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A Uniform Calculation Method for CO₂ Emissions from Large Civil Fixed-Wing Aircraft used for Air Transport

CUSTOMER: Ministry of Infrastructure and Water Management



Royal NLR - Netherlands Aerospace Centre

A Uniform Calculation Method for CO₂ Emissions from Large Civil Fixed-Wing Aircraft used for Air Transport



Problem area

Numerous parties are working towards reducing CO₂ emissions from aviation. Setting goals, monitoring progress and forecasting future emissions is hampered by the lack of a uniform calculation method for aviation CO₂ emissions. This is also noted by the Ministry of Infrastructure and Water Management and the parties to the Sustainable Aviation Roundtable, which have identified the need for such a method to be developed.

Description of work

To develop the calculation method for aviation CO₂ emissions, the Ministry has contracted Royal NLR. This report documents the approach and methodology followed to develop a uniform calculation method and presents the results that

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have been found. Specifically, various options to calculate or approximate aircraft fuel consumption, flight trajectory, payload and a number of miscellaneous aspects have been assessed in terms of accuracy, verifiability, usability and stakeholder support. Then, following a compatibility analysis and discussion of the highest-scored options, a uniform calculation method is proposed.

Results and conclusions

The most-suitable uniform calculation method for CO₂ emissions from large civil fixed-wing aircraft proposes to:

- Calculate CO₂ emissions from aircraft and engine-specific fuel consumption using a fixed emission index and taking into account the lifecycle CO₂ savings of SAF by applying a generic reduction factor based on the SAF-type to the tank-to-wake emissions.
- Calculate fuel consumption for a flight based on the distance-corrected great circle distance and aircraft type-specific trajectory information for climb, cruise and descent. Calculate fuel consumption for the landing- and take-off phases using aircraft and engine type-specific data and default times-in-mode for approach, landing and take-off, and airport-averaged taxi times.
- Model payload based on the typical aircraft type capacity and average load factors.
- Do not consider alternative (sustainable) taxi operations, wind effects, cruise speed deviations and tankering.

Neither of seven existing CO₂ emissions models reviewed exactly incorporate the calculation options, implying that the development of a new computer model is required. Recommendations on data sources, default values and development are given to support the steps towards the realisation of that computer model.

Applicability

The calculation method for aviation CO₂ emissions is developed to be applicable to large civil fixed-wing aircraft used for air transport operations. This includes all fixed-wing (i.e., non-helicopter) aircraft with a maximum take-off weight of at least 5700 kilogrammes used for civil purposes. Furthermore, the method is to be suitable for monitoring and forecasting CO₂ emissions from aircraft departing the Netherlands to international destinations, and applicable goals and targets. The Dutch context has been kept in mind during the entire work. Differences in aviation activity as well as stakeholder priorities observed in other countries or regions could have yielded different results.

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Summary

The Ministry of Infrastructure and Water Management and parties to the Sustainable Aviation Roundtable have identified a desire for a uniform calculation method for aviation CO₂ emissions to align studies and CO₂ reduction goals. The uniform method should therefore allow for systematic monitoring and forecasting CO₂ emissions from large civil aircraft departing the Netherlands to international destinations and, for example, help in target setting and monitoring. With this, the secretariat of the Dutch Sustainable Aviation Round Table is identified as anticipated user, in addition to the Government of the Netherlands and associated Ministries, Agencies and Institutes.

This report documents the approach and methodology followed to develop a uniform calculation method for CO₂ emissions from large civil aircraft departing the Netherlands to international destinations on air transport missions and presents the results that have been found. It is stressed that the methodology has been specifically developed with the aforementioned goals in mind and is not necessarily suitable for other uses.

Computation of aviation CO₂ emissions involves several parameters, with varying impact on fuel burn and CO₂ emissions. Selected parameters that could be used in the uniform calculation method for aviation CO₂ emissions include fuel type (CO₂ emission index and lifecycle CO₂ savings by alternative fuels), aircraft unit fuel consumption (i.e., per hour or per kilometre), trajectory (distance and flight phase), payload, alternative taxi operations, wind effects and cruise speed deviations.

Each of these parameters can be calculated or approximated using different calculation options. The best calculation option(s) per parameter have been identified by assessing – from higher to lower importance – the accuracy, verifiability (fraud-resistance and transparency), usability (data availability and computational effort) and stakeholder support (alignment with existing calculation methods, standards, regulations and models) of each of the options.

The resulting highest-scored options were discussed in terms of compatibility, consistency, robustness and future-proofness. The analysis of future-proofness identified a number of limitations associated to the highest-scored options. Addressing these by relying on the second highest-scored options for a number of trajectory-related parameters, have resulted in a proposed uniform calculation method for CO₂ emissions from large civil fixed-wing aircraft. This method proposes to:

- Calculate CO₂ emissions from aircraft and engine-specific fuel consumption using a fixed emission index and taking into account the lifecycle CO₂ savings of SAF by applying a generic reduction factor based on the SAF-type to the tank-to-wake emissions.
- Calculate fuel consumption for a flight based on the distance-corrected great circle distance and aircraft type-specific trajectory information for climb, cruise and descent. Calculate fuel consumption for the landing- and take-off phases using aircraft and engine type-specific data and default times-in-mode for approach, landing and take-off, and airport-averaged taxi times.
- Model payload based on the typical aircraft type capacity and average load factors.
- Not consider alternative (sustainable) taxi operations, wind effects, cruise speed deviations and tankering.

A review of seven existing CO₂ emissions models shows that neither of these models exactly incorporate the calculation options proposed above, implying that the development of a new computer model is required to apply the uniform calculation method. Recommendations on data sources, default values and development are given to support the steps towards the realisation of that computer model.

Samenvatting

Het Ministerie van Infrastructuur en Waterstaat en de partijen die aangesloten zijn bij de Duurzame Luchtvaarttafel hebben de behoefte geuit aan een uniforme set rekenregels voor CO₂-uitstoot van vliegtuigen, om daarmee studies naar CO₂-uitstoot van luchtvaart en CO₂-reductiedoelstellingen voor de luchtvaart beter op elkaar af te kunnen stemmen. Deze uniforme set rekenregels zou het mogelijk moeten maken om CO₂-emissies van grote, civiele, vanuit Nederland naar internationale bestemmingen vertrekkende en voor luchtvaarttransport ingezette vliegtuigen systematisch te kunnen voorspellen en monitoren om, bijvoorbeeld, het bepalen en monitoren van doelstellingen te ondersteunen. Het Secretariaat van de Duurzame Luchtvaarttafel is daarmee een voor de hand liggende gebruiker, naast de Rijksoverheid zelf, en de verschillende ministeries, planbureaus en kennisinstituten. Dit rapport beschrijft de aanpak en methode die is gevolgd om deze uniforme set rekenregels te ontwikkelen en presenteert de resultaten van dat proces. Benadrukt wordt dat de rekenregels specifiek voor de voornoemde toepassing zijn ontwikkeld en niet noodzakelijkerwijs geschikt zijn voor andere doelen.

Bij het berekenen van CO₂-uitstoot van vliegtuigen spelen verschillende parameters een rol, die allen een verschillend effect hebben op de hoeveelheid verbruikte brandstof en CO₂. Parameters die gebruikt zouden kunnen worden in deze uniforme set rekenregels zijn bijvoorbeeld brandstoftype (CO₂-emissieindex en het CO₂-reductiepotentieel van alternatieve brandstoffen), het brandstofverbruik per uur of per kilometer, de route (afstand en opdeling in vluchtfases), de belading, alternatieve manieren van taxiën, en de effecten van wind en variaties in kruissnelheid.

Elk van deze parameters kan op verschillende manieren worden berekend op benaderd. Voor iedere parameter is (zijn) de beste optie(s) bepaald via een beoordelingsproces, waarin iedere optie is gescoord op – van hogere naar lagere belangrijkheid – de nauwkeurigheid, verifieerbaarheid (fraudegevoeligheid en transparantie), bruikbaarheid (beschikbaarheid van data en benodigde rekentijd) en draagvlak bij stakeholders (aansluiting bij bestaande rekenmethoden, standaarden, wetgeving en modellen).

De hoogst-scorende opties zijn vervolgens geanalyseerd op het gebied van compatibiliteit, consistentie, robuustheid en toekomstbestendigheid. Die laatste analyse bracht een aantal beperkingen van de hoogst-scorende opties onder de aandacht. Die zijn verholpen door voor een aantal parameters, die te maken hebben met de vliegbaan, te opteren voor de op-één-na hoogst-scorende optie, resulterend in een voorgestelde uniforme set rekenregels voor het bepalen van CO₂-emissies van grote, civiele en vastvleugelige toestellen. Deze methode stelt het volgende voor:

- Bereken CO₂-emissie op basis van vliegtuig- en motortype-specifieke gegevens voor brandstofverbruik, een vaste emissie-index en door het percentage levenscyclus-CO₂-reductie van het gebruikte type SAF toe te passen op de *tank-to-wake* emissies.
- Bereken brandstofverbruik van een vlucht op basis van een afstandsgecorrigeerde grootcirkelafstand en vliegtuigtypeafhankelijke prestatiegegevens voor de klim-, kruisvlucht- en dalingsfases. Bereken brandstofverbruik voor de landing- en startfases op basis van vliegtuig- en motortype-specifieke data en generieke (standaard)tijden voor nadering, landing en start, en luchthaven-specifieke taxitijden.
- Modelleer belading op basis van de typische ladingscapaciteit van het gebruikte vliegtuigtype, gecombineerd met een gemiddelde bezettingsgraad.
- Houd geen rekening met alternatieve (duurzame) manieren van taxiën, windeffecten, afwijkingen in kruissnelheid en tankering.

Een analyse van zeven bestaande CO₂-emissiemodellen laat zien dat geen van deze modellen bovenstaande uniforme rekenregels precies toepast. Dat impliceert dat de ontwikkeling van een nieuw computermodel nodig is om de rekenregels toe te kunnen passen. Om dat te ondersteunen bevat dit rapport aanbevelingen over bruikbare databronnen, standaardwaarden en te maken keuzes in die ontwikkeling.

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Acronyms

ACRONYM	DESCRIPTION
4D	Four-dimensional (three physical dimensions + time)
AEM	Advanced Emissions Model
ANP	Aircraft Noise and Performance
ANSP	Air Navigation Service Provider
APU	Auxiliary power unit
BADA	Base of Aircraft Data
CEC	Carbon Emissions Calculator
CO ₂	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DLT	Duurzame Luchtvaarttafel (Sustainable Aviation Roundtable)
EASA	European Union Aviation Safety Agency
EC	European Commission
ECAC	European Civil Aviation Conference
ECMWF	European Centre for Medium-Range Weather Forecasts
EEA	European Environmental Agency
EMEP	European Monitoring and Evaluation Programme
EU	European Union
EU ETS	European Union Emission Trading System
FC	Forecast
GCD	Great circle distance
GP	Guiding principle
H ₂	Hydrogen
HC	Hindcast
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
KiM	Kennisinstituut voor Mobiliteitsbeleid (Netherlands Institute for Transport Policy Analysis)
LCA	Lifecycle analysis
LCAF	Low-Carbon Aviation Fuel
LTO	Landing and Take-off
m.e.r.	Milieueffectrapportage (environmental impact assessment)
MTOW	Maximum Take-off Weight
N/A	Not applicable
NGO	Non-governmental organisation
NLR	Royal NLR – Netherlands Aerospace Centre

ACRONYM	DESCRIPTION
OAG	Official Airline Guide
OEW	Operational Empty Weight
PBL	Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)
RCF	Recycled carbon fuels
RED	Renewable Energy Directive
RFNBO	Renewable fuel of non-biological origin
RIVM	Rijksinstituut voor Volksgezondheid en Milieu (National Institute for Public Health and the Environment)
RMSE	Root mean squared error
RMSRE	Root mean squared relative error
RRMSE	Relative root mean squared error
SAF	Sustainable Aviation Fuel
SET	Small Emitters Tool
SLFCF	Synthetic low carbon fuel
TOW	Take-off weight
UNFCCC	United Nations Framework Convention on Climate Change
US DOT	United States Department of Transport
Wnb	Wet natuurbeheer (environmental protection law)
WP	Work package
Zbo	Zelfstandig bestuursorgaan

1 Introduction

Aviation globally is “in the context of the Paris Agreement facing the challenge to turn the growing amount of greenhouse gas emissions around into a reducing trend”¹ (Ministry of Infrastructure and Water Management, 2020). Numerous parties are working towards achieving this goal, both at global, European and national scale. In the Netherlands, the Civil Aviation Policy Memorandum has set targets to reduce CO₂ emissions. Moreover, various organisations and stakeholders are collaborating as part of the Dutch Sustainable Aviation Roundtable (Duurzame Luchtvaarttafel; DLT) to review and possibly update these emission reduction goals, and a substantial number of reports has been published on the anticipated future aviation CO₂ emissions and ways to limit these, specifically for the Dutch situation².

The comparison and alignment of such goals, targets and studies is hampered by a multitude of models and calculation methods to determine the amount of CO₂ emitted by aircraft. This can create confusion and misunderstanding about, for example, historical CO₂ emissions and can make it more difficult to set well-supported future targets, or to monitor progress towards achieving those. Both the Ministry of Infrastructure and Water Management and the parties to the Sustainable Aviation Roundtable have explicitly identified a need for a clear, uniform and commonly used calculation method for aviation CO₂ emissions. To develop this uniform calculation method, the Ministry has contracted Royal NLR.

BOX 1: UNFCCC REPORTING BASED ON (BUNKER) FUEL SALES

Emissions from international aviation are addressed by the United Nations Framework Convention on Climate Change (UNFCCC) based on fuel sales (UNFCCC, 2025). To study global aviation emissions, this is an appropriate method – as all aviation emissions ultimately stem from aviation fuel that has been uplifted (tanked) somewhere on the planet. For monitoring national or regional aviation emissions, however, the approach based on fuel sales comes at a risk, as not all fuel consumed during a particular flight has been uplifted in the country (or region) where this flight originated. Various studies have shown this risk – associated to the practice of ‘tankering’ fuel – to be quite apparent for the Netherlands especially (EUROCONTROL, 2019c; Peeters, Uitbeijerse, Peerlings, & Geilenkirchen, 2021). Even though the anti-tankering provision included in ReFuelEU Aviation (EU, 2023c, Art. 5), which stipulates that the yearly quantity of fuel uplifted by an aircraft operator at a given airport shall be at least 90% of the fuel required for flights departing from that airport, limits tankering, the aforementioned risk is not fully mitigated. As such, a model-based approach, which is not susceptible to this risk, is still expedient.

Objective of the report

This report presents such a uniform calculation method for aviation CO₂ emissions, and describes the steps taken to develop that method. As such, it also summarises the ‘design requirements’ derived in this project and identifies various options by CO₂ emissions can be computed.

Reading guide

The remainder of this report is structured as follows. Chapter 2 presents the approach that has been followed and outlines the objectives, scope and guiding principles of the work. Further background information about the project, its structure and the interaction with stakeholders is given in Appendix A. Chapter 3, then, discusses the assessment criteria and associated weighing factors, as well as the scoring metrics developed. Next, Chapter 4 presents the calculation parameters and options as well as the scoring results (applying the scoring metrics from Chapter 3 and

¹ Also mentioned in the Civil Aviation Policy Memorandum of the Government of the Netherlands (Luchtvaartnota 2020-2050). The quote is translated from: “wereldwijd voor de uitdaging om de toenemende uitstoot van broeikasgassen om te buigen in een afname in het kader van het klimaatdoel van Parijs” (Ministry of Infrastructure and Water Management, 2020, p. 59).

² This, for example, includes work for Royal Schiphol Group (NLR, 2024), analyses that have been done for the possible national CO₂ cap for aviation (Juijn, Faber, & Grebe, 2021; Faber, et al., 2022; Grebe, Meijer, Király, & Leestemaker, 2022), and more general studies into the decarbonisation of aviation at Dutch (Davydenko & Hilbers, 2024; Davydenko, Hilbers, & de Wilde, 2024; Uitbeijerse, 2020; Uitbeijerse, 2018) and European level (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021; van der Sman, et al., 2025).

relying on details provided in dedicated appendices). Chapter 5 summarises and discusses these results and presents the proposed uniform calculation method for CO₂ emissions from large civil fixed-wing aircraft. Last, Chapter 6 lists recommendations, meant to support the process of implementing the uniform calculation method into a usable software tool.

Throughout the report, several boxes (such as Box 1 on the previous page) are used to present further background information that is considered relevant, but is not necessary to be able to properly digest the report. For example, it elaborates on the Dutch context, special use cases or provides additional explanations.

2 Approach

This chapter provides an overview of the research approach by explaining the objective of the project (Section 2.1) and defining the scope and key concepts (Section 2.2). The guiding principles for uniform calculation methods for aviation CO₂ emissions are explained in Section 2.3. Further information about the project structure, the timeline and the stakeholder interactions is given in Appendix A.

2.1 Objective of the project

As noted in Chapter 1, the objective of this project is to develop a uniform calculation method of aviation CO₂ emissions. Although such calculations could be relevant in a wide variety of different situations, the Ministry of Infrastructure and Water Management has specifically determined that the uniform calculation method should be suitable for monitoring and forecasting CO₂ emissions from aircraft departing the Netherlands to international destinations, and the applicable goals and targets. Such goals and targets have been set in the Civil Aviation Policy Memorandum (Luchtvaartnota 2020-2050) as well as by the Sustainable Aviation Roundtable³. These aforementioned monitoring (hindcasting, also abbreviated as HC) and forecasting (also abbreviated as FC) activities are typically concerned with larger sets of flights, such as all (international) traffic departing from the Netherlands, or from a particular airports. As users, one could primarily think of (the secretariat) of the Sustainable Aviation Roundtable, in addition to the Government of the Netherlands and associated Ministries, Agencies and Institutes⁴.

No quantitative requirements have been set on, for example, the minimum accuracy to be obtained or the maximum computational effort allowed. Rather, such trade-offs are part of the research project documented in this report. These trade-offs are guided by the aforementioned ‘use cases’ and a number of more specific example applications that are foreseen:

- Setting new CO₂ emission reduction targets by the Sustainable Aviation Roundtable, for which the uniform calculation method could be used to forecast ambitious yet realistic emission reduction scenarios;
- Monitoring whether progress towards set reductions targets has been made and indicating which actions have contributed towards the progress;
- Creating climate and energy outlooks specific to aviation, for which the calculation method could be used to provide fuel consumption and CO₂ emission estimates.

The above also implies the accuracy obtained for a single flight may be of lesser relevance than the accuracy obtained for a larger group of flights, such as the total set of flights departing from one airport in a given month or year. It is also stressed that the calculation method developed in this work is not a “one size fits all” solution, but rather is the result of a process targeted to find the calculation method best fit for the intended use.

BOX 2: A SPECIAL USE CASE – A NATIONAL CO₂-CEILING FOR AVIATION

A special case of the ‘monitoring’ use case would be the application of the uniform calculation method as a basis for enforcing a maximum amount of CO₂ emissions, as the Government of the Netherlands has proposed to do using a national

³ The difference between these goals – whether out-of-sector offsetting is accepted as a means of meeting the target – is noted, but not relevant for this work, as this research is limited to calculating CO₂ emissions from aircraft.

⁴ Such as the Netherlands Environmental Assessment Agency (Planbureau voor de Leefomgeving; PBL), the Netherlands Institute for Transport Policy Analysis (Kennisinstituut voor Mobiliteitsbeleid; KiM), Rijkswaterstaat and National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu; RIVM).

CO₂-ceiling⁵. Pending a final decision on the implementation of such a ceiling and remaining uncertainties about its exact workings, this application is not considered in detail in this work and would require further stakeholder interaction. Throughout this report, some reflections on the consequences of particular choices for such a use case are, however, shared in boxes similar to this one.

2.2 Scope and definitions

The uniform calculation method should be suitable for calculating the (anticipated) CO₂ emissions of large civil fixed-wing aircraft used for air transport:

- **Large** aircraft means that the scope is limited to aircraft with a maximum take-off weight greater than 5700 kg (EASA, 2023; EASA, 2010);
- **Civil** aircraft refer to aircraft used to operate all forms of non-military and non-state flights, including passenger as well as cargo operations;
- **Fixed-wing** aircraft means that helicopters are out-of-scope;
- Used for **air transport** means that the scope is limited to flights with the primary purpose of transporting passengers, cargo or mail.

The limitations with respect to take-off weight and flight purpose adhered to in this work are consistent with the scope of the EU Emissions Trading System (EU ETS) for aviation (EU, 2024, Annex I).

The uniform calculation method is furthermore limited to aircraft engine emissions (tank-to-wake), with the exception⁶ of lifecycle emissions savings through the use of alternative aircraft fuels.

In this work, four key concepts are used, which are outlined in Table 1.

Table 1: Definitions of key concepts

Calculation parameters	Calculation parameters are required inputs that are needed to perform a CO ₂ calculation, e.g.: aircraft type, distance.
Parameter options	For each calculation parameter, there are several options to take the parameter into account in CO ₂ calculations, often at varying level of fidelity. The calculation parameter ‘distance’ may for example be incorporated in CO ₂ calculation as great circle distance between origin and destination, the historic average flown distance between origin and destination, or the actually flown distance.
Assessment criteria	Assessment criteria are the aspects parameter options are assessed on, such as accuracy, transparency or computational time.
Uniform calculation method	A uniform calculation method consists of a combination of parameter options – one for each of the defined calculation parameters that can be used to compute aviation CO ₂ emissions.

⁵ Letter to Parliament “Principebesluit CO₂-plafond luchtvaart”, dd. March 17th, 2023, ref. IENW/BSK-2023/65343 and Letter to Parliament “Voortgang CO₂-plafond per luchthaven”, dd. December 12th, 2023, ref. IENW/BSK-2023/376975.

⁶ Determined during the development of the method, as elaborated in Section 4.2.3..

2.3 Guiding principles

To ensure the objectives stated in Section 2.1 are met, several points of attention are identified. These serve as guiding principles throughout the project:

- GP1. The uniform calculation method for aviation CO₂ emissions must result in an **accurate estimation** of the actual emissions.
- GP2. The uniform calculation method for aviation CO₂ emissions must be **transparent, verifiable** and **fraud-resistant**.
- GP3. The uniform calculation method for aviation CO₂ emissions must **not** be **overly complex**.
- GP4. The uniform calculation method for aviation CO₂ emissions must be **supported by anticipated users and stakeholders**.
- GP5. The uniform calculation method for aviation CO₂ emissions must be **sound, robust and future-proof**.

3 Assessment criteria, weighting factors and scoring metrics

The result of the assessment of the calculation parameters is a method that respects the guiding principles outlined in Section 2.3. In order to select the most suitable option for each of the calculation parameters (and thereby arriving at the most suitable calculation method), the various options are scored against a set of (weighted) assessment criteria.

In the remainder of this chapter, Section 3.1 first provides an overview of the assessment criteria considered and introduces the methods employed. Sections 3.2 up to and including 3.5 provide further details for these criteria.

3.1 Overview

From the guiding principles (GPs) in Section 2.3, a set of eight assessment criteria clustered in four groups has been defined. Table 2 shows these, alongside the weighting factors assigned to each of these criteria. These differ between hindcast (HC) and forecast (FC) applications. The former refers to monitoring CO₂ emissions by flights that have already been operated (and, as such, for which knowledge about departure airport, arrival airport and aircraft type is available); the latter considers forecasting CO₂ emissions for flights that have yet to take place (and, as such, for which traffic information only exists as plans).

The weighting factors have been set by the Ministry, following a recommendation of the project team. This recommendation, in turn, has been based on input collected from a larger group of NLR-experts regularly involved in emissions modelling work and from the stakeholders consulted in this project (listed in Appendix A.2). Following a recommended set of weighting factors proposed by the project team, in turn based on expert and stakeholder input, these were decided upon by the Ministry.

Table 2: Overview of assessment criteria and weighting factors, different for hindcast (HC) and forecast (FC) applications

Guiding principle	Group	Assessment criterion	Remarks	Weighting	
				HC	FC
GP1: "must result in an accurate estimation of the actual emissions"	Accuracy	Accuracy	Also taking into account the sensitivity of total CO ₂ emissions to the calculation parameter considered.	6	5
GP2: "must be transparent, verifiable and fraud-resistant"	Verifiability	Fraud-resistance		2	
		Transparency		3	
GP3: "must not be overly complex"	Usability	Availability of data	A method will only be usable if the required data is available.	3	
		Computational time	A method that will require a lot of computational time is less easy to use and might be too complicated or complex.	1	2

Guiding principle	Group	Assessment criterion	Remarks	Weighting	
				HC	FC
GP4: “must be supported by anticipated users and stakeholders”	Stakeholder support	Alignment with current methods, standards and regulations	If alignment is better, a method is likely to be better supported by stakeholders. Furthermore, re-use of data already collected for current methods, standards and regulations will reduce data collection efforts.	2	
		Incorporation in existing CO ₂ emission models	If a calculation option is also incorporated in other models, using that same calculation option is likely to be better supported by stakeholders. Moreover, it will reduce the likelihood that the method developed in this work will substantially deviate from existing models. Lastly, in relation to guiding principle 5 (“must be sound, robust and future-proof”), better alignment to existing models also speaks to the soundness of the method.	1	
		Stakeholder preference	Not assessed explicitly, but identified as possible ‘tie breaker’	N/A	

GP5 (“must be sound, robust and future-proof”) is not fully covered by these assessment criteria, as the assessment of individual calculation parameter options is not deemed to be the right “level” to test and ensure the method (overall) is robust and future-proof. As such, these elements are reflected upon at a later stage, when highest-scoring option(s) have been selected. Specifically, this is elaborated upon in Sections 5.2.3 (robustness) and 5.2.4 (future-proofness).

BOX 3: A SPECIAL USE CASE – A NATIONAL CO₂-CEILING FOR AVIATION

In case a calculation method for CO₂ emissions would be used to support a national CO₂-ceiling for aviation, the weighting factors might differ from the ones currently used. When providing their input, stakeholders explicitly stressed this. The project team could, for example, imagine that accuracy would receive a higher weighting factor: if a calculation method will play a role in determining whether a(n additional) flight may or may not take place. Similarly, in such a case, airlines might be more inclined to provide more detailed data, to also enable a more accurate calculation method to be practical.

The remainder of this chapter treats the four groups of assessment criteria in further detail. This not only includes a more extensive description, but also defines scoring metrics. These indicate how various options are scored. In all cases, the range of possible scores varies between 0 and 1 (0 for worst performance and 1 for best performance) in order to prevent introducing an additional ‘weighting factor’⁷. The scoring metrics have been developed for each criterion individually such that these reflect the assessed criterion best. Whereas some criteria could only be discretely scored (e.g. ‘alignment with current regulations’), others (e.g. ‘computational time’) could be scored on a continuous scale.

BOX 4: RESEARCH IN AND FOR A DUTCH CONTEXT

During the entire assessment, the Dutch context has been kept in mind – as the uniform calculation method is also developed to serve in such a Dutch context. This, for example, means Dutch stakeholders have been consulted in the process of setting weighting factors (shown in Table 2), that analyses to determine the accuracy of particular calculation options have been performed on data from flights departing the Netherlands (rather than the entire global flight network), and that methods, standards and regulations have been considered that apply in the Netherlands (rather than globally, or in other regions). This also implies that the highest-scored calculation options identified in this work – and consequently: the uniform calculation method developed – might not be equally highest-scoring when a uniform calculation method would be developed for use in the United States, or even another European country.

⁷ This would, for example, occur if the maximum score would have been ‘1’ for criterion A and ‘2’ (or even higher) for criterion B.

3.2 Accuracy

The criterion ‘accuracy’ is used to indicate to what extent the parameter option chosen increases the accuracy with which the uniform CO₂ calculation method reflects the actual emitted CO₂. Coarse modelling could, for example, be less accurate than very refined modelling.

The accuracy of a specific parameter option for determining the value of a particular calculation parameter is evaluated in a two-step process:

1. First, the accuracy of a single parameter option is assessed, relative to the most accurate parameter option (‘ground truth’) that could be modelled. For example: estimating the flight distance as the great circle distance underestimates the actual flight distance by a particular amount or percentage. Depending on the percentage deviation (or: relative error) from the most accurate reference data available, a scoring value is determined – according to the metrics specified below.
2. Second, the scoring value determined in the first step is multiplied by the sensitivity of CO₂ emissions with respect to the calculation parameter considered. If a 10% change in an input value (such as distance) would yield a 10% change in the calculated CO₂ emissions, the sensitivity is 1. If, on the other hand, a change in input value has no impact on the calculated CO₂ emissions, the sensitivity is 0. (Indeed, this sensitivity factor is identical for all calculation options identified for a calculation parameter.)

This scoring method yields higher scores for calculation options that are more accurate (i.e.: show a lower deviation with respect to the ‘ground truth’) and have a large impact on CO₂ emissions. It essentially provides an indication of how important it is that a parameter has a certain level of accuracy.

Weighting

For hindcast applications, accuracy is weighted by a factor 6 (out of a total of 18, i.e. 33%). For forecast applications, accuracy is given a weight of 5 (out of a total of 18, i.e. 28%).

Scoring and metrics

The deviation of a calculation option with respect to the ‘ground truth’ (or the most closely available approximation to that) has been determined using the root mean squared relative error (RMSRE, further explained in Box 12 on page 75). Based on the RMSRE, scores have been assigned:

- 1 point: if the RMSRE is below 1%
- 0.75 points: if the RMSRE is between 1 and 3%
- 0.5 points: if the RMSRE is between 3 and 5%
- 0.25 points: if the RMSRE is between 5 and 10%
- 0 points: if the RMSRE is larger than 10%

As noted before, the final score is determined from the product of the point-score based on the RMSRE and the sensitivity of total CO₂ emissions to the particular calculation parameter considered.

Example: the sensitivity of the total CO₂ emission is directly dependent on aircraft unit fuel consumption. The sensitivity of this parameter is hence 1. An analysis of the root mean squared relative error of estimating the unit fuel consumption by taking an aircraft class-averaged figure was found to be more than 10%. As such, this option gets 0 points for accuracy.

Box 5: A SPECIAL USE CASE – A NATIONAL CO₂-CEILING FOR AVIATION

In case a calculation method for CO₂ emissions would be used to support a national CO₂-ceiling for aviation, not the root mean squared relative error (based on a relative error computed for each individual flight modelled) might have been the

best option to determine the accuracy, but the overall mean error (based on the error observed for an entire group of flights) could have been more suitable. This is because the latter metric allows errors opposite in sign to (at least partially) cancel out: potentially harming accuracy at the level of a single flight, but possibly improving it when considering, for example, all flights that depart a given airport in a given year.

The logic of preferring the overall mean error for the analysis of groups of flights does not automatically extend to all groups of flights, as such an overall mean error could notably depend on the composition of the group of flights considered. Hence, using the overall mean error computed based on flight set A to determine a most suitable calculation option and then applying that to flight set B, might give unintended results. For the proposed national CO₂-ceiling, the composition of the groups is largely known (all flights departing from each of the airports of national interest), allowing the overall mean error to be computed for each of these sets, and then applied accordingly. For the application considered in this report, the composition of the flight set is not as defined: it could span all flights departing from the Netherlands, or a regional or temporal subset. To avoid the aforementioned unintended results, the RMSRE is considered more suitable⁸.

3.3 Verifiability

Verifiability is assessed by using the criteria fraud-resistance and transparency.

3.3.1 Fraud-resistance

The criterion ‘fraud-resistance’ assesses to what extent the selected parameter option is susceptible to dishonest or fraudulent use, for example, by the use of loopholes to reduce apparent CO₂ emissions.

N.B.: This criterion solely assesses the fraud-resistance (or the lack of fraud-susceptibility) of a parameter option. Although fraudulent behaviour is also possible when collecting or preparing input data required for a particular calculation option, such behaviour cannot be – and hence is not – assessed. (In other words, input data is always assumed to ‘be what it says it is’. To ensure that that is indeed the case, verification steps can be built-in into the data collection and preparation process.)

Weighting

For both hindcast and forecast applications, fraud-resistance is given a weight of 2 (out of a total of 18, i.e. 11%).

Scoring and metrics

The fraud-resistance of options is scored through an estimate of the availability of loopholes and the likelihood that these are used. As a detailed quantitative assessment, as applied for the assessment criterion accuracy (Section 3.2) could not be used, a simpler (ordinal) scale is used:

- 1 point No loopholes are foreseen
- 0.5 points A limited number of loophole(s) is (are) foreseen but is/are deemed unlikely to be used
- 0 points Loophole(s) is (are) foreseen and are deemed likely to be used

Example (for calculation parameter ‘Distance’, Section 4.3.1): if a calculation method would be based on the distance of the filed flight plan, airlines could theoretically file a (mock) flight plan with a lower distance, such that

⁸ To gauge the impact of this methodological choice, the overall mean error was computed for a few calculation parameters, in addition to the RMSRE (both calculated based on the set of flights defined in Appendix B.1). Determining the accuracy score based on overall mean error rather than RMSRE for the parameter ‘Distance’, for example, results in the highest and second-highest ranked options to change order, only changes the second-highest ranked option for the parameter ‘Aircraft unit fuel consumption’ and does not have any consequences for the final scores for the parameter ‘Taxi’.

associated (calculated) CO₂ emissions would also be lower. Although this possibility exists, it is considered unlikely. As such, this option scores 0.5 points.

3.3.2 Transparency

The criterion ‘transparency’ assesses to which extent the selected input parameter option allows for reproducible, verifiable results.

Weighting

For both hindcast and forecast applications, transparency is given a weight of 3 (out of a total of 18, i.e. 17%).

Scoring and metrics

To ensure reproducible, verifiable results not only the logic of the method must be available but also the underlying data. Again points are awarded on an ordinal scale:

- 1 point The option relies on data that is publicly available
- 0.66 points The option relies on data is not (yet) publicly available but can be requested
- 0.33 points Data for options cannot be publicly shared but may be viewed (e.g. privately or after signing a licence agreement)
- 0 points The option relies on data that cannot be viewed (e.g. proprietary or sensitive information)

Example (for calculation parameter ‘Aircraft unit fuel consumption’, Section 4.2.4): aircraft-specific fuel consumption figures are, for example, available in EUROCONTROLS Base of Aircraft Data (BADA). This data can be used by licenced organisations, but cannot be made public. As such, this option scores 0.33 points.

N.B.: The assessment criteria ‘Transparency’ and ‘Availability of data’ are related, in the sense that relate to data and its availability. The criterion ‘Availability of data’ is strictly concerned with likely availability of the data to the calculation (whether it exists at all, for example), largely irrespective of the owner of the data. The criterion ‘Transparency’ is focused on the extent to which data is confidential or (can be made) public.

3.4 Usability

The method of computing aviation CO₂ emissions may be used by various stakeholders to monitor current and forecast future CO₂ emissions. Therefore, the usability of uniform calculation method is assessed through two criteria: the availability of the data and the computational time, for which is reasoned that a fast-computing method that requires limited readily available data benefits usability.

3.4.1 Availability of data

The assessment criterion ‘availability of data’ is used to indicate to what extent the input data required for the selected parameter option is readily available, either openly, commercially or through a licence, or supplied by

responsible parties. Data acquisition effort and costs as well as possible future data needs (e.g. for new aircraft) are, hence, also included in this assessment criterion.

Weighting

For both hindcast and forecast applications, availability of data is given a weight of 3 (out of a total of 18, i.e. 17%).

Scoring and metrics

This criterion is assessed on a scale with five options. There are two options that result in a score of 0.75 points and there are also two options that result in a score of 0.5 points:

- 1 point All data is readily publicly available or available from the Ministry or other governmental bodies
- 0.75 points Data is readily available for purchase; or (source) data is publicly available or available from the Ministry or other governmental bodies, but requires further processing
- 0.5 points Data is readily available from at least one industry party; or (source) data is available for purchase, but requires further processing
- 0.25 point (Source) data is available from at least one industry party, but requires further processing
- 0 point Data is not available

The group “other governmental bodies”, referred to in scoring options for 1 and 0.75 points, refers to organisations over which one of the ministers of the Government of the Netherlands has direct authority⁹, as this authority implies that data available to such a body is also “available from the Ministry”. In the context of this work, it is stipulated that Air Traffic Control The Netherlands (LVNL) is not regarded as such a governmental body, as it is an independent administrative body (‘zelfstandig bestuursorgaan’ or Zbo).

Example (for calculation parameter ‘Distance’, Section 4.3.1): airline-dependent detour distances or detour factors are not readily available. Instead, information about actual flight distances can be obtained from, for example, FlightAware, and further processed to obtain the required information. As FlightAware is a paid service, this would start at a score of 0.75 points, from which 0.25 points would be subtracted to take into account the further processing required. As such, a final score of 0.5 points is obtained.

N.B.: The assessment criteria ‘Transparency’ and ‘Availability of data’ are related, in the sense that relate to data and its availability. The criterion ‘Availability of data’ is strictly concerned with likely availability of the data to the calculation (whether it exists at all, for example), largely irrespective of the owner of the data. The criterion ‘Transparency’ is focused on the extent to which data is confidential or (can be made) public.

3.4.2 Computational time

The criterion ‘computational time’ is used to indicate how large the computational time is when using specific parameter options, which may for example be of importance when analysing many flights or future scenarios.

⁹ In Dutch: ‘organisaties die direct onder het gezag van een minister vallen’. Based on Government of the Netherlands: Ministry of Finance (2025).

Weighting

For hindcast calculations a weighting of 1 out of 18 is given (i.e. 6%). For forecast calculations a weighting of 2 is given (11%).

Scoring and metrics

The computational effort required associated with calculating the CO₂ emissions of a group of flights is influenced by the computational time for processing each flight and the number of unique flights that has to be processed. Given the anticipated use of the calculation method developed here (Section 2.1), the number of flights to be processed will typically be rather large. As such, this element will primarily determine the overall computational effort.

With that in mind, the score is expressed as the percentage of unique flights that can be eliminated by aggregating to the parameter option fidelity level with a full year (2019) of large commercial civil aviation¹⁰.

Example (for calculation parameter ‘Distance’, Section 4.3.1): if a calculation method would analyse the exact trajectory of each and every flight, flights cannot be aggregated at all, as these trajectories will be unique. In this case, computational time will be scored 0. On the other hand, if a calculation method only requires information about the departure airport, arrival airport and aircraft type, a much smaller number of (unique) combinations has to be analysed in detail, which then can simply be multiplied with the number of times a given combination occurs. In such a case, the score for computational time will be higher.

