/8/9	SO10/11/12	Engine	Seats	Price
CBin-09	Pass	NI1@ SO3	NI3@ SO9	NI3@ SO9	NI3@ SO9	No Response	25	256	$119,435,310
CBin-09	Pass	NI1@ SO3	NI3@ SO9	NI3@ SO9	NI3@ SO9	No Response	25	257	$126,808,000
CBin-09	Pass	NI1@ SO3	NI3@ SO9	NI3@ SO9	NI3@ SO9	No Response	25	277	$132,388,990
CBin-09	Pass	Pass	Pass	Pass	Pass	Pass	07	256	$119,435,310
CBin-09	Pass	Pass	Pass	Pass	Pass	Pass	07	277	$132,388,990
CBin-10	NI3@ SO12	NI3@ SO12	NI3@ SO12	NI3@ SO12	NI3@ SO12	NI3@ SO12	32	350	$141,480,000
CBin-10	Pass	NI1@ SO3	NI3@ SO9	NI3@ SO9	NI3@ SO9	No Response	25	315	$132,388,990
CBin-10	Pass	NI1@ SO3	NI3@ SO9	NI3@ SO9	NI3@ SO9	No Response	25	318	$126,808,000
CBin-10	Pass	Pass	NI1@ SO5	NI3@ SO9	NI3@ SO9	No Response	22	305	$144,100,000
CBin-10	Pass	Pass	NI2M@ SO5	NI3@ SO9	NI3@ SO9	No Response	26	369	$161,392,000
CBin-10	Pass	Pass	Pass	Pass	Pass	Pass	07	315	$132,388,990
CBin-10	Pass	Pass	Pass	Pass	Pass	Pass	08	345	$201,238,972
CBin-10	Pass	Pass	Pass	Pass	Pass	Pass	08	365	$217,338,090

8.1.4.3 The undiscounted change in cumulative costs (2025-2042, 2012$B) and cost effectiveness results for the Path A and Path B WB-PAX market are shown in Figures 8.4a to 9.4f.

[25] Stringencies are clustered when there is no difference between the technology responses.

Figures 8.4a to 8.4f: Wide Body Passenger Market Results for Path-A and Path-B



TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

8.2 Outcome of Path-A and Path-B for All-Markets

8.2.1 Table 8.2 shows the all-market[26] level cost results for Path-A and Path-B for SO4 through SO12.[27] The only difference between the paths is for the 211-400 seat wide-bodied passenger market; i.e., forecast-based Path-B and alternate Path-A for WB-PAX aircraft. For SO10 through SO12, there is an $83.4B capital cost difference between the paths, which is the primary reason total costs shift from being less than the baseline for Path-B to significantly more than the baseline for Path-A.

Table 8.2: Path-A and Path-B Change in Cumulative Costs (2025-2042, 2012$B; All Market Level)

	Path-A	Path-B	Path-A	Path-B	Path-A	Path-B	Path-A	Path-B	Path-A	Path-B
	SO4	**SO4**	**SO5**	**SO5**	**SO6**	**SO6**	**SO7/8/9**	**SO7/8/9**	**SO10/11/12**	**SO10/11/12**
Total Costs	**$11.92**	**$13.37**	**$11.25**	**$12.70**	**$10.01**	**$11.02**	**$11.17**	**$12.18**	**$45.58**	**-$10.79**
Fuel Cost	$1.97	$3.00	$1.87	$2.90	$0.97	$1.84	$0.99	$1.86	-$33.12	-$21.39
Capital Cost	$0.00	$0.00	-$1.05	-$1.05	-$3.92	-$3.92	-$3.92	-$3.92	$80.59	-$2.83
Other-DOC	$0.00	$0.00	$0.00	$0.00	-$0.40	-$0.40	-$0.40	-$0.40	-$13.48	$1.74
NRC	$3.32	$3.32	$3.32	$3.32	$4.75	$4.75	$5.32	$5.32	$3.65	$3.65
AVL	$2.84	$2.98	$3.17	$3.32	$3.74	$3.82	$4.00	$4.08	$5.06	$5.14
Other Costs	$3.80	$4.07	$3.96	$4.22	$4.86	$4.93	$5.19	$5.25	$2.89	$2.90

"Other Costs" = lost revenue, spare engine, incremental build and maintenance costs.

8.2.2 Table 8.3 shows the Path-A and Path-B change in cumulative (2025-2042) total costs (2012$B) for all markets combined, effectiveness (total costs per emissions benefit), and the difference between the paths (last three rows) by stringency option combination (SO).

Table 8.3: Path-A and Path-B Total Cost (2012$B) **Results for All Markets Combined**

2012$ Billions	SO1	SO2	SO3	SO4	SO5	SO6	SO7/8/9	SO10/11/12
Path-A Total Costs	$0.99	$1.75	$1.47	$11.92	$11.25	$10.01	$11.17	$45.58
Path-B Total Costs	$0.99	$1.75	$1.47	$13.37	$12.70	$11.02	$12.18	-$10.79
Path-A Total Costs per nvPM Mass	$3.33	$1.41	$1.21	$1.51	$1.43	$1.10	$1.22	$2.33
Path-B Total Costs per nvPM Mass	$3.31	$0.96	$0.82	$1.10	$1.05	$0.86	$0.95	-$0.49
Path-A Total Cost per nvPM Number	$7.99	$2.43	$1.81	$2.37	$2.20	$1.61	$1.78	$3.93
Path-B Total Cost per nvPM Number	$7.96	$1.62	$1.25	$1.76	$1.65	$1.32	$1.44	-$0.86
Total Costs Difference	$0.00	$0.00	$0.00	-$1.44	-$1.44	-$1.02	-$1.01	$56.36
Total Costs per nvPM Mass Difference	$0.01	$0.45	$0.39	$0.41	$0.38	$0.24	$0.28	$2.83
Total Cost per nvPM Number Difference	$0.03	$0.81	$0.56	$0.61	$0.55	$0.29	$0.33	$4.79

[26] All-markets is the sum of the freighter, business jet, and the narrow and wide body passenger markets subject to the Standard.
[27] Results for SO7 through SO9 and SO10 through SO12 are clustered because they are identical. Results for SO1 through SO3 are in the Compendium files and are within $0.004B for the two paths.

9. CAEP/11 DECISION

9.1 During the CAEP/11 meeting the new nvPM mass and number SARPs were agreed. This included limit lines for nvPM mass and number, that would be applied to in-production and new engine types from 1 January 2023, providing some alleviation for smaller engines. These limit lines were adjusted according to the one engine characteristic level factor, and can be found in the proposed amendments to Annex 16, Volume II contained in Appendix A to Agenda Item 3 of the CAEP/11 Report.

9.2 The CAEP/11 decision amends Annex 16, Volume II, Part IV to include mandatory reporting of nvPM system losses to the certificating authority. The mandatory reporting of system losses allows for proper calculation of nvPM emissions for inventory purposes, is expected to be a minor burden on the competent authority, and is not part of the pass/fail compliance determination of an engine type during the certification process.

Figure 9.1 – nvPM Mass In-Production and New Type Regulatory Limits

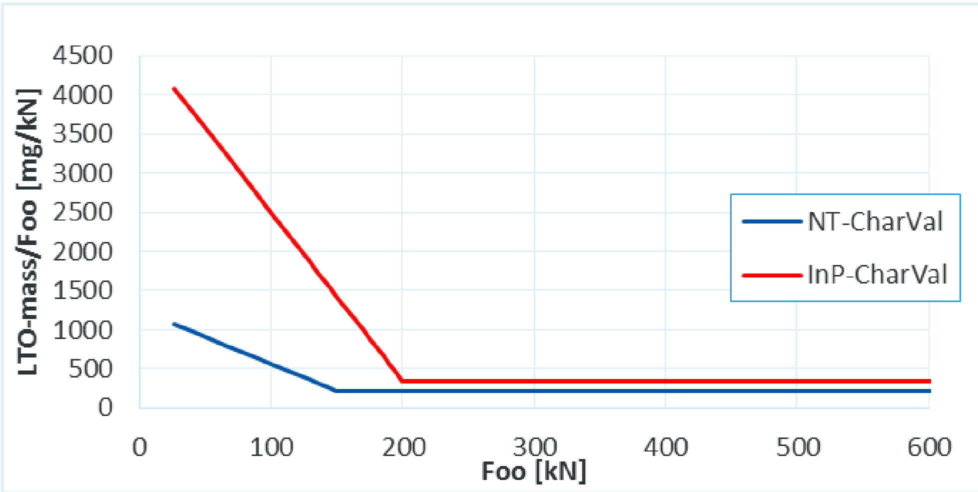
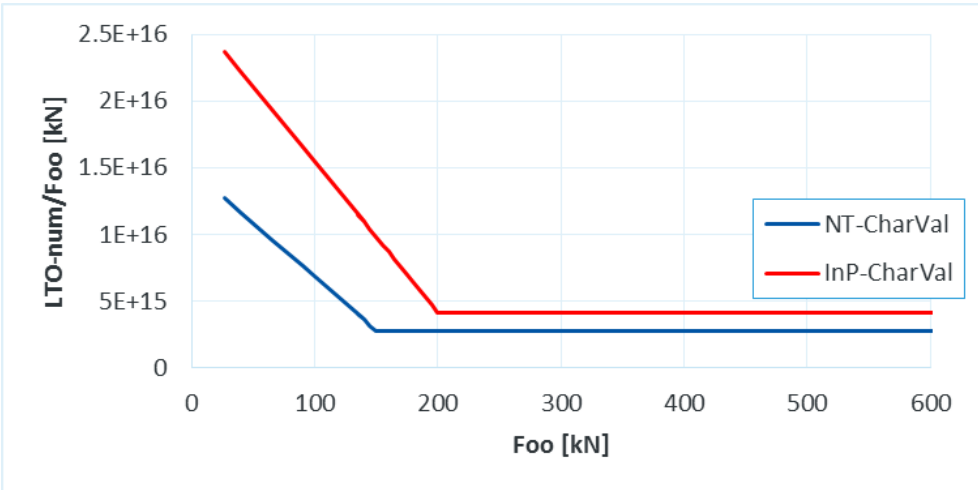


Figure 9.2 – nvPM Number In-Production and New Type Regulatory Limits



TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

7.2.3. Rationale for applicability end date on 1 January 2023 for the smoke number (SN) standard for engines with a maximum rated thrust greater than 26.7 kN (extract from CAEP/11 report (ICAO Doc 10126) Agenda Item 3 – Appendix C 'On the visibility of the exhaust plumes of aircraft engines')

ON THE VISIBILITY OF THE EXHAUST PLUMES OF AIRCRAFT ENGINES

1. INTRODUCTION

1.1 During CAEP/10, a mass concentration limit line was developed with the aim to "transition" towards a regulation "that is equivalent to the existing SN [Smoke Number] Standard" [CAEP10-WG3-PMTG10-WP6]. This transitional mass concentration Standard was developed by correlating SN with mass concentration, shifting this best fit line upwards by ~2 standard deviations and substituting the $SN = f(F_{00})$ limit line relationship into this. The goal of the transition was to allow for the collection of mass concentration data to create the framework for the regulation and thus it was developed to ensure all engines that pass the SN limit line would also pass the mass concentration limit line.