3.5 Stakeholder support

The Ministry values the support of stakeholders and the industry. As such, alignment with current (inter)national calculation methods and regulations is anticipated to be beneficial. Similarly, if calculation options are already applied in other models, this is likely to increase alignment and comparability with results obtained from such models.

3.5.1 Alignment with current methods, standards and regulations

The criterion ‘alignment with current (inter)national calculation methods, standards and regulations’ is used to indicate to what extent the parameter options are also the standard in existing (inter)national calculation methods, standards, regulations and reporting efforts. Five (groups of) calculation methods, standards and regulations have been studied¹¹:

- EASA / ReFuelEU Aviation Flight Emissions Label
- ECAC Doc29
- EU Emissions Trading System (EU ETS), including its reference to the EU Renewable Energy Directive (RED II and RED III)
- ICAO Aeroplane CO₂ Emissions Certification Standard

¹⁰ Taking, as example, an annual total of 500 thousand flights, a calculation parameter option that would allow to aggregate flights in such a way that only 250 thousand unique flights remain, would be awarded 0.5 points. A calculation parameter option that would reduce the number of flights to such an extent that only 125 thousand unique flights would have to be analysed in order to get a result for an entire year would get 0.75 points.

¹¹ The ICAO Aeroplane CO₂ (certification) standard (ICAO, 2017b) is not considered, as this is a “proxy of cruise fuel efficiency” (ICCT, 2017, p. 2) and as such does not provide (parts of) a methodology to compute the CO₂ emissions for a flight. Instead, this standard has been considered as one of the calculation options for the calculation parameter ‘Aircraft unit fuel consumption’, introduced in Section 4.2.

- Methods and best practices used in (local) environmental impact assessments for aviation (Milieueffectrapportage, m.e.r.) and assessments for the environmental protection law (Wet natuurbeheer, Wnb) in the Netherlands¹²

Appendix C.1 provides more information about these methods, standards and regulations.

Weighting

For both hindcast and forecast applications, alignment with current methods, standards and regulations is given a weight of 2 (out of a total of 18, i.e. 11%).

Scoring and metrics

The score of ‘alignment with current (inter)national calculation methods, standards and regulations’ comprises two sub-scores: one on obligatoriness and another on optionality. These scores are to be multiplied for each method, standard or regulation considered. The multiplication ensures the maximum possible score is 1. The final score is determined by the maximum of these values, as it is deemed more relevant whether an option aligns with a method, standard or regulation (which, for example, also means supporting data would already be collected), rather than how many methods, standards or regulations an option aligns with.

The first sub-score regards the obligatoriness of a method, standard or regulation. Alignment with a mandated method or standard or piece of regulation is considered more advantageous than alignment with a voluntary standard. Points are awarded as follows:

- 1 point The calculation option is part of a method, standard or regulation that is obligatory (ECAC Doc29, EU ETS, CORSIA);
- 0.5 points The calculation option is part of a method, standard or regulation that is voluntary or not standardised (others).

The second sub-score regards the optionality of an option within a given method, standard or regulation. This takes into account that methods, standards or regulation in which there are numerous means of compliance might be not as uniform as methods, standards or regulations that prescribe one single option. Similar to the scoring for obligatoriness, there are two options, detailed below.

- 1 point The calculation option is the only option recognised by the method, standard or regulation;
- 0.5 points The calculation option is one of multiple options recognised by the method, standard or regulation.

Example (1, for calculation parameter ‘lifecycle savings from SAF’, Section 4.2.3): CORSIA takes into account lifecycle savings from SAF in either of two ways: using a default lifecycle emission reduction factor or using a specifically computed factor for a particular batch of fuel. As CORSIA is a mandated standard (at least for applicable flights), it scores 1 point for obligatoriness. As multiple calculation options exist in the standard, the optionality is 0.5. As such, both calculation options get a final score of 0.5 each.

Example (2, for calculation parameter ‘lifecycle savings from SAF’, Section 4.2.3): EU ETS takes into account lifecycle savings from SAF in a uniform manner. As long as the SAF meets the relevant requirements, the well to tank emissions are set to 0. Given the fact that EU ETS is active legislation (obligatoriness: 1 point) and that it has one option to take this parameter into account (optionality: 1 point), that option scores 1 point.

¹² As part of this group, a proposal for a uniform method for the calculation of aviation landing and take-off emissions, currently being prepared by To70 on assignment of the Ministry of Infrastructure and Water Management, has also been considered (To70, 2023). It is stressed that this method is not mandated and was, at the moment of writing, under review.

Example (3): If one calculation option would align to both EU ETS (score 1) and CORSIA (score 0.5), the final score for the criterion ‘alignment with current methods, standards or regulations’ would be 1.

3.5.2 Incorporation in existing CO₂ emission models

The criterion ‘incorporation in existing CO₂ emission models’ indicates whether the selected input parameter option is used in many, few or none of a number of currently existing CO₂ emission models studied. Seven models have been studied¹³:

- AEOLUS
- European Environmental Agency EMEP Guidebook (Tier 3A)
- EUROCONTROL Advanced Emissions Model (AEM), as used in EUROCONTROL IMPACT
- EUROCONTROL Small Emitters Tool (SET)
- IATA CO₂ Connect
- ICAO Carbon Emissions Calculator (CEC)
- NLR BeyondCO₂-tool

Appendix C.2 provides more information about these models. Even though the analysed models vary in fidelity, all of these models are frequently used in the modelling/inventory of (Dutch) aviation emissions, such that their reported results may be compared with the results of the to be developed uniform calculation method, stipulating their relevance regardless of their individual quality.

Weighting

For both hindcast and forecast applications, incorporation in existing CO₂ emission models is given a weight of 1 (out of a total of 18, i.e. 6%).

Scoring and metrics

The scoring of incorporation in existing CO₂ emission models comprises two sub-scores. The first sub-score assesses the familiarity of stakeholders with the method and the second sub-score assesses whether that method is openly available to anyone. These metrics have been set up to reflect the notion that it is more important to align with a well-known and freely available model (as such a model would likely be a first choice for somebody wanting to validate the outcomes of the method developed in this work) than to align with a model that only few people know about and that is also not available for anybody else.

The points regarding familiarity are awarded as follows:

- 0.5 point Option is also part of a CO₂-model with which stakeholders are widely familiar (AEOLUS, EUROCONTROL AEM, EUROCONTROL SET, IATA CO₂ Connect, ICAO CEC, NLR BeyondCO₂ tool);
- 0 points Option is not part of a CO₂-model with which stakeholders are widely familiar.

Points concerning the availability of the method are awarded as follows:

- 0.5 points Option is part of a CO₂-model that is available to anyone, free of charge

¹³ Lissys Piano has not been studied in this comparison, as it is an aircraft performance analysis tool. Whereas it includes emissions assessments, it has not been designed to evaluate emissions for larger sets of flights. Rather, it provides the aircraft performance data that is used as input by the other models listed. Similarly, the Google Travel Impact Model has not been evaluated, as it relies on the EEA EMEP model to evaluate full-flight CO₂ emissions. (The Travel Impact Model does employ a specific methodology to determine CO₂ emissions per passenger. That, however, is beyond the scope of this work.)

(EEA EMEP, EUROCONTROL SET, ICAO CEC);

- 0 points Option is not part of a CO₂-model that is available to anyone, free of charge.

Table 3 clusters the CO₂ emission models considered in a matrix spanning the aforementioned two dimensions. Each cell indicates the applicable number of points awarded to an option if that option is also incorporated by the models listed in that cell. That value is found by summing the sub-scores listed above.

Table 3: Scores awarded in case of incorporation in an existing CO₂ emission model

	Widely familiar	Not widely familiar
Available to anyone, free of charge	EUROCONTROL SET ICAO CEC 1 point	EEA EMEP 0.5 points
Not available to anyone, free of charge	AEOLUS EUROCONTROL AEM IATA CO ₂ Connect NLR BeyondCO ₂ -tool 0.5 points	 0 points

In order to prevent an option scoring more than 1 point (alignment with all models considered would yield a total of 5 points) and to ‘promote’ options that align with more models¹⁴, the scores are to be normalised to the maximum number of points attainable. In most cases, this is 5. However, in some cases, an option is not applicable to all models. This holds for options for calculating the distance, which two models (EEA EMEP and EUROCONTROL SET) require the user to input, as the model does not include a distance calculation method. In that specific case, the maximum number of points 3.5.

Example (1, for calculation parameter ‘CO₂ emission index’, Section 4.2.1): all models considered use a generic, fixed CO₂ emission index. As such, it will get a final score of 1.

Example (2, for calculation parameter ‘APU’, Section 4.3.2): AEOLUS, EEA EMEP, EUROCONTROL AEM, EUROCONTROL SET and the NLR BeyondCO₂-tool do not incorporate APU emissions. Per Table 3, this implies a (non-normalised) score of 0.5 + 0.5 + 0.5 + 1 + 0.5 = 3 points. Normalised by 5 yields a final (normalised) score of 0.6 points.

3.5.3 Stakeholder preference

A final assessment criteria ‘stakeholder preference’, in which stakeholders are asked to indicate their preferred option, is not directly weighted nor scored, but kept for use as a ‘tie breaker’, in case two options have the exact same score based on the other assessment criteria, and no other factor indicates either one to be the better option.

¹⁴ This is a different approach from the scoring metrics used for assessing the alignment with current methods, standards and regulations (Section 3.5.1), as for the current criterion (incorporation in existing CO₂ emissions models), the number of existing models an option aligns to is deemed important – as that number speaks to the ‘standardness’ of a particular option and to the likely alignment with outcomes of the currently developed method in terms of CO₂.

4 Calculation parameters and options

Calculation of aviation CO₂ emissions involves several parameters, some influencing the resulting CO₂ more than others. This chapter gives an overview of parameters that could be addressed in the uniform calculation method for aviation CO₂ emissions. As parameters can be taken into account at various levels of fidelity, several options per parameter are presented. Using the assessment criteria and scoring metrics outlined in Chapter 3, all options have been scored, in order to identify the best two options for each parameter to be included in the uniform calculation method for aviation CO₂ emissions.

4.1 Overview

A proposed set of calculation parameters was identified by CE Delft (Meijer & Grebe, 2024): fuel consumption, distance, flight phases, payload (passenger/cargo), wind and weather, and energy carrier. In this work, these parameters are extended and specified. The ‘fuel consumption’ parameter is retained and explicitly includes fidelity of aircraft selection for fuel consumption data. The calculation parameter ‘flight phases’ is extended to also include ground phases where the aircraft is not in the air but still causes CO₂ emissions, through taxiing or usage of the APU (auxiliary power unit). The phases are individually shown as parameter such that a subset of the trip phases can be selected for modelling. ‘Payload’ as a calculation parameter is retained and includes here both payload capacity and load factors. Under the category “miscellaneous”, other calculation parameters are grouped which can be applied to the CO₂ calculation to increase its fidelity. This, for example, includes wind influences on fuel consumption and conversion factors for specific sustainable aviation fuel blends.

In summary, the following calculation parameters are considered, and further discussed in the remainder of this chapter:

- **Aircraft fuel consumption** (Section 4.2)
 - Dependent on fuel type
 - CO₂ emission index
 - Lifecycle savings from LCAF
 - Lifecycle savings from SAF
 - Aircraft unit fuel consumption
- **Trajectory** (Section 4.3)
 - Distance
 - Trip phase
 - APU
 - Taxi
 - Landing and take-off (up to 3000 ft, excl. taxi)
 - Non-LTO climb / descent (above 3000 ft)
 - Cruise
- **Payload** (Section 4.4)
- **Miscellaneous** (Section 4.5)
 - Alternative taxi operations
 - Wind
 - Deviation from fuel-optimised cruise speed
 - Tankering

In addition to a description of the calculation parameter and the various options, the remainder of this chapter also presents the overall scores for each of these. Final scores include a weighting (for hindcast and forecast applications separately, indicated using HC and FC) and have been rounded to the nearest integer value.

As the data presented in the remainder of this chapter will show, ranges of scores for the accuracy assessment are shown for a number of calculation options. In some cases, for example, the accuracy score of one option could only be determined relative to the accuracy score of another option, rather than to an absolute 'ground truth'. This has been indicated with scores that are 'at least' or 'at most' a particular value (in the 'Accuracy'-row). The 'Combined accuracy / sensitivity'-row therefore shows a range of scores in these cases¹⁵. For other parameter options, either the accuracy could not be unambiguously or precisely determined, or, after having filled in the scores of the other assessment criteria, a detailed evaluation of the accuracy assessment criterion was not required to determine the highest ranking options. In the latter cases, the accuracy score would not affect which calculation option will be identified as best and second-best. These cases are labelled with 'Not assessed'. A range of scores (in the 'Combined accuracy / sensitivity'-row) is shown to indicate the extent of the spread when scores for accuracy are varied between 0 and 1¹⁶. Appendix B.2 provides further details on that evaluation and Appendix B.3 gives a qualitative estimation whether the parameter options are likely to lead to an over – or underestimation of CO₂ emissions. Appendix D provides the detailed scores per calculation option, supported by the aforementioned analysis documented in Appendix B (on the combined accuracy and sensitivity assessment) and Appendix C (on the criteria related to stakeholder support).

4.2 Aircraft fuel consumption

The parameter group aircraft fuel consumption clusters the parameters CO₂ emission index (Section 4.2.1), lifecycle savings from low carbon aviation fuel (LCAF; Section 4.2.2) and sustainable aviation fuel (SAF; Section 4.2.2), and aircraft unit fuel consumption (Section 4.2.4). First, Table 4 defines the types of aviation fuel considered in this study: fossil fuel (alternatively known as conventional aviation fuel), low carbon aviation fuel (LCAF) and sustainable aviation fuel (SAF).

Table 4: Types of aviation fuel considered

Type of fuel	Description
Fossil fuel	Fossil-based aviation fuel
Low carbon aviation fuel (LCAF)	Fossil-based aviation fuel, produced in such a way that the lifecycle CO ₂ emissions are lower than for traditional fossil aviation fuel. This can, for example, be achieved through the use of renewable energy in the fuel production process. To be eligible for CORSIA, an LCAF has to meet certain sustainability criteria, including a 10% reduction in lifecycle emissions (ICAO, n.d., b).
Sustainable aviation fuel (SAF)	Aviation fuels that are either synthetic aviation fuels, aviation biofuels or recycled carbon aviation fuels (EU, 2023c, Art. 3(7)). Synthetic aviation fuels are aviation fuels that are fuels of non-biological origin (RFNBOs), "the energy content of which is derived from renewable sources other than biomass" (EU, 2018, Art. 2(36)). This includes (renewable) hydrogen. Aviation biofuels are aviation fuels which are produced from biomass (EU, 2018, Art. 2(33)). Recycled carbon aviation fuels are "produced from liquid or solid waste streams of non-renewable origin [...] or from waste processing gas and exhaust gas of non-renewable origin" (EU, 2018, Art. 2(35)).

¹⁵ An example can be found in Table 20 for LTO, where the accuracy of idealised LTO modelling is given as: At least +0.25 points w.r.t. 'Not modelled explicitly'.

¹⁶ An example can be found in Table 16 for APU, where the small sensitivity of 0.01 leads to the 'Combined accuracy / sensitivity'-score having no influence on the final outcome of which of the options will be the best and second-best.

4.2.1 CO₂ emission index

For kerosene, the CO₂ emissions of a flight have a direct and linear dependency on the fuel consumption of the flight. To relate the kerosene fuel consumption to CO₂ emissions, for example, an emission index of 3.16 kg CO₂ / kg kerosene can be used (Ministry of Infrastructure and Water Management, 2023). Other fuels or energy sources (e.g. hydrogen, electricity) will have different emissions indices.

Table 5: Calculation options for the calculation parameter ‘CO₂ emission index’

Calculation parameter	Calculation parameter options	Remarks
CO ₂ emission index	Generic emission index per type of fuel	E.g. 3.16 kg CO ₂ / kg fuel for kerosene, 0 for hydrogen
	Batch specific emission index	

After assessment, these have been scored as shown in Table 6. As the CO₂ emission index directly influences CO₂ emissions in a 1-to-1 relationship, the sensitivity of the CO₂ emissions is 1. Clearly, the option ‘Generic emission index’ scores better than the option ‘Batch-specific emission index’. Appendix D.1.1 provides further details.

Table 6: Assessment results for various options for the calculation parameter ‘CO₂ emission index’

Assessment criterion	Weight		Score (unweighted)	
	HC	FC	Generic emission index	Batch-specific emission index
Accuracy			Not assessed	1
Sensitivity			1	1
Combined accuracy / sensitivity	6	5	0 – 1	1
Fraud-resistance	2	2	0.5	1
Transparency	3	3	1	0
Availability of data	3	3	1	0.25
Computational time	1	2	1	0
Alignment with current methods, standards and regulations	2	2	1	0
Incorporation in existing CO ₂ emission models	1	1	1	0
Total (hindcast; HC)	18	18	11 – 17	9
Total (forecast; FC)	18	18	12 – 17	8

4.2.2 Lifecycle savings from LCAF

Low-carbon aviation fuel (LCAF) is fossil aviation fuel that has been produced in a way resulting in less greenhouse gases during the production phase. These reductions can be taken into account in the tank-to-wake (i.e., in-flight) emissions values in a variety of ways: using a generic lifecycle emissions reduction factor for LCAF, using a lifecycle emissions reduction factor per LCAF-type, or using the actual lifecycle emission reduction factor of the batch of LCAF used. It is also possible to not consider these savings, as is for example done in the EU ETS.

Table 7: Calculation options for the calculation parameter ‘Lifecycle CO₂ savings from Low-Carbon Aviation Fuel (LCAF)’

Calculation parameter	Calculation parameter options	Remarks
Lifecycle CO ₂ savings from Low-Carbon Aviation Fuel (LCAF)	Not considered	This is in line with EU ETS
	Tank-to-wake CO ₂ emissions of LCAF reduced by generic lifecycle emission reduction factor of LCAF	This approach is in line with CORSIA and the proposed EASA / ReFuelEU Aviation Flight Emissions Label

Calculation parameter	Calculation parameter options	Remarks
	Tank-to-wake CO ₂ emissions of LCAF reduced by generic lifecycle emission reduction factor of LCAF-type	
	Tank-to-wake CO ₂ emissions of LCAF reduced by lifecycle emission reduction factor of LCAF-batch uplifted	

After assessment, these have been scored as shown in Table 8. As LCAF could only reduce tank-to-wake CO₂ emissions by at most 20%, the sensitivity is set to 0.2 (Appendix B.1.1). The option ‘Not considered’ scores best, mainly due to better alignment with current methods, standards and regulations, and better alignment with existing CO₂ emission models. The option ‘Tank-to-wake emissions of LCAF reduced by generic lifecycle emission reduction factor of LCAF-type’ is the second-best, in line with the result obtained for SAF. Appendix D.1.2 Table 8 provides further details.

Table 8: Assessment results for various options for the calculation parameter ‘Lifecycle CO₂ savings from Low-Carbon Aviation Fuel (LCAF)’

Assessment criterion	Weight		Score (unweighted)			
	HC	FC	Not considered	TTW based on ERF, generic	TTW based on ERF, LCAF type	TTW based on ERF, LCAF batch
Accuracy			Not assessed	Not assessed	Not assessed	1
Sensitivity			0.20	0.20	0.20	0.20
Combined accuracy / sensitivity	6	5	0 – 0.2	0 – 0.2	0 – 0.2	0.2
Fraud-resistance	2	2	1	1	1	1
Transparency	3	3	1	1	1	0.33
Availability of data	3	3	1	1	1	0.5
Computational time	1	2	1	1	1	0
Alignment with current methods, standards and regulations	2	2	1	0	0.5	1
Incorporation in existing CO ₂ emission models	1	1	1	0	0	0
Total (hindcast; HC)	18	18	12 – 13	9 – 10	10 – 11	8
Total (forecast; FC)	18	18	13 – 14	10 – 11	11 – 12	7

4.2.3 Lifecycle savings from SAF

The options to take into account the lifecycle savings from sustainable aviation fuel (SAF) are similar to the calculation options presented for the lifecycle savings from LCAF. Tank-to-wake (i.e., in-flight) emissions can be reduced by a generic or more specific lifecycle emission reduction factor of the type of SAF considered (in line with CORSIA and the proposed EASA / ReFuelEU Aviation Flight Emissions Label), sourced for example from default lifecycle emission reduction factors published by ICAO (ICAO, 2024a) or included in the EU Renewable Energy Directive (EU 2018/2001, EU, 2018; EU 2023/2413, EU, 2023d). In this option, the “type of SAF” refers to the combination of feedstock and production process. Alternatively, batch-specific lifecycle emission reduction factors could be used. Due to the importance of SAF in many aviation decarbonisation roadmaps, the option not to consider SAF has been excluded up front. Rather, the option of setting tank-to-wake emissions to zero has been added, following EU ETS regulations and other accounting standards. Box 6 provides some background to these accounting standards.

BOX 6: EMISSION ACCOUNTING STANDARDS

The lifecycle emissions from SAF are lower than those of fossil kerosene. The relative reduction is determined through a lifecycle analysis (LCA), which for this application is used to analyse the (greenhouse gas) emissions produced during every

phase of the fuel lifecycle, from resource extraction (or, for SAF, feedstock collection) at the beginning, to use (i.e., combustion) at the end. For fuels, lifecycle phases are often grouped in two clusters: well-to-tank (WtT) covers all steps from resource collection to delivery in the aircraft fuel tank; tank-to-wake (TtW) then considers the use of the fuel. The entire lifecycle, hence, considers well-to-wake (WtW) emissions.

Methodologies of the Greenhouse Gas Protocol, the EU RED and the EU ETS, as well as guidance from the World Economic Forum, consider the TtW-emissions of sustainable (aviation) fuels to be 0 (WEF, 2022; EU, 2018; EU, 2003; GHGP, 2011). This is because the CO₂ released during combustion is equal to the CO₂ absorbed by the feedstock during its growth or, for synthetic SAF, equal to the CO₂ removed using carbon removal technologies.

Alternatively to these standards, and as far as the authors know only applied in aviation (ICAO, 2023; EC, 2024b; IATA, 2025), the total (percentage) WtW emissions reduction realised by sustainable fuels can be mathematically applied to the WtT and TtW components. In this approach, the reduction in TtW emissions is reduced proportionally to the overall reduction in WtW emissions, for example meaning that an 80% WtW reduction is accounted for through 80% reductions in both WtT and TtW emissions.

In this work, the parameter option ‘tank-to-wake CO₂ emissions of SAF set to zero’ follows the first approach. The other options align to the second approach.

Table 9: Calculation options for the calculation parameter ‘Lifecycle CO₂ savings from Sustainable Aviation Fuel (SAF)’

Calculation parameter	Calculation parameter options	Remarks
Lifecycle CO ₂ savings from Sustainable Aviation Fuel (SAF)	Tank-to-wake CO ₂ emissions of SAF set to zero	This is in line with EU ETS
	Tank-to-wake CO ₂ emissions of SAF reduced by generic lifecycle emission reduction factor of SAF	This approach is in line with CORSIA and the proposed EASA / ReFuelEU Aviation Flight Emissions Label
	Tank-to-wake CO ₂ emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type	
	Tank-to-wake CO ₂ emissions of SAF reduced by lifecycle emission reduction factor of SAF-batch uplifted	

After assessment, these have been scored as shown in Table 10. Based on the current SAF blending limit of 50%, the sensitivity for this parameter is set to 0.5 (Appendix B.1.1). As the accuracy for all options could not be determined, a range of total scores is found for three out of four options. Looking at the maximum values of these ranges, the options ‘Tank-to-wake emissions of SAF set to zero’ and ‘Tank-to-wake emissions of SAF reduced by generic lifecycle emissions reduction factor of SAF-type’ score highest, followed by the option ‘Tank-to-wake emissions of SAF reduced by generic lifecycle emissions reduction factor of SAF’. The option based on batch-specific data scores the lowest number of points, due to lower scores for transparency, availability of data and computational time. Appendix D.1.2 provides further details.

Table 10: Assessment results for various options for the calculation parameter 'Lifecycle CO₂ savings from Sustainable Aviation Fuel (SAF)'

Assessment criterion	Weight		Score (unweighted)			
	HC	FC	TTW 0	TTW based on ERF, generic	TTW based on ERF, SAF type	TTW based on ERF, SAF batch
Accuracy			0 – 0.75	0 – 0.75	At least +0.25 pt. w.r.t. 'TTW based on ERF, generic'	1
Sensitivity			0.50	0.50	0.50	0.50
Combined accuracy / sensitivity	6	5	0 – 0.38	0 – 0.38	0.13 – 0.5	0.50
Fraud-resistance	2	2	1	1	1	1
Transparency	3	3	1	1	1	0.33
Availability of data	3	3	1	1	1	0.5
Computational time	1	2	1	1	1	0
Alignment with current methods, standards and regulations	2	2	1	0	0.5	1
Incorporation in existing CO ₂ emission models	1	1	0	0.22	0.11	0
Total (hindcast; HC)	18	18	11 – 13	9 – 12	11 – 13	9
Total (forecast; FC)	18	18	12 – 14	10 – 12	12 – 14	9

4.2.4 Aircraft unit fuel consumption

The total fuel consumption depends on how the aircraft is modelled, and thus at what fidelity level fuel consumption data is required. Table 11 shows the inventoried unit fuel consumption data options. 'Unit fuel consumption' can relate to both consumption per unit of time, or per unit of distance. The option 'Unit fuel consumption per aircraft type and engine type (certification data)', based on the recently introduced ICAO CO₂ standard for aeroplanes (ICAO, 2017b), is crossed out due to the fact that certification data for (cruise) fuel consumption currently is only available for a very limited number of aircraft and engine combinations (EASA, 2024c)¹⁷.

Table 11: Calculation options for the calculation parameter 'Aircraft unit fuel consumption'

Calculation parameter	Calculation parameter options	Remarks
Aircraft unit fuel consumption	(Average) unit fuel consumption per aircraft size class (modelled)	
	Unit fuel consumption per aircraft type (modelled)	
	Unit fuel consumption per aircraft type and airframe age (modelled)	
	Unit fuel consumption per aircraft type and engine type (modelled)	
	Unit fuel consumption per aircraft type, engine type and airframe age (modelled)	
	Unit fuel consumption per aircraft type and engine type (certification data)	
	Unit fuel consumption per aircraft type and engine type (real-life data)	

¹⁷ This is a consequence of the rather recent introduction of the standard and its applicability: from January 1, 2020 for new designs of subsonic aeroplanes, including their derived versions, with the exception of jet aeroplanes with 19 seats or less; from January 1st, 2023 for derived versions of non-CO₂ certified aeroplanes, and new designs of jet aeroplanes with 19 seats or less; from January 1st, 2028 for all in-production aeroplanes.

After assessment, these have been scored as shown in Table 12. As CO₂ emissions are directly related to fuel consumption, the sensitivity is equal to 1. The option 'Unit fuel consumption per aircraft type and engine type (modelled)' scores highest, followed by the option that also takes into account the year (in forecast applications, this option is tied with 'Unit fuel consumption per aircraft type (modelled)'). The option sensitive to aircraft type, engine type and airframe age does not align as well to other methods, standards, regulations or models, but is considered more accurate. Options that disregard the engine type are more common, but notably less accurate. Real-life fuel consumption figures would give highest accuracy, but are anticipated not to be available and, due to the business-sensitive nature of the data, will not be shared publicly. This negatively affects transparency. Appendix D.1.4 provides further details.

Table 12: Assessment results for various options for the calculation parameter 'Aircraft unit fuel consumption'

Assessment criterion	Weight		Score (unweighted)					
	HC	FC	Modelled, aircraft size class	Modelled, aircraft type	Modelled, aircraft type + age	Modelled, aircraft + engine type	Modelled, aircraft + engine type + age	Actual data
Accuracy			0	0.25	0.25	0.75	1	1
Sensitivity			1	1	1	1	1	1
Combined accuracy / sensitivity	6	5	0	0.25	0.25	0.75	1	1
Fraud-resistance	2	2	0.5	1	0.5	1	0.5	1
Transparency	3	3	1	0.33	0.33	0.33	0.33	0
Availability of data	3	3	1	0.75	0.75	0.75	0.75	0.5
Computational time	1	2	0.99	0.98	0.97	0.97	0.97	0
Alignment with current methods, standards and regulations	2	2	0	0.75	0	0.75	0	0.25
Incorporation in existing CO ₂ emission models	1	1	0.11	0.89	0	0	0	0
Total (hindcast; HC)	18	18	8	10	7	12	11	10
Total (forecast; FC)	18	18	9	11	7	12	11	9

4.3 Trajectory

The fuel consumption described in Section 4.2 could be evaluated along a 4D trajectory. The trajectory is evaluated in several parameter options. This section discerns between the calculation parameter 'Distance' (Section 4.3.1) and various calculation parameters related to the different phases of the trip (Sections 4.3.2 up to and including 4.3.6). Splitting a trip into different trip phases is useful, as fuel flow can differ significantly between the different flight phases. An overview of the flight phases defined under trajectory can be seen in Figure 1.

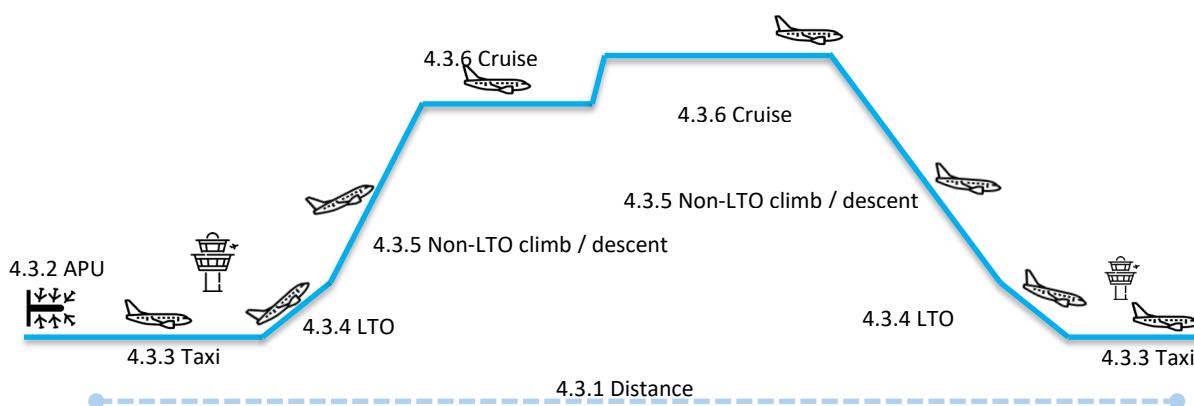


Figure 1: Trajectory phases

4.3.1 Distance

The distance of a flight can be modelled using a number of parameter options. Apart from the planned route, most options are based on the great circle distance (GCD; which can be readily calculated from the location of the origin and destination airports), potentially refined with a fixed distance or relative factor to account for the fact that flights (to a greater or lesser extent) deviate from the GCD, for example due to weather or airspace considerations.

Table 13: Calculation options for the calculation parameter ‘Distance’

Calculation parameter	Calculation parameter options	Remarks
Distance	Great Circle Distance (GCD)	
	GCD with generic detour distance/ detour factor	
	GCD with airline-dependent detour distance/ detour factor	
	GCD with region-dependent detour distance/ detour factor	
	GCD with airline-region-dependent detour distance/ detour factor	
	GCD with distance-dependent detour distance/ detour factor	
	GCD with airline-distance-dependent detour distance/ detour factor	
	GCD with route-dependent detour distance/ detour factor	
	GCD with airline-route-dependent detour distance/ detour factor	
	Planned route (filed flight plan)	
	Flown route	

After assessment, these have been scored as shown in Table 14. With a sensitivity determined to equal 0.84 (Appendix B.1.2), the distance is an important influence to CO₂. Of the many different options assessed, ‘Great circle distance’ and ‘GCD with distance-dependent detour distance/ detour factor’ were evaluated best, for both hindcast as well as forecast applications. The option ‘Actual’ would be a next-best, followed by the use of generic of region detour distances or factors. Options taking into account airline-dependent detour distances or factors have typically obtained lower scores, mainly due to lower scores for availability of data and transparency. Appendix D.2.1 provides further details.

Table 14: Assessment results for various options for the calculation parameter 'Distance'

Assessment criterion	Weight		Score (unweighted)					
	HC	FC	GCD	Generic detour	Airline detour	Region detour	Airline + region detour	Distance detour
Accuracy			0.25	0.25	0.25	0.25	0.5	0.5
Sensitivity			0.84	0.84	0.84	0.84	0.84	0.84
Combined accuracy / sensitivity	6	5	0.21	0.21	0.21	0.21	0.42	0.42
Fraud-resistance	2	2	1	1	1	1	1	1
Transparency	3	3	1	1	0.33	1	0.33	1
Availability of data	3	3	1	1	0.5	1	0.5	1
Computational time	1	2	1	1	1	1	0.99	0.98
Alignment with current methods, standards and regulations	2	2	1	0	0	0	0	0
Incorporation in existing CO ₂ emission models	1	1	0	0.33	0	0.22	0	0.5
Total (hindcast; HC)	18	18	12	10	7	10	8	12
Total (forecast; FC)	18	18	13	11	8	11	9	13

Assessment criterion	Weight		Score (unweighted)				
	HC	FC	Airline + dist. detour	Route detour	Airline + rte. detour	Planned	Actual
Accuracy			0.5	0.5	0.5	Not assessed	1
Sensitivity			0.84	0.84	0.84	0.84	0.84
Combined accuracy / sensitivity	6	5	0.42	0.42	0.42	0 – 0.84	0.84
Fraud-resistance	2	2	1	1	1	0.5	1
Transparency	3	3	0.33	0.33	0.33	0	0.33
Availability of data	3	3	0.5	0.5	0.5	0.5	0.75
Computational time	1	2	0.96	0.98	0.96	0	0
Alignment with current methods, standards and regulations	2	2	0	0	0	0.25	0.25
Incorporation in existing CO ₂ emission models	1	1	0	0.22	0	0.11	0.11
Total (hindcast; HC)	18	18	8	8	8	3 – 8	11
Total (forecast; FC)	18	18	9	9	9	3 – 7	10

4.3.2 APU

The amount of time the APU is used can be calculated using a number of options, as shown in Table 15.

Table 15: Calculation options for the calculation parameter 'APU'

Calculation parameter	Calculation parameter options	Remarks
APU	Not considered	Neglects APU fuel consumption / emissions altogether
	Not modelled explicitly / specifically	For example: APU fuel consumption / emissions taken into account by calculating a mission-averaged unit fuel burn that includes APU fuel
	Generic value	For example: from ICAO Doc. 9889
	Airline-averaged value	
	Actual	

After assessment, these have been scored as shown in Table 16. The sensitivity was determined to be 0.01 (Appendix B.1.2), following the limited share of APU fuel consumption relative to the fuel consumed during the entire mission. The option to not consider APU runtime (and associated) emissions scores highest, for both forecast and hindcast application. This is predominantly scored by the fact that neglecting APU usage is most in line with other methods, standards, regulations and existing CO₂ emissions models. As next-best options, 'Not modelled explicitly / specifically' (in which APU fuel burn would be included in an overall mission fuel consumption figure) or 'Generic' (which would assume a default APU runtime) have been scored an equal number of points. Appendix D.2.2 provides further details.

Table 16: Assessment results for various options for the calculation parameter 'APU'

Assessment criterion	Weight		Score (unweighted)				
	HC	FC	Not considered	Not modelled explicitly / sp.	Generic	Airline-averaged	Actual
Accuracy			Not assessed	Not assessed	Not assessed	Not assessed	1
Sensitivity			0.01	0.01	0.01	0.01	0.01
Combined accuracy / sensitivity	6	5	0 – 0.01	0 – 0.01	0 – 0.01	0 – 0.01	0.01
Fraud-resistance	2	2	1	1	1	1	1
Transparency	3	3	1	1	1	0	0
Availability of data	3	3	1	1	1	0.5	0.5
Computational time	1	2	1	1	1	0.96	0
Alignment with current methods, standards and regulations	2	2	0.5	0	0.17	0.17	0.17
Incorporation in existing CO ₂ emission models	1	1	0.67	0.33	0	0	0
Total (hindcast)	18	18	11	9	9	5	4
Total (forecast)	18	18	12	10	10	6	4

4.3.3 Taxi

Table 17 shows a number of options that were identified to describe the taxi-phase. As for APU, it is noted that expressing the taxi phase as a duration (taxi time rather than taxi distance) is considered more straightforward, for example due to availability of data.

Table 17: Calculation options for the calculation parameter 'Taxi'

Calculation parameter	Calculation parameter options	Remarks
Taxi	Not modelled explicitly / specifically	For example: taxi fuel consumption / emissions taken into account by calculating a mission-averaged unit fuel burn that includes taxi fuel
	Default taxi time	For example: from ICAO default certification LTO-cycle
	Average airport taxi time	For example: based on EUROCONTROL taxi time data
	Average airport-runway taxi time	
	Actual	

After assessment, these have been scored as shown in Table 18. The sensitivity was determined to be higher than for APU, but is still rather limited (Appendix B.1.2). The option 'Not modelled explicitly / specifically' scores best, followed by options to use a 'Default taxi time' or an 'Average airport taxi time', both of which get an equal (rounded) score. Key drivers for these higher scores are better evaluations in terms of transparency, availability of data and (although to a lesser extent) computational time and, compared to 'Average airport-runway taxi time' and 'Actual', better alignment with existing CO₂ emission models. Appendix D.2.3 provides further details.

Table 18: Assessment results for various options for the calculation parameter 'Taxi'

Assessment criterion	Weight		Score (unweighted)				
	HC	FC	Not modelled explicitly / sp.	Default	Avg. airport	Avg. runway	Actual
Accuracy			Not assessed	0	Not assessed	Not assessed	1
Sensitivity			0.036	0.036	0.036	0.036	0.036
Combined accuracy / sensitivity	6	5	0 – 0.036	0	0 – 0.036	0 – 0.036	0.036
Fraud-resistance	2	2	1	1	1	1	1
Transparency	3	3	1	1	1	0.33	0.33
Availability of data	3	3	1	1	1	0.5	0.75
Computational time	1	2	1	1	0.98	0.89	0
Alignment with current methods, standards and regulations	2	2	0.25	0	0	0.25	0.5
Incorporation in existing CO ₂ emission models	1	1	0.56	0.33	0.22	0	0
Total (hindcast)	18	18	10	9	9	6	6
Total (forecast)	18	18	11	10	10	7	6

4.3.4 LTO

The landing and take-off cycle (LTO-cycle) typically includes taxi-out, take-off, climb-out, approach, landing and taxi-in operations up to a maximum altitude of 3000 ft. Given this work treats the taxi phase as separate, calculation options for the calculation parameter 'LTO' are limited to alternative approach to define the take-off, climb-out, approach and landing phases. Options identified are shown in Table 19.

Table 19: Calculation options for the calculation parameter 'LTO'

Calculation parameter	Calculation parameter options	Remarks
LTO (excluding taxi)	Not modelled explicitly / specifically	For example: LTO fuel consumption / emissions taken into account by calculating a mission-averaged unit fuel burn that includes LTO fuel
	Generic (i.e., not aircraft type-specific)	ICAO default certification LTO-cycle

Calculation parameter	Calculation parameter options	Remarks
	Idealised (i.e., aircraft type-specific)	For example: modelled based on performance of aircraft type (and/or engine type, and/or weight, ...) considered
	Actual	

After assessment, these have been scored as shown in Table 20. Again, the sensitivity to this parameter is larger (at 0.063) than to the two previous parameters (Appendix B.1.2). ‘Not modelled explicitly / specifically’ scores best. In this option, fuel consumption and associated emissions during the LTO-cycle would be included in mission-average fuel consumption figures. ‘Generic’ modelling (using fuel flow figures at the fidelity-level defined for the calculation parameter ‘Aircraft unit fuel consumption’ and default times-in-mode for any of the LTO-phases considered) is considered more accurate, but an approach less widely used. Even more accurate would be the ‘Idealised’ option (which models an LTO-flightpath based on the horizontal and vertical speeds of the aircraft considered), but due to lower scores for (notably) transparency and availability of data, this option achieves a lower overall score. Appendix D.2.4 provides further details.

Table 20: Assessment results for various options for the calculation parameter ‘LTO’

Assessment criterion	Weight		Score (unweighted)			
	HC	FC	Not modelled explicitly / sp.	Generic	Idealised	Actual
Accuracy			0	0.25	At least +0.25 pt w.r.t. ‘Not modelled exp. / sp.’	1
Sensitivity			0.063	0.063	0.063	0.063
Combined accuracy / sensitivity	6	5	0	0.02	0.02 – 0.063	0.063
Fraud-resistance	2	2	1	1	1	1
Transparency	3	3	1	1	0.33	0.33
Availability of data	3	3	1	1	0.75	0.75
Computational time	1	2	1	1	0.98	0
Alignment with current methods, standards and regulations	2	2	0.25	0	1	0.25
Incorporation in existing CO ₂ emission models	1	1	0.56	0.33	0.11	0
Total (hindcast)	18	18	10	9	8 – 9	6
Total (forecast)	18	18	11	10	9 – 10	6

4.3.5 Non-LTO climb / descent

Between the LTO-segments and cruise flight, aircraft climb and descent to their cruise altitude. For the segment of flight between an altitude of 3000 ft (the end of the LTO-cycle) and top of climb or top of descent, a number of calculation options have been identified. These are shown in Table 21.

Table 21: Calculation options for the calculation parameter ‘Non-LTO climb / descent’

Calculation parameter	Calculation parameter options	Remarks
Non-LTO climb / descent	Not modelled explicitly / specifically	For example: climb and descent fuel consumption / emissions taken into account by calculating a mission-averaged unit fuel burn that includes climb and descent fuel
	Idealised (i.e., aircraft type-specific)	For example: modelled based on performance of aircraft type (and/or engine type, and/or weight, ...) considered
	Actual	

After assessment, these have been scored as shown in Table 22. The sensitivity of total CO₂ emissions to the non-LTO climb / descent phases was determined to be 0.3 (Appendix B.1.2). The option “Not modelled explicitly / specifically” obtained the highest score. In this option, fuel consumption and associated emissions during the non-LTO climb and descent phases would be included in mission-average fuel consumption figures. Next-best alternatives are ‘Actual’ (for hindcast applications) and ‘Idealised’ (for forecast applications). Appendix D.2.5 provides further details.

Table 22: Assessment results for various options for the calculation parameter ‘Non-LTO climb / descent’

Assessment criterion	Weight		Score (unweighted)		
	HC	FC	Not modelled explicitly / specifically	Idealised	Actual
Accuracy			0	Not assessed	1
Sensitivity			0.30	0.30	0.30
Combined accuracy / sensitivity	6	5	0	0 – 0.3	0.3
Fraud-resistance	2	2	1	1	1
Transparency	3	3	1	0.33	0.33
Availability of data	3	3	1	0.75	0.75
Computational time	1	2	1	0.98	0
Alignment with current methods, standards and regulations	2	2	0.25	0.5	0.75
Incorporation in existing CO ₂ emission models	1	1	0.78	0.22	0.11
Total (hindcast)	18	18	10	7 – 9	9
Total (forecast)	18	18	11	8 – 10	8

4.3.6 Cruise

For the majority of flights, the cruise phase is the longest. As shown in Table 23, four options have been inventoried by which the cruise phase can be described.

Table 23: Calculation options for the calculation parameter ‘Cruise’

Calculation parameter	Calculation parameter options	Remarks
Distance	Idealised (i.e., aircraft type-specific)	
	Idealised including step climbs	For example: modelled based on performance of aircraft type (and/or engine type, and/or weight, ...) considered
	Planned	
	Actual	

After assessment, these have been scored as shown in Table 24. Of all trip phases, the sensitivity of cruise is largest – at 0.59 (Appendix B.1.2). The options ‘Idealised’ and ‘Idealised including step climbs’ both score best for forecast, with ‘Actual’ scoring just as high as the other two for hindcast. Idealised modelling is more common, and hence aligns better to existing CO₂ emission models, but including step climbs is considered more accurate. For forecast applications, ‘Actual’ is the second-best option, scoring better in terms of accuracy and alignment with current methods, standards and regulations, but achieves lower points for computational time. Using the cruise phase as planned is considered the least favourable option, mainly due to lower scores for fraud-resistance, transparency and availability of data. Appendix D.2.6 provides further details.

Table 24: Assessment results for various options for the calculation parameter 'Cruise'

Assessment criterion	Weight		Score (unweighted)			
	HC	FC	Idealised	Ideal. + step climbs	Planned	Actual
Accuracy			0.5	0.75	Not assessed	1
Sensitivity			0.59	0.59	0.59	0.59
Combined accuracy / sensitivity	6	5	0.30	0.44	0 – 0.59	0.59
Fraud-resistance	2	2	1	1	0.5	1
Transparency	3	3	0.33	0.33	0	0.33
Availability of data	3	3	0.75	0.75	0.5	0.75
Computational time	1	2	0.98	0.98	0	0
Alignment with current methods, standards and regulations	2	2	0	0	0	0.25
Incorporation in existing CO ₂ emission models	1	1	0.90	0.11	0.11	0.11
Total (hindcast)	18	18	9	9	3 – 6	9
Total (forecast)	18	18	10	10	3 – 6	9

4.4 Payload

The payload capacity depends on the aircraft selection for the calculation parameter 'Aircraft and fuel consumption', which can result in a more generic or specific payload capacity. The extent to which this capacity is utilised can be expressed in terms of load factors for both passengers and cargo (including belly freight), and influences the aircraft weight and thence fuel consumption rate. Alternatively, total payload weight may be directly obtained, for example through flight plan data, or calculated from the actual take-off weight (TOW). The full array of options considered is shown in Table 25.

Table 25: Calculation options for the calculation parameter 'Payload'

Calculation parameter	Calculation parameter options	Remarks
Passenger and freight payload	Typical aircraft class capacity and average load factors	
	Typical aircraft type capacity and average load factors	
	Typical aircraft type capacity and average airline load factors	
	Typical aircraft type capacity and average region load factors	
	Typical aircraft type capacity and average airport pair load factors	
	Typical aircraft tail capacity and average airport pair load factors	
	Payload weight in filed flight plan	
	Calculated from actual take-off weight (TOW)	

After assessment, these have been scored as shown in Table 26. The sensitivity was determined to be 0.15 (Appendix B.1.3), meaning that accuracy improvements have a relatively limited effect on the overall score. The option 'Typical aircraft type capacity and average load factors' scores best, primarily due to the good alignment of this option with current methods, standards and regulations, as well as with existing CO₂ models. Next-best, separated by a larger difference than observed for many other calculation parameters, would be 'Typical aircraft class capacity and average

load factors' and 'Typical aircraft type capacity and average region load factors'. In terms of accuracy, fraud-resistance, transparency, availability of data and computational time, these options score as well (or better) than the highest-ranked alternative. However, both these alternative options are less aligned to standards and models currently used. Appendix D.3 provides further details.

Table 26: Assessment results for various options for the calculation parameter 'Payload'

Assessment criterion	Weight		Score (unweighted)				
	HC	FC	Aircraft class	Aircraft type	Aircraft type + airline	Aircraft type + region	Aircraft type + airport pair
Accuracy			0	Not assessed	Not assessed	At least + 0.25 pt w.r.t. 'Aircraft class'	At least + 0.25 pt w.r.t. 'Aircraft class'
Sensitivity			0.15	0.15	0.15	0.15	0.15
Combined accuracy / sensitivity	6	5	0	0 – 0.15	0 – 0.15	0.038 – 0.15	0.038 – 0.15
Fraud-resistance	2	2	1	1	1	1	1
Transparency	3	3	1	1	0.33	1	0.33
Availability of data	3	3	1	1	0.75	1	0.75
Computational time	1	2	0.99	0.98	0.97	0.99	0.98
Alignment with current methods, standards and regulations	2	2	0	1	0	0	0
Incorporation in existing CO ₂ emission models	1	1	0.1	0.7	0	0.22	0.11
Total (hindcast; HC)	18	18	9	12 – 13	6 – 7	9 – 10	6 – 7
Total (forecast; FC)	18	18	10	13	7 – 8	10 – 11	8

Assessment criterion	Weight		Score (unweighted)		
	HC	FC	Tail capacity + airport LF	From flight plan	From actual TOW
Accuracy			At least + 0.25 pt w.r.t. 'Aircraft class'	At least + 0.25 pt w.r.t. 'Aircraft class'	1
Sensitivity			0.15	0.15	0.15
Combined accuracy / sensitivity	6	5	0.038 – 0.15	0.038 – 0.15	0.15
Fraud-resistance	2	2	1	1	1
Transparency	3	3	0	0	0
Availability of data	3	3	0.5	0.5	0.5
Computational time	1	2	0.86	0	0
Alignment with current methods, standards and regulations	2	2	0.25	0.25	0
Incorporation in existing CO ₂ emission models	1	1	0	0	0
Total (hindcast; HC)	18	18	5 – 6	4 – 5	4
Total (forecast; FC)	18	18	6	4 – 5	4

4.5 Miscellaneous

Several other factors affect the CO₂ emissions of a certain flight that are not accounted for in the previous parameters and could be applied to increase fidelity of the method of computing aviation CO₂ emissions. Four are considered in

this section: alternative taxi operations (Section 4.5.1), wind (Section 4.5.2), deviation from fuel-optimal cruise speed (Section 4.5.3) and tankering (Section 4.5.4).

4.5.1 Alternative taxi operations

Alternative taxi operations may save CO₂ emissions during taxiing through single engine taxiing and/or electric taxi operations and can be accounted for through, for example, a reduction factor on taxi time, distance or fuel consumption.

Table 27: Calculation options for the calculation parameter 'Alternative taxi operations'

Calculation parameter	Calculation parameter options	Remarks
Alternative taxi operations	Not modelled	Combination of 'Not considered' and 'Not modelled explicitly / specifically': either neglected altogether, or taken into account by (for example) including alternative taxi savings in average unit fuel consumption figures
	Percentage of single engine taxiing	
	Percentage of single engine taxiing and percentage of electric taxiing (e.g. by (electric) tow truck)	

After assessment, these have been scored as shown in Table 28. As for the taxi phase (Section 4.3.3), the sensitivity has been set to 0.036 (Appendix B.1.4). Based on the scores, not modelling alternative taxi operations is considered be the best option. This is due to the good alignment with other methods and models and excellent scores for fraud-resistance, transparency, availability of data and computational time. Although the other options, of which 'Percent of single engine taxiing' scores slightly better than 'Percentage of single engine taxiing and percentage of electric taxiing', are potentially slightly more accurate, the low impact of overall taxi emissions on total CO₂ emissions do not – at the weighting factors used – make this worth-while. Appendix D.4.1 provides further details.

Table 28: Assessment results for various options for the calculation parameter 'Alternative taxi operations'

Assessment criterion	Weight		Score (unweighted)		
	HC	FC	Not modelled	% of single engine taxi	% of electric taxi
Accuracy			Not assessed	Not assessed	Not assessed
Sensitivity			0.036	0.036	0.036
Combined accuracy / sensitivity	6	5	0 – 0.036	0 – 0.036	0 – 0.036
Fraud-resistance	2	2	1	1	1
Transparency	3	3	1	0.33	0.33
Availability of data	3	3	1	0.5	0.5
Computational time	1	2	1	0.97	0.97
Alignment with current methods, standards and regulations	2	2	0.5	0.5	0
Incorporation in existing CO ₂ emission models	1	1	0.89	0.11	0.11
Total (hindcast)	18	18	11	7	6
Total (forecast)	18	18	12	8	7

4.5.2 Wind

Wind may lead to either an increased (e.g. with headwinds) or a reduced (e.g. with tailwinds) fuel consumption. A correction factor – at several levels of fidelity – can be applied to take the changes in fuel burn, especially in the cruise phase, into account. It is stressed that this correction is limited to the influence of wind on speed: weather impacts on flight distance (e.g. circumnavigating adverse weather, additional holding in case of poor visibility) are included in the parameter distance (Section 4.3.1), part of the trajectory set (Section 4.3).

Table 29: Calculation options for the calculation parameter ‘Wind’

Calculation parameter	Calculation parameter options	Remarks
Wind	Not modelled	Combination of ‘Not considered’ and ‘Not modelled explicitly / specifically’: either neglected altogether, or taken into account by (for example) using historical fuel consumption (including wind effects) to determine unit fuel consumption figures
	Averaged per region	
	Averaged per airport-pair	
	Averaged based on historic climatological data	
	Actual conditions	

After assessment, these have been scored as shown in Table 30. As wind effects mostly play a role during the cruise phase, the sensitivity has been set equal to that of the cruise phase – 0.59 (Section 4.3.6 and Appendix B.1.4). The option ‘Not modelled’ scores best, followed by the option to consider wind effects ‘Averaged per region’. These options are most common in other methods, standards, regulations and models and score high(er) in terms of transparency, availability of data and computational time, compared to the (potentially) more accurate options. Appendix D.4.2 provides further details.

Table 30: Assessment results for various options for the calculation parameter ‘Wind’

Assessment criterion	Weight		Score (unweighted)				
	HC	FC	Not modelled	Region	Airport-pair	Climatological	Actual
Accuracy			0 – 0.75	At least + 0.25 pt w.r.t. ‘Not modelled’	At least + 0.25 pt w.r.t. ‘Not modelled’	At least + 0.25 pt w.r.t. ‘Not modelled’	1
Sensitivity			0.59	0.59	0.59	0.59	0.59
Accuracy / sensitivity	6	5	0 – 0.44	0.15 – 0.59	0.15 – 0.59	0.15 – 0.59	0.59
Fraud-resistance	2	2	1	1	1	1	1
Transparency	3	3	1	0.66	0.66	0.66	0.33
Availability of data	3	3	1	0.75	0.5	0.5	0.5
Computational time	1	2	1	0.99	0.98	0.98	0.98
Alignment with current methods, standards and regulations	2	2	0.25	1	0	0	0.25
Incorporation in existing CO ₂ emission models	1	1	0.78	0	0.11	0	0.11
Total (hindcast)	18	18	10 – 13	10 – 13	8 – 10	7 – 10	9
Total (forecast)	18	18	11 – 14	11 – 13	8 – 10	8 – 10	8

4.5.3 Deviation from fuel-optimal cruise speed

Aircraft do not always fly at fuel optimised cruise speed, for example, with the intention to save time and the associated time costs, or increase flight connection options. The applicability (to which flights) and absolute value of the deviation from the fuel optimised cruise speed can be applied as a correction factor to the cruise phase.

Table 31: Calculation options for the calculation parameter 'Deviation from fuel-optimal cruise speed'

Calculation parameter	Calculation parameter options	Remarks
Deviation from fuel-optimal cruise speed (applicability and absolute value of deviation)	Not modelled	Combination of 'Not considered' and 'Not modelled explicitly / specifically': either neglected altogether, or taken into account by (for example) using historical fuel consumption (including speed deviations) to determine unit fuel consumption figures
	Generic correction	
	Regional correction	
	Actual	

After assessment, these have been scored as shown in Table 32. With a sensitivity of 0.35 (Appendix B.1.4), the accuracy score obtained by each calculation option has a rather modest influence on the final score. Not taking into account the deviation from fuel-optimal cruise speed is, per the scoring obtained, the best option. Crucial determinants therein are the higher scores for alignment with current methods, standards and regulations and incorporation in existing CO₂ emission models. Next best is a generic correction. Appendix D.4.3 provides further details.

Table 32: Assessment results for various options for the calculation parameter 'Deviation from fuel-optimal cruise speed'

Assessment criterion	Weight		Score (unweighted)			
	HC	FC	Not modelled	Generic corr.	Regional corr.	Actual
Accuracy			0.75	0.75 – 1	0.75 – 1	1
Sensitivity			0.35	0.35	0.35	0.35
Combined accuracy / sensitivity	6	5	0.26	0.26 – 0.35	0.26 – 0.35	0.35
Fraud-resistance	2	2	1	1	0.5	1
Transparency	3	3	1	1	0.66	0
Availability of data	3	3	1	1	0.25	0.5
Computational time	1	2	1	1	0.98	0
Alignment with current methods, standards and regulations	2	2	0.25	0	0	0.25
Incorporation in existing CO ₂ emission models	1	1	0.89	0	0	0.11
Total (hindcast)	18	18	12	11	6 – 7	6
Total (forecast)	18	18	13	11 – 12	7	6

4.5.4 Tankering

Tankering is the practice of loading more fuel than necessary for a trip, for example, to take advantage of lower fuel prices at the departure airport, or when fuel is short in supply at the destination. Tankering increases the weight of

the aircraft and thus total fuel consumption. The applicability (to which flights) and percentage of tankered fuel with respect to trip fuel can be applied as a correction factor to the total fuel consumption.

Table 33: Calculation options for the calculation parameter 'Tankering'

Calculation parameter	Calculation parameter options	Remarks
Distance	Not modelled	Combination of 'Not considered' and 'Not modelled explicitly / specifically': either neglected altogether, or taken into account by (for example) using historical fuel consumption (including possible tankering) to determine unit fuel consumption figures
	Generic correction	
	Regional correction	
	Actual	

After assessment, these have been scored as shown in Table 34. The sensitivity to tankering has been set equal to the sensitivity to payload (Section 4.4 and Appendix B.1.4), as tankering, too, increases the weight of the aircraft. In line with the other miscellaneous calculation parameters, the highest-scored option for the parameter 'Tankering' is 'Not modelled' – i.e., to neglect this altogether. In contrast to other parameters, the difference to the second-best option ('Generic correction') is rather large. This is fully due to the fact that most current methods, standards and regulations and all existing CO₂ emission models do not take tankering into account. Appendix D.4.4 provides further details.

Table 34: Assessment results for various options for the calculation parameter 'Tankering'

Assessment criterion	Weight		Score (unweighted)			
	HC	FC	Not modelled	Generic corr.	Regional corr.	Flight corr.
Accuracy			Not assessed	Not assessed	Not assessed	1
Sensitivity			0.15	0.15	0.15	0.15
Combined accuracy / sensitivity	6	5	0 – 0.15	0 – 0.15	0 – 0.15	0.15
Fraud-resistance	2	2	1	1	0.5	1
Transparency	3	3	1	1	0	0
Availability of data	3	3	1	1	0.25	0.5
Computational time	1	2	1	1	0.98	0
Alignment with current methods, standards and regulations	2	2	1	0	0	0.25
Incorporation in existing CO ₂ emission models	1	1	1	0	0	0
Total (hindcast)	18	18	12 – 13	9 – 10	3 – 4	5
Total (forecast)	18	18	13 – 14	10 – 11	4	5

5 Uniform calculation method

Following the description and assessment results of the various calculation options in Chapter 4, this chapter starts by summarising the key results – the two highest-ranked option per calculation parameter – in Section 5.1. Next, Section 5.2 discusses these outcomes. As part of that discussion, it assesses the compatibility and consistency of the highest-ranked options. Furthermore, it reflects on the alignment of the highest-ranked option to the fifth and last guiding principle (Section 2.3) – requiring the calculation method to be sound, robust and future-proof – as that was no part of the assessment criteria used to evaluate the individual options. Following these discussions, Section 5.3 presents the proposed uniform calculation method.

5.1 Summarised scoring results

Table 35 shows the two highest-ranked options for each calculation parameter for hindcast applications (left) and forecast applications (right). Expressed in the total number of points, the second highest-ranked options score 13% to 16% lower than the highest-ranked options.

The table shows that all highest-ranked options are equal for hindcast and forecast applications. It also holds for most second highest-ranked option, with two exceptions, shown in italics in the table:

- For the parameter ‘Non-LTO climb / descent’, the option ‘Actual’ is identified as second-best option for hindcast applications, whereas this would be the option ‘Idealised’ for forecast applications.
- For the parameter ‘Cruise’, the option ‘Actual’ is ranked equal to ‘Idealised using step climbs’ and ‘Idealised’ for hindcast applications, but is not found among the two highest-ranked options for forecast applications.

Furthermore, highest- and second highest-ranked options that have obtained identical (rounded) scores are printed in bold. This is the case for three parameters:

- Lifecycle savings from SAF
 - Tank-to-wake emissions of SAF set to zero
 - Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type
- Distance:
 - Great Circle Distance (GCD)
 - GCD with distance-dependent detour distance / detour factor
- Cruise:
 - Actual (only for hindcast applications)
 - Idealised including step climbs
 - Idealised
- Wind (only for hindcast applications):
 - Not modelled
 - Averaged per region

Box 7: A SPECIAL USE CASE – A NATIONAL CO₂-CEILING FOR AVIATION

In case a calculation method for CO₂ emissions would be used to support a national CO₂-ceiling for aviation, this analysis might have found different highest-ranked options. If, for example, accuracy would be given twice the weight as currently used, other options for especially the more sensitive calculation parameters (such as CO₂ emission index, aircraft unit fuel consumption, distance, cruise, and deviation from fuel-optimal cruise speed, per Appendix B.1) might get substantially higher scores.

Table 35: Highest-ranked and second highest-ranked options for each calculation parameter for hindcast (left) and forecast (right) applications. Options with identical scores for highest and second-highest ranked options are printed in bold; options not equal for hindcast and forecast applications are printed in italics.

Group	Calculation parameter	Hindcast application				Forecast application			
		Highest-ranked option	score	Second highest-ranked option	score	Highest-ranked option	score	Second highest-ranked option	score
Aircraft fuel consumption	CO ₂ emission index	Generic emission index per type of fuel	11-17	Batch specific emission index	9	Generic emission index per type of fuel	12-17	Batch specific emission index	8
	Lifecycle savings from LCAF	Not considered	12-13	Tank-to-wake emissions of LCAF reduced by generic lifecycle emission reduction factor of LCAF-type	10-11	Not considered	13-14	Tank-to-wake emissions of LCAF reduced by generic lifecycle emission reduction factor of LCAF-type	11-12
	Lifecycle savings from SAF	Tank-to-wake emissions of SAF set to zero	11-13	Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type	11-13	Tank-to-wake emissions of SAF set to zero	12-14	Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type	12-14
	Aircraft unit fuel consumption	Unit fuel consumption per aircraft type and engine type (modelled)	12	Unit fuel consumption per aircraft type, engine type and airframe age (modelled)	11	Unit fuel consumption per aircraft type and engine type (modelled)	12	Unit fuel consumption per aircraft type, engine type and airframe age (modelled)	11
Trajectory	Distance	Great Circle Distance (GCD)	12	GCD with distance-dependent detour distance/ detour factor	12	Great Circle Distance (GCD)	13	GCD with distance-dependent detour distance/ detour factor	13
	APU	Not considered	11	– Not modelled explicitly / specifically – Generic	9	Not considered	12	– Not modelled explicitly / specifically – Generic	10
	Taxi	Not modelled explicitly / specifically	10	– Default taxi time – Average airport taxi time	9	Not modelled explicitly / specifically	11	– Default taxi time – Average airport taxi time	10
	LTO	Not modelled explicitly / specifically	10	Generic	9	Not modelled explicitly / specifically	11	Generic	10
	Non-LTO climb / descent	Not modelled explicitly / specifically	10	<i>Actual</i>	9	Not modelled explicitly / specifically	11	<i>Idealised (i.e., aircraft type-specific)</i>	8-10
	Cruise	Actual	9	– Idealised – Idealised including step climbs	9	Idealised including step climbs	10	Idealised	10
Payload	Payload	Typical aircraft type capacity and average load factors	12-13	Typical aircraft type capacity and average region load factors	9-10	Typical aircraft type capacity and average load factors	13	Typical aircraft type capacity and average region load factors	10-11
Miscellaneous	Alternative taxi operations	Not modelled	11	Percentage of single engine taxiing	7	Not modelled	12	Percentage of single engine taxiing	8
	Wind	Not modelled	10-13	Averaged per region	10-13	Not modelled	11-14	Averaged per region	11-13
	Deviation from fuel-optimal cruise speed	Not modelled	12	Generic correction	11	Not modelled	13	Generic correction	11-12
	Tankering	Not modelled	12-13	Generic correction	9-10	Not modelled	13-14	Generic correction	10-11
Total score			165-179		144-152		179-191		153-163

5.2 Discussion

As already noted in Section 5.1, the summarised scoring results show that the highest-ranked options are (mostly) identical for hindcast and forecast applications. This is expected, given the limited differences in the weighting factors assigned to the different criteria for hindcast and forecast applications (Section 3.1). Furthermore, the differences between the scores for the highest-ranked and second highest-ranked options are limited – and even non-existent in a number of cases.

A further inspection of the results presented in Table 35 also shows that for several parameters, not modelling or considering these is found to be the highest-ranked option – given the assessment criteria and weighting factors used in this work. This is the case for the six parameters listed below:

- Lifecycle savings from LCAF
- APU
- Alternative taxi operations
- Wind
- Deviation from fuel-optimal cruise speed
- Tankering

Following the highest-ranked options as identified in Table 35 implies that the uniform calculation method would not be sensitive to these parameters. In turn, this means the (reference) emissions and emissions savings related to these parameters (the result of industry action) would not be reflected in the results. Whereas this might raise some concerns, these results follow from the assessment criteria and weighting factors applied – which ultimately stem from an intended purpose (“monitoring and forecasting CO₂ emissions from aircraft departing the Netherlands to international destinations, and the applicable goals and targets”, as set in Section 2.1). Box 8 further reflects on and addresses possible concerns.

BOX 8: CONCERNS REGARDING NOT-SPECIFICALLY MODELLED PARAMETERS

For six parameters, the option to not consider or not model said parameter was identified as highest scoring option. This might raise concerns, from both industry (e.g. “our efforts are not recognised”) as well as by the general public (e.g. “part of aviation CO₂ emissions are neglected”). This box aims to elaborate the scoring leading to disregard these parameters in the highest-ranked set of parameters, and subsequently, indicate how underlying concerns might be alternatively addressed.

Lifecycle savings from LCAF

Not considering lifecycle savings from LCAF was identified as highest-ranked option, mainly due to the fact that other methods, standards, regulations (such as the EU ETS) and existing CO₂ emission models also do not consider these savings, leading to an overestimation of the emissions. Given the limited use of LCAF and its exclusion from ReFuelEU eligible fuels yet inclusion in CORSIA, the use of LCAF may currently be best monitored through the CORSIA Central Registry.

APU

Not considering APU emissions, too, was identified as highest-ranked option because many other methods, standards, regulations and existing models also do not take these emissions into account, leading to an underestimation of these emissions. This is likely related to the fact that APU emissions typically only make a small contribution to full flight CO₂ – approximately 1%, per Appendix B.1.2 (and citing Penner et al., 1999, the UK Department for Transport, 2017, and Seymour et al., 2020) – which also means that a 1% inaccuracy elsewhere in the method, overshadows any changes in APU emissions. This limited share does not mean APU emissions should not decrease (Schiphol, n.d.; Hartenberg, 2024) but does indicate its inclusion in a calculation method on full flight CO₂ emissions might be less appropriate. In line with this, the Dutch Sustainable Aviation Roundtable also considers APU emission reductions in a different target (towards zero emission ground operations) than the target for emissions from international aviation. Given that, a calculation method specifically designed for monitoring the emissions in scope of that target (possibly derived from methods and standards used in local environmental impact assessments, as described in Appendix C.1.5) seems more suitable for addressing APU emissions.

Alternative taxi operations

Not modelling alternative taxi operations (such as single-engine taxi or various forms of electric taxiing), was identified as highest-ranked option mainly due to higher scores for transparency and availability of data (or, correspondingly, lower scores for these criteria for calculation options taking alternative taxi operations into account). Similar to the (reduction in) APU-emissions, reductions in taxi emissions due to alternative taxi operations might be better monitored using a calculation

method focused on LTO-emissions, such as methods and standards used in local environmental impact assessments (as described in Appendix C.1.5). The neglect of these actions in the uniform calculation method likely result in an overestimation of the actual taxi emissions.

Wind

Not modelling wind influences was identified as highest-ranked option, mainly due to the fact that most existing CO₂ emission models also do not consider these deviations and no data is required for this option. In line with the varying nature of wind speeds, the effect of not taking this into account in the uniform calculation method also results in varying over- and underestimations of actual emissions.

Deviation from fuel-optimal cruise speed

Not modelling deviation from fuel-optimal cruise speed was identified as highest-ranked option, mainly due to the fact that other methods, standards, regulations (such as the EU ETS) and existing CO₂ emission models also do not consider these deviations. Any deviation from the fuel-optimal cruise speed would lead to an increase in emissions, such that by neglecting this in the uniform calculation method an underestimation of the cruise emissions may be encountered.

Tankering

Not modelling tankering, too, was identified as highest-ranked option because other methods, standards, regulations and existing models also (with one exception) do not take these emissions into account. However, the impact on the emissions of an individual flight could be rather large (Appendix B.1.4 notes a sensitivity of 0.15), and the practice of economic tankering is a clear example of socialising damages (i.e., additional CO₂ emissions and associated climate impact) and privatising benefits (i.e., avoided costs), such that society demands the industry to stop these practices (Dickinson, 2019) and may expect progress in this regard to be visible in the calculation method. Given that ReFuelEU Aviation (EU, 2023c) includes a limit on tankering (10%) from 2025 onwards, for which airlines are obliged to indicate required and uplifted (tanked) fuel, the resulting verified annual reports may, however, provide more appropriate means to monitor tankering practices.

It is also noted that the assessment leading up to the results presented in Table 35 relies on a methodology that guarantees that the best option(s) to determine each of the calculation parameters of interest is (are) identified, that methodology only considers single calculation options in comparison to other options for the same parameters. As such, it does not take the *combination* of parameter calculation options – the calculation method, in other words – into account. The remainder of this section adds that perspective to the discussion. Specifically, Section 5.2.1 addresses compatibility, Section 5.2.2 treats consistency, Section 5.2.3 discusses robustness and Section 5.2.4 reflects on future-proofness. With that, these last two sections address the remaining – and as of yet unaddressed – elements of the fifth guiding principle (“The uniform calculation method for aviation CO₂ emissions must be sound, robust and future-proof”), identified in Sections 2.3 and 3.1.

5.2.1 Compatibility

The first discussion section concerns compatibility. A calculation method could be considered incompatible when, for example, it would use aircraft unit fuel consumption figures based on class-averaged performance and at the same time model the climb and descent performance from individual aircraft types, or take into account the exact take-off weight of a particular airframe.

Within the sets of highest- and second highest-ranked options summarised in Table 35, no such compatibility issues have been identified.

5.2.2 Consistency

Related to but different from compatibility is consistency, which is treated as second discussion item. Consistency mainly concerns the question whether the options selected for each of the calculation parameters are a consistent set

that, simply put, makes sense. An example that could be considered inconsistent would be a calculation method that models APU usage in great detail and only very coarsely approximates the cruise phase – even though the latter has a much higher impact on CO₂ emissions.

Between the highest- and second highest-ranked options, one such inconsistency has been identified. The highest-ranked options for the calculation parameters ‘Taxi’, ‘LTO’ and ‘Non-LTO climb / descent’ are all rather simple approaches, in which these phases are not considered at all (Taxi) or are not modelled explicitly / specifically. On the other hand, for the parameter ‘Cruise’, the comparatively much more detailed options ‘Actual’ (hindcast only) and ‘Idealised including step climbs’ (hindcast and forecast) are one of two or three (equally) highest-scoring options. Given the options ‘Idealised including step climbs’ and ‘Idealised’ (without considering step climbs) were already tied, the latter (and slightly simpler) option is proposed as preferred one for these consistency reasons. Similarly, for wind, ‘Not modelled’ would be recommended. For determining the distance of a flight, the inclusion of a distance-dependent detour distance or detour factor is argued to be consistent with the simpler trajectory options. Although the detour factor is also a more elaborate calculation option than just relying on the great circle distance, the sensitivity of CO₂ emissions to distance (0.84, per Appendix B.1.2) and the fact that a distance-based detour factor could be a simple mathematic formula, support this recommendation.

Consistency considerations also help to resolve the tied scores for two options of taking lifecycle savings from SAF into account. The second highest-scoring option, in which the tank-to-wake emissions of the SAF are reduced through the application of a generic lifecycle emission reduction factor of the type of SAF (i.e., feedstock and production process), is recommended. This recommendation does not follow from internal consistency (i.e., consistency with respect to the selected calculation options for other parameters) but from external consistency – notably with respect to the Dutch Sustainable Aviation Agreement (Akkoord Duurzame Luchtvaart) which, too, uses a percentage reduction applied to tank-to-wake emissions based on the overall lifecycle emission reduction (Ontwerpakkoord Duurzame Luchtvaart, 2019; Ministry of Infrastructure and Water Management, n.d.; Ministry of Infrastructure and Water Management, 2020). This reasoning yields the possible uniform calculation method shown in Table 36.

Table 36: Possible uniform calculation method, based on highest-ranked options and with consistency issues resolved, for both hindcast and forecast applications

Group	Calculation parameter	Calculation option
Aircraft fuel consumption	CO ₂ emission index	Generic emission index per type of fuel
	Lifecycle savings from LCAF	Not considered
	Lifecycle savings from SAF	Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type
	Aircraft unit fuel consumption	Unit fuel consumption per aircraft type and engine type (modelled)
Trajectory	Distance	Great Circle Distance (GCD) with distance-dependent detour distance / detour factor
	APU	Not considered
	Taxi	Not modelled explicitly / specifically
	LTO	Not modelled explicitly / specifically
	Non-LTO climb / descent	Not modelled explicitly / specifically
	Cruise	Idealised
Payload	Payload	Typical aircraft type capacity and average load factors
Miscellaneous	Alternative taxi operations	Not modelled
	Wind	Not modelled
	Deviation from fuel-optimal cruise speed	Not modelled
	Tankering	Not modelled

5.2.3 Robustness

The third discussion item addressed is robustness. This is the second element of the fifth guiding principle identified in Section 2.3¹⁸ and has been evaluated by means of a sensitivity analysis. As reported in Appendix E in greater detail, this analysis investigated the sensitivity of the final results with respect to the scoring metrics, specifically for the assessment criteria accuracy, availability of data, alignment with current methods, standards and regulations, and incorporation in existing CO₂ emissions models.

For accuracy, the analysis found adjustments in scoring metrics to influence scores for a number of parameters, but only to affect the highest-ranked option in a few cases:

- For ‘Lifecycle savings from SAF’, the option ‘Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type’ obtains a higher score if the relative accuracy of the option ‘Tank-to-wake emissions of SAF set to zero’ decreases. This further supports the recommendation for that calculation option in Section 5.2.2.
- For ‘Aircraft fuel consumption’, the (previously second highest-ranked) option including the airframe age would score better than the highest-ranked option, but only for hindcast applications, and in a scenario where the scoring metric is adjusted downwards (essentially promoting accuracy). For forecast applications, both would rank the same. As a scenario with an upwards adjustment of the scoring metric confirms the original ranking, this result is argued not to warrant a revision of the results presented in Table 36.
- For ‘Cruise’, for which Table 35 already showed identical scores for the top-2 or top-3 options, the sensitivity analysis influences the results for hindcast applications. In the upward adjustment of the scoring metric, the option ‘Idealised including step climbs’ achieves a higher score than the option ‘Actually flown’. In a scenario with downwards adjustment of the metric, the original ranking is however maintained.
- For ‘Wind’, the (previously second highest-ranked) option ‘Averaged per region’ obtains a higher score if the relative accuracy of that option increases. This occurs for both hindcast and forecast applications. Lacking a definitive estimate on the accuracy of various options (as discussed in Appendix B.2.4), however, the original ranking is maintained.

The results of the scoring metric sensitivity analysis for the other criteria – availability of data, alignment with current methods, standards and regulations, and incorporation in existing CO₂ emissions models – did show some impact on scores, but was also found not to affect the highest-ranked option.

Overall, the results of the sensitivity analysis show the results (as summarised in Table 35) can be considered robust.

5.2.4 Future-proofness

This last discussion section concerns future proofness, the final element of the fifth guiding principle identified in Section 2.3. It is used to address two elements:

1. Future-proofness of the calculation method: whether the method identified is (conceptually) future-proof, in the sense that the method will not require large modifications when future aircraft concepts or aviation fuels will enter the market or progress in currently unanticipated actions is to be monitored.

¹⁸ The first element – soundness – was operationalised in the assessment criterion ‘Incorporation in existing CO₂ emission models’, as noted in Section 3.1.

2. Future-proofness of the data used by the calculation method: what elements – notably: numerical inputs – of the method would need to be updated regularly, in order to (continue to) accurately reflect the emissions of large civil fixed-wing aircraft departing the Netherlands.