1.2 A corollary of this ~2 standard deviation shift is that statistically we expect approximately 97.5% of engines that lie on the CAEP/10 limit line to be above the SN limit line. A schematic portrayal of this was provided in CAEP11-WG3-PMTG08-Flimsy06. These conclusions suggest that the method used to convert the SN limit line to an equivalent mass concentration limit line does not provide the clarity required for regulatory purposes to assess whether the CAEP/10 limit prevents the visibility of smoke plumes.

1.3 Aerosol optical theory and a visibility criterion can be used to identify the mass concentration at which the smoke plume may become visible, which formed the basis for developing the SN limit line. An introduction to this theory was provided in CAEP11-WG3-PMTG09-Flimsy03, which included a preliminary method to estimate the core nozzle diameter of unmixed turbofan engines. In this paper, we improve upon and extend the analysis presented during PMTG/09 with a validated, iterative gas turbine model used to estimate the exhaust nozzle diameter, a modern update to the optics theory equations and constants, and a model for estimating the transmissivity of exhaust plumes for mixed and unmixed turbofan engines.

1.4 During CAEP/11 meeting it was agreed that 1 January 2023 would be the end date for the applicability of the SN SARPs for engines of a rated thrust > 26.7kN.

2. VISIBILITY OF THE SMOKE NUMBER LIMIT LINE FOR TURBOJETS

2.1 A derivation of the smoke number (SN) that has a transmission of 98% is covered in Munt (1979), which finds that the limit line has a transmission slightly greater than this. This means that, according to the method developed by Munt, the SN limit line conservatively prevents the visibility of an exhaust plume at the 98% transmission level.

2.2 The derivation requires three pieces of information. First, optics theory and associated absorption coefficients gives a relationship to estimate the transmission as a function of concentration and path length. The optics theory is based on a method described in Champagne (1971) and the absorption coefficient is derived analytically in Stockham and Betz (1970) for graphite rather than soot from a kerosene flame. Second, a relationship between mass concentration and smoke number is required, which is also described in Champagne (1971). Finally, a relationship between rated thrust and path length is derived based on measurements made by Munt.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.
An agency of the European Union

2.3 These three parts can be combined together to produce an estimate of the SN with a transmission of 98% as a function of rated thrust. Munt finds this line to lie slightly above the EPA NPRM (equivalent to the SN limit line) as shown in the diagram below.

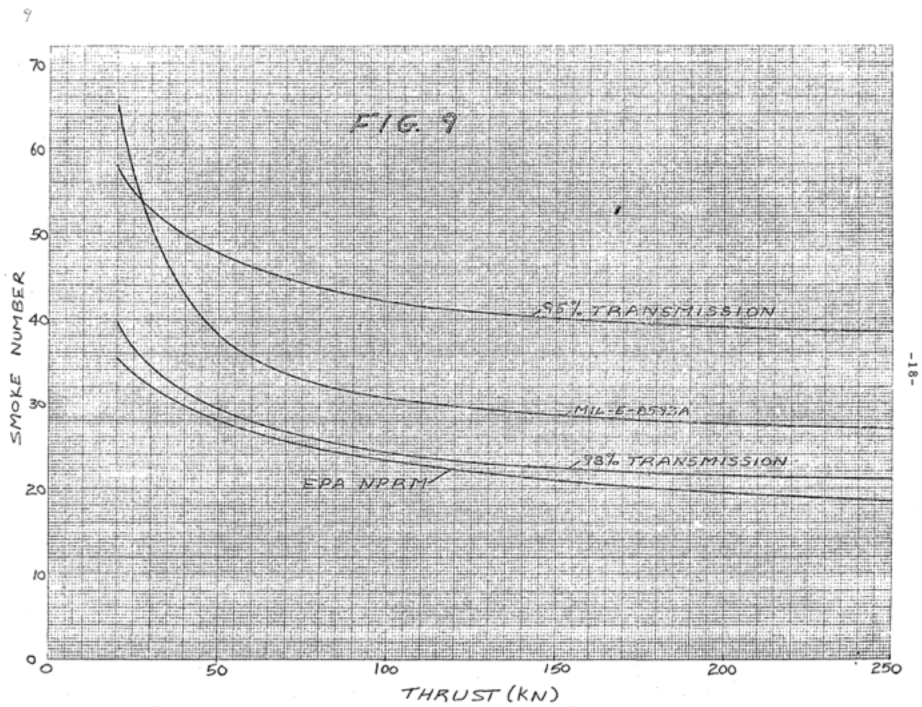


FIGURE B3: RELATIONSHIP BETWEEN SN AND RATED THRUST ADAPTED FROM MUNT (1979). THE EPA NPRM IS IDENTICAL TO THE SN LIMIT LINE, THE MIL-E-8593A IS THE CORRESPONDING MILITARY LIMIT LINE AND THE 98% AND 95% TRANSMISSION LINES ARE DERIVED BY MUNT.

2.4 The analysis by Munt can be reproduced on a mass concentration versus rated thrust basis. This is useful to help identify the mass concentration at 98% transmission according to the method developed by Munt. Unfortunately, the path length versus rated thrust relationship was not provided by Munt, so we use his data points to estimate the best fit line. The relationship is shown in **FIGURE B4** and Eq 1 shows the coefficients and form of the equation.

$$L = 1.23 - 0.95 \cdot e^{-0.011 \cdot F_{00}} \quad \text{Eq 1}$$

where L is the path length in meters and F_{00} is the rated thrust in kN.

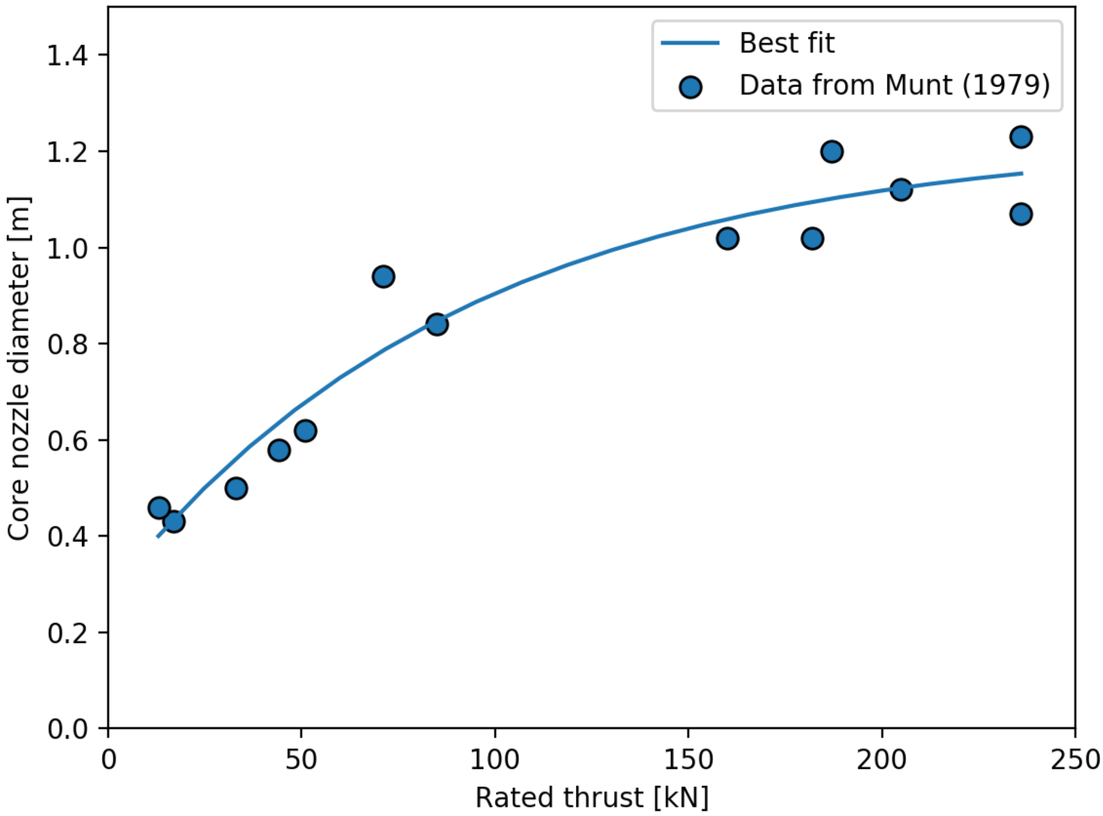


FIGURE B4: BEST FIT LINE BETWEEN RATED THRUST AND CORE NOZZLE DIAMETER USING DATA TABULATED IN MUNT (1979).

2.5 With this relationship, we can apply the optics theory from Champagne (1971) to estimate the mass concentration at a transmission of 98% and 95%, which is shown in **FIGURE B5**. These results suggest that the SN limit line in mass concentration space is at a transmission of ~98% according to this particular optics theory. It is also noticeable that the shape of the 98% transmission points differ from the SN limit line, particularly at low rated thrust. This is an artefact of the relationship between rated thrust and path length, where our best fit line is slightly higher than that derived by Munt at a rated thrust below ~50 kN.