Future-proofness of the calculation method

In general, the highest-scored options summarised in Table 35 combine to a rather simple model. Whereas this can be understood from the weighting of the criteria used for the assessment (outlined in Chapter 3), which put a limited emphasis on accuracy, a simpler model could prove more limiting in accurately modelling the impact of decarbonisation solutions in forward-looking analyses, making the method potentially less future-proof. Improvements to reduce fuel consumption during the climb phase, for example, could only be estimated by a (rather generic) percentage improvement, multiplied by a percentage indicating the share of the flight the improvement is considering. Especially when the applicability of such measures would be limited to a smaller set of flights, an approach relying on ‘correction factors’ could be (perceived as) a less sound approach.

In a more refined calculation method, which does allow for specific modelling of all flight phases, such issues would be largely mitigated. Noting that the highest-ranked and second highest-ranked calculation options for ‘Cruise’ scored the exact same number of points, and that the difference in score is only one point for ‘Taxi’, ‘LTO’ and ‘Non-LTO climb / descent’ (for hindcast applications, a one to three point different for forecast applications), these second-best options for modelling trajectory-related parameters could be used instead without a notable reduction in the total score. This would yield a calculation method reliant on the options shown in Table 37. Differences compared to Table 36 are shown in bold. For ‘Taxi’, the calculation option ‘Airport averaged taxi time’ is recommended (over the equally-scored ‘Default taxi time’), again to better take into account already existing differences in taxi times between airports or future changes in airport average taxi times, e.g. due to the opening of new runways. Expressed in terms of the total number of points, the score of the set shown in Table 37 is 3 to 5 points (2-3%) lower than the score associated to the set in Table 36, comprised of highest-ranked options.

Table 37: Possible uniform calculation method, preferring more detailed and flexible second-best options for trajectory-related calculation parameters and with consistency issues resolved, for both hindcast and forecast applications

Group	Calculation parameter	Calculation option
Aircraft fuel consumption	CO ₂ emission index	Generic emission index per type of fuel
	Lifecycle savings from LCAF	Not considered
	Lifecycle savings from SAF	Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type
	Aircraft unit fuel consumption	Unit fuel consumption per aircraft type and engine type (modelled)
Trajectory	Distance	Great Circle Distance (GCD) with distance-dependent detour distance / detour factor
	APU	Not considered
	Taxi	Airport averaged taxi time
	LTO	Generic (i.e., default ICAO times in mode, aircraft and engine-dependent fuel consumption)
	Non-LTO climb / descent	Idealised (i.e., aircraft type-specific)
Payload	Cruise	Idealised including step climbs
	Payload	Typical aircraft type capacity and average load factors
Miscellaneous	Alternative taxi operations	Not modelled
	Wind	Not modelled
	Deviation from fuel-optimal cruise speed	Not modelled
	Tankering	Not modelled

Future-proofness of data used by the calculation method

Apart from future-proofness of the methodology itself, the data on which the method relies should be kept up to date to ensure accurate calculations of CO₂ emissions in future years. For example, future airspace may be less restricted enabling more direct trajectories, which should be reflected in the distance-dependent detour(factor)s of future years. For each of the calculation parameters identified in Table 37, Table 38 notes the input data that should be kept up to date.

Table 38: Input data to be kept up to date

Group	Calculation parameter	Parameters to be kept up to date	Suggested update frequency
Aircraft fuel consumption	CO ₂ emission index	Generic emission index per type of fuel	When fuel specifications change (e.g. lower aromatics content)
	Lifecycle savings from LCAF	(None)	
	Lifecycle savings from SAF	Average lifecycle emission reduction factors of SAF types	When amendments to Annex V of the RED (EU, 2018) or the ICAO document "CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels" are introduced
	Aircraft unit fuel consumption	Aircraft and engine-type specific fuel consumption	When new aircraft / engine types are introduced into the traffic studied
Trajectory	Distance	Average distance dependent detour factors/distances	Annually
	APU	(None)	
	Taxi	Airport averaged taxi times	Annually
	LTO	Times in mode	When default times-in-mode change
	Non-LTO climb / descent	Aircraft-type specific performance data	When new aircraft types are introduced into the traffic studied
	Cruise	Aircraft-type specific performance data	When new aircraft types are introduced into the traffic studied
Payload	Payload	Typical aircraft type capacity and average load factors	Annually
Miscellaneous	Alternative taxi operations	(None)	
	Wind	(None)	
	Deviation from fuel-optimal cruise speed	(None)	
	Tankering	(None)	

Box 9: PERIODIC REVIEW OF THE UNIFORM CALCULATION METHOD

The recommendations provided in this section – on the selected calculation options as well as on input data to be kept up to date – help ensure the future-proofness of the calculation method developed. However, as calculation options were scored and assessed based on currently available information, it is recommended to plan a periodic review of the calculation method. Whereas the accuracy of options might not change, the sensitivity of parameters might evolve (due to an increased SAF blending limit, for example). Similarly, method, standards and regulations could develop, as well as (the familiarity or availability) of other CO₂ emission models, or the availability of data.

5.3 Proposed uniform calculation method

Following the scoring results presented in Section 5.1 and the discussion thereof in Section 5.2, this section presents the proposed uniform calculation method this work has identified as most suitable for the goal considered: monitoring and forecasting CO₂ emissions from aircraft departing the Netherlands to international destinations, and the applicable goals and targets (Section 2.1).

Section 5.3.1 provides an overview of the proposed uniform calculation method, after which Section 5.3.2 describes the suitability of the uniform calculation method for modelling various (anticipated) decarbonisation measures. Next, Section 5.3.3 (mostly qualitatively) reflects on the anticipated performance of the method. Last, Section 5.3.4 evaluates to what extent existing CO₂ emissions models already fit the description of the uniform calculation method proposed.

5.3.1 Overview

As the most suitable options for hindcast and forecast applications showed large overlap, one calculation method – suitable for both applications – is proposed. Following this calculation method, CO₂ emissions from large civil fixed-wing aircraft are to be computed in the following manner. As noted in Chapter 3, it is stressed that this uniform calculation method has been developed in and for a Dutch context, with parameter options assessed for flights departing the Netherlands, and as such is not guaranteed to be suitable for other contexts.

Calculate CO₂ emissions from aircraft and engine-specific fuel consumption using a fixed emission index and taking into account the lifecycle CO₂ savings of SAF by applying a generic reduction factor based on the SAF-type to the tank-to-wake emissions.

- A fixed emission index of 3.16 kilogramme CO₂ per kilogramme fuel is recommended, as that aligns best with European and international standards.
- Aircraft unit fuel consumption figures should be based on the characteristics of both the aircraft and engine type used to ensure adequate accuracy.
- Tank-to-wake emissions of SAF should be reduced by the percentage of lifecycle emission reductions realised by the SAF, based on generic lifecycle emission reduction factors for the type of SAF (i.e., feedstock and production process) used, as for example documented in the Renewable Energy Directive (EU, 2018; EU, 2023d).
- Lifecycle savings from low-carbon aviation fuels should not be included, also in line with the Renewable Energy Directive (EU, 2018; EU, 2023d).

Calculate fuel consumption for a flight based on the distance-corrected great circle distance and aircraft type-specific trajectory information for climb, cruise and descent. Calculate fuel consumption for the landing- and take-off phases using aircraft and engine type-specific data and default times-in-mode for approach, landing and take-off, and airport- and seasonally-averaged taxi times.

- The flight distance should be computed as great circle distance, corrected by a detour distance or factor dependent on distance. A distance-dependent detour factor is recommended over detour distance, as a generic detour distance is likely to over- and underestimate the actual detour distance for different groups of flights, and as a detour distance that varies for discrete domains of the great circle distance range will introduce discontinuities and associated over- or underestimations.
- Trajectories for the landing and take-off cycle (LTO) should be calculated based on default time-in-mode data and aircraft- and engine-specific fuel consumption figures. As an exception to default times-in-mode, taxi times dependent on airport should be used.
- Trajectories for the non-LTO climb and descent phases and cruise should be modelled per aircraft type (depending on aircraft type-specific performance data). Step climbs during cruise should be modelled.
- APU fuel consumption should not be considered.

Model payload based on the typical aircraft type capacity and average load factors.

- “Typical” aircraft type capacities should be based on manufacturer specifications.
- “Average” load factors should be based on industry averages.

Do not consider alternative (sustainable) taxi operations, wind effects, cruise speed deviations and tankering.

5.3.2 Suitability

The proposed calculation method can aid monitoring of CO₂ emissions and the setting of new CO₂ emission reduction targets. As future flight operations are likely to differ from current operation procedures due to sustainability measures being taken it is of importance to know to which decarbonisation measures the proposed method is sensitive and which decarbonisation methods will not result in lower emissions when modelled using the proposed method. In Table 39, anticipated measures per group in- and out-of-scope of the proposed calculation method are presented.

Table 39: Decarbonisation measures in-scope and out-of-scope of the proposed uniform calculation method

Group of measures	Example measures in-scope	Example measures out-of-scope
Aircraft	<ul style="list-style-type: none"> – SAF-usage (e.g. DLT ambition: 14% of fuel used in 2030 should be SAF) – Fleet renewal (e.g. DLT goal: 30% of flights departing from Schiphol Airport should be performed using latest generation aircraft types by 2030) – Engine replacement – Fleet assignment optimisations 	<ul style="list-style-type: none"> – Measures to incentivise SAF-usage with higher energy density – Maintenance activities such as (more frequent) engine washing – Modifications to the exterior to improve aerodynamic efficiency, such as sharkskin – Weight reduction measures on aircraft equipment such as overhead bins
Trajectory	<ul style="list-style-type: none"> – Improvements in average detours due to measures regarding airspace optimisation – Improvements in average airport taxi times 	<ul style="list-style-type: none"> – Continuous climb and descent operations – Single engine taxi operations
Payload	<ul style="list-style-type: none"> – Load factor increase and seat densification 	<ul style="list-style-type: none"> – Cargo/luggage packaging weight reduction measures, such as cardboard pallets
Miscellaneous		<ul style="list-style-type: none"> – Anti-tankering measures – Anti-high speed flying measures – Electric taxi operations. – N-1 engine taxi operations

5.3.3 Reflection on anticipated performance

As the uniform calculation method proposed in this work is the result of a careful analysis and assessment process, it can be considered the most suitable for the goal for which it was designed. Determining precisely *how well* the method proposed performs requires the development and subsequent testing of a computer implementation of the method – something that is outside the scope of the present work¹⁹. To still address the underlying question as best as currently possible, this section provides a (mostly qualitative) reflection on the anticipated performance. It does so based on the information presented in this report. The reflection follows the (groups of) assessment criteria presented in Chapter 3.

Box 10: SUITABILITY FOR CALCULATING CO₂ EMISSIONS OF FLIGHTS OUTSIDE THE SCOPE OF THIS WORK

The uniform calculation method developed in this work has been specifically designed for calculating CO₂ emissions of (groups of) flights that fit within the scope defined in Section 2.2 – and repeated below for convenience. That means, for example, that assessments that have been performed to determine the most suitable calculation option for all parameters considered (as described in Chapters 3 and 4) are based on and valid for flights that fit this scope.

- **Large aircraft** means that the scope is limited to aircraft with a maximum take-off weight greater than 5700 kg (EASA, 2023; EASA, 2010);
- **Civil aircraft** refer to aircraft used to operate all forms of non-military and non-state flights, including passenger as well as cargo operations;
- **Fixed-wing aircraft** means that helicopters are out-of-scope;

¹⁹ Section 6.3 includes the recommendation to test the accuracy early on in the development process (e.g. based on a proof-of-concept or prototype).

- Used for **air transport** means that the scope is limited to flights with the primary purpose of transporting passengers, cargo or mail.

It has not been tested whether the method developed in this work can also be used to calculate CO₂ emissions for flights that deviate from the aforementioned scope. For flights that only slightly deviate from the scope as described, the authors see little to no immediate issue. For flights that differ more substantially from the defined scope, however, the authors suggest reluctance and caution. This is illustrated by a number of examples:

- A flight to repatriate people from an area struck by a natural disaster operated using a large, civil, fixed-wing aircraft chartered from a typical passenger airline by the state. Such a flight would invalidate the ‘civil’ scope, but would be unlikely to differ substantially from a regular commercial flight in the way it would be operated. As such, the method might be suitable.
- A state or military flight used for government transport using a large, civil, fixed-wing aircraft. Such a flight, too, would invalidate the ‘civil’ scope. The ability of such an aircraft to use military airspace, influencing the detour distance, and the possible differences in layout and MTOW of these aircraft, could result in differences in CO₂ emissions.
- A flight operated by a typical passenger airline to move a large, civil, fixed-wing aircraft from one airport to the other without carrying any passengers, mail or cargo. Such a flight would invalidate the ‘air transport’ scope and have a zero load factor – thereby deviating notably from the industry average load factor used in the calculation methodology (Section 5.3.1). As such, the method could be expected to yield larger inaccuracies.
- A sight-seeing flight operated using a large, civil, fixed-wing aircraft chartered from a typical passenger airline. Such a flight, too, would invalidate the ‘air transport’ scope. Moreover, it is likely to return to its departure airport after completion of the flight, implying a great circle distance of zero kilometres and likely resulting in a significant difference in CO₂ emissions.

Accuracy

Following the analysis presented in Appendix B.3, the proposed calculation method is likely to underestimate CO₂ emissions – as the calculation options for ‘Aircraft unit fuel consumption’ and ‘APU’, ‘LTO’, ‘Non-LTO climb / descent’, ‘Deviation from fuel-optimal cruise speed’ and ‘Tankering’ cause an underestimation of CO₂ emissions. The anticipated overestimations for other calculation options used for other parameters (‘Lifecycle savings from LCAF’ and ‘Alternative taxi operations’, but mostly ‘Cruise’) are deemed unlikely to offset the aforementioned underestimations.

In an attempt to quantify the (in)accuracy that can be expected, Table 40 summarises the results from the accuracy and sensitivity assessment documented in Appendix B²⁰. Specifically, it combines the parameter sensitivities (Appendix B.1) with anticipated root mean squared relative error values (RMSRE) for the selected options (based on Appendix B.2) and the estimated error ‘direction’ (over- or underestimation, based on Appendix B.3). As option errors could not be determined for all calculation options, some cells in the table are left blank.

Table 40: Anticipated inaccuracy of the proposed uniform calculation method, based on parameter sensitivities and root mean squared relative error values (RMSRE)

Group	Calculation parameter	Parameter sensitivity	Calculation option	Option error	Sensitivity × Error
Aircraft fuel consumption	CO ₂ emission index	1	Generic emission index per type of fuel		
	Lifecycle savings from LCAF	0.20	Not considered		
	Lifecycle savings from SAF	0.50	Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type		
	Aircraft unit fuel consumption	1	Unit fuel consumption per aircraft type and engine type (modelled)	– 2.8%	– 2.8%
Trajectory	Distance	0.84	Great Circle Distance (GCD) with distance-dependent detour distance / detour factor	± 4.75%	± 3.99%
	APU	0.01	Not considered		
	Taxi	0.036	Airport averaged taxi time		

²⁰ This assessment has been performed at the (granularity) level of individual flights. When studying larger groups of flights, some inaccuracies – especially those which could lead to either an over- or an underestimation – are likely to (partiality) cancel out.

Group	Calculation parameter	Parameter sensitivity	Calculation option	Option error	Sensitivity × Error
	LTO	0.063	Generic (i.e., default ICAO times in mode, aircraft and engine-dependent fuel consumption)	+ < 9.5%	+ < 0.6%
	Non-LTO climb / descent	0.30	Idealised (i.e., aircraft type-specific)	– < 28.2%	– < 8.46%
	Cruise	0.59	Idealised including step climbs	+ 2%	+ 1.18%
Payload	Payload	0.15	Typical aircraft type capacity and average load factors		
Miscellaneous	Alternative taxi operations	0.036	Not modelled		
	Wind	0.59	Not modelled	± 2.2% - 15%	± 1.30% - 8.85%
	Deviation from fuel-optimal cruise speed	0.59	Not modelled	– < 3%	– < 1.77%
	Tankering	0.15	Not modelled		

For the calculation parameters for which a strictly overestimated or underestimated error could be determined (aircraft unit fuel consumption, LTO, non-LTO climb/descent, cruise, and deviation from fuel-optimal cruise speed), a combined (multiplicative) error of approximately 12% (underestimation) can be found. Depending on whether the errors for ‘Distance’ leads to an over- or underestimation, this figure could change by 3 to 4%, yielding a total (multiplicative) underestimation of 9 to 16%. Also including the maximum error for ‘Wind’ and assuming it results in a further underestimation (i.e., an error value of -15%), a total (multiplicative) underestimation of 23% is found.

Key drivers for these values are the up to 28.2% option error for the ‘Non-LTO climb / descent’ parameter (derived in Appendix B.2.2) and the 15% (maximum) error for the parameter ‘Wind’. Both these parameters are quite uncertain. If these uncertainties would be disregarded altogether, a total (multiplicative) error of 8% (underestimation) to 1% (overestimation) could be expected. If, instead, this uncertainty would be one-third of the error ranges listed in Table 40 (i.e., underestimations of 9.4% and 5%, respectively), the total (multiplicative) error can be expected to lie between -13% and -6%²¹.

Of the calculation parameters for which no error value could be estimated, ‘CO₂ emission index’, ‘Lifecycle savings from LCAF’, ‘Lifecycle savings from SAF’ and ‘Payload’ have a parameter sensitivity that is large enough to possibly materially influence the aforementioned combined error values:

- The option error associated to the generic emission index per type of fuel is likely very low and/or publicly accepted, as calculation methods used today also rely on a generic emission index.
- The option errors associated to the lifecycle savings from LCAF and SAF increase with increasing LCAF and SAF use. For the upcoming few years, uptake is likely to be low, and will therefore be unlikely to cause a material error.
- The option error associated to modelling payload based on typical aircraft type capacity and aircraft load factors could be an under- or overestimation, thereby increasing or decreasing the combined error.

It is stressed that the above (in)accuracy estimate only concerns the calculation method itself. Inaccuracies in input data (such as in a traffic data file) could increase the anticipated errors, or partly alleviate (‘overcompensate’) these. Moreover, it is noted that for smaller sets of flights than the ones used for this analysis (documented in Appendix B.1), and for single flights especially, inaccuracies are expected to be larger. On the other hand, for larger traffic sets, inaccuracies might (partially) cancel out, reducing the anticipated inaccuracy.

²¹ On average, this is comparable with the 9% difference observed between full-flight CO₂ emissions for flights departing EU27+EFTA airports as modelled (147 MtCO₂, EUROCONTROL IMPACT) and reported (156 MtCO₂, UNFCCC) in the 2025 European Aviation Environmental Report (EASA, 2025).

Verifiability: fraud-resistance and transparency

In terms of fraud-resistance, no likely-to-be-used loopholes are foreseen in the proposed uniform calculation method. For transparency, the majority of calculation parameters rely on publicly available data and no parameters use options that cannot be viewed at all.

Usability: availability of data and computational time

The proposed uniform calculation method performs well in terms of availability of data. The data required for the majority of calculation parameters is readily available publicly or from the Ministry (or other governmental bodies). Aircraft (and engine) performance and fuel consumption, which is required for four calculation parameters, likely needs to be purchased.

In terms of computational time, the calculation options selected in the proposed uniform calculation method allow for aggregating large numbers of flights, helping to reduce the number of unique flights to be analysed and thus required computational time.

Stakeholder support: alignment with current methods, standards and regulations and incorporation in existing CO₂ emissions models

Based on the alignment with current methods, standards, regulations and existing CO₂ emissions models, anticipated stakeholder support of the proposed uniform calculation method is varied. This is notably due to the fact that in some cases, the proposed uniform calculation method deliberately deviates from current practices, for example in order to improve accuracy. Given the close involvement of and positive interaction with relevant Dutch stakeholders, their support of the proposed uniform calculation method is generally expected.

5.3.4 Comparison with existing CO₂ emissions models

The uniform calculation method proposed in Section 5.3.1 is the result of a bottom-up investigation into the most suitable methods – given the objective and intended applications (Section 2.1, scope (Section 2.2), and assessment criteria and priorities (Chapter 3) – of estimating the parameter values that are relevant in the calculation of aircraft CO₂ emissions. Whereas the set presented in this report is indeed most suitable, this section compares the uniform calculation method that has been found to a number of existing CO₂ emissions models, previously introduced in Section 3.5.2 and more extensively described in Appendix C.2.

Table 41 shows the results of that comparison. Options in **bold** are identical to the calculation parameter option as proposed in the uniform calculation method; options in *italic* are not identical, but match close. It is clear that from the current models, none perfectly fit the proposed calculation method. However, there are some things to note:

- While many models do not incorporate SAF effects directly, this could be addressed in a relatively simple post-processing calculation step.
- Regarding the distance parameter: some models take the distance as user input. This input could be given as the preferred distance metric being GCD with distance dependent detour factor.
- The selected calculation option for aircraft unit fuel consumption, sensitive to the aircraft and engine type, is not used by any of the considered models.

Looking at the parameters Taxi, Non-LTO climb/descent and cruise, only the EUROCONTROL AEM and NLR BeyondCO₂-tool take the required calculation parameters into account. These models both have the largest overlap

with the required parameters, with some parameters having a higher fidelity level than required – and therefore, possibly, requiring additional data input or data collection efforts.

Table 41: Overview of calculation options used in the proposed uniform calculation method and in various existing CO₂ emissions models

Group	Calculation parameter	Uniform calculation method (this work)	AEOLUS	EEA EMEP	EUROCONTROL AEM	EUROCONTROL SET	IATA CO2 Connect	ICAO CEC	NLR BeyondCO ₂ -tool
Aircraft fuel consumption	CO ₂ emission index	Generic emission index per type of fuel	Generic emission index per type of fuel	Generic emission index per type of fuel	Generic emission index per type of fuel	Generic emission index per type of fuel	Generic emission index per type of fuel	Generic emission index per type of fuel	Generic emission index per type of fuel
	Lifecycle savings from LCAF	Not considered	Not considered	Not considered	Not considered	Not considered	Not considered	Not considered	Generic emission index per type of fuel
	Lifecycle savings from SAF	Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF	Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF	Not considered	Not considered	Not considered	Not considered	Not considered	Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type
	Aircraft unit fuel consumption	Unit fuel consumption per aircraft type and engine type (modelled)	(Average) unit fuel consumption per aircraft size class (modelled)	Unit fuel consumption per aircraft type (modelled)	Unit fuel consumption per aircraft type (modelled)	Unit fuel consumption per aircraft type (modelled)	Unit fuel consumption per aircraft type (modelled)	Unit fuel consumption per aircraft type (modelled)	Unit fuel consumption per aircraft type (modelled)
Trajectory	Distance	Great Circle Distance (GCD) with distance-dependent detour distance / detour factor	GCD with region-dependent detour distance/ detour factor	N/A (user specified)	Planned route (filed flight plan) Flown route	N/A (user specified)	GCD with distance-dependent detour distance/ detour factor (among other options)	GCD with distance-dependent detour distance/ detour factor	GCD with distance-dependent detour distance/ detour factor (among others options)
	APU	Not considered	Not considered	Not considered	Not considered	Not considered	Not modelled explicitly / separately	Not modelled explicitly / separately	Not considered
	Taxi	Airport averaged taxi time	Default taxi time	Default taxi time	Average airport taxi time	Not modelled explicitly / separately	Not modelled explicitly / separately	Not modelled explicitly / separately	Average airport taxi time (Among others)

Group	Calculation parameter	Uniform calculation method (this work)	AEOLUS	EEA EMEP	EUROCONTROL AEM	EUROCONTROL SET	IATA CO2 Connect	ICAO CEC	NLR BeyondCO2-tool
	LTO	Generic (i.e., default ICAO times in mode, aircraft and engine-dependent fuel consumption)	Generic	Generic	Generic	Not modelled explicitly / separately	Not modelled explicitly / separately	Not modelled explicitly / separately	<i>Idealised</i>
	Non-LTO climb / descent	Idealised (i.e., aircraft type-specific)	Not modelled explicitly / separately	Not modelled explicitly / separately	Idealised (among others)	Not modelled explicitly / separately	Not modelled explicitly / separately	Not modelled explicitly / separately	Idealised
	Cruise	Idealised including step climbs	Idealised	Idealised	<i>Idealised (among others)</i>	Idealised	Idealised	Idealised	Idealised including step climbs
Payload	Payload	Typical aircraft type capacity and average load factors	Typical aircraft class capacity and average load factors	Typical aircraft type capacity and average load factors	Typical aircraft type capacity and average load factors	Typical aircraft type capacity and average load factors	Typical aircraft type capacity and average load factors (among others)	<i>Typical aircraft type capacity and average region load factors</i>	Typical aircraft type capacity and average load factors
Miscellaneous	Alternative taxi operations	Not modelled	Not modelled	Not modelled	<i>Not modelled explicitly / separately</i>	Not modelled	Not modelled	Not modelled	Percentage of single engine taxiing Percentage of electric taxiing (e.g. by (electric) tow truck)
	Wind	Not modelled	Not modelled	Not modelled	Actual	Not modelled	Not modelled	Not modelled	Not modelled
	Deviation from fuel-optimal cruise speed	Not modelled	Not modelled	Not modelled	Actual	Not modelled	Averaged per airport-pair	Not modelled	Not modelled
	Tankering	Not modelled	Not modelled	Not modelled	<i>Not modelled explicitly / separately</i>	Not modelled	Not modelled	Not modelled	Not modelled

6 Recommendations

Based on the results from Section 5.3.4, which found that none of the existing CO₂ emissions models analysed completely aligns with the calculation options found to be most suitable for the uniform calculation method developed in this work, the application of the method requires the development of a computer model. In order to support the steps between the calculation method proposed in this work and that computer model, this chapter outlines a number of recommendations.

These recommendations are split across four groups. Section 6.1, first, summarises the recommendations made in Section 5.3.1, for example on the fixed emission index, on the choice between a distance-based detour *distance* or *factor* and on data sources. Sections 6.2 and 6.3 are concerned with development, with Section 6.2 specifically focused on recommendations which are relevant before starting the development, and Section 6.3 mostly focused on the logic of the model, making recommendations on the implementation of the calculation options selected in the uniform calculation method. Last, Section 6.4 lists recommendations targeted at users of the model.

6.1 Data source and recommended and default values

For the calculation parameters that make up the uniform calculation method (except for parameters not considered), Table 42 provides data sources and, if applicable, recommended and default values.

Table 42: Data sources and recommended and/or default values for calculation options used in the proposed uniform calculation method. Calculation parameters that are not considered in the method are not shown

Group	Calculation parameter	Uniform calculation method	Recommendation	Data source / default value
Aircraft fuel consumption	CO ₂ emission index	Generic emission index per type of fuel	Use 3.16 kgCO ₂ / kg fuel (CEN, 2023)	
	Lifecycle savings from SAF	Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF		<p>Typical lifecycle emission reductions per feedstock and production type are available from the Renewable Energy Directive (Directive (EU) 2018/2001, EU, 2018, Annex V). Alternatively, lifecycle emission values can be obtained from the ICAO CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels (ICAO, 2024a). The reduction factor should be computed by using a reference value for lifecycle emissions of fossil kerosene of 94 gCO₂e/MJ (Directive (EU) 2018/2001, EU, 2018, Annex V).</p> <p><u>Default value:</u> 65%, based on the minimum lifecycle emission reduction factor specified in the Renewable Energy Directive (Directive (EU) 2018/2001, EU, 2018, Annex V).</p>
	Aircraft unit fuel consumption	Unit fuel consumption per aircraft type and engine type (modelled)		<p>Specific aircraft fuel consumption per aircraft type can be sourced from EUROCONTROL BADA with fuel flows scaled to match engine types specified in the EASA Emission Data Bank (EASA, 2024b; EASA, 2024c). Lissys Piano-X could be an alternative to EUROCONTROL BADA. The most common engine type per aircraft model can be determined from e.g. CIRIUM ASCEND or sourced from literature (e.g. Teoh, Engberg, Shapiro, Dray, & Stettler, 2024).</p> <p><u>For forecasting applications:</u> fuel flows may be determined from the combination of the fuel flow of a known aircraft and engine type and a fuel burn improvement percentage.</p> <p><u>Default value:</u> not applicable.</p>
Trajectory	Distance	Great Circle Distance (GCD) with distance-dependent detour distance / detour factor	Use a distance-dependent detour factor	<p>Great circle distance can be computed from the latitude and longitude of airports, available from various open-source datasets, and the Haversine formula. A distance-dependent detour factor can be derived from e.g. FlightAware (n.d.) or EUROCONTROL (n.d., a).</p> <p><u>Default value:</u> based on an analysis of EUROCONTROL DDR2 data for flights departing the Netherlands in 2024, the factor equals $1.2842 \times \text{GCD}^{-0.0236}$.</p>
	Taxi	Airport averaged taxi time		<p>Taxi time statistics for a large number of airports are available from EUROCONTROL (e.g. EUROCONTROL, 2019a; 2019b; 2020).</p> <p><u>Default value:</u> mean of all served airports in the network, weighted by frequency.</p>
	LTO	Generic (i.e., default ICAO certification times in mode, aircraft and engine-dependent fuel consumption)		<p>ICAO Doc 9889 (ICAO, 2020) and EASA Emission Data Bank (EASA, 2024b; EASA, 2024c).</p> <p><u>Default value:</u> not applicable.</p>
	Non-LTO climb / descent	Idealised (i.e., aircraft type-specific)		<p>Aircraft performance data can be sourced from e.g. BADA. Instantaneous aircraft weight can be computed from take-off weight and (partial) fuel consumption (see: above, and Section 6.3).</p>

Group	Calculation parameter	Uniform calculation method	Recommendation	Data source / default value
	Cruise	Idealised including step climbs		Aircraft performance data can be sourced from e.g. BADA. Instantaneous aircraft weight can be computed from take-off weight and (partial) fuel consumption (see: above, and Section 6.3). <u>Default value:</u> not applicable.
Payload	Payload	Typical aircraft type capacity and average load factors		Typical aircraft type capacity may be obtained from manufacturers (airport planning manuals) and average load factors may be obtained from ICAO CEC (ICAO, 2024c) and IATA Market Analyses (2024b). <u>For forecasting applications (future aircraft types):</u> capacity of future aircraft types may be directly assumed, or determined from the combination of the capacity of a known aircraft and a (absolute or relative) difference. <u>Default value (load factor):</u> IATA and ICAO average load factors for flights departing Europe, currently (2024) at 82.7% passenger load factor, 68% cargo load factor

6.2 Before development

Before starting the development process, it is recommended to:

1. Establish requirements and, possibly, targeted performance levels. These could for example address
 - a. the interface of the application, e.g., command-line or graphical user interface;
 - b. the extent to which user input and choices should be validated: would the model only be operated by expert users, or should it be more 'foolproof'?
 - c. the operating system;
 - d. anticipated modes of operation: one analysis at a time, or possibilities to analyse multiple scenarios in one run;
 - e. data output: export to screen or to file, tabular or graphical output, ...;
 - f. data input: are users supposed to be able to change or update data sets, is that done by the model owner, or does it differ between different input files and use cases (with, for example, more restrictions with respect to aircraft performance data and more freedom with respect to traffic and scenario definition files).
2. For the calculation parameters for which multiple possible input data sets have been suggested, start with the selection of a single input data set, as this is likely to influence the further development. As data availability options have been scored from the perspective of the Ministry, the Ministry might need to take an active role in (facilitating) this data collection process. Related to the definitive selection of input data, it is recommended to investigate and clarify any interfaces with possible pre-processing tools.
3. Design a procedure to collect updated data at the recommended interval(s) and ensure that that data is included in the model. This procedure could address which organisation should be responsible for overseeing this process, but could also include agreements with other stakeholders that could submit data. Similarly, it could include verification procedures to ensure input data is correct and complete, or is substituted by default values.

Although the current research did not find any of seven rather well-known (at least in the Dutch context) CO₂ emissions models to match the uniform calculation method proposed, it is in addition recommended to keep looking out for (new, in-development or generally lesser-known) models that do match the proposal – especially as further requirements are determined (step 1).

6.3 During development

Conceptually, the model is to calculate the fuel consumption (Section 4.2.4) of a particular combination of aircraft and engine type with a particular mass (Section 4.4) over a particular trajectory (Section 4.3), operated at a particular speed. This section provides modelling recommendations for these elements. In general, to reduce the computational effort of a model run, it is recommended the application includes a feature to first aggregate the flight set to a set of unique flights in terms of the relevant characteristics (origin and destination, aircraft type and engine type), of which the resulting CO₂ emissions can then be readily multiplied by the number of flights meeting these characteristics.

Trajectory

Data sources for computing **distance**, average airport **taxi times** and **LTO** fuel consumption are provided in Table 42.

In addition:

- For the idealised **non-LTO climb and descent** phases, it is recommended to use fuel consumption as specified in e.g. BADA whilst adhering to the minimum rate of climb and descent.
- The **cruise** phase can be solved for after the LTO and non-LTO climb and descent phases have been defined, and during which some of the total flight distance has already been covered. Based on the (semi-continuous) evaluation of instantaneous aircraft weight and maximum or typical operating altitudes as function of aircraft weight (available from, e.g. BADA), it can be determined when step climbs should be modelled.

Weight

The aircraft weight can be estimated as sum of the operating empty weight (OEW), payload weight and fuel weight. The operating empty weight can be sourced from the manufacturer. Payload is specified in the calculation standard to be sourced from typical payload capacity as specified by manufacturers (if necessary, converting seats to passengers using a default weight of 100 kilogrammes, including luggage) and average industry load factors. However, fuel weight is to be computed based on the estimated consumption during trip phase and any fuel weight for reserves and contingency which can be specified as a percentage of trip fuel. The trip fuel itself is recommended to be derived iteratively, with initialisation possible starting at the default weights per aircraft type and stage length as specified in the ANP-database published as part of the European Environmental Noise Directive 2002/49/EC (EC, 2002). Given the fact that this database assumes a 65% load factor (ICAO, 2018b, Annex I), the fuel weight needs to be updated based on the increase in load, for example using a factor for cost of weight or transport loss (e.g. 3.5%, as used in van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021).

Speed

As deviations from fuel-optimal cruise speed are not to be considered (Sections 4.5.3 and 5.3), a typical cruise speed should be assumed. This speed is likely to show (some) variation between aircraft types, as different aircraft are designed and optimised for (slightly) different cruise speeds.

Aircraft and engine fuel consumption

- Aircraft-specific fuel consumption can be refined to take into account the engine type by assuming differences in certification fuel flow data (EASA, 2024b; available from EASA, 2024c) between engines are representative for differences during cruise flight.
- Aircraft-specific fuel consumption can be sourced from the data sets listed in Table 42, such as EUROCONTROL BADA. Such datasets typically provide fuel consumption as function of altitude, weight and speed.

General

In general, it is recommended to perform extensive testing to verify modelling output and build confidence in the results. Moreover, through testing the convergence of the model can be further specified and a minimal flight set size – for which accuracy has increased to the predefined or preferred level – can be defined. It is recommended in case of this analysis to not only take into account the size of the flight set, but also the composition, as for a larger-than-average share of, for example, freighter aircraft or low-cost carrier flights, industry-average data might be less representative. To provide users with an indication of how the results of the uniform calculation method differ from reality, validation of the model may be performed using observed data e.g. from flight data records. As data from bunker fuel sales is sensitive to, for example, tankering (as further explained in Box 1 on page 9), such data is deemed unsuitable for validation purposes.

Once the initial development of the uniform calculation method has been performed, a continuous effort is required to keep the software up to date. Similarly, the input data needs to be kept up to date, in line with the recommendations provided in Section 5.2.4. The developed software and all underlying assumptions should be documented clearly and are recommended to be made publicly available (including source code) to increase transparency and, in turn, stakeholder support. Moreover, a user manual should be developed which states how users can use the model and for which purposes.

6.4 During use

After development, the model will see use in practice. For that phase, a final set of recommendations is provided:

- When publishing results, it is recommended to always be explicit about the calculation methodology used. That could be through a reference to this document, or in greater detail in the document describing the results. Guaranteeing clarity on the way that SAF and LCAF emissions are (not) taken into account, especially, is considered essential: due to the various accounting methodologies that exist, data can easily be interpreted in an incorrect manner.
- Similarly, it is recommended to always specify the input data that has been used to generate a set of results. In case the data cannot be openly specified, a clear mention of the name (and version) of the dataset used could be an acceptable alternative. Regardless of the ability of publishing the data, users are highly recommended to store input data alongside output data. This could be supported by the model itself, for example by including input data and settings into the output file being generated.
- When using the model in forecasting and hindcasting efforts, guaranteeing clarity on the inputs, assumptions and differences with respect to reality is considered essential for monitoring and evaluation.

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Appendix A Background information about the project

Appendix A.1 Structure of the project

Royal NLR has conducted this project commissioned by the Ministry of Infrastructure and Water Management and has structured the work in four work packages (WPs). The technical work packages 2 and 3 contained the development of the calculation method of computing aviation CO₂ emissions. Work package 1 was concerned with project management; work package 4 with the finalisation and closure of the project.

The calculation method of computing aviation CO₂ emissions has been developed following a two-step principle.

1. First, options for calculation parameters and options have been identified and criteria to assess their goodness-of-fit for the calculation method of computing aviation CO₂ emissions have been determined. This can be thought of as 'setting up an evaluation matrix'.
2. Second, the options have been evaluated and scored using the criteria to select a preferred uniform calculation method of computing aviation CO₂ emissions. This can be thought of as filling in the evaluation matrix and identifying preferred options.

Appendix A.2 Stakeholder interaction

Over the course of this project, stakeholders have been consulted multiple times. The group of stakeholders involved has been jointly selected by Royal NLR and the Ministry, supported by an Advisory Committee (discussed in Appendix A.3), and includes the organisations shown in Table 43.

Table 43: Stakeholders involved in the project

Organisation	Type
Corendon B.V.	Airline
easyJet Company Limited	Airline
Duurzame Luchtvaarttafel (DLT) – secretariaat	Trade association
Eindhoven Airport N.V.	Airport
Groningen Airport Eelde	Airport
Koninklijke Luchtvaartmaatschappij Nederland N.V. (KLM)	Airline
Lelystad Airport	Airport
Luchtverkeersleiding Nederland (LVNL)	ANSP
Maastricht Aachen Airport B.V.	Airport
Natuur & Milieu	NGO
Neste	Fuel supplier
Rotterdam The Hague Airport B.V.	Airport
Royal Schiphol Group	Airport
Shell International B.V.	Fuel supplier
Transavia Airlines C.V.	Airline
TUI Airlines Netherlands B.V.	Airline
Vereniging Energie voor Mobiliteit en Industrie (VEMOBIN)	Trade association

Besides the aforementioned stakeholders, the organisations listed in Table 44 were also invited to participate in the project and provide feedback but unfortunately were not able to do so.

Table 44: Other stakeholders invited to the project

Organisation	Type
Air Cargo Netherlands (ACN)	Trade association
Board of Airline Representatives In the Netherlands (BARIN)	Trade association
Greenpeace	NGO
Milieudefensie	NGO
Nederlandse Vereniging van Luchthavens (NvL)	Trade association
SkyNRG B.V.	Fuel supplier

Stakeholders have been consulted and/or informed on five occasions:

1. In October 2024, stakeholders have been invited to provide feedback on a draft report outlining the requirements for the uniform calculation method. This draft covered calculations parameters, calculation options and assessment criteria. Furthermore, stakeholders were invited to suggest weighting factors for these assessment criteria.
2. In November 2024, stakeholders have been informed about the weighting factors selected by the Ministry, based on stakeholder and expert input.
3. In December 2024, an initial draft version of this report – including first assessment results and preliminary findings on the uniform calculation method – has been presented to stakeholders.
4. In January 2025, the previously shared draft report has been discussed with stakeholders, leading to a number of suggestions taken on board in the final draft report.
5. In May 2025, the previously shared final draft report has been discussed with stakeholders, leading to a number of clarifications taken on board in this final report.

Appendix A.3 Review and quality control

The work was closely overseen by the Ministry of Infrastructure and Water Management, supported by a dedicated Advisory Committee, set up by the Ministry. The advisory committee consisted of Igor Davydenko of the Netherlands Environmental Assessment Agency (PBL), Gabrielle Uitbeijerse of the Netherlands Institute for Transport Policy Analysis (KiM), and Joris Melkert from the Faculty of Aerospace Engineering of Delft University of Technology. Throughout the course of the project, representatives from the Ministry as well as the Advisory Committee have provided guidance on, for example, choices to make and have shared feedback on (draft versions) of this report. The Advisory Committee bears no responsibility for the contents and outcomes of this report.

In addition to the Advisory Committee, the Ministry has also contracted CE Delft as independent reviewer. Experts from CE Delft have provided written feedback on three occasions:

1. In October 2024, CE Delft provided feedback on a draft report outlining the requirements for the uniform calculation method. (This draft report has also been discussed with stakeholders.)
2. In January 2025, CE Delft provided feedback on the initial draft version of this report. (This draft report has also been discussed with stakeholders.)
3. In April 2025, CE Delft provided feedback on the final draft version of this report.

Feedback received from CE Delft – in written form, or verbally in subsequent meetings – has been incorporated in subsequent (versions of) reports by the project team.

In parallel of the interactions with the Ministry, Advisory Committee and independent reviewer, various other NLR-experts have provided valuable input and feedback during the course of this project. This, too, has been incorporated in the final text.

The authors of this report are grateful for all useful suggestions, questions and remarks that have been received.

Appendix B Accuracy and sensitivity assessment

As noted in Section 3.2, the accuracy of choosing a specific parameter option for determining the value of a particular calculation parameter has been evaluated in a two-step process. This takes into account the sensitivity of the entire parameter to total CO₂ emissions as well as the accuracy of an approximated value with respect to the ‘ground truth’. This scoring method rewards accuracy improvement for the parameters that have a larger impact on CO₂ emissions.

Lacking, in some cases, information about the ‘ground truth’, the accuracy assessment is not straightforward. These assessments might, however, not always be necessary: if the sensitivity of CO₂ emissions to a calculation parameter is very low, the scores obtained for other assessment criteria might already determine the highest-scoring option overall. Box 11 provides an illustrative example.

Box 11: (IR)RELEVANCE OF ACCURACY ASSESSMENTS

Consider a calculation option A that has scored the maximum number of points available on all other criteria in the other assessment categories (verifiability, usability and stakeholder support). Given the weighting factors (listed in Section 3.1), this means an option already gets 12 or 13 points (forecast and hindcast application). If another option B scores 0 points on all these criteria, and the maximum score for accuracy is 1 with a weighting of 5 (forecast) or 6 (hindcast), option B will never obtain a higher total score than option A. With this, it also becomes irrelevant to determine the accuracy scores for A and B.

Given the above, the sensitivities of the different calculation parameters have been assessed first. This is reported in Appendix B.1. Then, using the scores awarded for other assessment criteria (documented in Appendix D), it has been determined for which calculation parameters and associated calculation options the accuracy assessment was still relevant. If so, this accuracy assessment has subsequently been conducted. These latter two steps are described in Appendix B.2. A qualitative reflection on whether the highest and second-highest scoring calculation options is likely to lead to an over – or underestimation of CO₂ emissions is provided in Appendix B.3.

Appendix B.1 Sensitivity assessment

The sensitivity of total CO₂ emissions to the different calculation parameters has been assessed using literature search or dedicated modelling using the BeyondCO₂-tool. This model, also described in Appendix C.2.7, has been developed by NLR and can accordingly be altered for specific needs or analyses, such as the sensitivity analyses conducted as part of this work.

Results obtained that way are based on the analysis of a set of flights representative for the scope and targeted application of the calculation method that is developed in this work, defined in Chapter 2. Specifically, the analyses have covered:

- scheduled flights, included in data from the Official Airline Guide (OAG);
- departing from any of the five main Dutch airports (Amsterdam Airport Schiphol, Eindhoven Airport, Groningen Airport Eelde, Maastricht Aachen Airport and Rotterdam The Hague Airport);
- to international destinations
- in 2019;
- using aircraft with a maximum take-off weight of at least 5700 kilogrammes.

Whenever the subsequent (sub)sections refer to ‘total CO₂’, this refers to the total CO₂ emissions associated to these flights.

Appendix B.1.1 Aircraft fuel consumption

CO₂ emission index

The sensitivity of total CO₂ to (changes in) the CO₂ emission index (i.e., amount of CO₂ produced by the combustion of a particular amount of kerosene) is 1. If the emission index changes by 10%, the total CO₂ also changes by 10%.

Lifecycle savings from LCAF

The sensitivity of total CO₂ to (changes in) the lifecycle savings from LCAF (low-carbon aviation fuel) depends on the blending level and the lifecycle savings from the blended LCAF. LCAF is fossil kerosene that has been produced in such a way to reduce upstream emissions. For conventional kerosene, upstream emissions are typically estimated at some 20% (Google, 2024; based on ICAO, 2024b, p. 38; CEN, 2023, pp. 88, 90 (ISO 14083:2023)), such that the maximum lifecycle emissions reduction is 20%. With a (maximum) blending level of 100%, the sensitivity is 0.20.

Lifecycle savings from SAF

The sensitivity of total CO₂ to (changes in) the lifecycle savings from SAF (sustainable aviation fuel), in line with the sensitivity of total CO₂ to the lifecycle savings from LCAF, depends on the blending level and the lifecycle savings from the blended SAF. In this work, the current blending limit of 50% has been used. With a (maximum) lifecycle emissions reduction of 100%, the sensitivity is 0.50. In the future, this limit will likely be increased beyond 50%, with the goal of reaching 100%. If or when this happens, this sensitivity value should be re-addressed.

Aircraft unit fuel consumption

The sensitivity of total CO₂ to (changes in) the aircraft unit fuel consumption is 1, as CO₂ directly and linearly scales with fuel consumption.

Appendix B.1.2 Trajectory

Distance

The sensitivity of total CO₂ to (changes in) distance has been determined using the BeyondCO₂-tool (using the previously described traffic set) as 0.84. This means that a change in flight distance of 10% results in a change of 8.4% in total CO₂ emissions.

This value differs when parts of the traffic set are considered. For intra-European flights departing from Amsterdam Airport Schiphol, a sensitivity of 0.79 has been found. For intra-European flights departing from the other airports considered, the sensitivity was determined to be 0.85. For intercontinental flights departing from all five considered airports (mostly from Amsterdam Airport Schiphol), the sensitivity has been found to equal 1.01. The value greater than 1 for these longer flights is explained by the cost of weight of the additional fuel that needs to be carried to be able to fly the extra distance. For the intra-European flights as well as for the overall figure (determined by taking the average weighted by the number of flights), the value is below 1. This is explained by the fact that a change in distance mostly affects the cruise phase, in which the fuel consumption per kilometre is lower than, for example, during the take-off and climb phases.

Flight phases: APU, taxi, LTO, non-LTO climb and descent, and cruise

The sensitivity of total CO₂ to (changes in) the emissions during a particular flight phase has been determined by quantifying the share of the emissions during the flight phase of interest compared to the total amount of emissions produced during the entire flight. The results are shown in Table 45.

For APU, the value shown has been determined from literature. Lacking information for the situation in the Netherlands, this analysis has relied on broader literature. Penner et al. quantified this in 1999 as 1%, and more recently, the UK Department for Transport (2017) and Seymour et al. (2020) have published that same value. It also aligns with research by Stettler et al. (2011), which shows APU emissions to equal 16% of LTO emissions, which using the BeyondCO₂-model results in about 1.6% of total flight emissions. For the other flight phases, the shares of total flight emissions have been determined using the BeyondCO₂-tool, modelling the aforementioned representative flight set.

Table 45: Sensitivities of total CO₂ to (changes in) emissions from individual flight phases considered

Flight phase	Share of total flight emissions	Sensitivity
APU	1%	0.01
Taxi	3.6%	0.036
LTO (excluding taxi)	6.3%	0.063
Non-LTO climb / descent	30%	0.30
Cruise	59%	0.59

Appendix B.1.3 Payload

The sensitivity of total CO₂ to (changes in) payload has been determined using the BeyondCO₂-tool (using the previously described traffic set) as 0.15. This means that a change in payload weight of 10% results in a change of 1.5% in total CO₂ emissions.

Appendix B.1.4 Miscellaneous

Alternative taxi operations

The sensitivity of total CO₂ to (changes in) alternative taxi operations is set equal to the sensitivity of total CO₂ to (changes in) taxi emissions. Per Appendix B.1.2, this yields a sensitivity value of 0.036.

Wind

The sensitivity of total CO₂ to (changes in) wind is set equal to the sensitivity of total CO₂ to (changes in) the cruise flight phase, as wind effects mostly affect the cruise phase of flight. Per Table 45, this yields a sensitivity value of 0.59.

Deviation from fuel-optimal cruise speed

The sensitivity of total CO₂ to (changes in) cruise speed is determined by combining the sensitivity of cruise CO₂ to (changes in) cruise speed and the sensitivity of total CO₂ to (changes in) cruise CO₂. The former sensitivity is based on (Boeing, 2007), which shows a 1% fuel penalty when increasing speed by 1.7% Mach, such that a sensitivity of 59% with respect to fuel is obtained. Combining this with the sensitivity of total CO₂ to (changes in) cruise CO₂ of 0.59 (Table) yields a total sensitivity of 0.35.

Tankering

The sensitivity of total CO₂ to (changes in) tankering is identical to the sensitivity of total CO₂ to (changes in) payload weight: 0.15. This logic holds because both changes in payload as well as changes in tankering are changes in weight, which is the ultimate driver for changes in fuel consumption and associated CO₂ emissions.

Appendix B.2 Accuracy assessment

Following the determination of sensitivities in Appendix B.1 and scores for other assessment criteria (documented in Appendix D), it has been determined to what extent changes in the score for accuracy could still influence the highest-scoring option per calculation parameter. If the scores awarded for other assessment criteria were found to already determine this highest-scoring (and thus preferred) option, no accuracy assessment was made. If, on the other hand, the scores awarded for other assessment criteria were found to not determine the highest-scoring option, the accuracy of each of the (relevant) calculation options was scored using the metrics outlined in Section 3.2.

For many of the accuracy assessments, use was made of the ‘root mean squared relative error’. This statistical concept is explained and illustrated in Box 12.

Box 12: ROOT MEAN SQUARED RELATIVE ERROR

The root mean squared relative error (RMSRE) is a measure of the relative difference between the true value and the value predicted by an ‘estimator’ – such as a particular approximation or rule of thumb. For example, if the RMSRE of an estimation is 10%, it means that – on average – estimated values differ plus or minus 10% from the true value.

The RMSRE is closely related to the more widely known root mean squared error (RMSE). The RMSE, however, finds the error in an absolute value, expressed in the same units as the original quantity. The RMSE of an approximation of a distance expressed in kilometres will also be a distance in kilometres. In this work, the RMSRE was used rather than the RMSE, for two reasons in particular:

- Differences observed between estimated and true values for, for example, distance and fuel consumption, will likely be larger for flights operated over a longer distance and/or consuming more fuel. This affects the RMSE, such that these flights ‘over-influence’ the result with respect to other flights (e.g. ones operated over smaller distances and/or consuming less fuel).
- Scoring metric rules have, in Section 3.2, been defined in terms of relative differences: the *percentage* difference rather than the absolute difference determines the score. This is not compatible with the RMSE. That could also be solved by dividing the RMSE by the average value of the (ground truth) data (to find the relative RMSE, or RMSRE), but that would not solve the previous problem.

Appendix B.2.1 Aircraft fuel consumption

CO₂ emission index

The scores awarded for the other assessment criteria have been found sufficient to determine the two highest-scoring options with respect to the CO₂ emission index. The accuracy of the various options has therefore not been assessed.

Lifecycle savings from LCAF

The scores awarded for the other assessment criteria have been found sufficient to determine the highest-scoring option with respect to the way lifecycle savings from LCAF are modelled. That is not the case for the second highest-scoring option. Noting, however, that the use of an ‘emission reduction factor per LCAF-type’ is (by definition) at least as accurate as the use of a ‘generic emission reduction factor of LCAF’, the second highest-scoring option is also determined by the scores awarded to the other criteria. The accuracy of the various options has therefore not been assessed in detail.

Lifecycle savings from SAF

The scores awarded for the other assessment criteria have not been found sufficient to determine the two highest-scoring options with respect to the way lifecycle savings from SAF are modelled. Lacking detailed data about the actual lifecycle emission reductions achieved by SAF that is currently in use, or that is foreseen to be used in the coming years, it is impossible to further assess the accuracy. However, logic dictates that the option ‘Tank-to-wake

emissions of SAF reduced by generic emissions reduction factor of SAF-type' will be more accurate than the option 'Tank-to-wake emissions of SAF reduced by generic emissions reduction factor of SAF'.

As far as possible, Table 46 summarises the (unweighted) scores obtained.

Table 46: Root mean squared relative error and associated accuracy score for various calculation options for lifecycle savings from SAF

Calculation option	Root mean squared relative error (RMSRE) w.r.t. 'ground truth'	Score
Tank-to-wake emissions of SAF set to zero		Cannot be higher than 'generic ERF of SAF-type'.
Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF		at least -0.25 pt w.r.t. 'generic ERF of SAF-type'.
Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type		at least +0.25 pt w.r.t. 'generic ERF of SAF'.
Tank-to-wake emissions of SAF reduced by lifecycle emission reduction factor of SAF-batch uplifted	0 (by definition, 'ground truth')	1

Aircraft unit fuel consumption

The scores awarded for the other assessment criteria have not been found sufficient to determine the highest-scoring option with respect to the aircraft unit fuel consumption. The accuracy of the various options has therefore been assessed in greater detail.

By definition, the option 'Unit fuel consumption per aircraft type and engine type (real-life data)' is perfectly accurate and hence has been awarded 1 point. Lacking that information as 'ground truth', the next most detailed option ('Unit fuel consumption per aircraft type, engine type and airframe age (modelled)') was regarded as 'ground truth' and, accordingly, also awarded 1 point. For the other options, Table 47 shows the (unweighted) scores obtained. These are based on the root mean squared relative error (RMSRE, explained in Box 12 on page 75) values.

The fuel consumption of departing flights from the five main Dutch airports to international destinations in 2019 was estimated using data from the CIRIUM-database (CIRIUM, 2019), containing (among others) information about the year of build of individual airframes. Using this, the airframe age could be determined for 94.2% of the flights. The influence of airframe age on engine degradation was modelled using correlations from Seymour et al. (2020) for medium and long-haul aircraft. The specific engine type for each aircraft was identified using an allocation based on market share data for the 23 most commonly used passenger aircraft types from Teoh et al. (2024). Lacking unit fuel consumption data per combination of aircraft and engine type for an entire flight mission, data from the standard LTO cycle used for engine certification purposes, sourced from the ICAO Aircraft Engine Emissions Databank (EASA, 2024b), was used (in line with Meijer & Grebe, 2024).

For calculations that did not account for engine type or airframe age, the most common engine type according to Teoh et al. (2024) was used, and the correlations from Seymour et al. (2020) were not applied. For the calculation option unit fuel burn per aircraft size class, two options were considered: using the fuel burn value of the most occurring aircraft for each class (short-/medium range aircraft; long range aircraft with two engines; and long range aircraft with four engines), or assigning the average fuel burn value per aircraft class based on the most detailed method.

The estimated LTO cycle values were then compared to the values obtained from the most detailed calculation method available and the RMSRE was used to determine the deviation in unit fuel consumption for the different calculation options. The RMSRE for both options for determining a fuel consumption per aircraft size class yielded the

same result, with a value of 10.1%. According to the scoring metrics outlined in Section 3.2, this results in a score of 0 points.

Table 47: Root mean squared relative error and associated accuracy score for various calculation options for unit fuel consumption

Calculation option	Root mean squared relative error (RMSRE) w.r.t. 'ground truth'	Score
(Average) unit fuel consumption per aircraft size class (modelled)	10.1%	0
Unit fuel consumption per aircraft type (modelled)	6.0%	0.25
Unit fuel consumption per aircraft type and airframe age (modelled)	5.5%	0.25
Unit fuel consumption per aircraft type and engine type (modelled)	2.8%	0.75
Unit fuel consumption per aircraft type, engine type and airframe age (modelled)	0 (regarded as 'ground truth')	1
Unit fuel consumption per aircraft type and engine type (real-life data)	-	1 (by definition)

Appendix B.2.2 Trajectory

Distance

The scores awarded for the other assessment criteria have not been found sufficient to determine the highest-scoring option with respect to the distance. The accuracy of the various options has therefore been assessed in greater detail.

By definition, the option 'Flown route' is perfectly accurate and hence has been awarded 1 point. This option is regarded as 'ground truth' for the comparison of the other calculation options. The flown routes have been determined for a traffic set of departing international aircraft (>5700 kg MTOW) from the five main Dutch airports from September 2023 to September 2024²² (EUROCONTROL, n.d., a). For the Great Circle Distance (GCD) related options, the root mean squared relative error (RMSRE, explained in Box 12 on page 7575) was evaluated with respect to the flown routes. For each subset of flights (depending on the calculation option), an averaged detour factor was determined. Then, these detour factors were assigned to each of the flights to which a particular detour factor would correspond. For the RMSRE, the relative difference of the modelled route length (based on the GCD with the assigned detour factor) to the actually flown route length was compared. The RMSRE values and associated scores (according to the scoring metrics defined in Section 3.2) are shown in Table 48. Lacking information about the difference between routes planned in the final flight plans and routes actually flown, the RMSRE of the option 'Planned route (filed flight plan)' could not be determined. However, the score awarded to that calculation option was found to not affect the two highest-scoring options.

Table 48: Root mean squared relative error and associated accuracy score for various calculation options for distance

Calculation option	Root mean squared relative error (RMSRE) w.r.t. 'ground truth'	Score
Great Circle Distance (GCD)	9.30%	0.25
GCD with generic detour distance/ detour factor	5.76%	0.25
GCD with airline-dependent detour distance/ detour factor	5.23%	0.25
GCD with region-dependent detour distance/ detour factor	5.22%	0.25
GCD with airline-region-dependent detour distance/ detour factor	4.78%	0.5
GCD with distance-dependent detour distance/ detour factor	4.75%	0.5

²² A more recent dataset than the reference traffic set described in Appendix B.1 has been used in order to be able to study current flight patterns (e.g. avoiding Ukrainian and, for various carriers, Russian airspace).

Calculation option	Root mean squared relative error (RMSRE) w.r.t. 'ground truth'	Score
GCD with airline-distance-dependent detour distance/ detour factor	4.32%	0.5
GCD with route-dependent detour distance/ detour factor	3.81%	0.5
GCD with airline-route-dependent detour distance/ detour factor	3.68%	0.5
Planned route (filed flight plan)		(not relevant)
Flown route	0 (by definition, 'ground truth')	1

Supporting the RMSRE values found for especially the region- and/or airline-dependent detour factors, a number of more detailed analysis results are shown. Figure 2 shows the variation in detour factors depending on the destination region. A further split to country-specific detour factors for Europe (regions E and L) is shown in Figures Figure 3 and Figure 4, again showing a larger spread in detour factor. In Figure 2, especially flights to the (East-)Asian/Pacific regions (P, R, U, V and Z) have high detour factors. Zooming in on flights to China (region Z, Figure 5), a split per airline shows that in the analysed dataset spanning 2023-2024, KLM flights have higher detour factors than flights operated by other airlines – a possible result of the current political situation. Despite these variations, and likely due to the relatively limited number of flights, the RMSRE values shown in Table 48 only reduce by a limited extent when differentiating detour factors between airlines: the difference between region- and airline-region dependent RMSRE is only 0.44%-point, the difference between distance- and airline-distance dependent RMSRE is 0.43%-point and the difference between route and airline-route dependent RMSRE is 0.13%-point. Given the scoring metrics outlined in Section 3.2, this does not (or only to a limited extent) affect the scores awarded to each of these options.

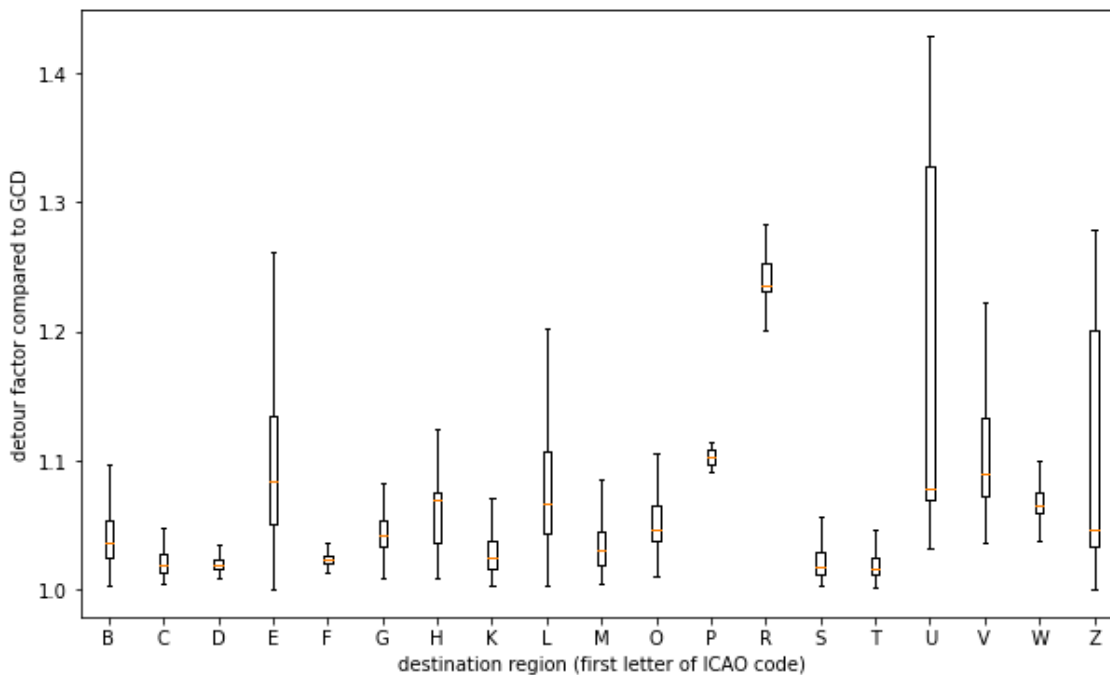


Figure 2: Detour factors with respect to GCD for different destination regions in 2023-2024

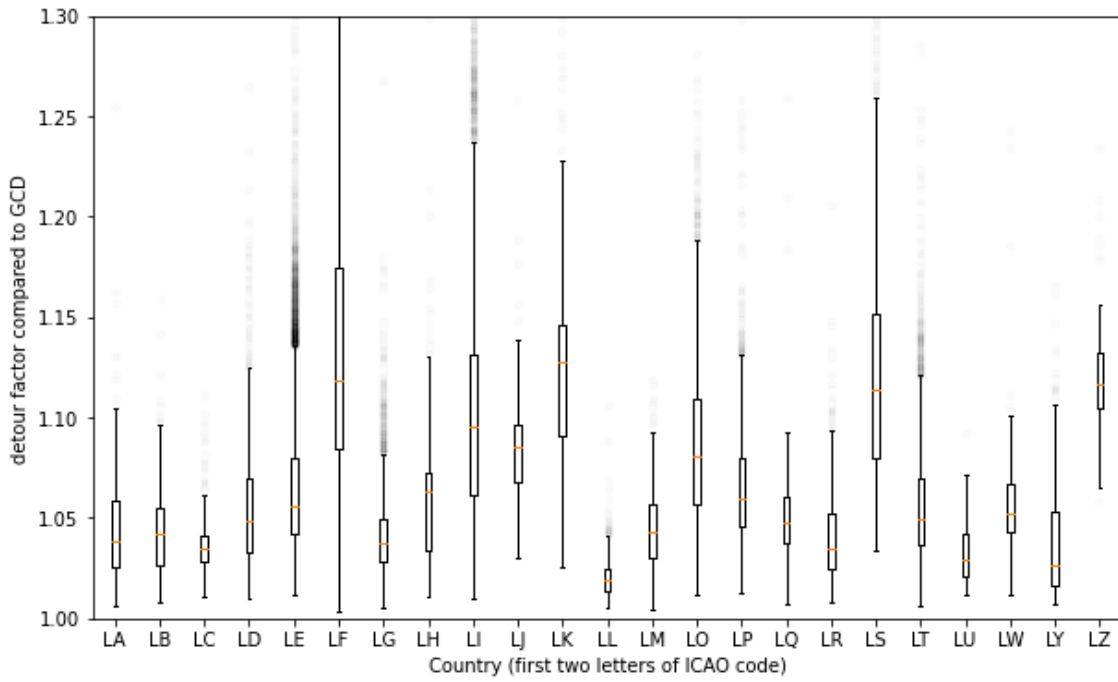


Figure 3: Detour factors with respect to GCD for flights to Southern Europe per country in 2023-2024, outliers are shown as semi-transparent dots

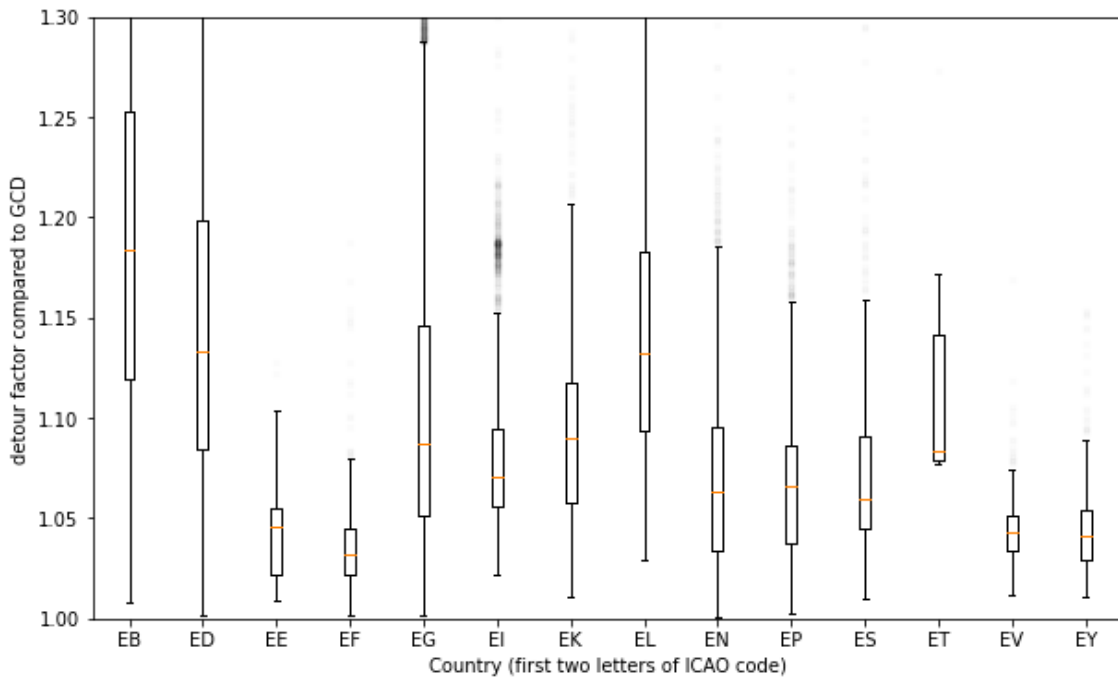


Figure 4: Detour factors with respect to GCD for flights to Northern Europe per country in 2023-2024, outliers are shown as semi-transparent dots

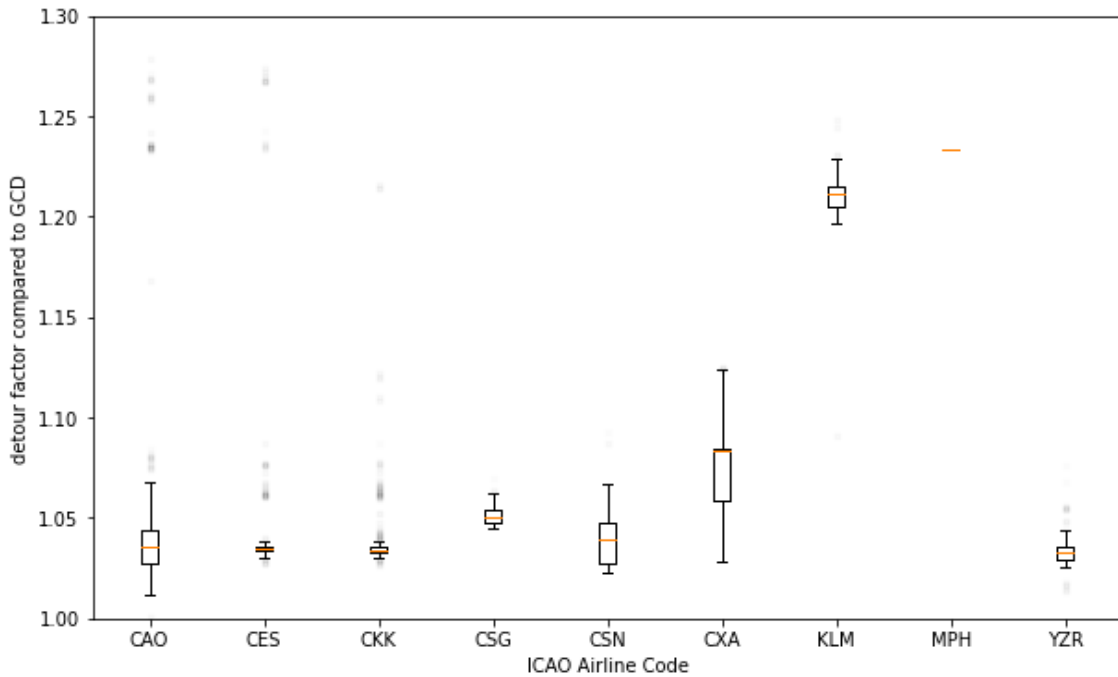


Figure 5: Detour factors with respect to GCD for flights to China in 2023-2024 split per airline, outliers are shown as semi-transparent dots

An analysis of detour factors per distance bin (rounded down to the nearest multiple of 1000 km, Figure 6) shows that for smaller distances the detour factors are relatively high, which can be explained by the smaller overall distance and larger LTO fraction within these flights. For flights with a great circle distance of 8000-9000 km, the large spread observed may be explained by various airlines currently not being able to fly over Russia and several countries in the Middle East.

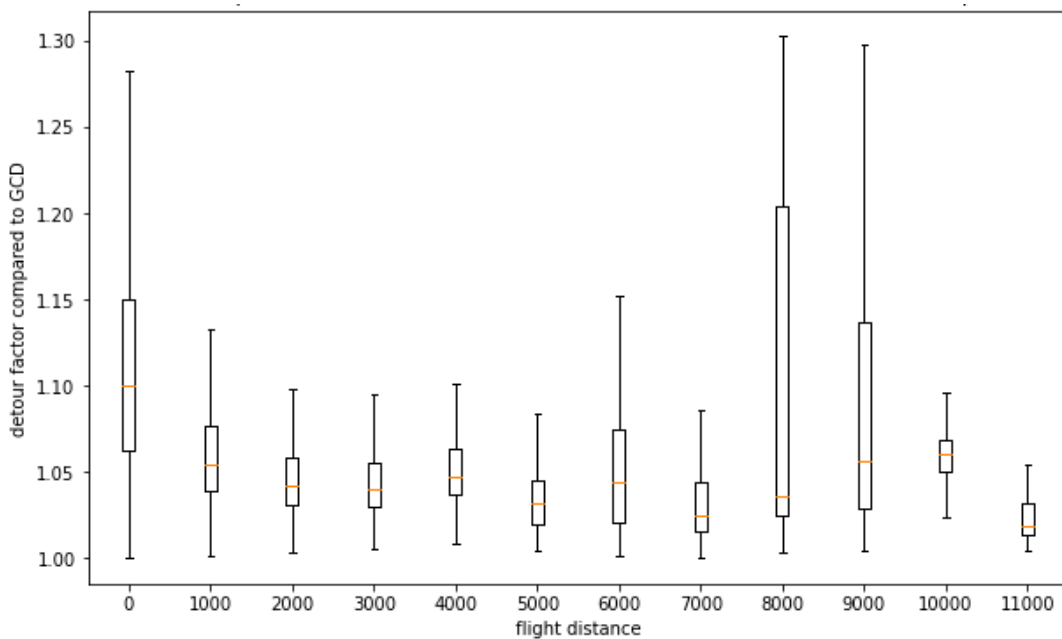


Figure 6: Detour factors with respect to GCD for different flight distances in 2023-2024 (rounded down to nearest multiple of 1000km)

APU

The scores awarded for the other assessment criteria have been found sufficient to determine the two highest-scoring options with respect to the way APU emissions are taken into account. The accuracy of the various options has therefore not been assessed.

Taxi

The scores awarded for the other assessment criteria have been found sufficient to determine the highest-scoring option with respect to the way taxi emissions are taken into account. That is not the case for the second highest-scoring option. The accuracy of the various options has therefore been assessed in greater detail.

By definition, the option 'Actual' is perfectly accurate and hence has been awarded 1 point. For the options 'Not modelled explicitly / specifically', 'Average airport taxi time', and 'Average airport-runway taxi time', the score awarded to the accuracy assessment criterion does not affect the overall ranking. As such, these scores have not been determined.

Lacking publicly available information about actual taxi times, taxi time data available from EUROCONTROL (2019a; 2019b; 2020) has been used as a 'ground truth'. Finding annual taxi times by averaging the seasonal data (weighted by the number of months included in each season) and in turn weighting these taxi times by the number of flights to the airports considered yields an average taxi-in time of 5.7 minutes and an average taxi-out time of 12.8 minutes²³. Compared to airport-specific taxi times, using these averaged values yields root mean squared relative errors (RMSRE, explained in Box 12 on page 75) of 25% for taxi-in and 16% for taxi-out. From this, it can be concluded that the calculation option 'Default taxi time' gets 0 points.

For the relevant options, Table 49 summarises the (unweighted) scores obtained.

Table 49: Root mean squared relative error and associated accuracy score for various calculation options for taxi time

Calculation option	Root mean squared relative error (RMSRE) w.r.t. 'ground truth'	Score
Not modelled explicitly / specifically		(not relevant)
Default taxi time	> 10%	0
Average airport taxi time		(not relevant)
Average airport-runway taxi time		(not relevant)
Actual	0 (by definition, 'ground truth')	1

LTO

The scores awarded for the other assessment criteria have been found sufficient to determine the two highest-scoring options with respect to the way the LTO-phase is modelled. That is not the case for their relative order, however. The accuracy of the various options has therefore been assessed in greater detail.

By definition, the option 'Actual' is perfectly accurate and hence has been awarded 1 point. Analysis of the reference traffic set (described in Appendix B.1) using the BeyondCO₂-tool indicates an average underestimation of approximately 210 kilogrammes and a root mean squared relative error (RMSRE, explained in Box 12 on page 75) of 68.9% with respect to the reference (idealised) LTO emissions, which is in this case seen as the 'ground truth'. (These results exclude the taxi-phase of the LTO-cycle.) Additionally, non-taxi LTO fuel burn data (based on default time-in-mode times for take-off, climb-out and approach of 42, 132 and 240 seconds, respectively) for several common aircraft types was sourced from the ICAO Aircraft Engine Emissions Databank (EASA, 2024b) (with engine-type prevalence sourced from Teoh et al., 2024) and compared to idealised modelling using the BeyondCO₂-tool. This yields

²³ Lacking information about taxi times at Maastricht Aachen Airport, this information is solely based on taxi times for the other four airports of national interest.

a RMSRE of 9.6% when modelling fuel consumption of the most-common engine type per aircraft type considered, or a RMSRE of 9.5% when modelling fuel consumption based on a weighted average of engine types.

Compared to the 'Actual', these differences would – by definition – be at least as large. This confirms that the option 'Not modelled explicitly / specifically' would score 0 points. The score of the option 'Generic' depends on the (unknown) difference between the actual and the idealised values. If that is very limited, a score of 0.25 would be awarded. If the difference was larger (than 0.4%), the score for 'Generic' would also be 0. Table 50 summarises these results.

Table 50: Root mean squared relative error and associated accuracy score for various calculation options for the LTO flight phase

Calculation option	Root mean squared relative error (RMSRE) w.r.t. 'ground truth'	Score
Not modelled explicitly / specifically	At least 68.9%	0
Generic (i.e., not aircraft type-specific)	At least 9.5 or 9.6%	At most 0.25
Idealised (i.e., aircraft type-specific)	(regarded as 'ground truth')	at least +0.25 pt w.r.t. 'Not modelled explicitly / specifically'.
Actual	0 (by definition)	1

Lacking further information, but realising that the 'Generic' modelling approach at least improves the accuracy (just not necessarily 'enough' to get extra points, per the scoring metrics outlined in Section 3.2), it is deemed valid to score that option 0.25 points higher than the option 'Not modelled explicitly / specifically'. This then settles the order of the best- and second-best option.