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

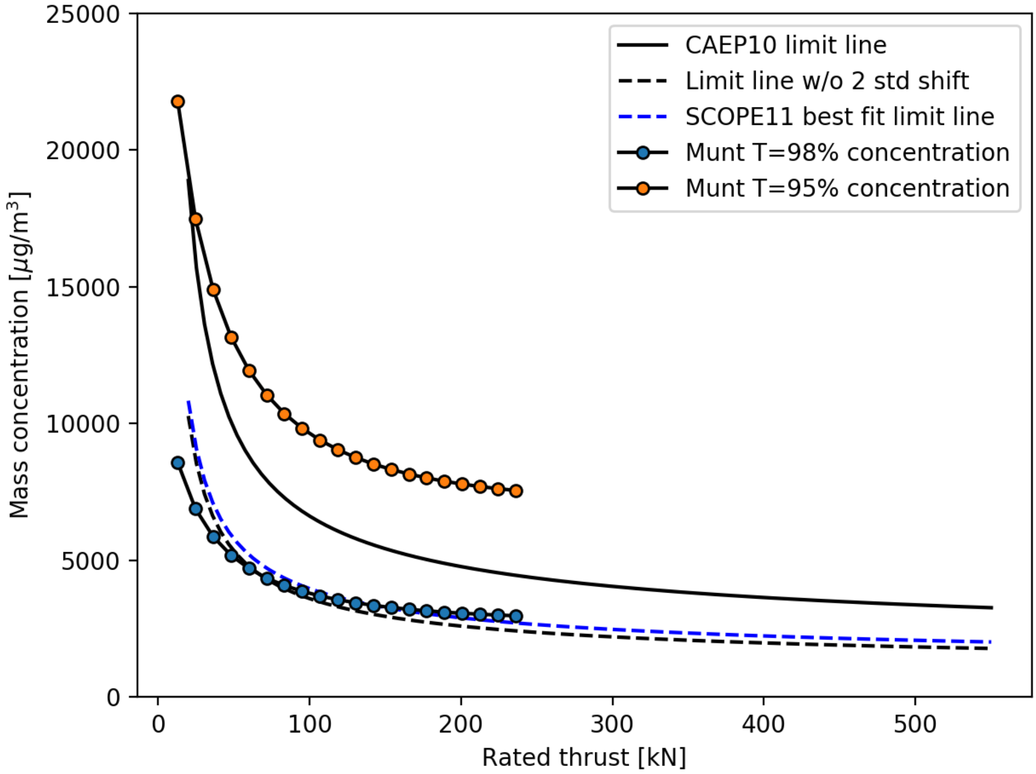


FIGURE B5: MASS CONCENTRATION AT A TRANSMISSION OF 98% (BLUE) AND 95% (ORANGE) AS A FUNCTION OF RATED THRUST DERIVED USING THE SAME METHOD AS IN MUNT (1979). THE SOLID BLACK LINE SHOWS THE CAEP/10 LIMIT LINE, THE DASHED BLACK LINE IS THE LIMIT LINE WITHOUT THE 2 STANDARD DEVIATION SHIFT IN THE SN – MASS CONCENTRATION RELATIONSHIP AND THE DASHED BLUE LINE IS THAT BUT USING THE SCOPE11 RELATIONSHIP.

3. IMPROVEMENTS TO MUNT'S ANALYSIS

3.1 There are three caveats to Munt's analysis which we address.

3.1.1 First, the optics theory that Munt used is now outdated and the modern version of it is shown in Eq 2. In addition, the absorption coefficient was based on theoretical estimates starting from the refractive index of black carbon. Recent literature finds that experimentally measured mass-normalized absorption coefficients are 7.5±1.2 m^2/g at a light wavelength of 550 nm (Bond and Bergstrom (2006)), ~50% higher than the equivalent value in Munt (1979) (~5.76 m^2/g at a wavelength of 490 nm).

$$C_{m,e} = \frac{\rho_{soot}\,\lambda \log(1/T)}{K_e\,L} \qquad \text{Eq 2}$$

3.1.2 Second, the exhaust nozzle diameters tabulated in Munt (1979) were measured from photographs and include the size of the exhaust cone. This means that the nozzle diameters represent the physical outer diameter of the core nozzle, while the area-equivalent diameter would be smaller than this. Instead of using measured values, we have developed a simple turbojet cycle model that is able to estimate the area-equivalent nozzle diameter. The model only requires the overall pressure ratio (OPR) and rated thrust, and assumes values for the air-fuel ratio (AFR) of 55 at rated thrust and

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

that the exhaust nozzle is choked. The full method is described in Appendix J.1 and the final equation to estimate the nozzle diameter is shown in Eq 3.

$$L = \sqrt{\frac{4F_{00}}{\pi \gamma_c P_9}} \quad \text{Eq 3}$$

where F_{00} is the rated thrust in N, $\gamma_c = 1.4$ is the heat capacity ratio in the compressor and P_9 is the static pressure at the exit plane found using the method described in Appendix J.1.

3.1.3 Third, the measurement system upon which the mass concentration limit line was developed corrects all measurements to standard temperature and pressure (STP) conditions and leads to the loss of particles as the flow passes through it. This information was not available to Munt and so we correct to STP conditions by scaling the mass concentration from Eq 2 by the ratio of density at STP (1.2 kg/m^3) to the density at the exhaust of the engine. The latter density can be found using the turbojet cycle model. System losses can be accounted for using the correlation found in the SCOPE11 method that relates losses to mass concentration in reverse.

3.2 Using a subset of engines in the Engine Emissions Data Bank (EEDB), we have used the method introduced by Munt to predict the mass concentration at a transmission of 98%. The results are shown in **FIGURE B6** in the blue circles. We then apply each of the 3 changes discussed earlier to show the effect of the changes.

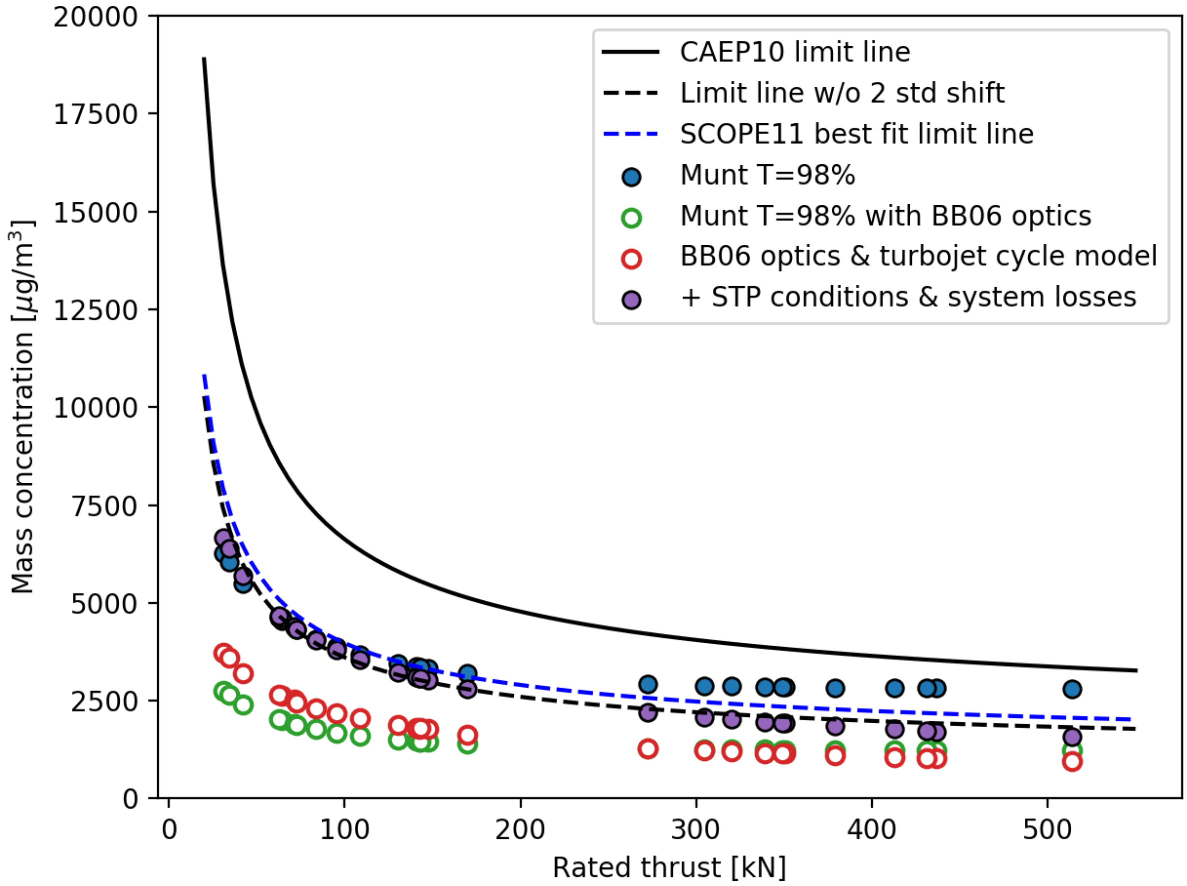


FIGURE B6: THE MASS CONCENTRATION AT 98% VISIBILITY AGAINST RATED THRUST. BLUE FILLED CIRCLES SHOW THE RESULTS USING THE METHOD IN MUNT (1979). THE GREEN

OPEN CIRCLES APPLY THE UPDATED OPTICS THEORY BUT USE THE RATED THRUST TO PATH LENGTH RELATIONSHIP FROM MUNT. THE RED OPEN CIRCLES THEN USE OUR TURBOJET CYCLE MODEL TO PREDICT PATH LENGTH FOR A GIVEN RATED THRUST. FINALLY, THE PURPLE FILLED CIRCLES CORRECT THE RESULTS TO STP CONDITIONS AND INCLUDE THE EFFECT OF SYSTEM LOSSES.

3.3 The green circles use the rated thrust to path length relationship derived by Munt, but use the optics theory and coefficients from Bond and Bergstrom (2006). Relative to the blue circles, we find that the mass concentration at 98% transmission reduces by 44%. This is an expected change since the dimensionless absorption coefficient in Bond and Bergstrom (2006) is ~50% larger than that used by Munt (1979).

3.4 The red circles then include the effect of using our turbojet cycle model to predict the nozzle diameter. In this case, we find the effect on the mass concentration depends on the thrust. On average, the nozzle diameter decreases by 10% compared with Munt (1979) leading to an increase in mass concentration of 13%. At rated thrust above ~300 kN, where the Munt (1979) correlation is extrapolated, the nozzle diameter is 13% larger and the mass concentration is 11% lower.

3.5 Finally, the correction to STP conditions and including system losses has the largest effect on the mass concentration. On average, the mass concentration at 98% transmission increases by 78%. The other noticeable feature is that the purple circles more closely follow the shape of the dashed line.

3.6 The three updates to the method show that we can reproduce the SN limit line in mass concentration space, finding this to have a transmission of approximately 98% for turbojet engines. The modern optics theory reduces the allowable mass concentration and this is offset mainly by the correction to STP conditions.

4. VISIBILITY FOR UNMIXED TURBOFAN ENGINES

4.1 The previous section showed the ability to reproduce the SN limit line in mass concentration space for turbojet engines. In this case, there was a single nozzle that contained all of the emissions and it was this nozzle diameter that we were interested in. For an unmixed turbofan engine, the nozzle is split into a core and bypass stream. The emissions are all contained within the core stream and thus the relationship between the rated thrust and core nozzle diameter is now of interest. Compared to turbojet engines, this relationship is more complicated, so we must develop a new gas turbine cycle model that is capable of modelling unmixed turbofan engines. The optics theory, required correction to STP conditions and artificially including system losses, are all applied in the same way as in Section 3.

4.2 The gas turbine model we have developed extracts the rated thrust, overall pressure ratio, bypass ratio and fuel flow rate at rated thrust from the EEDB and assumes the bypass to jet velocity ratio is fixed at 0.9. The calculation method requires iterating over the fan pressure ratio to begin until we obtain the desired jet velocity ratio. The implementation is conducted in Python and leads to the rapid estimation of the conditions within the engine and thus the core nozzle diameter and exhaust density. This model is described in Appendix J.2.

4.3 To validate the results of iterative model, we have estimated the fan diameter and compared with publicly available values for a range of engines as shown in **FIGURE B7**. The engines chosen include mixed and unmixed engines, however every engine has been modelled as unmixed. Estimating fan diameter requires knowledge of the air mass flow rate through the engine, which is estimated in the iterative model, but also the hub-to-tip ratio of the fan blade. Although this value varies between engines, we assume it to be 0.33 to create **FIGURE B7**.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

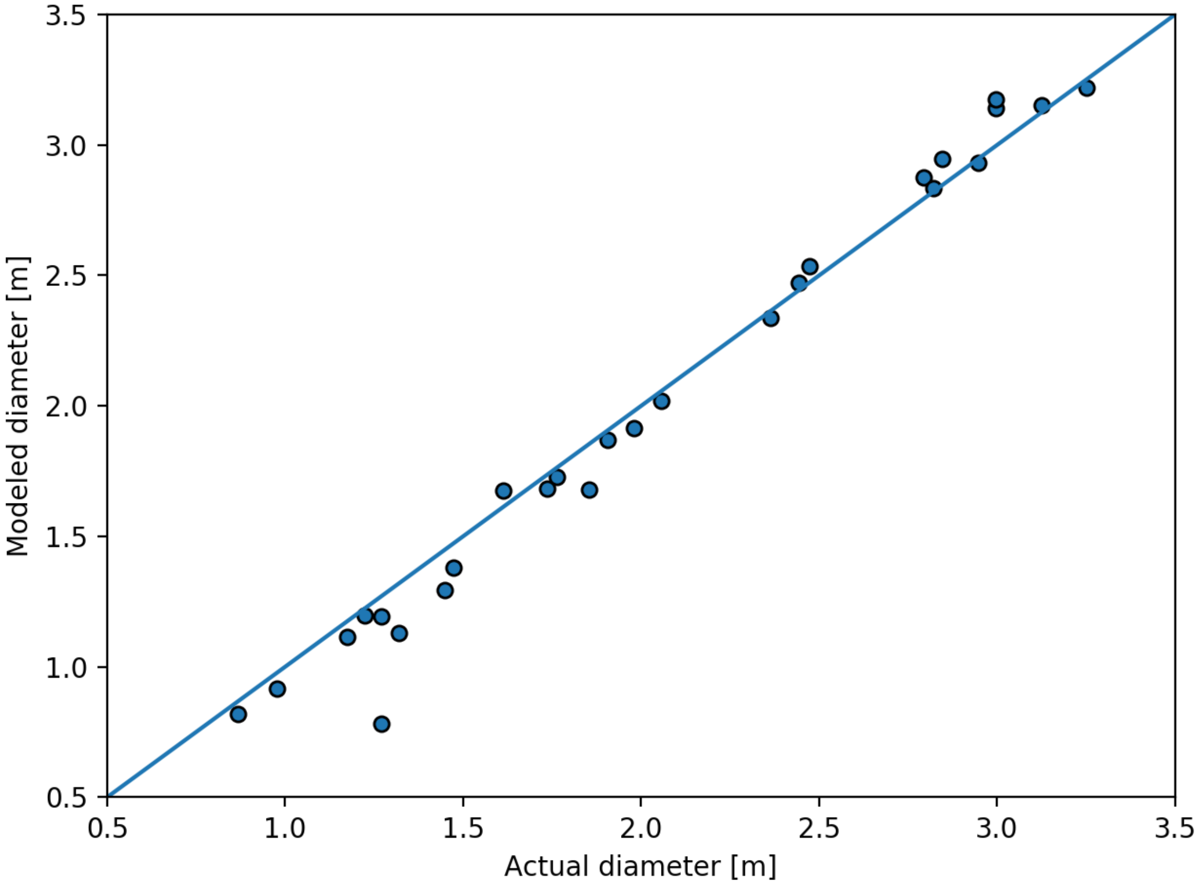


FIGURE B7: ACTUAL VERSUS MODELED FAN DIAMETER [IN]. BOTH MIXED AND UNMIXED ARE INCLUDED, BUT ALL ENGINES ARE MODELED AS UNMIXED.

4.4 We find the error in predicting fan diameter to be 3% on average. There is a skew of -1.56[28] in the residuals and we find too small a diameter at low rated thrust and too large a diameter at high rated thrust. We expect that this is driven by the variation in hub-to-tip ratio as a function of rated thrust. The largest error is 38%, however we expect this is an incorrect measured diameter that includes the size of the nacelle, rather than just the fan blade diameter.

4.5 To further validate the results, we have run simulations in GasTurb, a detailed gas turbine cycle programme, which is capable of modelling a variety of aircraft engine configurations. For unmixed engines, the OPR and BPR were fixed as per the EEDB. Three iteration variables were then set: (1) the turbine inlet temperature until the required fuel flow rate was attained; (2) the fan pressure ratio (FPR) for a fixed jet velocity ratio; and the air mass flow rate for a fixed fan diameter.

4.6 Upon convergence of the GasTurb simulations, we compared the core nozzle diameter with that found using the turbojet cycle discussed above. A comparison of the results is shown in **FIGURE B8**. The error for all engines was found to be less than 5%, except for one engine with an error of 15%. This particular engine was modelled as unmixed, however is actually a mixed-flow engine leading to a larger error in predicting the core nozzle diameter.

[28] A skew between ±2 are considered acceptable to prove normally distributed residual

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

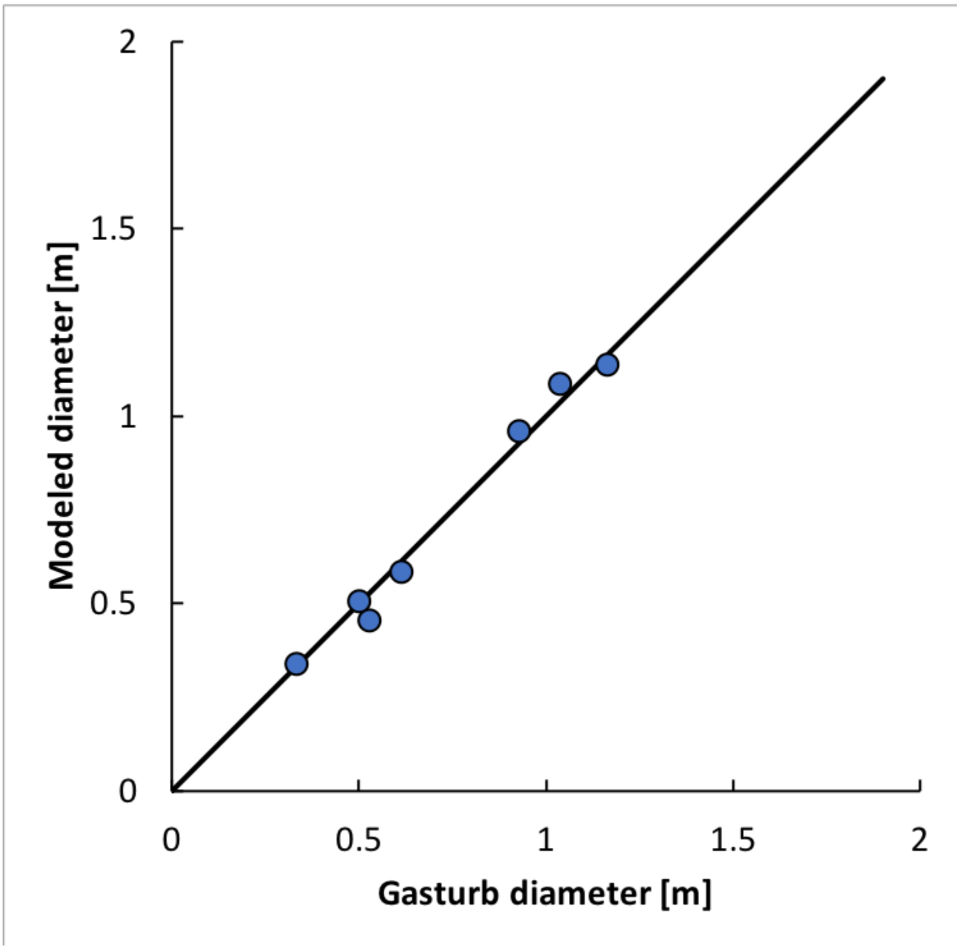


FIGURE B8: COMPARISON BETWEEN CORE NOZZLE DIAMETER FROM GASTURB AND THE MODELED, ITERATIVE GAS TURBINE CYCLE FOR UNMIXED ENGINES.