Climb and descent

The scores awarded for the other assessment criteria have been found sufficient to determine the two highest-scoring options with respect to the way the (non-LTO) climb and descent phases are modelled. That is not the case for their relative order, however. The accuracy of the various options has therefore been assessed in greater detail.

By definition, the option 'Actual' is perfectly accurate and hence has been awarded 1 point. Lacking information about the 'Actual' climb and descent phases, however, the inaccuracy caused by instead assuming 'Idealised' climb and descent phases, cannot be determined. As such, its score could vary anywhere between 0 and 1.

The inaccuracy introduced by not explicitly / specifically modelling the climb and descent phases (i.e., assuming average cruise fuel consumption during this part of the flight), on the other hand, could be estimated – in this case taking the 'idealised' climb and descent phases as reference (i.e. the 'ground truth' in this case). The simplification of not explicitly modelling these flight phases was found to underestimate fuel burn and associated CO₂ emissions. Specifically, analysis of the reference traffic set (described in Appendix B.1) using the BeyondCO₂-tool indicates an average underestimation of approximately 570 kilogrammes and a root mean squared relative error of 28.2% with respect to the reference (idealised) climb and cruise emissions. Compared to the 'Actual' climb and descent phases, the difference would – by definition – be at least as large. As such, according to the scoring metrics outlined in Section 3.2, a score of 0 points has been awarded. These results have been summarised in Table 51.

Table 51: Root mean squared relative error and associated accuracy score for various calculation options for the (non-LTO) climb and descent phases

Calculation option	Root mean squared relative error (RMSRE) w.r.t. 'ground truth'	Score
Not modelled explicitly / specifically	At least 28.2%	0

Calculation option	Root mean squared relative error (RMSRE) w.r.t. 'ground truth'	Score
Idealised (i.e., aircraft type-specific)	Used as reference / 'ground truth'	at least +0.25 pt w.r.t. 'Not modelled'.
Actual	0 (by definition)	1

Lacking further information, but realising that the 'Idealised' modelling approach at least improves the accuracy (just not necessarily 'enough' to get extra points, according to the scoring metrics outlined in Section 3.2), it is deemed valid to score that option 0.25 points higher than the option 'Not modelled explicitly / specifically'. This then settles the order of the best- and second-best option.

Cruise

The scores awarded for the other assessment criteria have not been found sufficient to determine the highest-scoring option with respect to the way the cruise phase is modelled. The accuracy of the various options has therefore been assessed in greater detail.

By definition, the option 'Actual' is perfectly accurate and hence has been awarded 1 point, it is seen as the 'ground truth'. For the option 'Planned', the score awarded to the accuracy assessment criterion does not affect the overall (weighted) score/ranking. The overall (weighted) score does depend on the difference between the accuracy-related scores awarded to the options 'Idealised' and 'Idealised including step climbs'. Literature notes that optimizing step climbs in cruise can result in a cruise fuel reduction of 1-2% compared to using the step climbs in actually flown routes (Jense, Tran, & Hansman, 2015). Taking the 2% value for the RMSRE, this would give the 'idealised including step climbs' option a score of 0.75.

For the 'idealised' option, literature was used from Airbus on fuel economic flying (Airbus, 2004). While this source might be relatively older, the data and insights in the effect of step climbs on fuel economy are still deemed relevant. The report goes into typical distances between step climbs for different aircraft types and the extra fuel burn associated with not flying at optimal altitudes. Applying this to the flight data used throughout this report, an RMSRE of 1.7% was calculated w.r.t. the 'Idealised including step climbs' option. This as the report compares the extra fuel burn with an idealised flight, not with actual flown flight data. This results in the 'Idealised' option in having an RMSRE w.r.t. the ground truth of 3.7%, giving it a score of 0.5. This is summarised in Table 52.

Table 52: Root mean squared relative error and associated accuracy score for various calculation options for the cruise flight phase

Calculation option	Root mean squared relative error (RMSRE) w.r.t. 'ground truth'	Score
Idealised (i.e., aircraft type-specific)	3.7%	0.5
Idealised including step climbs	2%	0.75
Planned		(not relevant)
Actual	0 (by definition, 'ground truth')	1

Appendix B.2.3 Payload

The scores awarded for the other assessment criteria have been found sufficient to determine the highest-scoring option with respect to the way payload is modelled. That is not the case for the second highest-scoring option. The accuracy of the various options has therefore been assessed in greater detail.

By definition, the option 'Calculated from actual take-off weight (TOW)' is perfectly accurate and hence has been awarded 1 point. For the options 'typical aircraft type capacity and average load factors', typical aircraft type capacity

and average airline load factors’, ‘typical aircraft type capacity and average airport pair load factors’, ‘typical aircraft tail capacity and average airport pair load factors’ and ‘payload weight filed in flight plan’, the scores awarded to the accuracy assessment criterion does not affect the overall (weighted) score. As such, these scores have not been determined. Rather, the second highest-scoring option is determined by the (difference in) scores for ‘typical aircraft class capacity and average load factors’ and ‘typical aircraft type capacity and average region load factors’.

Lacking detailed information about the load factor observed per flight, that element of the options is difficult to compare. The impact of using aircraft *class* versus aircraft *type* capacity, however, has been assessed. Defining average seat counts for various classes²⁴, the root mean squared relative error (RMSRE, explained in Box 12 on page 75) of the class-averaged seat count compared to the type-averaged seat count of the reference traffic dataset (Appendix B.1) was determined to equal 21% - yielding a score of 0 points for the option ‘typical aircraft class capacity and average load factors’. These results are summarised in Table 53.

Table 53: Root mean squared relative error and associated accuracy score for various calculation options for payload weight

Calculation option	Root mean squared relative error (RMSRE) w.r.t. ‘ground truth’	Score
Typical aircraft class capacity and average load factors		0
Typical aircraft type capacity and average load factors		(not relevant)
Typical aircraft type capacity and average airline load factors		(not relevant)
Typical aircraft type capacity and average region load factors	Lower than ‘typical aircraft class capacity ...’	At least +0.25pt w.r.t. ‘typical aircraft class capacity ...’
Typical aircraft type capacity and average airport pair load factors		(not relevant)
Typical aircraft tail capacity and average airport pair load factors		(not relevant)
Payload weight in filed flight plan		(not relevant)
Calculated from actual take-off weight (TOW)	0 (by definition)	1

The above, however, does not yet yield a final ranking. Noting, though, that using ‘typical aircraft type capacity and average region load factors’ would at least improve the accuracy (just not necessarily ‘enough’ to get extra points, per the scoring metrics outlined in Section 3.2), it is deemed valid to score that option (at least) 0.25 points higher. This then settles the order of the best- and second-best option.

Appendix B.2.4 Miscellaneous

Alternative taxi operations

As for calculation options for modelling taxi emissions, the scores awarded for the other assessment criteria have been found sufficient to determine the highest-scoring option(s) with respect to the way alternative taxi operations are taken into account. The accuracy of the various options has therefore not been assessed.

Wind

The scores awarded for the other assessment criteria have been found sufficient to determine the two highest-scoring options with respect to wind effects. That is not the case for their relative order, however. The accuracy of the various options has therefore been assessed in greater detail.

²⁴ Piston-powered aircraft (5 seats), business turboprops (8 seats), business jets (11 seats), commuter aircraft (12 seats), regional turboprops (67 seats), regional jets (93 seats), single-aisle (169 seats), small/medium twin-aisle (281 seats) and large twin-aisle aircraft (363 seats).

By definition, the option ‘Actual conditions’ is perfectly accurate and hence has been awarded 1 point, it is seen as the ‘ground truth’. Lacking detailed flight and wind data for the traffic network considered, the errors associated to the other calculation options – and the corresponding scores – have been determined from literature. This analysis has focused on the effect of the jet stream, upper level fast flowing air currents driven by the Coriolis force, which on the northern hemisphere flow in easterly direction. Strongest jet streams are found near the polars, where strong polar jets are found at altitudes of 9-12 kilometres, coinciding with aircraft cruise flight levels.

Research by Mangini et al. (2018) shows average wind speeds over the North Atlantic at three altitudes and as a function of latitude. For latitudes of 35 to 75°N, the difference between average wind speeds reported for the highest and lowest altitude is some 5 metres per second, with largest differences observed between 55 to 75°N. Over the entire range of latitudes considered, wind speeds (for a given altitude) vary by approximately 15 metres per second. For both parameters combined, average wind speeds range from about 13 to 32 metres per second. Compared to typical cruise speeds of 750 to 800 kilometres per hour, the wind can, on these routes, be computed to have an effect of 6 to 15%. Only a subset of international flights departing the Netherlands, however, operate across the North Atlantic. In the traffic set described in Appendix B.1, 6.8% of flights is destined for North-, Central- or South-America (ICAO airport codes starting with letters C, K, M, T or S).

Eastbound flights are also affected by the jet stream. 6.2% of the flights included in the reference traffic set is bound for Asia (ICAO airport codes starting with letters U, Z, O, V, R, W, A, Y and N). Noting that Asian destinations served from the Netherlands are typically located more southerly than destinations in the Americas, flights to Asia are likely to experience a lower jet stream effect than flights crossing the Atlantic. Assuming the North-Atlantic data (6-15%) would also apply on eastbound flights would be a conservative estimate.

As the variation in wind speed is still quite large, applying these estimates to the reference traffic set to find a root mean squared relative error (RMSRE, explained in Box 12 on page 75) of ‘Not modelled’ versus ‘Averaged per region’, yields rather mixed results:

- In a best case scenario, where intercontinental traffic to the West and the East would be affected by a 6% wind effect and where other traffic would face no (net) wind, the RMSRE would equal 2.2%, scoring 0.75 points for the option ‘Not modelled’. A higher score for that option is deemed unlikely.
- In a worst case scenario, in which all traffic would be affected by a 15% wind, the RMSRE would also equal 15%, yielding a score of 0 points for the option ‘Not modelled’.

Various intermediate scenarios can also be analysed, but without additional information that helps to more accurately pinpoint wind effects, this does not yield conclusive outcomes. This has been summarised in Table 54.

Table 54: Root mean squared relative error and associated accuracy score for various calculation options for distance

Calculation option	Root mean squared relative error (RMSRE) w.r.t. ‘ground truth’	Score
Not modelled	> 2.2%	At most 0.75
Averaged per region		At least + 0.25 pt w.r.t. ‘Not modelled’
Averaged per airport-pair		At least + 0.25 pt w.r.t. ‘Not modelled’
Averaged based on historic climatological data		At least + 0.25 pt w.r.t. ‘Not modelled’
Actual conditions	0 (by definition, ‘ground truth’)	1

The above, however, does not yet yield a final ranking. Noting, though, that using ‘averaged per region’ would at least improve the accuracy (just not necessarily ‘enough to get extra points, according to the scoring metrics outlined in Section 3.2), it is deemed valid to score that option (at least) 0.25 points higher. The same applies to ‘Averaged per airport pair’ and ‘Averaged based on historic climatological conditions’.

Deviation from fuel-optimal cruise speed

The scores awarded for the other assessment criteria have been found sufficient to determine the highest-scoring option with respect to the way deviations from fuel-optimal cruise speed are taken into account. That is not the case for the second highest-scoring option. The accuracy of the various options has therefore been assessed in greater detail.

By definition, the option 'Actual' is perfectly accurate and hence has been awarded 1 point, it is seen as the 'ground truth'. Lacking detailed flight data for the traffic network considered, the errors associated to the other calculation options – and the corresponding scores – have been determined from literature. EUROCONTROL (2022a, p. 52) notes a difference in fuel consumption between nominal speeds and long range cruise of 0.3% (without any cost increase) and between nominal speeds and maximum range cruise of 1% (with cost increases). Given a 0.35 sensitivity of cruise speed to fuel consumption (Appendix B.1.4), these fuel consumption differences imply cruise speed differences of 0.86 to 2.86%. Data shown in Delgado & Prats (2009, p. 7), suggesting a difference of 1 to 2% in speed, is consistent with this. As not modelling these deviations would introduce such variations, this implies a score of 0.75 points for the option 'Not modelled'. Any improvements in modelling – either through 'Generic correction' or 'Regional correction' – would, as such, also at least get that score. These scores then determine the total score of the second highest-option. Table 55 summarises these results.

Table 55: Root mean squared relative error and associated accuracy score for various calculation options for deviation from fuel optimal cruise speed

Calculation option	Root mean squared relative error (RMSRE) w.r.t. 'ground truth'	Score
Not modelled	< 3%	0.75
Generic correction		At least 0.75
Regional correction		At least 0.75
Actual	0 (by definition, 'ground truth')	1

Tankering

The scores awarded for the other assessment criteria have been found sufficient to determine the highest-scoring option with respect to the way tankering is taken into account. The accuracy of the various options has, therefore, not been assessed.

Appendix B.3 Reflection on over- or underestimation of the CO₂ emissions by the highest-scoring and second highest-scoring parameters

This appendix provides a reflection on the expected deviation of choosing particular calculation options to approximate a calculation parameter, for the two highest-ranked options identified in Table 35 in Section 5.1. In case an option is likely to yield an **underestimation**, the amount of CO₂ emissions calculated is lower than the amount of CO₂ actually emitted. In case an option is likely to yield an **overestimation**, the reverse is true. For various options, deviations in both directions can occur. This is indicated as '**Undecisive**'. For calculation options that rely on actual data, no deviation is expected.

Calculation parameter	Parameter option	Deviation	Remarks
CO ₂ emission index	Generic emission index per type of fuel	Undecisive	It depends on which generic value is chosen.

Calculation parameter	Parameter option	Deviation	Remarks
	Batch specific emission index	N/A	
Lifecycle savings from LCAF	Not considered	Overestimation	
	Tank-to-wake emissions of LCAF reduced by generic lifecycle emission reduction factor of LCAF-type	Undecisive	Generic data can over- or underestimate specifics of a batch / flight
Lifecycle savings from SAF	Tank-to-wake emissions of SAF set to zero	Underestimation	Compared to parameter options where a lifecycle emission factor is used, this option leads to an underestimation of the CO2 emissions.
	Tank-to-wake emissions of SAF reduced by generic lifecycle emission factor of SAF-type	Undecisive	Generic data can over- or underestimate specifics of a batch / flight
Aircraft unit fuel consumption	Unit fuel consumption per aircraft type and engine type (modelled)	Underestimation	Not considering the aging of the engines and the airframe leads to an underestimation of the aircraft unit fuel consumption, as aircraft fuel efficiency typically decreases with age
	Unit fuel consumption per aircraft type, engine type and airframe age (modelled)	Undecisive	Including the airframe age addresses the risk of underestimation, but in case aircraft are maintained at shorter intervals, the age-correction might overshoot, leading to a possible overestimation.
Distance	GCD	Underestimation	The GCD underestimates the flown routes.
	GCD with distance-dependent detour distance / detour factor	Undecisive	The detour factors / distances are determined on a larger flight set using actual flight data. For a similar flight set, there is no significant under-/overestimation. If the flight set differs significantly, an estimation error is more likely.
APU	Not considered	Underestimation	Not considering APU emissions underestimates total fuel consumption.
	Not modelled explicitly / specifically	Overestimation	Cruise fuel burn rates are higher than APU fuel burn rates, meaning that including APU fuel consumption in cruise figures could lead to an overestimation.
	Generic	Undecisive	Depends on the chosen value in relation to actual consumption.
Taxi	Not modelled explicitly / specifically	Overestimation	Cruise fuel burn rates are higher than taxi fuel burn rates, meaning that including taxi fuel consumption in cruise figures could lead to an overestimation.
	Default taxi time	Undecisive	For smaller airports likely an overestimation and for larger airports likely an underestimation.
	Average airport taxi time	Undecisive	Quite accurate.
LTO	Not modelled explicitly / specifically	Undecisive	If LTO is modelled as cruise, this could lead to an underestimation of emissions during take-off/climb and an overestimation of emissions during descent.
	Generic	Overestimation	Idealised ICAO certification LTO fuel flows are considered more likely to overestimate than underestimate actual fuel consumption, as actual use could include fuel efficiency measures, such as derated take-offs.
Non-LTO climb / descent	Not modelled explicitly / specifically	Undecisive	If non-LTO climb/descent is modelled as cruise, this could lead to an underestimation of emissions during take-off/climb and an overestimation of emissions during descent.
	Actual	N/A	

Calculation parameter	Parameter option	Deviation	Remarks
	Idealised (i.e., aircraft type-specific)	Underestimation	Idealised profiles are likely to be more efficient than actual profiles, leading to an underestimation of fuel consumption and CO ₂ .
Cruise	Actual	N/A	
	Idealised	Overestimation	A cruise phase at one single cruise altitude leads to higher fuel burn than an (actual) trajectory which performs step climbs.
	Idealised including step climbs	Overestimation	Including step climbs will better approximate the actual flight profile, but is still likely to be sub-optimal compared to an actual ('eco-piloted') flight, yielding an overestimation of fuel consumption and CO ₂ emissions.
Payload	Typical aircraft type capacity and average load factors	Undecisive	There will be deviations if the averaged load factors are used on sub-set of flights. Low-cost carrier likely underestimated, legacy carriers likely overestimated.
	Typical aircraft type capacity and average region load factors	Undecisive	There will be deviations if the averaged load factors are used on sub-set of flights. Low-cost carrier likely underestimated, legacy carriers likely overestimated.
Alternative taxi operations	Not modelled	Overestimation	Alternative taxi operations would save fuel. Not modelling this saving yields an overestimation on fuel consumption.
	Percentage of single engine taxiing	Overestimation	Other alternative taxi savings not taken into account.
Wind	Not modelled	Undecisive	Depends on destination.
	Averaged per region	Undecisive	Depends on destination.
Deviation from fuel-optimal cruise speed	Not modelled	Underestimation	If the fuel-optimal cruise speed is modelled, this would lead to an underestimation as most aircraft fly (slightly) faster.
	Generic correction	Undecisive	On average quite accurate.
Tankering	Not modelled	Underestimation	Tanking leads to additional CO ₂ emissions which would be neglected.
	Generic correction	Undecisive	On average quite accurate.

Appendix C Calculation methods, standards, regulations and CO₂ emissions models considered

This appendix provides further detail about a number of calculation methods, standards and regulations applicable to aviation in the Netherlands (Appendix C.1) and CO₂ emissions models used in the Netherlands, Europe and globally (0). These have been studied as part of the evaluation and scoring of calculation options. As further explained in Section 3.5, alignment with existing calculation methods, standards and regulations and/or existing CO₂ emissions models is considered a benefit of a calculation option.

Appendix C.1 Calculation methods, standards and regulations

Four (groups of) calculation methods, standards and regulations have been studied.

Appendix C.1.1 EASA / ReFuelEU Aviation Flight Emissions Label

Building on the work carried out by the European Union Aviation Safety Agency (EASA, 2024a), and following the environmental labelling scheme for flights created as part of the ReFuelEU Aviation Regulation (EU, 2023c, Art. 14), the European Commission has recently proposed a methodology to set such a (voluntary) label (EC, 2024b). In particular, the Annex to the proposed Commission Implementing Regulation outlines a method to determine the CO₂ emissions from a flight (EC, 2024c [draft]; EC, 2024d [draft]).

Two methods are identified for determining the fuel consumption. The first (Art. 3a) is based on “primary data” (i.e.: historical data that “tallies with the operating conditions of the scheduled flight” for which CO₂ emissions are to be computed); the second (Art. 3b) – used if primary data is not available – on the Breguet range equation, calibrated in order to “minimise the estimated difference [...] between the observed aviation fuel consumption and the estimated value” (EC, 2024d [draft], Annex II.1, Art. 3b). Even though the equation is quoted to estimate “the overall cruise performance”, it is used to calculate the fuel burn over the “distance travelled” (EC, 2024d [draft], Annex II.1, Art. 3b). This means that taxi, LTO, climb and descent fuel consumption is not modelled specifically. On the other hand, the aforementioned calibration is surely intended to yield fuel consumption figures that approximate the average fuel burn over the entire flight, including these non-cruise phases.

For each of the applicable calculation parameters of interest, Table 56 identifies the option used. As the method is voluntary, applicable options are scored 0.5 point for obligatoriness (per Section 3.5). Furthermore, if more than one option is or seems applicable, each option is scored a part-point (1/n, with n the number of options) for optionality (per Section 3.5). The final score awarded to each option (for alignment with the EASA / ReFuelEU Aviation Flight Emissions Label) is the product of these two sub-scores (per Section 3.5). The total score for the assessment criterion is determined by the maximum score of each of the alignment evaluations (per Section 3.5).

Table 56: Calculation method used in EASA / ReFuelEU Aviation Flight Emissions Label

Group	Calculation parameter	Option	Remarks
Aircraft fuel consumption	CO ₂ emission index	– Generic emission index per type of fuel	Default lifecycle emissions value and prescribed energy content yields generic emission index per type of fuel (Annex II.1, Art. 1 and Art. 2)
	Lifecycle savings from LCAF	– Tank-to-wake emissions of LCAF reduced by generic lifecycle emission reduction factor of LCAF-batch uplifted	“Aviation fuel lifecycle emissions of a batch” (Annex II.1, Art. 1 and Art. 2)
	Lifecycle savings from SAF	– Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-batch uplifted	“Aviation fuel lifecycle emissions of a batch” (Annex II.1, Art. 1 and Art. 2)
	Aircraft unit fuel consumption	– Unit fuel consumption per aircraft type and engine type (modelled) – Unit fuel consumption per aircraft type and engine type (real-life data)	Art. 3a and Art. 3b
Trajectory	Distance	– Planned route – Flown route	“distance travelled” (Annex II.1, Art. 3b)
	APU	– Not considered	Limited to block fuel, defined as “the amount of aviation fuel consumed by an aircraft when operating a flight, from its initial movement from its parking position at the departure airport until it comes to a complete stop at the arrival airport” (Art. 2(20))
	Taxi	– Not modelled explicitly / separately – Actual	Not modelled explicitly / separately, but included in fuel consumption of “past operations” (Annex II.1, Art. 3a) or correlated to “observations of aircraft fuel consumption” (Annex II.1 Art. 3b).
	LTO		
	Non-LTO climb / descent	– Actual	
Cruise	– Generic		
Payload	Payload	– Typical aircraft tail capacity and average airport pair load factors – Payload weight in filed flight plan	For full-flight fuel consumption: not modelled explicitly, but included in fuel consumption of “past operations” (Annex II.1, Art. 3a) or correlated to “observations of aircraft fuel consumption” (Annex II.1, Art. 3b). However, as part of determining CO ₂ emissions per passenger, data is to be reported for estimated number of passengers (Annex II.2, Art. 2). To that, options ‘Typical aircraft tail capacity and average airport pair load factors’ and ‘Payload weight in filed flight plan’ correspond best.
Miscellaneous	Alternative taxi operations	– Not modelled explicitly / separately	Potential savings will be included in historical data
	Wind	– Not modelled	Not modelled explicitly / separately, but included in fuel consumption of “past operations” (Annex II.1, Art. 3a) or correlated to “observations of aircraft fuel consumption” (Annex II.1 Art. 3b).
	Deviation from fuel-optimal cruise speed	– Actual	
	Tankering		

Appendix C.1.2 ECAC Doc29

ECAC Doc29 describes a harmonised method to calculate noise exposure in the vicinity of civil airports as used in Europe (ECAC, 2016) that can be used for both forecast and hindcast applications. It is also used in the Netherlands, for example for environmental impact reports (Milieueffectrapportages, m.e.r.) (e.g. Hebli, Derei, & Hogenhuis, 2019).

As Doc29 is a method to calculate noise (rather than fuel consumption or emissions), some of the calculation parameters identified in this research do not directly apply to that model. Indirectly, however, there are some links. Calculations in Doc29, for example, are mostly based on performance and noise data dependent on the combination of aircraft and engine type. For forecasts, a mix of engine types based on a historical reference is used; for hindcast, calculations for Amsterdam Airport Schiphol use the exact combination of aircraft and engine type used to operate a flight.

For each of the applicable calculation parameters of interest, Table 57 identifies the option used, considering the specific application of Doc29 in the Netherlands. As the method is obligatory, applicable options are scored 1 point for obligatoriness (per Section 3.5). Furthermore, if more than one option is or seems applicable, each option is scored a part-point (1/n, with n the number of options) for optionality (per Section 3.5). The final score awarded to each option (for alignment with Table) is the product of these two sub-scores (per Section 3.5). The total score for the assessment criterion is determined by the maximum score of each of the alignment evaluations (per Section 3.5).

Table 57: Calculation method used in ECAC Doc29

Group	Calculation parameter	Option	Remarks
Aircraft fuel consumption	CO ₂ emission index	N/A	Does not include CO ₂ emissions calculation
	Lifecycle savings from LCAF	N/A	
	Lifecycle savings from SAF	N/A	
	Aircraft unit fuel consumption	N/A, but considered in line with <ul style="list-style-type: none"> – Unit fuel consumption per aircraft type (modelled) – Unit fuel consumption per aircraft type and engine type (modelled) 	Doc29 does not calculate aircraft unit fuel consumptions. Noise calculations, however, are based on performance and noise data dependent on the combination of aircraft and engine type
Trajectory	Distance	– Great Circle Distance (GCD)	Take-off weight based on default weights (per ANP / ICAO 9911) as a function of stage length (binned), estimated as great circle distance.
	APU	N/A	
	Taxi	N/A	Taxi noise is out of scope (ECAC, 2016, p. 2)
	LTO	– Idealised	Trajectories are represented by a most accurate reference trajectory.
	Non-LTO climb / descent	– Idealised – Actual	The modelling scope includes (part of) the non-LTO climb and descent phases. As for LTO, trajectories are represented by a most accurate reference trajectory. As multiple trajectories are available for each combination of aircraft and engine type, Doc29 somewhat sits in between of the calculations options ‘Idealised’ (which has a single, idealised, trajectory per aircraft engine type) and ‘Actual’.
	Cruise	N/A	

Group	Calculation parameter	Option	Remarks
Payload	Payload	– Typical aircraft type capacity and average load factors	Take-off weight based on default weights (per ANP / ICAO 9911) as a function of stage length (binned), estimated as great circle distance. ANP-database with default weights is based on a 65% passenger load factor (ICAO, 2018b, Annex I).
Miscellaneous	Alternative taxi operations	N/A	Taxi noise is out of scope (ECAC, 2016, p. 2)
	Wind	– Averaged per region	During all flight phases, an 8 kt headwind is modelled.
	Deviation from fuel-optimal cruise speed	N/A	
	Tankering	Not modelled	Included in typical / reference weights considered

Appendix C.1.3 EU Emissions Trading System (EU ETS) and its reference to the EU Renewable Energy Directive (RED II and RED III)

CO₂ emissions from aviation activities have been included in the EU ETS since 2012 (EU, 2008), and are presently limited in scope to intra-European flights (EU, 2024, Art. 28b). Emissions are determined from fuel consumption records if possible, although in some cases, operators can submit emissions data computed from modelling (Part B to Annex IV)²⁵. The EU ETS directive itself does not prescribe a calculation method, but does include a number of specifications that are relevant to the current work.

For each of the applicable calculation parameters of interest, Table 58 identifies the option used. As the method is obligatory, applicable options are scored 1 point for obligatoriness (per Section 3.5). Furthermore, if more than one option is or seems applicable, each option is scored a part-point (1/n, with n the number of options) for optionality (per Section 3.5). The final score awarded to each option (for alignment with the EU Emissions Trading System (EU ETS) and its reference to the EU Renewable Energy Directive (RED II and RED III)) is the product of these two sub-scores (per Section 3.5). The total score for the assessment criterion is determined by the maximum score of each of the alignment evaluations (per Section 3.5).

Table 58: Calculation method used in the EU Emissions Trading System (EU ETS) and its reference to the EU Renewable Energy Directive (RED II and RED III)

Group	Calculation parameter	Option	Remarks
Aircraft fuel consumption	CO ₂ emission index	– Generic emission index per type of fuel	“The emission factor for jet kerosene (Jet A1 or Jet A) shall be 3.16 (t CO ₂ /t fuel).” (Directive (EU) 2023/958, EU, 2023a)
	Lifecycle savings from LCAF	– Not modelled	LCAF is not taken into account in EU ETS
	Lifecycle savings from SAF	– Tank-to-wake emissions of SAF set to zero	“The emission factor for biomass that complies with the sustainability criteria and greenhouse gas emission-saving criteria for the use of biomass established by Directive (EU) 2018/2001, with any necessary adjustments for application under this Directive, as set out in the implementing acts referred to in Article 14 of this Directive, shall be zero.” (Directive (EU) 2023/959, EU, 2023b)

²⁵ This is done using EUROCONTROLS Small Emitters Tool (discussed in 0).

Group	Calculation parameter	Option	Remarks
			In later revisions, the “zero-rating” was also extended to “emissions from the combustion of renewable fuels of non-biological origin (RFNBOs), recycled carbon fuels (RCFs) and synthetic low carbon fuels (SLCFs) in the ETS, subject to compliance with the criteria set out in the Renewable Energy Directive (RED II)” (EC, 2024a)
	Aircraft unit fuel consumption	N/A	
Trajectory	Distance	N/A	
	APU	N/A	
	Taxi	N/A	
	LTO	N/A	
	Non-LTO climb / descent	N/A	
	Cruise	N/A	
Payload	Payload	N/A	
Miscellaneous	Alternative taxi operations	N/A	
	Wind	N/A	
	Deviation from fuel-optimal cruise speed	N/A	
	Tankering	N/A	

It is stressed that EU ETS only considers SAF to have a zero emission factor if that SAF complies with the sustainability criteria laid out in the Renewable Energy Directive (Directive (EU) 2018/2001, EU, 2018). Whereas it is considered likely that SAF supplied in Europe (especially from 2025, when the ReFuelEU Aviation mandate starts) will meet these requirements, it is not guaranteed. SAF supplied elsewhere in the world might also (or potentially even further) deviate from these requirements.

Appendix C.1.4 ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

In determining an aircraft operator’s CO₂ offsetting requirement, CORSIA recognises reductions in lifecycle CO₂ emissions of certain fuels (so-called CORSIA eligible fuels). A number of elements of this method bear relevance to the present work.

For each of the applicable calculation parameters of interest, Table 59 identifies the option used. As the method is obligatory, applicable options are scored 1 point for obligatoriness (per Section 3.5). Furthermore, if more than one option is or seems applicable, each option is scored a part-point (1/n, with n the number of options) for optionality (per Section 3.5). The final score awarded to each option (for alignment with CORSIA) is the product of these two sub-scores (per Section 3.5). The total score for the assessment criterion is determined by the maximum score of each of the alignment evaluations (per Section 3.5).

Table 59: Calculation method used in ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSA)

Group	Calculation parameter	Option	Remarks
Aircraft fuel consumption	CO ₂ emission index	– Generic emission index per type of fuel	The “fuel conversion factor” is specified as 3.16 kg CO ₂ / kg fuel for kerosene. Baseline life cycle emissions values for aviation fuel equal 89 gCO ₂ e/MJ for kerosene (ICAO, 2023, Art. 3.3.1).
	Lifecycle savings from LCAF	– Tank-to-wake emissions of LCAF reduced by generic lifecycle emission reduction factor of LCAF-type – Tank-to-wake emissions of LCAF reduced by generic lifecycle emission reduction factor of LCAF-batch uplifted	Emission reductions from the use of CORSA eligible fuels is calculated based on a lifecycle emissions reduction factor (ICAO, 2023, Art. 3.3.1). The lifecycle emission reduction factor can be computed based on the actual fuel used (Actual Life Cycle Emissions value) or can be determined from a set of default life cycle emissions values (Default Life Cycle Emissions value) (ICAO, 2023, Art. 3.3.2 and 3.3.3). For the former case, the methodology outlined in <i>CORSA Default Life Cycle Emissions Values for CORSA Eligible Fuels</i> (ICAO, 2024a) should be followed. For the latter case, the default values should be sourced from <i>CORSA Methodology for Calculating Actual Life Cycle Emissions Values</i> (ICAO, 2024a).
	Lifecycle savings from SAF	– Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type – Tank-to-wake emissions of SAF reduced by lifecycle emission reduction factor of SAF-batch uplifted	
	Aircraft unit fuel consumption	N/A	
Trajectory	Distance	N/A	
	APU	N/A	
	Taxi	N/A	
	LTO	N/A	
	Non-LTO climb / descent	N/A	
	Cruise	N/A	
Payload	Payload	N/A	
Miscellaneous	Alternative taxi operations	N/A	
	Wind	N/A	
	Deviation from fuel-optimal cruise speed	N/A	
	Tankering	N/A	

Appendix C.1.5 Methods and standards used in (local) environmental impact assessments for aviation in the Netherlands

Unlike for the calculation of aircraft noise (using ECAC Doc29, described in Appendix C.1.2), air quality (Nieuw Nationaal Model en standaardrekenmethode luchtkwaliteit 3 (SRM-3): IPLO, 2022) and (nitrogen) deposition (Passende Beoordeling: Bij12, n.d.), there is no legally mandated approach to calculate aircraft emissions in the Netherlands. As a result, the methods used for modelling aircraft emissions in, for example, environmental impact reports (Milieueffectrapportages, m.e.r.) or as part of permit approval and enforcement (Wet natuurbeheer, Wnb) differ in approach, assumptions and fidelity.

In order to increase transparency and comparability, the Ministry of Infrastructure and Water Management commissioned To70 (2023) to develop a standardised methodology to calculate aircraft emissions. This proposal,

which is currently being reviewed²⁶, is based on the *Advanced Approach* as outlined in ICAO Doc. 9889 (ICAO, 2020), relying on airport, traffic and performance data used for the prescribed noise calculation methodology used in the Netherlands (Government of the Netherlands, 2024), in turn based on ECAC Doc29 (ECAC, 2016; Government of the Netherlands, 2024, Art. 1). It considers emissions produced below 3000 ft.

For each of the applicable calculation parameters of interest, Table 60 identifies the option used. This identification is mostly based on To70 (2023). It is noted, however, that, for example, Royal NLR has employed its BeyondCO₂-tool (described in Appendix C.2.7) for calculating full-flight CO₂ emissions in various environmental impact assessments.

As the method proposed by To70 is (at this moment) not mandated or widely adopted²⁶, applicable options are scored 0.5 point for obligatoriness (per Section 3.5). Furthermore, if more than one option is or seems applicable, each option is scored a part-point (1/n, with n the number of options) optionality (per Section 3.5). The final score awarded to each option (for alignment with the methods and standards used in (local) environmental impact assessments for aviation in the Netherlands) is the product of these two sub-scores (per Section 3.5). The total score for the assessment criterion is determined by the maximum score of each of the alignment evaluations (per Section 3.5).

Table 60: Calculation method used in Methods and standards used in (local) environmental impact assessments for aviation in the Netherlands

Group	Calculation parameter	Option	Remarks
Aircraft fuel consumption	CO ₂ emission index	– Generic emission index per type of fuel	Emissions are computed per species, movement, combination of aircraft and engine type, traffic type and type of flight; not per fuel batch (To70, 2023, p. 20)
	Lifecycle savings from LCAF	– Not considered	
	Lifecycle savings from SAF		
	Aircraft unit fuel consumption	– Unit fuel consumption per aircraft type (modelled) – Unit fuel consumption per aircraft type and engine type (certification data)	Fuel flows per combination of aircraft type and (proxy) engine type (To70, 2023, pp. 22-24, 13-14, 16).
Trajectory	Distance	N/A	Not specified: emissions are computed based on the combination of thrust settings and time-in-mode data (To70, 2023, pp. 24-26).
	APU	– Generic value – Airline-averaged value – Actual	Based on the emission per unit of time per APU type and the APU runtime per flight (To70, 2023, p. 24), although not all types and not all operating modes are included. APU runtime per flight is based on actual information if available, but can be determined from (e.g.) airline-sourced information about (average) APU runtime (To70, 2023, pp. 14, 17). In various calculations, generic values have been used.
	Taxi	– Average airport-runway taxi time – Actual	Actual information if available (especially hindcast applications); fall-back to “representative information” (To70, 2023, pp. 14, 16)
	LTO	– Idealised	Based on the applicable “performance profile” (To70, 2023, p. 24). This profile is to be defined for each flight (To70, 2023, p. 9), but refers to the Dutch guidelines for using

²⁶ At the moment of writing, the proposed method is under review. Lacking information about the reviewers findings and possible changes following these, the report referenced has been used.

Group	Calculation parameter	Option	Remarks
			ECAC Doc29 for other [than Schiphol] civil airports. As such, and per 0, the LTO is considered to be 'Idealised'.
	Non-LTO climb / descent	N/A	
	Cruise	N/A	
Payload	Payload	– Typical aircraft type capacity and average load factors	Not specified: emissions are computed based on the combination of thrust settings and time-in-mode data (To70, 2023, pp. 24-26). This implies typical / reference weights, corresponding to reference aircraft type capacity and load factor data.
Miscellaneous	Alternative taxi operations	– Percentage of single engine taxiing	Calculations should consider “the number of engines used during taxiing” (To70, 2023, p. 13 (translated))
	Wind	N/A	
	Deviation from fuel-optimal cruise speed	N/A	
	Tankering	– Not modelled	Included in typical / reference weights considered

Appendix C.2 CO₂ emissions models

Seven models evaluating the CO₂ emissions of (groups of) flights have been studied. For some models, calculating CO₂ emissions might be the core purpose, whereas for others, it is only an element.

Appendix C.2.1 AEOLUS

AEOLUS is a model that has been used for various studies on future aviation and policy commissioned by the Ministry of Infrastructure and Water Management, for horizon years 2030 and 2050. Owned by the ministry, the model is a default option for such studies. The main focus of the model is to forecast and simulate the number of air travellers and the amount of cargo transported, and the associated number of aircraft movements. In its prognoses, the model distinguishes between aircraft classes defined by the combination of size (based on maximum take-off weight) and technology. For routes, the model discerns between various passenger- and freight zones (Significance, 2023, p. 8). The former get progressively coarser when further away from the Netherlands (Significance, 2023, pp. 150-154).

For each of the applicable calculation parameters of interest, Table 61 identifies the option used. As the model is considered widely familiar but not available to anyone, applicable options are scored 0.5 point (per Section 3.5). The final score awarded to each option is the sum of the scores per option, normalised to the number of applicable models (per Section 3.5).