4.7 We can now apply the diameter estimated using our gas turbine cycle model with the optics theory described in Section 3 to estimate the mass concentration at 98% transmission of unmixed turbofan engines at the exit plane. These results are shown by the orange circles in **FIGURE B9** and include the correction to STP conditions and system losses. We also include the results for turbojets (blue circles).

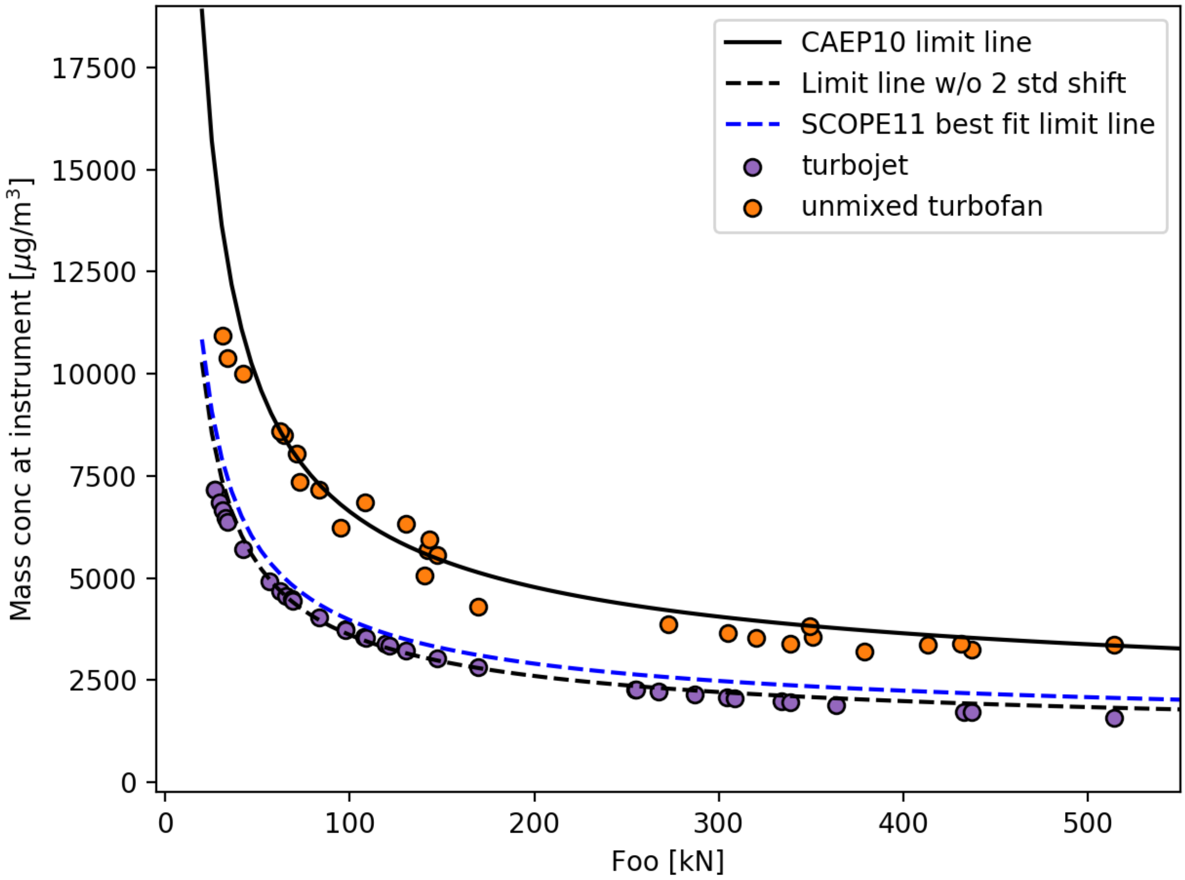


FIGURE B9: THE MASS CONCENTRATION AT 98% VISIBILITY AGAINST RATED THRUST FOR TURBOJETS AS FOUND IN FIGURE B5 IN PURPLE AND FOR UNMIXED TURBOFANS IN ORANGE.

4.8 These results show that the CAEP/10 limit line is at a transmission of around 98% for unmixed turbofan engines. The variation in the results around the limit line is driven by differences in the bypass ratio. Modern engines have gas generators with a higher specific power, driven by improvements in component efficiency and higher turbine inlet temperatures. Furthermore, the trends also have reduced fan pressure ratio for increased propulsive efficiency. These trends result in a smaller core nozzle diameter and larger bypass ratio. Thus, modern turbofan engines have a higher allowable mass concentration to prevent a visibility of 98%.

5. VISIBILITY FOR MIXED-FLOW ENGINES

5.1 The mixing between the core and bypass streams of mixed-flow engines changes the visibility of the plume at the exit plane. Firstly, the relevant nozzle diameter changes. For unmixed changes, we were interested in the core nozzle diameter, but for mixed-flow engines, there is only one exhaust diameter to measure. Secondly, the mixing process leads to a lower density at the exit plane and accordingly a smaller correction to STP conditions. Combining these two effects together, we expect that the mass concentration at a 98% transmission to be lower for mixed-flow engines compared with unmixed engines. At the same time, for a given core nvPM mass concentration, the mixing process reduces the mass concentration at the exit plane by the factor $(1 + \mathrm{BPR})$. This gives mixed-flow engines an advantage under the current CAEP/10 limit line.

5.2 To study the visibility of mixed-flow engines, we must adapt our iterative gas turbine model to account for the mixing process. In the engine, the static pressure at the location of mixing

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

should be equal. This condition requires knowledge of the internal velocities or areas, which is difficult to estimate in our simple model. Instead, we impose that the stagnation pressure must be equal at this stage. Although this is technically incorrect, it may be reasonable if we assume the velocities are low and similar in the core and bypass streams prior to mixing. This model is described in Appendix J.3.

5.3 As with the unmixed engines, we have attempted to predict fan diameter using our predicted mass flow rate and a hub-to-tip ratio of 0.33. The results are shown in **FIGURE B10**, which shows engines that are actually unmixed in blue and engines that are actually mixed-flow in yellow. It should be noted that all the engines were modelled as mixed-flow whether they are actually mixed or unmixed.

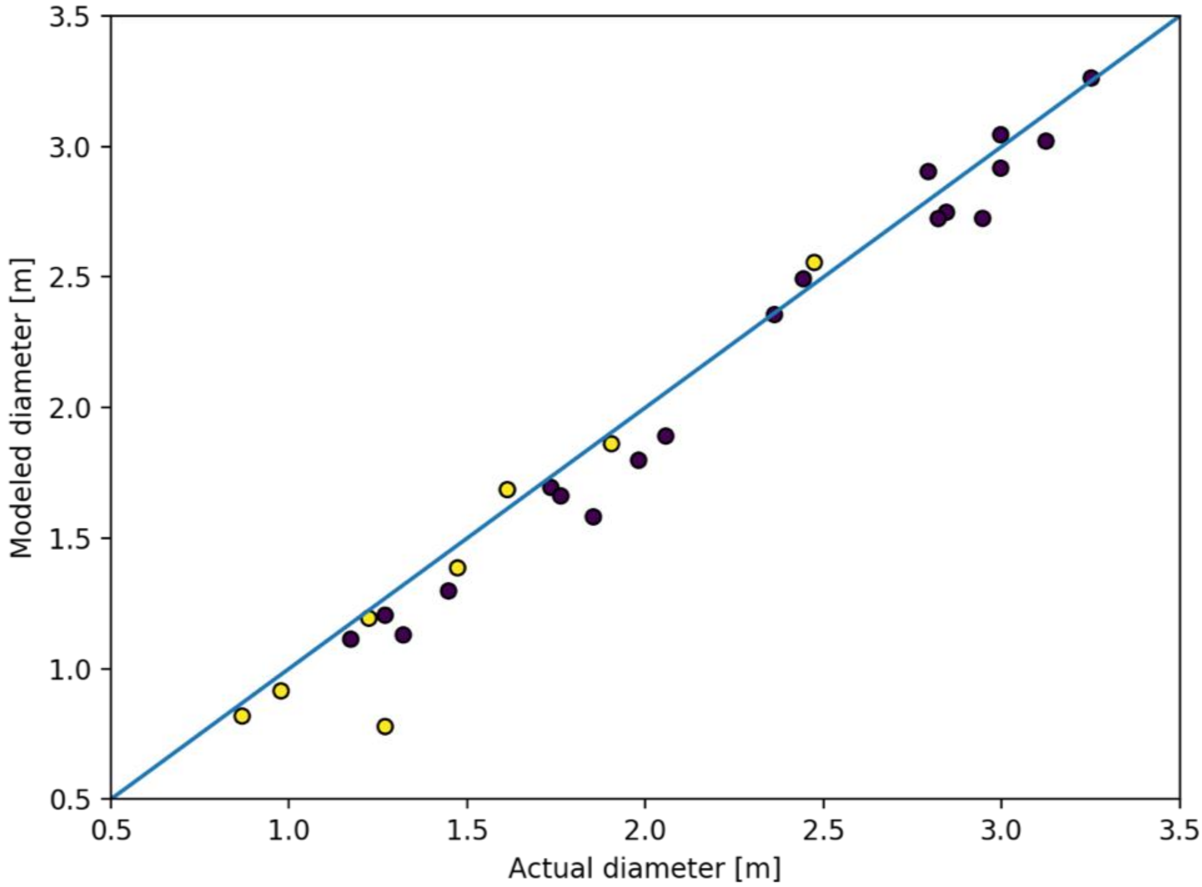


FIGURE B10: ACTUAL VERSUS PREDICTED DIAMETER USING THE SIMPLE GAS TURBINE MODEL. ALL ENGINES WERE MODELED AS IF THEY WERE MIXED-FLOW. ENGINES THAT ARE ACTUALLY MIXED-FLOW ARE SHOWN IN YELLOW AND THOSE THAT ARE UNMIXED ARE SHOWN IN BLUE.

5.4 For all the mixed-flow engines, the error in predicting fan diameter is under 10%, except for 1 engine where the actual fan diameter includes the nacelle size. We also run a subset of mixed-flow engines in GasTurb and the ability to predict exhaust nozzle diameter is shown in **FIGURE B11**. These results suggest that we consistently under-predict the exhaust nozzle diameter and we expect this to be caused by the stagnation pressure condition that was enforced at the mixing plane.

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

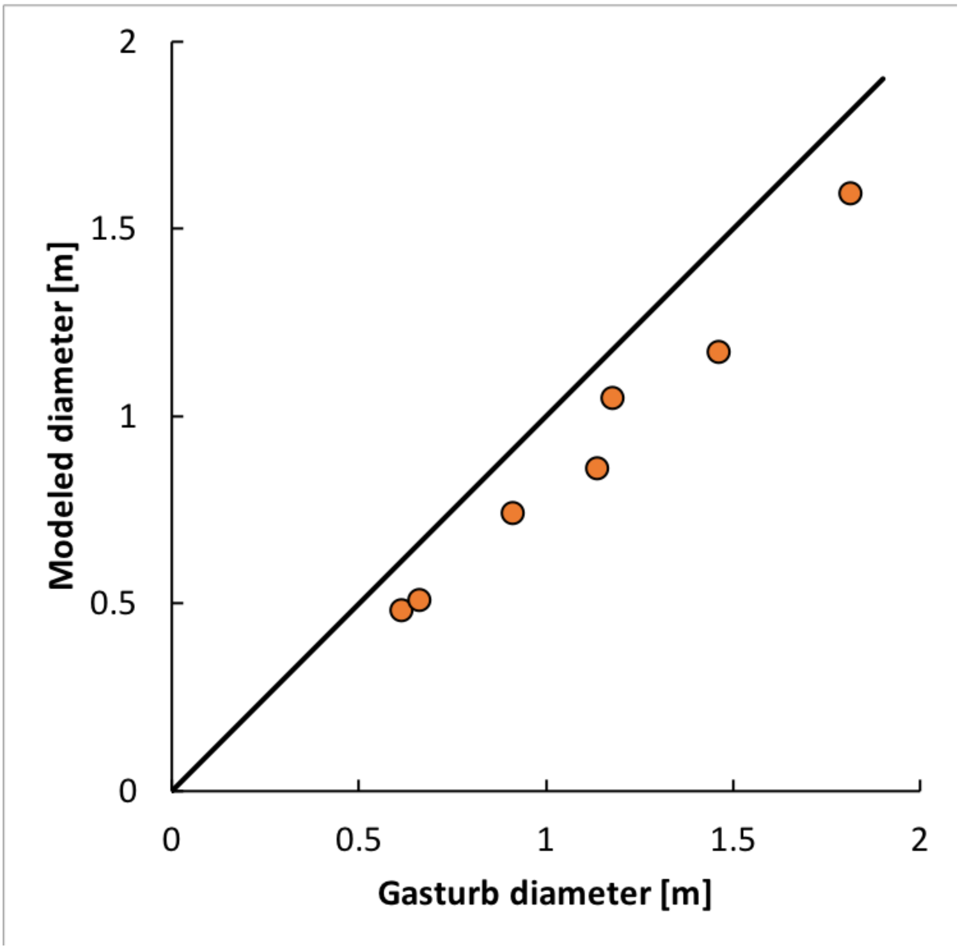


FIGURE B11: COMPARISON BETWEEN NOZZLE DIAMETER FROM GASTURB AND THE MODELED, ITERATIVE GAS TURBINE CYCLE FOR MIXED-FLOW ENGINES.

5.5 Despite this consistent under-prediction of nozzle diameter, the results from our iterative model can still be used to provide a mass concentration at 98% transmission. The absolute value of this mass concentration would be slightly higher than using the GasTurb diameter, however would provide an upper bound on the results. These results, as well as those for the turbojet and unmixed turbofan, are shown in **FIGURE B12**.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

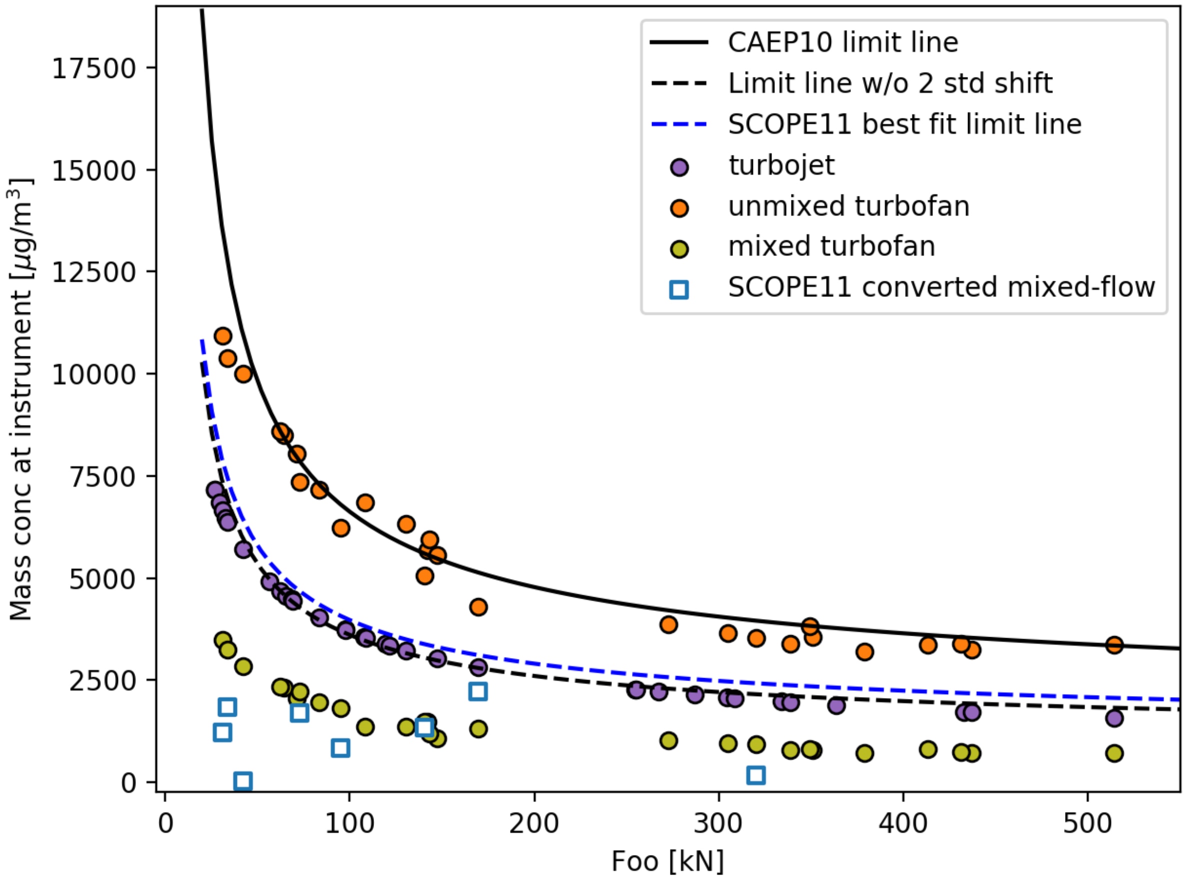


FIGURE B12: THE MASS CONCENTRATION AT 98% VISIBILITY AGAINST RATED THRUST FOR TURBOJETS IN PURPLE, UNMIXED TURBOFANS IN ORANGE AND MIXED-FLOW ENGINES IN GREEN. THE UNFILLED BLUE SQUARES REPRESENT THE MASS CONCENTRATION OF MIXED-FLOW ENGINES ESTIMATED BY CONVERTING THE MAXIMUM SN FROM THE EDB USING THE SCOPE11 METHOD.

5.6 On average, the mass concentration at 98% transmission for mixed-flow engines is 25% that for unmixed engines. The mixed-flow results lie below the SN limit line in mass concentration space and the mass concentration at 98% transmission of turbojet engines. This trend occurs in spite of the under-estimate in the nozzle diameter and so we expect the mass concentration at 98% transmission of mixed flow engines to be even lower. These results suggest that the SN and CAEP/10 limit lines would not prevent the visibility of plumes from mixed-flow engines at the 98% transmission level.

5.7 **FIGURE B12** also includes the mass concentration of mixed flow engines estimated by converting the maximum SN from the EDB using the SCOPE11 method in the unfilled blue squares. These results show that all but one of the selected engines lie below our estimated mass concentration at 98% transmission for mixed-flow engines. Only one other engine lies within 10% of the estimated mass concentration at 98% transmission. These results suggest that mixed flow engines with a mass concentration at the CAEP/10 limit line or a smoke number at the SN limit line would have a transmission below 98% and thus may be visible.

An agency of the European Union
TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

6. CONCLUSIONS

6.1 The SN limit line is reproducible if we consider turbojet engines and apply appropriate corrections to STP conditions and system losses. Our results suggest that the SN limit line is at a transmission of 98% for these engines.

6.2 First-order cycle models can be used to estimate the nozzle diameter of unmixed and mixed-flow engines using data from the EEDB, which is needed to determine the mass concentration at 98% transmission. Validation using publicly available fan diameters and GasTurb simulations showed that the unmixed turbofan model is accurate within 3%, while the mixed-flow turbofan model underestimates nozzle diameter by ~20%.