Table 61: Calculation method used in AEOLUS

Group	Calculation parameter	Option	Remarks
Aircraft fuel consumption	CO ₂ emission index	– Generic emission index per type of fuel	Fixed amount of CO ₂ emitted per minute per flight phase per aircraft class (Significance, 2023, p. 69)
	Lifecycle savings from LCAF	– Not considered	LCAF does not seem to be taken into account in AEOLUS, although the modelling input for SAF could be used to also model LCAF. References in text however are limited to “sustainable fuels” (e.g. Significance, 2023, pp. 71, 79)
	Lifecycle savings from SAF	– Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF	SAF can be modelled using an “effectivity”-parameter. This seems to be a global variable (i.e., not varying per flight or per type of SAF) (Significance, 2023, pp. 71, 79).
	Aircraft unit fuel consumption	– (Average) unit fuel consumption per aircraft size class (modelled)	CO ₂ emission is determined as a function of flight time, based on data from ICAO and SEO Amsterdam Economics. Relation of CO ₂ emission to flight time seems specific to a particular aircraft class (size and technology level) (Significance, 2023, pp. 68-71).
Trajectory	Distance	– GCD with region-dependent detour distance/ detour factor	Average flight time per destination region (Significance, 2023, pp. 68-71).
	APU	– Not considered	Emissions modelling is limited to LTO-cycle and non-LTO flight phase (Significance, 2023, pp. 66-68)
	Taxi	– Default taxi time	Default LTO emission quantity per aircraft of particular class (size and technology level).

Group	Calculation parameter	Option	Remarks
	LTO	– Generic	Time in mode per aircraft type (e.g. piston, turbo fan, ...) (Significance, 2023, p. 68). Options ‘default taxi time’ and ‘generic LTO cycle’ are considered to match best.
	Non-LTO climb / descent	– Not modelled explicitly / separately	Included in “flight phase”, with fuel consumption per passenger only dependent on total flight time. Relation however shows non-linearity, indicating sensitiveness to Climb/descent as well as cost of weight aspects (Significance, 2023, pp. 68-71).
	Cruise	– Idealised	
Payload	Payload	– Typical aircraft class capacity and average load factors	Payload capacity depends on aircraft class (size and technology level) (Significance, 2023, p. 50); load factor per route type (Significance, 2023, p. 56)
Miscellaneous	Alternative taxi operations	– Not modelled	
	Wind	– Not modelled	Included in “flight phase”, with (ICAO-sourced) fuel consumption data “corrected based on available in-service fuel consumption data” (ICAO, 2024c, pp. 6-7)
	Deviation from fuel-optimal cruise speed		
	Tankering		

Appendix C.2.2 European Environmental Agency EMEP Guidebook (Tier 3A)

The Google Travel Impact Model, used in Google Flights, uses full-flight CO₂ emissions calculated using the EEA EMEP methodology (Google, 2024). This methodology discerns between estimates based on fuel sales (Tier 1 and Tier 2) and estimates based on modelling per flight (Tier 3). Of the latter option, an A and a B variant are described. Tier 3A uses “specific aircraft type/engine data” from an EEA/EMEP maintained spreadsheet²⁷; Tier 3B relies on external modelling, such as the EUROCONTROL Advanced Emissions Model (described in Appendix C.2.3) (EEA/EMEP, 2023, p. 15). In this work (as well as in the Google Travel Impact Model), Tier 3A is considered.

For each of the applicable calculation parameters of interest, Table 62 identifies the option used. As the model is not considered widely familiar but available to anyone, applicable options are scored 0.5 point (per Section 3.5). The final score awarded to each option is the sum of the scores per option, normalised to the number of applicable models (per Section 3.5).

Table 62: Calculation method used in the European Environmental Agency EMEP Guidebook (Tier 3A)

Group	Calculation parameter	Option	Remarks
Aircraft fuel consumption	CO ₂ emission index	– Generic emission index per type of fuel	Settable in spreadsheet, cell F21.
	Lifecycle savings from LCAF	– Not considered	Can be included, however, by adjusting the CO ₂ emission index.
	Lifecycle savings from SAF		
	Aircraft unit fuel consumption	– Unit fuel consumption per aircraft type (modelled)	Modelling based on most common engine type (spreadsheet, cell K14) ²⁷
Tier 3	Distance	N/A	User-specified distance.

²⁷ Elsewhere in the documentation, it is however noted that “in Tier 3A, inventories are modelled using average fuel consumption and emissions data for the LTO phase and various CCD phase lengths, for an array of representative aircraft categories.” (EEA/EMEP, 2023, p. 25). As the publicly available spreadsheet does include various aircraft types (i.e., make and model), this latter text is not further considered. Moreover, the accompanying spreadsheet does list the “most common engine [...] used for modelling this aircraft type”, it does not provide an option to choose an engine type. The related EEA EMEP “aviation LTO emissions calculator” does include the possibility to model different combinations of aircraft and engine type, but that model is limited to the LTO-cycle and does not compute emissions related to other flight phases, such as cruise. Given the importance of these segments in relation to the total flight and the objective and scope of the current research (Sections 2.1 and 2.2), only the (full-flight) “aviation emissions calculator” (without engine selection) is considered in this comparison.

Group	Calculation parameter	Option	Remarks
	APU	– Not considered	APU fuel consumption is not considered as “In total terms, the fuel consumption and emissions contribution from this source is regarded as very small” (EEA/EMEP, 2023, pp. 33-34)
	Taxi	– Default taxi time	Based on time-in-mode as defined in default ICAO certification LTO-cycle or from a typical “busy European airport, year 2022” (spreadsheet, cell E26+E27).
	LTO	– Generic	
	Non-LTO climb / descent	– Not modelled explicitly / separately	Included in cruise/climb/descent phase.
	Cruise	– Idealised	
Payload	Payload	– Typical aircraft type capacity and average load factors	Likely to take aircraft type capacity into account, as fuel consumption figures are specified per aircraft type. Load factors are thought to either be based on ANP assumptions (65%, per Annex I of ICAO Doc 9911), per the reference to ANP in an older EMEP/EEA guidebook (EUROCONTROL, 2016), or be aligned with the nominal weight from BADA, on which the fuel consumption data included in the EEA/EMEP supposedly relies ²⁸ .
Misc.	Alternative taxi operations	– Not modelled	
	Wind		
	Deviation from fuel-optimal cruise speed		
	Tankering		

Appendix C.2.3 EUROCONTROL Advanced Emissions Model (AEM), as used in EUROCONTROL IMPACT

The EUROCONTROL Advanced Emissions Model (AEM) is one of the more advanced models considered in this work. Specifically, AEM is able to calculate fuel burn and emissions along a 4-dimensional trajectory (EUROCONTROL, 2024a). It is also integrated in EUROCONTROLs integrated aircraft noise and emissions modelling platform IMPACT (EUROCONTROL, 2022b; EUROCONTROL, 2024d).

For each of the applicable calculation parameters of interest, Table 63 identifies the option used. As the model is widely familiar but not available to anyone, applicable options are scored 0.5 point (per Section 3.5). The final score awarded to each option is the sum of the scores per option, normalised to the number of applicable models (per Section 3.5).

²⁸ Personal communication with the International Council of Clean Transportation, Secretariat of the Google Travel Impact Model.

Table 63: Calculation method used in the EUROCONTROL Advanced Emissions Model (AEM), as used in EUROCONTROL IMPACT

Group	Calculation parameter	Option	Remarks
Aircraft fuel consumption	CO ₂ emission index	– Generic emission index per type of fuel	EUROCONTROL (2022b, p. 15)
	Lifecycle savings from LCAF	– Not considered	
	Lifecycle savings from SAF		
	Aircraft unit fuel consumption	– Unit fuel consumption per aircraft type (modelled)	Based on BADA (EEA/EMEP, 2023, p. 48; EUROCONTROL, 2022b, pp. 12, 17)
Trajectory	Distance	– Planned route (filed flight plan) – Flown route	Based on 4D trajectory, either sourced from radar tracks or other receivers (e.g. ADS-B) or from simulations and models (EUROCONTROL, 2022b, p. 7).
	APU	– Not considered	
	Taxi	– Average airport taxi time	EEA/EMEP (2023, p. 49).
	LTO	– Generic	Modelled based on default ICAO certification LTO cycle (EEA/EMEP, 2023, p. 49).
	Non-LTO climb / descent	– Idealised – Actual	Specified in 4D trajectory.
	Cruise	– Idealised – Planned – Actual	Specified in 4D trajectory. However, EUROCONTROL (2022b, p. 17) also notes that the “aircraft weight decrease [during cruise] is not modelled”, suggesting idealisation (without step climbs).
Payload	Payload	– Typical aircraft type capacity and average load factors	Relies on BADA fuel consumption figures for “nominal weight” (EUROCONTROL, 2022b, p. 13)
Miscellaneous	Alternative taxi operations	– Not modelled explicitly / separately	
	Wind	– Actual	AEM allows to specify a (simulated) 4D trajectory and a fuel flow per segment (EUROCONTROL, 2022b, p. 11). This enables a correction for wind and/or cruise speed.
	Deviation from fuel-optimal cruise speed	– Actual	
	Tankering	– Not modelled explicitly / separately	Relies on BADA fuel consumption figures for “nominal weight” (EUROCONTROL, 2022b, p. 13)

Appendix C.2.4 EUROCONTROL Small Emitters Tool (SET)

The EUROCONTROL Small Emitters Tool is an Excel-based tool that calculates CO₂ emissions associated to a flight over a user-specified distance and operated by a user-specified aircraft type. Fuel consumption and emissions models “are built on a statistical approach based on fuel burn samples of real life flight operations” (EUROCONTROL, 2023).

For each of the applicable calculation parameters of interest, Table 64 identifies the option used. As the model is considered widely familiar and available to anyone, applicable options are scored 1 point (per Section 3.5). The final score awarded to each option is the sum of the scores per option, normalised to the number of applicable models (per Section 3.5).

Table 64: Calculation method used in the EUROCONTROL Small Emitters Tool (SET)

Group	Calculation parameter	Option	Remarks
Aircraft fuel consumption	CO ₂ emission index	– Generic emission index per type of fuel	“The fuel burn estimate is converted to CO ₂ emissions by applying a conversion factor of 3.15 for aircraft [...]” (EUROCONTROL, 2023, spreadsheet, tab 'Info', Note 4).
	Lifecycle savings from LCAF	– Not considered	
	Lifecycle savings from SAF		
	Aircraft unit fuel consumption	– Unit fuel consumption per aircraft type (modelled)	
Trajectory	Distance	N/A	User-specified distance. In case of using the great circle distance, the model includes the option (and, for EU ETS reporting purposes, requires) to add 95 kilometres “as indicated in the EU [ETS] regulation” (EUROCONTROL, 2023, spreadsheet, tab 'Info', remark 5).
	APU	– Not considered	
	Taxi	– Not modelled explicitly / separately	The entire flight is modelled at once, without distinguishing between various flight or mission phases.
	LTO		
	Non-LTO climb / descent		
	Cruise	– Idealised	
Payload	Payload	– Typical aircraft type capacity and average load factors	Unknown, likely based on typical aircraft type capacity and average load factors given fuel consumption modelling based on real life flight operations.
Misc.	Alternative taxi operations	– Not modelled	
	Wind		
	Deviation from fuel-optimal cruise speed		
	Tankering		

Appendix C.2.5 IATA CO₂ Connect

IATA CO₂ Connect is a CO₂ emissions calculator developed by IATA, based on airline submitted fuel consumption data. Its website used to offer a publicly accessible “simplified version of CO₂ Connect” that estimates CO₂ emissions based on a combination of origin and destination airports, aircraft type and seating class – possibly combining multiple flight legs (IATA, 2024c), but at the moment of writing (April 2025), only a paid version seems available. Upstream CO₂ and non-CO₂ climate effects are explicitly not included (IATA, §1.4 and §1.5).

For each of the applicable calculation parameters of interest, Table 65 identifies the option used. As the model is considered widely familiar and available to anyone, applicable options are scored 1 point (per Section 3.5). The final score awarded to each option is the sum of the scores per option, normalised to the number of applicable models (per Section 3.5).

Table 65: Calculation method used by IATA CO₂ Connect

Group	Calculation parameter	Option	Remarks
Aircraft fuel consumption	CO ₂ emission index	– Generic emission index per type of fuel	“Emissions factor for converting jet fuel [...] to CO ₂ : 3.16” (IATA, §2.3.3)
	Lifecycle savings from LCAF	– Not considered	Not mentioned.
	Lifecycle savings from SAF	– Not considered	

Group	Calculation parameter	Option	Remarks
	Aircraft unit fuel consumption	<ul style="list-style-type: none"> Unit fuel consumption per aircraft type (modelled) 	"The CO ₂ emissions calculation is aircraft type-specific" (IATA, §1.2)
Trajectory	Distance	<ul style="list-style-type: none"> GCD with generic detour distance/ detour factor GCD with distance-dependent detour distance/ detour factor GCD with route-dependent detour distance/ detour factor 	IATA recommends Members to "use their own historical data (fuel burn, seat configuration, payload, etc.) based on flown data to calculate the CO ₂ emissions of their operating flights" (IATA, §2.2.1), and further recommends to use "averages based on their historical data", with a recommended time range of 12 months (IATA, §2.2.2). The methodology furthermore notes that "in case where data sets available covering a shorter time range than 12 months, for example where a new flight destination was introduced during the calendar year, data can be complemented with data stemming from other destinations that cover a similar distance serviced by the same aircraft type over a 12-month period." (IATA, §2.2.2.1). As the (online) publicly available version does not require to select an airline, it is deemed likely that calculations are (at best) based on route-specific reference fuel consumption figures or (more likely) on a distance-based or generic data.
	APU	<ul style="list-style-type: none"> Not modelled explicitly / separately 	Included in reference fuel consumption figures. IATA recommends to align "at which point monitoring of fuel consumption starts and ends" with methods and procedures applied for CORSIA (IATA, §1.1). This, in turn, recommends a process that would include APU fuel (ICAO, 2023, Attachment C).
	Taxi		
	LTO		
	Non-LTO climb / descent	<ul style="list-style-type: none"> Idealised 	
Cruise			
Payload	Payload	<ul style="list-style-type: none"> Typical aircraft type capacity and average load factors Typical aircraft type capacity and average airport pair load factors 	IATA recommends Members to "use their own historical data (fuel burn, seat configuration, payload, etc.) based on flown data to calculate the CO ₂ emissions of their operating flights" (IATA, §2.2.1), and further recommends to use "averages based on their historical data", with a recommended time range of 12 months (IATA, §2.2.2). The methodology furthermore notes that "in case where data sets available covering a shorter time range than 12 months, for example where a new flight destination was introduced during the calendar year, data can be complemented with data stemming from other destinations that cover a similar distance serviced by the same aircraft type over a 12-month period." (IATA, §2.2.2.1). As the (online) publicly available version does not require to select an airline, it is deemed likely that calculations are (at best) based on route-specific reference fuel consumption (and payload) figures or (more likely) on more generic data.
Misc.	Alternative taxi operations	<ul style="list-style-type: none"> Not modelled 	Included in reference fuel consumption figures.
	Wind	<ul style="list-style-type: none"> Averaged per airport-pair 	Modelling takes a time-based approach (hourly fuel consumption is multiplied by scheduled block time per route; IATA, 2024c),

Group	Calculation parameter	Option	Remarks
			in which it is assumed that differences in (scheduled) block time are completely explained by differences in wind. Whereas wind effects might play the most important role, there are other factors that may affect flight duration and block time (e.g. deviation from fuel-optimal cruise speed, variation in taxi time, ...)
	Deviation from fuel-optimal cruise speed	– Not modelled	Inexplicitly included in reference fuel consumption figures.
	Tankering	– Not modelled	Inexplicitly included in reference fuel consumption figures.

Appendix C.2.6 ICAO Carbon Emissions Calculator

The ICAO Carbon Emissions Calculator (CEC) is an online and publicly available emissions estimation tool which relies on an “internationally approved methodology developed for estimating the amount of carbon emissions (CO₂) generated by a passenger in a flight, for use in carbon offsetting programmes” (ICAO, 2024c, p. 3).

For each of the applicable calculation parameters of interest, Table 66 identifies the option used. As the model is widely familiar and available to anyone, applicable options are scored 1 point (per Section 3.5). The final score awarded to each option is the sum of the scores per option, normalised to the number of applicable models (per Section 3.5).

Table 66: Calculation method used in the ICAO Carbon Emissions Calculator

Group	Calculation parameter	Option	Remarks
Aircraft fuel consumption	CO ₂ emission index	– Generic emission index per type of fuel	Uses a constant of 3.16 (ICAO, 2024c, p. 6)
	Lifecycle savings from LCAF	– Not considered	
	Lifecycle savings from SAF		
	Aircraft unit fuel consumption	– Unit fuel consumption per aircraft type (modelled)	“The process by which [fuel consumption formulas] were developed is to start with fuel consumption figures as published by in aircraft manufacturers’ handbooks as a baseline estimate of fuel consumption by trip distance. These figures are then corrected based on available in-service fuel consumption data. Most of the in-service data comes from the US DOT Form 41.” (ICAO, 2024c, pp. 6-7).
Trajectory	Distance	– GCD with distance-dependent detour distance/ detour factor	An absolute correction distance is added to the great circle distance, depending on the GCD (less than 550 km, between 550 and 5500 km, and above 5500 km) (ICAO, 2024c, p. 7).
	APU	– Not modelled explicitly / separately	Included in in-service fuel consumption data.
	Taxi		
	LTO		
	Non-LTO climb / descent		
Cruise	– Idealised		

Group	Calculation parameter	Option	Remarks
Payload	Payload	<ul style="list-style-type: none"> Typical aircraft type capacity and average region load factors 	“Both a passenger load factor and a pax-to-cargo factor is assigned to the user-defined city-pair based on the corresponding route groups (53 international route groups plus 11 domestic areas plus 11 intra areas).” (ICAO, 2024c, pp. 4, 11-12).
Misc.	Alternative taxi operations	<ul style="list-style-type: none"> Not modelled 	Possibly included in reference fuel consumption figures.
	Wind		
	Deviation from fuel-optimal cruise speed		
	Tankering		

Appendix C.2.7 NLR BeyondCO₂-tool

The NLR BeyondCO₂-tool is a model that has been specifically developed to calculate CO₂ emissions of (groups of) flights. It models the fuel burn of each unique flight (defined by a combination of an aircraft type, origin and destination) and subsequently calculates emissions: CO₂ is one of the main outputs, but other emission species are also estimated. The model has been applied in various national and international studies (e.g. Lammen, Peerlings, van der Sman, & Kos, 2022; Peerlings, Wijn, Engler Faleiros, & Söffing, 2024).

For each of the applicable calculation parameters of interest, Table 67 identifies the option used. As the model is considered widely familiar but not available to anyone, applicable options are scored 0.5 point (per Section 3.5). The final score awarded to each option is the sum of the scores per option, normalised to the number of applicable models (per Section 3.5).

Table 67: Calculation method used in the NLR BeyondCO₂-tool

Group	Calculation parameter	Option	Remarks
Aircraft fuel consumption	CO ₂ emission index	<ul style="list-style-type: none"> Generic emission index per type of fuel 	
	Lifecycle savings from LCAF	<ul style="list-style-type: none"> Not modelled 	Although SAF-options could be used.
	Lifecycle savings from SAF	<ul style="list-style-type: none"> Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type 	Both options supported.
	Aircraft unit fuel consumption	<ul style="list-style-type: none"> Unit fuel consumption per aircraft type (modelled) 	Based on EUROCONTROL BADA flight performance data (EUROCONTROL, 2024b).
Trajectory	Distance	<ul style="list-style-type: none"> GCD with region-dependent detour distance/ detour factor GCD with distance-dependent detour distance/ detour factor GCD with route-dependent detour distance/ detour factor 	Detour factor primarily based on route. If not available, fall-back to detour factor based on region. If not available, fall-back to detour factor based on distance.
	APU	<ul style="list-style-type: none"> Not considered 	

Group	Calculation parameter	Option	Remarks
	Taxi	<ul style="list-style-type: none"> – Default taxi time – Average airport taxi time 	Average airport taxi time is available; fall-back to default taxi time.
	LTO	<ul style="list-style-type: none"> – Idealised 	Based on performance per aircraft type.
	Non-LTO climb / descent		
	Cruise	<ul style="list-style-type: none"> – Idealised including step climbs 	Step climbs modelled dependent on instantaneous aircraft weight (reducing over the course of the flight due to fuel consumption)
Payload	Payload	<ul style="list-style-type: none"> – Typical aircraft type capacity and average load factors 	
Miscellaneous	Alternative taxi operations	<ul style="list-style-type: none"> – Percentage of single engine taxiing – Percentage of electric taxiing (e.g. by (electric) tow truck) 	
	Wind	<ul style="list-style-type: none"> – Not modelled 	
	Deviation from fuel-optimal cruise speed		
	Tankering		

Appendix D Detailed scores per calculation option

This appendix shows the detailed scores per calculation option, following the scoring metrics defined in Chapter 3 and the analysis details provided in Appendix B and Appendix C.

Each of the sections consider a group of calculation parameters, with further sub-sections discussing the detailed scoring for each of the options identified for a calculation parameters included in the group. Overviews showing the unweighted scores of each option side by side, as well as the weighted (rounded) total scores per option – for both hindcast (HC) and forecast (FC) applications, are included in Chapter 4.

As the scores awarded to the assessment criteria related to verifiability, usability and stakeholder support were found to, in numerous cases, already determine the two highest-scoring options of a particular calculation parameter (further detailed in Appendix B.2), the accuracy of (some of) the options has not been assessed. This is indicated with the text 'Not assessed' or with scores that are 'at least' or 'at most' a particular value (in the 'Accuracy'-row). In case quantified accuracy scores are shown, these first appear according to the accuracy scoring metrics defined in Chapter 3, and then in weighted score, in which the original scoring values have been multiplied with the sensitivity of the overall CO₂ emission with respect to changes in the calculation parameter of interest. In case the accuracy score could not be unambiguously or precisely determined, this shows as a range of scores.

Appendix D.1 Aircraft fuel consumption

Appendix D.1.1 CO₂ emission index

Generic emission index per type of fuel

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	1	
Combined accuracy / sensitivity	0 – 1	
Fraud-resistance	0.5	Airlines could theoretically try to source fuel with higher energy content (MJ/kg), such that the amount of fuel required would decrease and CO ₂ emissions would be underestimated by using the default. Deemed (very) unlikely.
Transparency	1	The generic emission index can be communicated publicly.
Availability of data	1	A generic emission index based on available international standards, such as specified in ISO 14083 (CEN, 2023), can be selected.
Computational time	1	All flights can be modelled with same value
Alignment with current methods, standards and regulations	1	Used by all applicable methods, standards and regulations considered (EASA / ReFuelEU Aviation Flight Emissions Label; EU ETS; CORSIA; methods for local environmental impact assessments)
Incorporation in existing CO ₂ emission models	1	Used by all models considered

Batch-specific emission index

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	1	
Combined accuracy / sensitivity	1	
Fraud-resistance	1	
Transparency	0	Batch specific emission indices are proprietary data which cannot be publicly communicated.
Availability of data	0.25	Emission indices of fuel supplied at each origin airport is known to at least one party but to derive the batch specific emission index of a flight, computations to reflect on mixing levels are required.
Computational time	0	Each flight must be modelled with flight specific value.
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

Appendix D.1.2 Lifecycle savings from LCAF

Not considered

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.20	
Combined accuracy / sensitivity	0 – 0.2	
Fraud-resistance	1	No loopholes foreseen, although possibly dependent on the clarity of agreements on types / quality of SAF to be included
Transparency	1	No logic nor data has to be shared publicly
Availability of data	1	No data is required
Computational time	1	No computation required
Alignment with current methods, standards and regulations	1	EU ETS; at the moment of writing, no uniform methodology exists for taking into account the lifecycle savings from LCAF in local environmental impact assessment studies
Incorporation in existing CO ₂ emission models	1	Used by all models considered

Tank-to-wake emissions of LCAF reduced by generic lifecycle emission reduction factor of LCAF

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.20	
Combined accuracy / sensitivity	0 – 0.2	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Data on generic lifecycle emission reductions factors of LCAF can be shared publicly
Availability of data	1	Data on generic lifecycle emission reduction factors of LCAF is publicly available from e.g. ICAO (n.d., b)
Computational time	1	Assuming equal blending level per airport, aggregation reduces unique flights by 100%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

Tank-to-wake emissions of LCAF reduced by generic lifecycle emission reduction factor of LCAF-type

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.20	
Combined accuracy / sensitivity	0 – 0.2	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Data on generic lifecycle emission reductions factors per LCAF-type can be shared publicly
Availability of data	1	Data on generic lifecycle emission reduction factors of LCAF-types is publicly available, e.g. from ICAO (n.d., b), Bauen et al. (2022)
Computational time	1	Assuming equal blending level and LCAF-type per airport, aggregation reduces unique flights by 100%
Alignment with current methods, standards and regulations	0.5	Option in CORSIA
Incorporation in existing CO ₂ emission models	0	

Tank-to-wake emissions of LCAF reduced by lifecycle emission reduction factor of LCAF-batch uplifted

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	0.20	
Combined accuracy / sensitivity	0.2	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	The emission reduction factor can be viewed but not publicly shared
Availability of data	0.5	Data on the emission reduction factor of the LCAF-batch uplifted will be known to at least one party in the DLT (airline, airport, aviation fuel supplier)
Computational time	0	Each flight must be modelled with flight specific blending percentage
Alignment with current methods, standards and regulations	1	Prescribed by the EASA / ReFuelEU Aviation Flight Emissions Label; option in CORSIA
Incorporation in existing CO ₂ emission models	0	

Appendix D.1.3 Lifecycle savings from SAF*Tank-to-wake emissions of SAF set to zero (EU-ETS)*

Assessment criterion	Score	Rationale
Accuracy	0 – 0.75	Not more accurate than 'Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF'
Sensitivity	0.50	
Combined accuracy / sensitivity	0 – 0.38	
Fraud-resistance	1	Clear methodology
Transparency	1	Data and logic can be communicated publicly
Availability of data	1	Data is publicly available
Computational time	1	Assuming equal blending level per airport, aggregation reduces unique flights by 100%
Alignment with current methods, standards and regulations	1	EU ETS
Incorporation in existing CO ₂ emission models	0	

Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF

Assessment criterion	Score	Rationale
Accuracy	0 – 0.75	At least -0.25pt w.r.t. 'Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type'
Sensitivity	0.50	
Combined accuracy / sensitivity	0 – 0.38	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Data and logic can be communicated publicly
Availability of data	1	Data on generic lifecycle emission reduction factors of SAF is publicly available from e.g. van der Sman et al. (2021), the EU (Directive EU 2018/2001, EU, 2018) or ICAO (2024a)
Computational time	1	Assuming equal blending level per airport, aggregation reduces unique flights by 100%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.22	AEOLUS; option in NLR BeyondCO ₂ -tool

Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type

Assessment criterion	Score	Rationale
Accuracy	0 – 1	At least +0.25 pt w.r.t. 'Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF'
Sensitivity	0.50	
Combined accuracy / sensitivity	0.13 – 0.5	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	The data on lifecycle reduction factors per SAF type can be shared publicly
Availability of data	1	Data on generic lifecycle emission reduction factors per SAF type can be obtained from public sources such as the "Default Life Cycle Emissions Values for CORSIA Eligible Fuels" (ICAO, 2024a)
Computational time	1	Assuming equal blending level and SAF-mix per airport, aggregation reduces unique flights by 100%
Alignment with current methods, standards and regulations	0.5	Option in CORSIA
Incorporation in existing CO ₂ emission models	0.11	Option in NLR BeyondCO ₂ -tool

Tank-to-wake emissions of SAF reduced by lifecycle emission reduction factor of SAF-batch uplifted

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	0.50	
Combined accuracy / sensitivity	0.50	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	The emission reduction factor can be viewed but not publicly shared
Availability of data	0.5	Data on the emission reduction factor of the SAF-batch uplifted will be known to at least one party in the DLT (airline, airport, aviation fuel supplier)
Computational time	0	Each flight must be modelled with flight specific blending percentage
Alignment with current methods, standards and regulations	1	Prescribed by EASA / ReFuelEU Aviation Flight Emissions Label; option in CORSIA
Incorporation in existing CO ₂ emission models	0	

Appendix D.1.4 Aircraft unit fuel consumption

(Average) unit fuel consumption per aircraft size class (modelled)

Assessment criterion	Score	Rationale
Accuracy	0	
Sensitivity	1	
Combined accuracy / sensitivity	0	
Fraud-resistance	0.5	Airlines could theoretically keep flying (longer) with aircraft with a higher-than-class-average fuel burn, but given other pressures on fleet renewal, this is deemed unlikely (for the anticipated use of the uniform calculation method)
Transparency	1	Data on average fuel consumption per aircraft size class can be shared publicly
Availability of data	1	Data on average fuel consumption per aircraft size class is available to the Ministry through AEOLUS and is publicly available through sources such as Thor, et al. (2023)
Computational time	0.99	Aggregation per size class reduces unique flights by 99%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.11	AEOLUS

Unit fuel consumption per aircraft type (modelled)

Assessment criterion	Score	Rationale
Accuracy	0.25	
Sensitivity	1	
Combined accuracy / sensitivity	0.25	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data can be viewed on licence but not publicly shared
Availability of data	0.75	Data is available for purchase from e.g. EUROCONTROL (2024b)
Computational time	0.98	Aggregation per aircraft types reduces unique flights by 98%
Alignment with current methods, standards and regulations	0.75	In line with ECAC Doc29; methods used in local environmental impact assessment studies (depending on the situation)
Incorporation in existing CO ₂ emission models	0.89	EEA EMEP; EUROCONTROL AEM; EUROCONTROL SET; IATA CO ₂ Connect; ICAO CEC; NLR BeyondCO ₂ -tool (all but AEOLUS)

Unit fuel consumption per aircraft type and airframe age (modelled)

Assessment criterion	Score	Rationale
Accuracy	0.25	
Sensitivity	1	
Combined accuracy / sensitivity	0.25	
Fraud-resistance	0.5	Airframes may be older but have had recent overhauls
Transparency	0.33	Data can be viewed on licence but not publicly shared
Availability of data	0.75	Data is available for purchase from e.g. EUROCONTROL (2024b)
Computational time	0.97	Aggregation per aircraft and age reduces unique flights by 97%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

Unit fuel consumption per aircraft type and engine type (modelled)

Assessment criterion	Score	Rationale
Accuracy	0.75	
Sensitivity	1	
Combined accuracy / sensitivity	0.75	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data can be viewed on licence but not publicly shared
Availability of data	0.75	Data is available for purchase through e.g. EUROCONTROL (2024b), (EASA, 2024b) and CIRIUM (2019)
Computational time	0.97	Aggregation per aircraft and engine type reduces unique flights by 97%
Alignment with current methods, standards and regulations	0.75	Option for EASA / ReFuelEU Aviation Flight Emissions Label; in line with ECAC Doc29
Incorporation in existing CO ₂ emission models	0	

Unit fuel consumption per aircraft type, engine type and airframe age (modelled)

Assessment criterion	Score	Rationale
Accuracy	1	Lacking more detailed data, regarded as 'ground truth'.
Sensitivity	1	
Combined accuracy / sensitivity	1	
Fraud-resistance	0.5	Airframes and engines may be older but have had recent overhauls
Transparency	0.33	Data can be viewed on licence but not publicly shared
Availability of data	0.75	Data is available for purchase through e.g. EUROCONTROL (2024b) and CIRIUM (2019)
Computational time	0.97	Aggregation per aircraft and engine type and age reduces unique flights by 97%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

Unit fuel consumption per aircraft type and engine type (real-life data)

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	1	
Combined accuracy / sensitivity	1	
Fraud-resistance	1	No loopholes foreseen
Transparency	0	Data is proprietary and cannot be publicly shared
Availability of data	0.5	Data is known to at least one party in the DLT (airline)
Computational time	0	Each flight has to be modelled separately
Alignment with current methods, standards and regulations	0.25	Option for EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0	

Appendix D.2 Trajectory

Appendix D.2.1 Distance

Great Circle Distance (GCD)

Assessment criterion	Score	Rationale
Accuracy	0.25	
Sensitivity	0.84	
Combined accuracy / sensitivity	0.21	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Data on great circle distances can be publicly shared
Availability of data	1	Data on great circle distances are publicly available
Computational time	1	Aggregation per great circle distances reduces unique flights by nearly 100%
Alignment with current methods, standards and regulations	1	ECAC Doc29
Incorporation in existing CO ₂ emission models	0	

GCD with generic detour distance/ detour factor

Assessment criterion	Score	Rationale
Accuracy	0.25	
Sensitivity	0.84	
Combined accuracy / sensitivity	0.21	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	A generic detour distance/factor can be shared publicly
Availability of data	1	Data on generic detour distances, such as +95km, and detour factors are publicly available from e.g. EUROCONTROL (n.d., a) and ICAO (2017a)
Computational time	1	Aggregation per great circle distances with generic detour reduces unique flights by nearly 100%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.33	IATA CO ₂ Connect (distance not applicable to EEA EMEP and EUROCONTROL SET)

GCD with airline-dependent detour distance/ detour factor

Assessment criterion	Score	Rationale
Accuracy	0.25	
Sensitivity	0.84	
Combined accuracy / sensitivity	0.21	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data on airline dependent detours can be viewed but not publicly shared
Availability of data	0.5	Data on flight specific detours can be purchased e.g. from FlightAware (n.d.) or EUROCONTROL (n.d., a) but require further computations to yield airline dependent detour distances/factors
Computational time	1	Aggregation per great circle distances with airline-dependent detour reduces unique flights by nearly 100%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

GCD with region-dependent detour distance/ detour factor

Assessment criterion	Score	Rationale
Accuracy	0.25	
Sensitivity	0.84	
Combined accuracy / sensitivity	0.21	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	A region dependent detour distance/factor can be shared publicly
Availability of data	1	Data on region dependent detour factors are publicly available from e.g. ICAO (2017a)
Computational time	1	Aggregation per great circle distances with regional detour reduces unique flights by nearly 100%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.22	AEOLUS; option in NLR BeyondCO ₂ -tool (distance not applicable to EEA EMEP and EUROCONTROL SET)

GCD with airline-region-dependent detour distance/ detour factor

Assessment criterion	Score	Rationale
Accuracy	0.5	
Sensitivity	0.84	
Combined accuracy / sensitivity	0.42	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data on airline-region dependent detours can be viewed but not publicly shared
Availability of data	0.5	Data on flight specific detours can be purchased e.g. from FlightAware (n.d.) or EUROCONTROL (n.d., a) but require further computations to yield airline-region dependent detour distances/factors
Computational time	0.99	Aggregation per great circle distances with airline-region specific detour reduces unique flights by 99%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

GCD with distance-dependent detour distance/ detour factor

Assessment criterion	Score	Rationale
Accuracy	0.5	
Sensitivity	0.84	
Combined accuracy / sensitivity	0.42	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Data on distance-dependent detour distances/factors can be publicly shared
Availability of data	1	Data on distance-dependent detour distances/factors is available from public sources such as ICAO CEC
Computational time	0.98	Aggregation per great circle distances with distance specific detour reduces unique flights by 98%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.5	IATA CO ₂ Connect; ICAO CEC; option in NLR BeyondCO ₂ -tool (distance not applicable to EEA EMEP and EUROCONTROL SET)

GCD with airline-distance-dependent detour distance/ detour factor

Assessment criterion	Score	Rationale
Accuracy	0.5	
Sensitivity	0.84	
Combined accuracy / sensitivity	0.42	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data on airline-distance dependent detours can be viewed but not publicly shared
Availability of data	0.5	Data on flight specific detours can be purchased e.g. from FlightAware (n.d.) or EUROCONTROL (n.d., a) but require further computations to yield airline-distance dependent detour distances/factors
Computational time	0.96	Aggregation per great circle distances with airline-distance specific detour reduces unique flights by 96%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

GCD with route-dependent detour distance/ detour factor

Assessment criterion	Score	Rationale
Accuracy	0.5	
Sensitivity	0.84	
Combined accuracy / sensitivity	0.42	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data on route dependent detours can be viewed but not publicly shared
Availability of data	0.5	Data on flight specific detours can be purchased e.g. from FlightAware (n.d.) or EUROCONTROL (n.d., a) but require further computations to yield route dependent detour distances/factors
Computational time	0.98	Aggregation per great circle distances with route specific detour reduces unique flights by 98%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.22	IATA CO ₂ Connect; option in NLR BeyondCO ₂ -tool (distance not applicable to EEA EMEP and EUROCONTROL SET)

GCD with airline-route-dependent detour distance/ detour factor

Assessment criterion	Score	Rationale
Accuracy	0.5	
Sensitivity	0.84	
Combined accuracy / sensitivity	0.42	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data on airline-route dependent detours can be viewed but not publicly shared
Availability of data	0.5	Data on flight specific detours can be purchased e.g. from FlightAware (n.d.) or EUROCONTROL (n.d., a) but require further computations to yield airline-route dependent detour distances/factors
Computational time	0.96	Aggregation per great circle distances with airline-route specific detour reduces unique flights by 69%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

Planned route (filed flight plan)

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.84	
Combined accuracy / sensitivity	0 – 0.84	
Fraud-resistance	0.5	Airlines could theoretically file a (mock) fuel-optimised flight plan, although this is considered unlikely (for the anticipated use of the uniform calculation method)
Transparency	0	Planned routes are proprietary data and cannot be shared
Availability of data	0.5	The planned route is known to at least one of the parties in the DLT (airline, ANSP)
Computational time	0	Each flight has to be modelled separately
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0.11	Possible in EUROCONTROL AEM (distance not applicable to EEA EMEP and EUROCONTROL SET)

Flown route

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	0.84	
Combined accuracy / sensitivity	0.84	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Distances of actual flight trajectories can be viewed but not publicly shared
Availability of data	0.75	Flight distances can be purchased e.g. from FlightAware (n.d.)
Computational time	0	Each flight has to be modelled separately
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0.11	Possible in EUROCONTROL AEM (distance not applicable to EEA EMEP and EUROCONTROL SET)

Appendix D.2.2 APU*Not considered*

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.01	
Combined accuracy / sensitivity	0 – 0.01	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	No logic nor data has to be shared publicly
Availability of data	1	No data is required
Computational time	1	No computation to be performed
Alignment with current methods, standards and regulations	0.5	EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0.67	AEOLUS; EEA EMEP; EUROCONTROL AEM; EUROCONTROL SET; NLR BeyondCO ₂ -tool