6.3 For unmixed turbofan engines, the mass concentration at 98% transmission was found to be close to the CAEP/10 limit line, however there was variability around this line driven by the differences in bypass ratio.

6.4 For mixed-flow engines, the mass concentration at 98% transmission was found to be below both the CAEP/10 and SN limit lines. This means that both these limit lines would not prevent the visibility of plumes from mixed-flow engines.

6.5 Comparing the mass concentration at a 98% transmission with mass concentration estimated using the SCOPE11 method for in-production mixed-flow engines, we found that all mixed-flow engines, except 1, lay below the mass concentration at 98% transmission, suggesting that these mixed-flow engines would not have a visible plume.

7. REFERENCES

Agarwal, A., Speth, R.L. Understanding the statistics between the SN and mass concentration limit lines. International Civil Aviation Organization. 2018; CAEP10-WG3-PMTG08-Flimsy06

Agarwal, A., Speth, R.L. Mass concentration at constant transmission. International Civil Aviation Organization. 2018; CAEP10-WG3-PMTG09-Flimsy03

Bond, T.C., Bergstrom, R.W., Light Absorption by Carbonaceous Particles: An Investigative Review. Aerosol Science and Technology. 2006; DOI: 10.1080/02786820500421521

Champagne, D.L. Standard measurement of aircraft gas turbine engine exhaust smoke. United States Air Force. 1971; 71-GT-88

METRICS ad hoc group. Recommendation for a non-volatile Particulate Matter (nvPM) Regulatory Limit Line Equation. International Civil Aviation Organization. 2015; CAEP10-WG3-PMTG10-WP06

Munt, R.W. Evaluation of aircraft smoke standards for the criterion of invisibility. Environmental Protection Agency. 1979; EPA-AA-SDSB 79-25

Stockham, J., Betz, H. Study of visible exhaust smoke from aircraft jet engines. Department of Transportation – Federal Aviation Administration. 1971; FAA-RD-71-22

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

8. APPENDIX J.1 – TURBOJET CYCLE MODEL

8.1 Eq 4 shows how the engine nozzle diameter is found

$$L = \sqrt{\frac{4F_{00}}{\pi \gamma_c P_9}} \qquad \text{Eq 4}$$

where F_{00} is the engine rated thrust, γ_c is the heat capacity ratio in the compressor and P_9 is the static pressure at the exit plane. To estimate P_9, we have developed a turbojet cycle model. This also lets us estimate the density at the exit plane in order to correct the mass concentration to STP conditions.

8.2 The model requires the input of two variables: the overall pressure ratio (OPR) and the air-fuel ratio (AFR). The OPR is found from the EEDB, where we use rated thrust and OPR pairs in order to sample the domain space. The AFR is assumed to be 55 for all turbojets and we assume overall compressor and turbine polytropic efficiencies to be 0.78 and 0.83 respectively. Gas properties are also assumed to change after combustion with the heat capacity ratio reducing from 1.4 to 1.3 and the heat capacity at constant pressure increasing from $c_{pc} = 1{,}005$ to $c_{pt} = 1{,}250$ J/kg/K. The fuel is assumed to have a lower calorific value (LCV) of 43.2 MJ/kg.

8.3 Conditions at the combustor exit are calculated using Eq 5.

$$P_{t3} = \mathrm{OPR} \cdot P_{t2}$$
$$T_{t3} = T_{t2}\mathrm{OPR}^{\frac{\gamma_c - 1}{\gamma_c \eta_c}} \qquad \text{Eq 5}$$

where subscript t2 refers to conditions at the engine inlet and t3 to conditions downstream of the compressor, and η_c is the polytropic efficiency of the compressor assumed to 0.78.

8.4 We assume no stagnation pressure loss in the combustor such that $P_{t4} = P_{t3}$ and then apply an energy balance across the combustor to estimate the turbine inlet conditions (subscript t4).

$$T_{t4} = \frac{\mathrm{AFR} c_{pc} T_{t3} + \mathrm{LCV}}{c_{pt}(1 + \mathrm{AFR})} \qquad \text{Eq 6}$$

8.5 The turbine is used to drive the compressor and thus we use a power balance to estimate conditions downstream of the turbine (subscript t5). The pressure is calculated using a similar version of the second equation in Eq 5.

$$T_{t5} = T_{t4} - (T_{t3} - T_{t2})\frac{c_{pc}}{c_{pt}}$$
$$P_{t5} = P_{t4}\left(\frac{T_{t5}}{T_{t4}}\right)^{\frac{\gamma_t}{(\gamma_t - 1)\eta_t}} \qquad \text{Eq 7}$$

8.6 To calculate conditions at the engine exit plane (subscript 9), we assume that the nozzle is choked. Isentropic relations can thus be used to estimate the static temperature and pressure:

$$T_9 = \frac{T_{t5}}{1 + \frac{\gamma_t - 1}{2}} \qquad \text{Eq 8}$$

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

$$P_9 = P_{t5}\left(\frac{T_9}{T_{t5}}\right)^{\frac{\gamma_t}{\gamma_t - 1}}$$

We then use the ideal gas equation to estimate the exit plane density.

$$\rho_9 = \frac{P_9}{R_{air}T_9} \quad \text{Eq 9}$$

where R_{air} is the specific gas constant for air.

9. APPENDIX J.2 – UNMIXED TURBOFAN CYCLE MODEL

9.1 For unmixed turbofans, the typical method to estimate conditions within the engine are to specify a rated thrust, OPR, BPR and turbine inlet temperature (T_{t4}), while setting the jet velocity ratio to be ~0.9. The EEDB does not provide T_{t4} at take-off conditions, instead supplying the fuel flow rate. This requires us to use an iterative process to converge on a solution for this engine.

9.2 We use a least-squares solver in Python in order to identify the value of fan pressure ratio (FPR) that leads to a converged solution. The first step therefore involves guessing a FPR. With this value, we can estimate the conditions downstream of the fan as well as the bypass jet velocity.

$$\mathrm{P_{t13}} = \mathrm{FPR} \cdot \mathrm{P_{t2}} \quad \text{Eq 10}$$
$$T_{t13} = T_{t2}\mathrm{FPR}^{\frac{\gamma_c - 1}{\gamma_c \eta_f}}$$

where subscript 13 refers to conditions downstream of the fan in the bypass stream and η_f is the fan polytropic efficiency assumed to be 0.9. The bypass jet velocity (V_{19}) is then found using Eq 11.

$$V_{19} = \sqrt{2c_{pc}T_{t13}\left(1 - \left(\frac{P_{amb}}{P_{t13}}\right)^{\frac{\gamma_c - 1}{\gamma_c}}\right)} \quad \text{Eq 11}$$

where subscript 19 refers to the bypass nozzle exit plane and P_{amb} is the ambient pressure. This method assumes that the bypass nozzle is perfectly expanded. This may not be reasonable particularly for smaller engines with a higher FPR. Thus, we check the exit Mach number to see if it is subsonic. If it is supersonic, we force the Mach number to be 1 and back out the exit plane pressure accordingly.

9.3 The conditions in the gas generator can then be estimated following a similar method to that for turbojet engines. We apply Eq 5 to estimate conditions downstream of the compressor assuming $\eta_c = 0.9$. Before we apply the combustor energy balance in Eq 6, we must identify the AFR. This is found using the jet velocity ratio of 0.9 to estimate the core jet velocity (V_9) from the bypass jet velocity found in Eq 11 and then applying a momentum balance around the whole engine.

$$V_9 = \frac{V_{19}}{\alpha} \quad \text{Eq 12}$$
$$\dot{m}_c = \frac{F_{00}}{V_9(1 + \mathrm{BPR} \cdot \alpha)}$$

An agency of the European Union

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

Knowing the core mass flow rate, $\dot{m}_c$, we can the calculate the AFR $= \frac{\dot{m}_c}{\dot{m}_f}$ and subsequently apply Eq 6 to estimate conditions at the combustor exit/turbine inlet location.

9.4 We then conduct a power balance similar to that for turbojet engines but extending to include the power drawn by the fan to estimate conditions downstream of the turbine.

$$T_{t5} = T_{t4} - (T_{t3} - T_{t2})\frac{c_{pc}}{c_{pt}} - (T_{t13} - T_{t2})\frac{c_{pc}}{c_{pt}}\,\text{BPR}$$
$$P_{t5} = P_{t4}\left(\frac{T_{t5}}{T_{t4}}\right)^{\frac{\gamma_t}{(\gamma_t - 1)\eta_t}} \qquad \text{Eq 13}$$

where $\eta_t = 0.95$ is the polytropic efficiency of the turbine.

9.5 We can now use the turbine exit conditions to estimate the core jet velocity following Eq 14.

$$V_9 = \sqrt{2c_{pt}T_{t5}\left(1 - \left(\frac{P_{amb}}{P_{t5}}\right)^{\frac{\gamma_t - 1}{\gamma_t}}\right)} \qquad \text{Eq 14}$$

9.6 V_9 was also estimated in Eq 12 using the jet velocity ratio. To ensure that the original FPR used is correct, we compare the two V_9 values in order to check if they are equal. If they are equal, then the calculation procedure is complete, otherwise we loop round again with a different value of the FPR.

9.7 Upon completing the cycle calculations, the core exit nozzle diameter can be found using the core mass flow rate.

$$d_9 = \sqrt{\frac{4\dot{m}_c}{\pi\rho_9 V_9}} \qquad \text{Eq 15}$$

where ρ_9 is found using Eq 9.

10. APPENDIX J.3 – MIXED-FLOW TURBOFAN CYCLE MODEL

10.1 For mixed-flow engines, the jet velocity ratio cannot be fixed since there is a single stream exiting the engine. Instead, the static pressure in the core and bypass stream must be equal at the mixer. To force this condition, we require information on the velocities at the mixer, which in turn requires details of the areas at these locations. An alternative, less accurate option is to enforce that the stagnation pressures at the mixer match. This is expected to give reasonable results since the velocity tends to be subsonic and thus leads to stagnation pressures being close to matching.

10.2 The method begins in a similar fashion to unmixed turbofan engines. We guess a FPR and apply Eq 10 to estimate conditions downstream of the fan in the bypass stream.

10.3 We then need a method to estimate the core mass flow rate that leads to the stagnation pressure downstream of the turbine being equal to that downstream of the fan in the bypass. This requires a second, embedded iteration loop where we cycle over the core mass flow rate,

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

solving Eq 6 across the combustor and Eq 13 across the turbine until the stagnation pressure condition is found. This gives us the stagnation conditions at the turbine exit.

10.4 The final step involves modelling the mixing process between the core and bypass streams. We assume that the flow perfectly mixes with no stagnation pressure loss and calculate the mixed out conditions by mass-averaging between the core and bypass conditions.

$$T_{tm} = \frac{T_{t13}\mathrm{BPR} + T_{t5}}{1 + \mathrm{BPR}} \qquad \text{Eq 16}$$
$$c_{pm} = \frac{c_{pc}\mathrm{BPR} + c_{pt}}{1 + \mathrm{BPR}}$$

where subscript m refers to the mixed out conditions.

10.5 Finally, these mixed out conditions can be used to find the jet velocity and thus the gross thrust of the engine. This is compared with the rated thrust input to the solver and if the error is low enough then the solver completes. If not then, the iteration loops over a different FPR.

11. APPENDIX J.4 – GASTURB SIMULATIONS

11.1 To validate both the unmixed and mixed flow solvers, we have used the GasTurb software to model a subset of engines.

11.2 GasTurb is a fast and accurate solver that allows us to iterate over certain variables to model engines. The OPR and BPR are provided in the EEDB and set as fixed variables in the solver.

11.2.1 For unmixed engines, we set three variables that we iterate over: (1) T_{t4} until the desired fuel flow rate from the EEDB is found; (2) FPR until the jet velocity ratio, set as 0.9, is found; and (3) air mass flow rate until the fan diameter is found. The fan diameter is publicly available and we believe is better for estimating the nozzle dimensions than rated thrust.

11.2.2 For mixed flow engines, a very similar set of variables are selected to iterate over, however the jet velocity ratio is no longer available to us.

12. APPENDIX J.5 – SN LIMIT LINE CONVERTED USING THE SCOPE11 CORRELATION

12.1 The SCOPE11 method provides a correlation to convert smoke number to mass concentration and so we can use this to convert the smoke number limit line to a mass concentration basis. This is found to be

$$\text{SCOPE11 best fit limit}\left[\frac{\mu\mathrm{g}}{\mathrm{m}^3}\right] = \frac{648.4\, e^{6.4F_{00}^{-0.274}}}{1 + e^{-1.098\cdot(83.6F_{00}^{-0.274} - 3.064)}} \qquad \text{Eq 17}$$

12.2 The SCOPE11 best fit limit line is between 5% and 12% greater than the limit line without a 2 standard deviation shift.

— — — — — — — —

7.3. Appendix 3 — ICAO Annex 16 Volume III amendments

7.3.1. Summary of presentations, discussions, conclusions, recommendations and proposed general changes to ICAO Annex 16 Volume III and ETM Volume III (extract from the CAEP/11 (ICAO Doc 10126) Report — Agenda Item 3 'Aircraft engine emissions')

3.6 PROPOSED AMENDMENTS TO ANNEX 16, VOLUME III AND ETM (DOC 9501), VOLUME III

3.6.1 The co-Rapporteurs of WG3 presented the report on the proposed amendments to Annex 16, Volume III and the corresponding amendments to ICAO Doc 9501, *Environmental Technical Manual*, Volume III – *Procedures for the CO_2 Emissions Certification of Aeroplanes*. These changes include, amongst others, improvements for definitions, reference condition specification, clarifications for exemption issuing authority and applicability for CO_2-certified derived versions.

3.6.2 The meeting agreed with the WG3 proposed amendments to Annex 16, Volume III as shown in Appendix B to the report on this agenda item and the corresponding ETM, Volume III, as shown in the report of the working group.

3.6.3 **Recommendations**

3.6.3.1 In light of the foregoing discussion, the meeting developed the following recommendations:

RSPP

Recommendation 3/4 — Amendments to Annex 16 — *Environmental Protection,* Volume III — *Aeroplane CO_2 Emissions*

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

Recommendation 3/5 — Amendments to the *Environmental Technical Manual*, Volume III — *Procedures for the CO_2 Emissions Certification of Aeroplanes*

That the Environmental Technical Manual, Volume III be amended and published, and that revised versions approved by subsequent CAEP Steering Groups be made available, free of charge, on the CAEP website.

7.3.2. Proposed amendments to Annex 16 Volume III (extract from CAEP/11 Report (ICAO Doc 10126) — Agenda Item 3 — Appendix B)

APPENDIX B

PROPOSED AMENDMENTS TO ANNEX 16, VOLUME III

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

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

TEXT OF THE PROPOSED AMENDMENTS TO THE 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

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

APPENDICES

. . .

. . . …

. . .

a) INTERNATIONAL STANDARDS
b) AND RECOMMENDED PRACTICES

c) PART I. DEFINITIONS AND SYMBOLS

d) CHAPTER 1. DEFINITIONS

…

Derived version of a CO_2-certified aeroplane. An aeroplane which incorporates ~~changes~~ a change in the type design that either ~~increase~~ increases its maximum take-off mass, or that ~~increase~~ increases its CO_2 emissions evaluation metric value by more than:

a) 1.35 per cent at a maximum take-off mass of 5 700 kg, decreasing linearly to;

b) 0.75 per cent at a maximum take-off mass of 60 000 kg, decreasing linearly to;

c) 0.70 per cent at a maximum take-off mass of 600 000 kg; and

d) a constant 0.70 per cent at maximum take-off masses greater than 600 000 kg.

Note.— In some States, ~~Where~~ where the certificating authority finds that the proposed change in design, configuration, power or mass is so extensive that a substantially ~~new~~ complete 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~~ requires a new Type Certificate.

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~~ a change in the type design ~~are~~ is made prior to the issuance of the aeroplane's first certificate of airworthiness that ~~increase~~ increases its CO_2 emissions evaluation metric value by more than 1.5 per cent or ~~are~~ is considered to be a significant CO_2 ~~changes~~ change.

…

Type design. The set of data and information necessary to define an aircraft, engine or propeller type for airworthiness determination.

---

e)

f) 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 (cycle 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 airspeed (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~~

…

g)

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

h) PART II. CERTIFICATION STANDARD FOR AEROPLANE
i) CO_2 EMISSIONS BASED ON THE CONSUMPTION OF FUEL

j) CHAPTER 1. ADMINISTRATION

…

1.11 Contracting States shall recognize valid aeroplane exemptions granted by ~~an~~ the competent authority of another Contracting State which is responsible for the production organisation of the aeroplane provided that an acceptable process was used.

...

k) CHAPTER 2.
l)
m) 1.—n) SUBSONIC JET AEROPLANES OVER 5 700 kg
o) p)
q) 2.—r) PROPELLER-DRIVEN AEROPLANES OVER 8 618 kg

s) 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 specialized operational requirements, aeroplanes designed with zero reference geometric factor (RGF), and those aeroplanes specifically designed or modified and used for fire-fighting purposes, be applicable to:

3. …

4. d) derived versions of non-CO_2-certified subsonic jet aeroplanes, including their subsequent CO_2-certified derived versions, 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;

5. e) derived versions of non-CO_2 certified propeller-driven aeroplanes, including their subsequent CO_2-certified derived versions, 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;

6. ...
7.

Note.— Aeroplanes initially designed or modified and used for specialized operational requirements refer to aeroplane type ~~configurations~~ designs 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.

…

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

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~~ The certificating authority or the competent authority responsible for the production organisation of the aeroplane may grant exemptions from the applicability specified in §2.1.1. In such cases, the authority shall issue an exemption document. The grant of exemption shall be noted in the permanent aeroplane record. ~~Certificating authorities~~ The authority shall take into account the ~~numbers~~ number 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.

…

t) 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:

8. a) the aeroplane gross masses defined in 2.3;

9. b) a combination of altitude and airspeed selected by the applicant ~~for each of the specified reference aeroplane gross masses~~;

10. …
11.

12. **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~~ type design for which certification is requested.

…

u) APPENDIX 1. DETERMINATION OF THE AEROPLANE CO_2 EMISSIONS EVALUATION METRIC VALUE

v)

w) 1.— x) SUBSONIC JET AEROPLANES OVER 5 700 kg

y) z)

aa) 2.— bb) PROPELLER-DRIVEN AEROPLANES OVER 8 618 kg

…

3. SPECIFIC AIR RANGE CERTIFICATION TEST AND MEASUREMENT CONDITIONS

cc) 3.1 General

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

This section prescribes the conditions under which SAR certification tests shall be conducted and the measurement procedures that shall be used.

Note.— ~~Many applications~~ An application for certification of a CO_2 emissions metric value may involve only a minor ~~changes~~ change to the aeroplane type design. The resultant ~~changes~~ change in the CO_2 emissions metric value can often be established reliably by way of an equivalent ~~procedures~~ procedure without the necessity of resorting to a complete test.

dd) 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:

13. a) ***Aeroplane conformity***. The test aeroplane shall be confirmed to be in conformance with the type design ~~configuration~~ for which certification is sought.

…

5. CALCULATION OF REFERENCE SPECIFIC AIR RANGE FROM MEASURED DATA

…

ee) 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 are not at the reference conditions:

...

~~***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.~~

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~~.

…

— — — — — — —

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union

8. Quality of the document

If you are not satisfied with the quality of this document, please indicate the areas which you believe could be improved and provide a short justification/explanation:

— technical **quality** of the draft proposed rules and/or regulations and/or the draft proposed amendments to them

— text clarity and readability

— quality of the impact assessment (IA)

— others (please specify)

Note: Your replies and/or comments to this section shall be considered for internal quality assurance and management purposes only and will not be published in the related CRD.

TE.RPRO.00034-010 © European Union Aviation Safety Agency. All rights reserved. ISO 9001 certified.
Proprietary document. Copies are not controlled. Confirm revision status through the EASA intranet/internet.

An agency of the European Union