Not modelled explicitly / separately

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.01	
Combined accuracy / sensitivity	0 – 0.01	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	No logic nor data has to be shared publicly
Availability of data	1	No data is required
Computational time	1	No computation to be performed
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.33	IATA CO ₂ Connect (likely); ICAO CEC (likely)

Generic value

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.01	
Combined accuracy / sensitivity	0 – 0.01	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Generic values for APU usage can be publicly shared
Availability of data	1	Generic values for APU usage are publicly available, e.g. 1% (Penner, Lister, Griggs, Dokken, & McFarland, 1999) or values per distance class from ICAO Doc 9889
Computational time	1	All flights can be modelled with same value
Alignment with current methods, standards and regulations	0.17	Option for methods used in local environmental impact assessment studies
Incorporation in existing CO ₂ emission models	0	

Airline-averaged value

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.01	
Combined accuracy / sensitivity	0 – 0.01	
Fraud-resistance	1	No loopholes foreseen
Transparency	0	Data is proprietary and cannot be publicly shared
Availability of data	0.5	Data is known to at least one party in the DLT (airline)
Computational time	0.96	Aggregation per airline reduces unique flights by 96%
Alignment with current methods, standards and regulations	0.17	Option for methods used in local environmental impact assessment studies
Incorporation in existing CO ₂ emission models	0	

Actual

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	0.01	
Combined accuracy / sensitivity	0.01	
Fraud-resistance	1	No loopholes foreseen
Transparency	0	Data is proprietary and cannot be publicly shared
Availability of data	0.5	Data is known to at least one party in the DLT (airline)
Computational time	0	All flights have to be computed separately
Alignment with current methods, standards and regulations	0.17	Option for methods used in local environmental impact assessment studies
Incorporation in existing CO ₂ emission models	0	

Appendix D.2.3 Taxi*Not modelled explicitly / specifically*

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.036	
Combined accuracy / sensitivity	0 – 0.036	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	No logic nor data has to be shared publicly
Availability of data	1	No data is required
Computational time	1	No computation to be performed
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0.56	EUROCONTROL SET; IATA CO ₂ Connect; ICAO CEC

Default taxi time

Assessment criterion	Score	Rationale
Accuracy	0	
Sensitivity	0.036	
Combined accuracy / sensitivity	0	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Default taxi times can be shared publicly
Availability of data	1	Default taxi times are publicly available from sources such EUROCONTROL (n.d., b)
Computational time	1	All flights can be modelled with same value
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.33	AEOLUS; EEA EMEP; NLR BeyondCO ₂ -tool

Average airport taxi time

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.036	
Combined accuracy / sensitivity	0 – 0.036	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Average airport taxi times are publicly shared
Availability of data	1	Average airport taxi times are publicly available from sources such as EUROCONTROL (2019a; 2019b; 2020)
Computational time	0.98	Aggregation per airport specific taxi time reduces unique flights by 98%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.22	EUROCONTROL AEM; NLR BeyondCO ₂ -tool

Average airport-runway taxi time

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.036	
Combined accuracy / sensitivity	0 – 0.036	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data can be viewed but not publicly shared
Availability of data	0.5	Actual taxi times can be purchased from sources such as FlightAware (n.d.) but require further computation to derive average airport-runway taxi times
Computational time	0.89	Aggregation per airport-runway specific taxi time reduces unique flights by at least 89%
Alignment with current methods, standards and regulations	0.25	Option in methods used in local environmental impact assessment studies
Incorporation in existing CO ₂ emission models	0	

Actual

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	0.036	
Combined accuracy / sensitivity	0.036	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data can be viewed but not publicly shared
Availability of data	0.75	Actual taxi times can be purchased from sources such as FlightAware (n.d.)
Computational time	0	All flights have to be modelled separately
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0	

Appendix D.2.4 LTO

Not modelled explicitly / specifically

Assessment criterion	Score	Rationale
Accuracy	0	
Sensitivity	0.063	
Combined accuracy / sensitivity	0	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	No logic nor data has to be shared publicly
Availability of data	1	No data is required
Computational time	1	No computation to be performed
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0.56	EUROCONTROL SET; IATA CO ₂ Connect; ICAO CEC

Generic

Assessment criterion	Score	Rationale
Accuracy	0 – 0.25	
Sensitivity	0.063	
Combined accuracy / sensitivity	0 – 0.02	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Generic LTO-cycles can be shared publicly
Availability of data	1	Generic values for LTO cycles are available through e.g. ICAO standard LTO-cycle
Computational time	1	All flights can be computed with the same generic value
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.33	AEOLUS; EEA EMEP; EUROCONTROL AEM

Idealised

Assessment criterion	Score	Rationale
Accuracy	0.25 – 1	As 'Generic' or higher.
Sensitivity	0.063	
Combined accuracy / sensitivity	0.02 – 0.063	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data for idealisation can be viewed but not shared publicly
Availability of data	0.75	Idealisation data for LTO-cycles can be purchased e.g. through EUROCONTROL (2024b)
Computational time	0.98	Idealising LTO per aircraft type and origin destination pair reduces the unique number of flights to be computed by 98%
Alignment with current methods, standards and regulations	1	ECAC Doc29; methods used in local environmental impact assessment studies
Incorporation in existing CO ₂ emission models	0.11	NLR BeyondCO ₂ -tool

Actual

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	0.063	
Combined accuracy / sensitivity	0.063	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data on actual LTO profiles can be viewed but not shared publicly
Availability of data	0.75	Actual LTO profiles can be purchased e.g. from FlightAware (n.d.)
Computational time	0	All flights have to be computed separately
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0	

Appendix D.2.5 Non-LTO climb / descent*Not modelled explicitly / specifically*

Assessment criterion	Score	Rationale
Accuracy	0	
Sensitivity	0.30	
Combined accuracy / sensitivity	0	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	No logic nor data has to be shared publicly
Availability of data	1	No data is required
Computational time	1	No computation to be performed
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0.78	AEOLUS; EEA/EMEP; EUROCONTROL SET; IATA CO ₂ Connect; ICAO CEC

Idealised

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.30	
Combined accuracy / sensitivity	0 – 0.3	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data can be viewed but not publicly shared
Availability of data	0.75	Idealising climb/descent requires data which can be purchased from e.g. EUROCONTROL (2024b)
Computational time	0.98	Idealising Climb/descent per aircraft type and origin destination pair reduces the unique number of flights to be computed by 98%
Alignment with current methods, standards and regulations	0.5	ECAC Doc29
Incorporation in existing CO ₂ emission models	0.22	EUROCONTROL AEM; NLR BeyondCO ₂ -tool

Actually flown

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	0.30	
Combined accuracy / sensitivity	0.3	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data on actual climb and descent profiles can be viewed but not shared publicly
Availability of data	0.75	Actual climb and descent profiles can be purchased e.g. from FlightAware (n.d.)
Computational time	0	All flights have to be computed separately
Alignment with current methods, standards and regulations	0.75	Option in EASA / ReFuelEU Aviation Flight Emissions Label; ECAC Doc29
Incorporation in existing CO ₂ emission models	0.11	EUROCONTROL AEM

Appendix D.2.6 Cruise*Idealised*

Assessment criterion	Score	Rationale
Accuracy	0.5	
Sensitivity	0.59	
Combined accuracy / sensitivity	0.33	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data can be viewed but not publicly shared
Availability of data	0.75	Idealising cruise requires data which can be purchased from e.g. EUROCONTROL
Computational time	0.98	Idealising cruise per aircraft type and origin destination pair reduces the unique number of flights to be computed by 98%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.90	AEOLUS; EEA EMEP; EUROCONTROL AEM; EUROCONTROL SET; IATA CO ₂ Connect; ICAO CEC (all but NLR BeyondCO ₂ -tool)

Idealised including step climbs

Assessment criterion	Score	Rationale
Accuracy	0.75	At most; at least 0.25 points more than 'Idealised'.
Sensitivity	0.59	
Combined accuracy / sensitivity	0.44	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data can be viewed but not publicly shared
Availability of data	0.75	Idealising cruise including step climbs requires data which can be purchased from e.g. EUROCONTROL (2024b)
Computational time	0.98	Idealising cruise per aircraft type and origin destination pair reduces the unique number of flights to be computed by 98%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.11	NLR BeyondCO ₂ -tool

Planned

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.59	
Combined accuracy / sensitivity	0 – 0.59	
Fraud-resistance	0.5	Airlines could theoretically plan a (more) fuel-optimal cruise segment, although this is considered unlikely (for the anticipated use of the uniform calculation method)
Transparency	0	Planned flight trajectories are proprietary data and cannot be shared
Availability of data	0.5	Planned flight trajectories are known to at least one party in the DLT (airline, ANSP)
Computational time	0	All flights have to be computed separately
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.11	EUROCONTROL AEM

Actual

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	0.59	
Combined accuracy / sensitivity	0.59	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data on actual cruise trajectories can be viewed but not shared publicly
Availability of data	0.75	Actual cruise trajectories can be purchased e.g. from FlightAware (n.d.)
Computational time	0	All flights have to be computed separately
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0.11	EUROCONTROL AEM

Appendix D.3 Payload

Typical aircraft class capacity and average load factors

Assessment criterion	Score	Rationale
Accuracy	0	
Sensitivity	0.15	
Combined accuracy / sensitivity	0	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Typical aircraft class capacity and average load factor can be shared publicly
Availability of data	1	Typical aircraft class capacity and average load factor can be obtained through public sources such as ANP, ICAO CEC and IATA Market Analyses (2024b)
Computational time	0.99	Aggregating per aircraft class capacity the unique number of flights to be computed by 99%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.1	AEOLUS

Typical aircraft type capacity and average load factors

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.15	
Combined accuracy / sensitivity	0 – 0.15	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Typical aircraft type capacity and average load factor can be shared publicly
Availability of data	1	Typical aircraft type capacity and average load factor can be obtained through public sources such as ICAO CEC and IATA Market Analyses (2024b)
Computational time	0.98	Aggregating per aircraft type capacity the unique number of flights to be computed by 98%
Alignment with current methods, standards and regulations	1	ECAC Doc29; methods used in local environmental impact assessment studies
Incorporation in existing CO ₂ emission models	0.7	EEA EMEP; EUROCONTROL AEM; EUROCONTROL SET; IATA CO ₂ Connect (likely); NLR BeyondCO ₂ -tool

Typical aircraft type capacity and average airline load factors

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.15	
Combined accuracy / sensitivity	0 – 0.15	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Average airline load factors cannot be shared publicly
Availability of data	0.75	Typical aircraft type capacity and average airline load factor can be purchased from sources such as ICAO (ICAO, n.d., a)
Computational time	0.97	Aggregating per aircraft type and airline capacity the unique number of flights to be computed by 97%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

Typical aircraft type capacity and average region load factors

Assessment criterion	Score	Rationale
Accuracy	0.25 – 1	As 'typical aircraft class capacity and average load factors', or higher.
Sensitivity	0.15	
Combined accuracy / sensitivity	0.038 – 0.15	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Average regional load factors can be shared publicly
Availability of data	1	Typical aircraft type capacity and average regional load factors can be obtained from public sources such as IATA Market Analyses (2024b) or ICAO CEC
Computational time	0.99	Aggregating per aircraft type capacity and region reduces the unique number of flights to be computed by 99%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.22	ICAO CEC

Typical aircraft type capacity and average airport pair load factors

Assessment criterion	Score	Rationale
Accuracy	0.25 – 1	As 'typical aircraft class capacity and average load factors', or higher.
Sensitivity	0.15	
Combined accuracy / sensitivity	0.038 – 0.15	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Average airport pair load factors cannot be shared publicly
Availability of data	0.75	Typical aircraft type capacity and average airport pair load factor can be purchased from sources such as ICAO (ICAO, n.d., a)
Computational time	0.98	Aggregating per aircraft type capacity and origin destination pair reduces the unique number of flights to be computed by 98%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.11	IATA CO ₂ Connect (likely)

Typical aircraft tail capacity and average airport pair load factors

Assessment criterion	Score	Rationale
Accuracy	0.25 – 1	As 'typical aircraft class capacity and average load factors', or higher.
Sensitivity	0.15	
Combined accuracy / sensitivity	0.038 – 0.15	
Fraud-resistance	1	No loopholes foreseen
Transparency	0	Data is proprietary and cannot be shared
Availability of data	0.5	Data is known to at least one party in the DLT (airline)
Computational time	0.86	Aggregating per aircraft tail capacity reduces the unique number of flights to be computed by 86%
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0	

Payload weight in filed flight plan

Assessment criterion	Score	Rationale
Accuracy	0.25 – 1	As 'typical aircraft class capacity and average load factors', or higher.
Sensitivity	0.15	
Combined accuracy / sensitivity	0.038 – 0.15	
Fraud-resistance	1	Airlines could theoretically file a flight plan with a lower payload weight, but due to the inherent safety issues, this is only considered a theoretical risk
Transparency	0	Data is proprietary and cannot be shared
Availability of data	0.5	Data is known to at least one party in the DLT (airline)
Computational time	0	All flights have to be computed separately
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0	

Calculated from actual take-off weight (TOW)

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	0.15	
Combined accuracy / sensitivity	0.15	
Fraud-resistance	1	No loopholes foreseen
Transparency	0	Data is proprietary and cannot be shared
Availability of data	0.5	Data is known to at least one party in the DLT (airline)
Computational time	0	All flights have to be modelled separately
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

Appendix D.4 Miscellaneous

Appendix D.4.1 Alternative taxi operations

Not modelled

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.036	
Combined accuracy / sensitivity	0 – 0.036	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	No logic nor data has to be shared publicly
Availability of data	1	No data is required
Computational time	1	No computation to be performed
Alignment with current methods, standards and regulations	0.5	EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0.89	AEOLUS; EEA EMEP; EUROCONTROL AEM; EUROCONTROL SET; IATA CO ₂ Connect; ICAO CEC (all but NLR BeyondCO ₂ -tool)

Percentage of single engine taxiing

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.036	
Combined accuracy / sensitivity	0 – 0.036	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data can be viewed but not shared publicly ²⁹
Availability of data	0.5	Data is known to at least one party in the DLT (airline)
Computational time	0.97	Aggregating per aircraft type, airline and airport, the unique number of flights to be computed reduces by 97%
Alignment with current methods, standards and regulations	0.5	Methods used in local environmental impact assessment studies
Incorporation in existing CO ₂ emission models	0.11	Option in NLR BeyondCO ₂ -tool

Percentage of single engine taxiing and percentage of electric taxiing (e.g. by (electric) tow truck)

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.036	
Combined accuracy / sensitivity	0 – 0.036	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Data can be viewed but not shared publicly
Availability of data	0.5	Data is known to at least one party in the DLT (airline)
Computational time	0.97	Aggregating per aircraft type, airline and airport, the unique number of flights to be computed reduces by 97%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.11	Option in NLR BeyondCO ₂ -tool

²⁹ As part of annual monitoring for the environmental permit ('Natuurvergunning') for Amsterdam Airport Schiphol, the airport has queried airlines on their use of single engine taxi (or "n-1 taxi operations"). Even though the report in which that data is presented (in an aggregated way) is anticipated to be shared with Parliament (and hence will become publicly available), it is limited to Amsterdam Airport Schiphol and does not include data for the other airports of national interest.

Appendix D.4.2 Wind

Not modelled

Assessment criterion	Score	Rationale
Accuracy	0 – 0.75	
Sensitivity	0.59	
Combined accuracy / sensitivity	0 – 0.44	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	No logic nor data has to be shared publicly
Availability of data	1	No data is required
Computational time	1	No computation to be performed
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0.78	AEOLUS; EEA EMEP; EUROCONTROL SET; ICAO CEC; NLR BeyondCO ₂ -tool (all but EUROCONTROL AEM)

Averaged per region

Assessment criterion	Score	Rationale
Accuracy	0.25 – 1	At least 0.25 points more than 'Not modelled'.
Sensitivity	0.59	
Combined accuracy / sensitivity	0.15 – 0.59	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.66	Once computed data can be shared publicly
Availability of data	0.75	Data is publicly available from e.g. ERA-5 (ECMWF, 2024) but requires further computation to derive average winds
Computational time	0.99	Aggregating per region, the unique number of flights to be computed reduces by 99%
Alignment with current methods, standards and regulations	1	ECAC Doc29
Incorporation in existing CO ₂ emission models	0	

Averaged per airport-pair

Assessment criterion	Score	Rationale
Accuracy	0.25 – 1	At least 0.25 points more than 'Not modelled'.
Sensitivity	0.59	
Combined accuracy / sensitivity	0.15 – 0.59	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.66	Once computed data can be shared publicly
Availability of data	0.5	Route specific flight trajectories must be purchased from e.g. (EUROCONTROL, n.d., a) or (Flightaware, n.d.) and combined with wind data from e.g. ERA-5 (ECMWF, 2024) to derive average winds per airport pair
Computational time	0.98	Aggregating per airport pair, the unique number of flights to be computed reduces by 98%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0.11	IATA CO ₂ Connect

Averaged based on historic climatological data

Assessment criterion	Score	Rationale
Accuracy	0.25 – 1	At least 0.25 points more than 'Not modelled'.
Sensitivity	0.59	
Combined accuracy / sensitivity	0.15 – 0.59	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.66	Once computed data can be shared publicly
Availability of data	0.5	Route specific flight trajectories must be purchased from e.g. (EUROCONTROL, n.d., a) or (Flightaware, n.d.) and combined with historic wind data from e.g. ERA-5 (ECMWF, 2024) to derive average winds per airport pair
Computational time	0.98	Aggregating per historical route, the unique number of flights to be computed reduces by 98%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

Actual conditions

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	0.59	
Combined accuracy / sensitivity	0.59	
Fraud-resistance	1	No loopholes foreseen
Transparency	0.33	Wind on actual flight may be viewed but cannot shared publicly
Availability of data	0.5	Actual flight trajectories must be purchased from e.g. (EUROCONTROL, n.d., a) or (Flightaware, n.d.) and combined with wind data from e.g. ERA-5 (ECMWF, 2024) to derive actual wind conditions
Computational time	0	All flights have to be computed separately
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0.11	EUROCONTROL AEM

Appendix D.4.3 Deviation from fuel-optimal cruise speed*Not modelled*

Assessment criterion	Score	Rationale
Accuracy	0.75	
Sensitivity	0.35	
Combined accuracy / sensitivity	0.26	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	No logic nor data has to be shared publicly
Availability of data	1	No data is required
Computational time	1	No computational to be performed
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0.89	AEOLUS; EEA EMEP; EUROCONTROL SET; IATA CO ₂ Connect; ICAO CEC; NLR BeyondCO ₂ -tool (all but EUROCONTROL AEM)

Generic correction

Assessment criterion	Score	Rationale
Accuracy	0.75 – 1	
Sensitivity	0.35	
Combined accuracy / sensitivity	0.26 – 0.35	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Generic deviations from fuel-optimised cruise speeds can be shared publicly
Availability of data	1	Generic deviations from fuel-optimised cruise speeds can be obtained from literature
Computational time	1	All flights can be computed with the same value
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

Regional correction

Assessment criterion	Score	Rationale
Accuracy	0.75 – 1	
Sensitivity	0.35	
Combined accuracy / sensitivity	0.26 – 0.35	
Fraud-resistance	0.5	Airlines could theoretically operate on fuel-optimised speeds to create a reference data set that might underestimate actual (potentially less fuel-optimal) flights but this is considered unlikely
Transparency	0.66	Once computed regional corrections to fuel optimal cruise speeds may be shared publicly
Availability of data	0.25	Regional corrections from fuel optimal cruise speeds may be derived from data available to parties at the DLT (airlines)
Computational time	0.98	Aggregating per region, the unique number of flights to be computed reduces by 98%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

Actual

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	0.35	
Combined accuracy / sensitivity	0.35	
Fraud-resistance	1	No loopholes foreseen
Transparency	0	Data is proprietary and cannot be shared publicly
Availability of data	0.5	Data on cruise speed deviation is known to at least one party at the DLT (airline)
Computational time	0	All flights have to be modelled separately
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0.11	EUROCONTROL AEM

Appendix D.4.4 Tankering

Not modelled

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.15	
Combined accuracy / sensitivity	0 – 0.15	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	No logic nor data has to be shared publicly
Availability of data	1	No data is required
Computational time	1	No computation to be performed
Alignment with current methods, standards and regulations	1	ECAC Doc29; option in EASA / ReFuelEU Aviation Flight Emissions Label; Methods used in local environmental impact assessment studies
Incorporation in existing CO ₂ emission models	1	Used by all models considered

Generic correction

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.15	
Combined accuracy / sensitivity	0 – 0.15	
Fraud-resistance	1	No loopholes foreseen
Transparency	1	Generic tankering correction values based on Europe (Peeters, Uitbeijerse, Peerlings, & Geilenkirchen, 2021) can be shared publicly
Availability of data	1	Generic tankering correction values are available from public sources for flights departing Europe (Peeters, Uitbeijerse, Peerlings, & Geilenkirchen, 2021)
Computational time	1	All flights can be computed with the same value
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

Regional correction

Assessment criterion	Score	Rationale
Accuracy	0 – 1	Not assessed.
Sensitivity	0.15	
Combined accuracy / sensitivity	0 – 0.15	
Fraud-resistance	0.5	Airlines could theoretically stop tankering for a given period to create a reference data set than might underestimate actual (potential) tankering, but this is considered unlikely
Transparency	0	Tankering is proprietary data which cannot be shared publicly
Availability of data	0.25	No tankering correction values per region are available through public sources such that data available to at least one party in the DLT (airline) must be used to compute these regional corrections
Computational time	0.98	Aggregating per region, the unique number of flights to be computed reduces by 98%
Alignment with current methods, standards and regulations	0	
Incorporation in existing CO ₂ emission models	0	

Actual

Assessment criterion	Score	Rationale
Accuracy	1	By definition.
Sensitivity	0.15	
Combined accuracy / sensitivity	0.15	
Fraud-resistance	1	No loopholes foreseen
Transparency	0	Tankering is proprietary data that cannot be shared publicly
Availability of data	0.5	Data is known to at least one party to the DLT (airline)
Computational time	0	All flights have to be modelled separately
Alignment with current methods, standards and regulations	0.25	Option in EASA / ReFuelEU Aviation Flight Emissions Label
Incorporation in existing CO ₂ emission models	0	

Appendix E Scoring metric sensitivity

Chapter 3 outlined the assessment criteria, weighting factors and scoring metrics used in the evaluation of different calculation parameter options. To test the robustness of this evaluation, the sensitivity of results (i.e.: highest-scoring options) with respect to choices in scoring metrics has been analysed for a number of criteria: accuracy (Appendix E.1), availability of data (Appendix E.2), alignment with current methods, standards and regulations (Appendix E.3) and incorporation in existing CO₂ emission models (Appendix E.4).

Appendix E.1 Accuracy

The accuracy of various calculation options was assessed using an analysis of the root mean squared relative error (RMSRE, explained in Box 12 on page 75). Different ranges of RMSRE were then used to assign options a particular score (Section 3.2). To gather insight into the sensitivity of that scoring metric, the analysis presented in this section varies the metric ranges by $\pm 1\%$, yielding the metric values as shown below. A visual comparison with the original metric values is shown in Figure 7.

High

- 1 point: if the RMSRE is below 2%
- 0.75 points: if the RMSRE is between 2 and 4%
- 0.5 points: if the RMSRE is between 4 and 6%
- 0.25 points: if the RMSRE is between 6 and 11%
- 0 points: if the RMSRE is larger than 11%

Low

- 1 point: if the RMSRE is below 0.5% (as 0% would be infeasible)
- 0.75 points: if the RMSRE is between 0.5 and 2%
- 0.5 points: if the RMSRE is between 2 and 4%
- 0.25 points: if the RMSRE is between 4 and 9%
- 0 points: if the RMSRE is larger than 9%

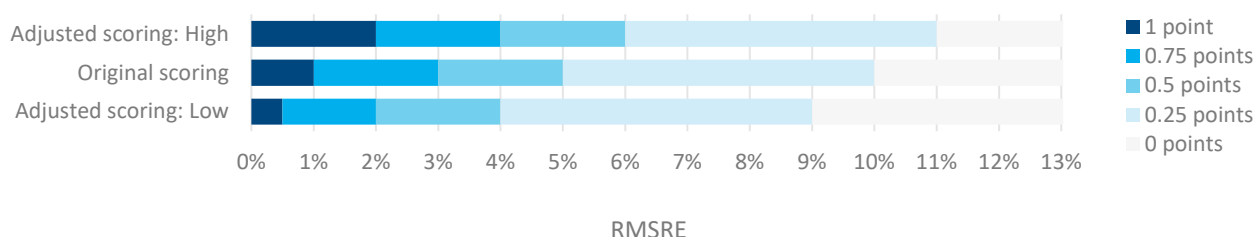


Figure 7: Original and adjusted (high and low) scoring metrics for accuracy

For some categories, the RMSRE metric were not or could not be used to determine the accuracy score due to a.o. lack of data, literature or other information. For these categories, the accuracy scores were given ranges of possible scores. The potential ranges of accuracy scores have also been assessed in this sensitivity study. Also, it is noted that rounded scores are used in the final scoring tables. This section, however, shows scoring values with one decimal to show the effect of the sensitivity analysis in more detail.

Appendix E.1.1 Aircraft fuel consumption

CO₂ emission index

For the CO₂ emission index, the difference in (original) scores is substantial. Changing any of the accuracy scores has no effect on the final ranking.

Lifecycle savings from LCAF

For the LCAF parameter, assuming that the emission factor per LCAF-type is as least as, if not more accurate than the generic emission factor, the parameter ranking will not change for the full 0-1 score accuracy scoring range.

Lifecycle savings from SAF

For this category, an evaluation using the RMSRE could not be used, leading to a range of possible accuracy scores which are evaluated here. The main sensitivity in lifecycle savings from SAF lies in the score difference between the EU-ETS method ('Tank-to-wake emissions of SAF set to zero'), and the ReFuelEU/CORSIA method ('Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF'). Looking at the table below, it can be seen that a score difference of 0.25 or higher will lead to a different ranking. However, in order to acquire and compare an exact accuracy score between these two options is not as straightforward as with other options due to the fact that it is a choice of which method/regulation to adhere to. This is quantified in Table 68, where the accuracy of the EU-ETS method is kept at 0 while the accuracy score of the ReFuelEU/CORSIA method is increased.

Table 68: Scoring metric sensitivity results for 'Lifecycle savings from SAF': **Highest ranked** and **Second highest ranked**

Parameter	Hindcast application				Forecast application			
	Score diff = 0	Score diff = 0.25	Score diff = 0.5	Score diff = 0.75	Score diff = 0	Score diff = 0.25	Score diff = 0.5	Score diff = 0.75
Tank-to-wake emissions of SAF set to zero (<i>kept constant</i>)	11.0	11.0	11.0	11.0	12.0	12.0	12.0	12.0
Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF (<i>varied parameter</i>)	9.2	10.0	10.7	11.5	10.2	10.8	11.5	12.1
Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF-type (<i>varied along with above parameter</i>)	10.9	11.6	12.4	13.1	11.7	12.4	13.0	13.6
Tank-to-wake emissions of SAF reduced by lifecycle emission reduction factor of SAF-batch uplifted (<i>kept constant</i>)	9.5	9.5	9.5	9.5	9.0	9.0	9.0	9.0

Also, as mentioned in Appendix B.1.1, there is a possibility that in the future the 50% SAF blend limit will be increased. When this happens, the sensitivity value of 0.5 will need to be updated. Looking at a hypothetical scenario where the blend ratio goes to 100%, so sensitivity equals 1.0, the combined accuracy/sensitivity score will increase for each parameter option. However, this will not affect the current ranking order.

All in all, in this sensitivity analysis, possible variations of scores are discussed along with their effect on the ranking. However, we cannot with certainty quantify this score difference, resulting in an identical range of scores for the 'Tank-to-wake emissions of SAF set to zero' and 'Tank-to-wake emissions of SAF reduced by generic lifecycle emission reduction factor of SAF' options. Alternative argumentation for method choice can be found in Section 5.2.2.

Aircraft unit fuel consumption

Applying the high and low RMSRE values, the order of the two highest-ranked options changes slightly, as shown in Table 69. For the high scenario, the #2 option becomes 'Unit fuel consumption per aircraft type (modelled)', with the

#1 option remaining the same. For the low option, there are some more changes, where for hindcast, the best option becomes 'Unit fuel consumption per aircraft type, engine type and airframe age (modelled)' with 'Unit fuel consumption per aircraft type and engine type (modelled)' becoming # 2. For forecast, the result is the same as the original, only with a score that is almost identical, making the difference between #1 and #2 almost nothing. This analysis shows that, while the results do change, they do not change substantially, and the top 2 remains generally the same.

Table 69: Scoring metric sensitivity results for 'Aircraft unit fuel consumption': **Highest ranked** and **Second highest ranked**

Parameter	Hindcast application			Forecast application		
	Original	High	Low	Original	High	Low
(Average) unit fuel consumption per aircraft size class (modelled)	8.1	8.1	8.1	9.1	9.1	9.1
Unit fuel consumption per aircraft type (modelled)	10.1	11.6	10.1	10.8	12.1	10.8
Unit fuel consumption per aircraft type and airframe age (modelled)	6.7	8.2	6.7	7.4	8.7	7.4
Unit fuel consumption per aircraft type and engine type (modelled)	12.2	12.2	10.7	12.4	12.4	11.2
Unit fuel consumption per aircraft type, engine type and airframe age (modelled)	11.2	11.2	11.2	11.2	11.2	11.2
Unit fuel consumption per aircraft type and engine type (real-life data)	10.0	10.0	10.0	9.0	9.0	9.0

Appendix E.1.2 Trajectory

Distance

As can be seen in the table, changing RMSRE scoring had almost no effect on the final ranking. However, it should be noted that using the low RMSRE option, which is equivalent to a stricter scoring, the differences between the #1 and #2 parameter options become significantly smaller. This is shown in Table 70.

Table 70: Scoring metric sensitivity results for 'Distance': **Highest ranked** and **Second highest ranked**

Parameter	Hindcast application			Forecast application		
	Original	High	Low	Original	High	Low
Great Circle Distance (GCD)	12.3	12.3	11.0	13.0	13.0	12.0
GCD with generic detour distance/ detour factor	10.6	11.8	10.6	11.4	12.4	11.4
GCD with airline-dependent detour distance / detour factor	6.7	8.0	6.7	7.5	8.6	7.5
GCD with region-dependent detour distance/ detour factor	10.5	11.7	10.5	11.3	12.3	11.3
GCD with airline-region-dependent detour distance / detour factor	8.0	8.0	6.7	8.6	8.6	7.5
GCD with distance-dependent detour distance/ detour factor	12.0	12.0	10.7	12.6	12.6	11.5
GCD with airline-distance-dependent detour distance / detour factor	8.0	8.0	6.7	8.5	8.5	7.5
GCD with route-dependent detour distance/ detour factor	8.2	9.5	8.2	8.8	9.8	8.8
GCD with airline-route-dependent detour distance / detour factor	8.0	9.2	8.0	8.5	9.5	8.5
Planned route	3.7	3.7	3.7	3.6	3.6	3.6
Flown route	10.9	10.9	10.9	10.0	10.0	10.0

APU

Due to the low sensitivity value of 0.01, any change in accuracy score has little effect on the final score and no effect on the final ranking.

Taxi

For taxi, the accuracy of the options 'Not modelled', 'Average airport taxi time', and 'Average airport runway taxi time' could not be assessed as there was not enough data to accurately compare them to each other, or the actual taxi time. This does not matter, as the entire score range from 0-1 for each of these parameters does not change the final

ranking. For the ‘Default taxi time’ option, the RMSRE value is 16 and 25% for taxi-out and -in, respectively, meaning that assessing the high and low RMSRE scenarios would have no effect on the final score and ranking.

LTO

The only score affected by the RMSRE changes would be the ‘Generic’ option with an RMSRE of at least 9.6%. The low RMSRE scenario would change this score from 0.25 to 0. However, due to the low sensitivity value of 0.063, this change has little effect on the final score and no effect on the final ranking.

Non-LTO climb / descent

For non-LTO climb and descent, varying the RMSRE does not have any effect on the final score. However, the ‘Idealised’ calculation option was given “at least +0.25 pt w.r.t. ‘Not modelled explicitly’”. This still gives it a range of 0.25-1. Applying this range, as shown Table 71, does have a small effect on #2 ranking for hindcast application. It can be seen that it switches from ‘Actual’ to ‘Idealised’ for the range 0.75-1. While this is a change, the scores are very close together, and are even identical when rounding to the nearest integer.

Table 71: Scoring metric sensitivity results for ‘Non-LTO climb / descent’: **Highest ranked** and **Second highest ranked**

Parameter	Hindcast application				Forecast application			
	Original (Idealised =0.25)	Idealised =0.5	Idealised =0.75	Idealised =1	Original (Idealised =0.25)	Idealised =0.5	Idealised =0.75	Idealised= 1
Not modelled explicitly / specifically (kept constant)	10.3	10.3	10.3	10.3	11.3	11.3	11.3	11.3
Idealised (i.e., aircraft type-specific) (varied parameter)	7.9	8.3	8.8	9.2	8.8	9.2	9.5	9.9
Actual (kept constant)	8.7	8.7	8.7	8.7	8.4	8.4	8.4	8.4

Cruise

Applying the high and low RMSRE scenarios as shown in

Table , shows the effect of the varying scores. For forecast, the #1 option remains the same for all scenarios, with only the #2 option changing in the low scenario, but with almost no difference in score.

For hindcast, the variations are a bit larger. The high RMSRE scenario allows for ‘Idealised including step climbs’ to become the #1 choice and ‘Idealised’ the #2. This higher sensitivity is due to the fact that cruise has a relatively high accuracy sensitivity value of 0.59, and due to the RMSRE of the ‘Idealised’ and ‘Idealised including step climbs’ parameters. They are 3.7 % and 2%, respectively, meaning that they are on the edge of the defined RMSRE scoring metrics.

Table 72: Scoring metric sensitivity results for ‘Cruise’: **Highest ranked** and **Second highest ranked**

Parameter	Hindcast application			Forecast application		
	Original	High	Low	Original	High	Low
Idealised	8.9	9.8	8.9	9.6	10.3	9.6
Idealised including step climbs	9.0	9.9	8.1	9.5	10.3	8.8
Planned	2.6	2.6	2.6	2.6	2.6	2.6
Actually flown	9.4	9.4	9.4	8.8	8.8	8.8

Appendix E.1.3 Payload

Regarding the payload parameter, varying the RMSRE values does not have any effect on the final scoring. Also, varying the ranges of the 'Not assessed' parameters between 0-1 does not affect the final ranking. Lastly, the parameter 'Typical aircraft type capacity and average region load factors' was given a score of at least 0.25 higher than 'Typical aircraft class capacity and average load factors'. Varying this from 0.25-1 also does not affect the final ranking.

Appendix E.1.4 Miscellaneous

Alternative taxi operations

Due to the low sensitivity value of 0.036, any change in accuracy score has little effect on the final score and no effect on the final ranking.

Wind

For this category, an evaluation using the RMSRE could not be used, leading to a range of possible accuracy scores which are evaluated here. For wind, the main sensitivity lies in the score difference between 'Not modelled' and 'Averaged per region'. It is assumed that all parameters taking into account wind conditions in some form are at least 0.25 pt more accurate than the 'Not modelled' parameter. However, by increasing this difference all the way to 1 leads to different outcomes in the final ranking. Note, however, that the top 2 options do remain the same, only the highest ranking option changes. This is shown in Table 73.

Table 73: Scoring metric sensitivity results for 'Wind': **Highest ranked** and **Second highest ranked**

Parameter	Hindcast application				Forecast application			
	Original (diff 0.25)	Score diff = 0.5	Score diff= 0.75	Score diff = 1	Original (diff 0.25)	Score diff = 0.5	Score diff= 0.75	Score diff = 1
Not modelled (<i>kept constant</i>)	10.3	10.3	10.3	10.3	11.3	11.3	11.3	11.3
Averaged per region (<i>varied parameter</i>)	10.1	11.0	11.9	12.8	10.9	11.7	12.4	13.2
Averaged per airport-pair (<i>varied along with above parameter</i>)	7.5	8.3	9.2	10.1	8.3	9.0	9.8	10.5
Averaged based on historic / predicted climatological data (<i>varied along with above parameter</i>)	7.3	8.2	9.1	10.0	8.2	8.9	9.7	10.4
Actual conditions (<i>kept constant</i>)	8.6	8.6	8.6	8.6	8.1	8.1	8.1	8.1

Deviation from fuel-optimal cruise speed

The 'Not modelled' option, which ranks #1, is given a score of 0.75 due to its RMSRE of 0.86-2.86%. In the RMSRE low case, its score would be decreased to 0.5. This change does not alter the final ranking, even taking into account the 0.75-1 range of the 'Generic correction' and 'Regional correction' parameters.

Tankering

All 'Not assessed' parameters, when subjected to their entire range of possible scores between 0-1, have little influence on the final score and none on the final ranking.

Appendix E.2 Availability of data

Compared to the scoring metrics presented in Section 3.4.1, it has been investigated to what extent more emphasis on readily and publicly available data influences the final result. To do so, scores up to 0.75 points have been reduced by 0.25 points, to yield the following scoring metrics:

- 1 point All data is readily publicly available or available from the Ministry or other governmental bodies
- 0.5 points Data is readily available for purchase; or
(Source) data is publicly available or available from the Ministry or other governmental bodies, but requires further processing
- 0.25 points Data is readily available from at least one industry party; or
(Source) data is available for purchase, but requires further processing
- 0 point (Source) data is available from at least one industry party, but requires further processing;
or
Data is not available

This change has a limited effect on the (unrounded) scores for various options, but does not affect rounded scores or the highest-ranked options.

Appendix E.3 Alignment with current methods, standards and regulations

Compared to the scoring metrics presented in Section 3.5.1, it has been investigated to what extent disregarding the sub-scoring for 'optionality' (in which calculation options that are one of multiple options recognised by a method, standard or regulation are awarded 0.5 points rather than 1 point) influences the final result.

This change has a limited effect on the (rounded) scores for various options. This does not affect the highest-ranked option but, in some cases, does change the second highest-ranked option:

- For the parameter 'Aircraft unit fuel consumption', the option 'Unit fuel consumption per aircraft type and airframe age' now scores slightly higher than 'Unit fuel consumption per aircraft type, engine type and airframe age' and thereby ranks second for forecast applications
- For the parameter 'APU', the option 'Generic value' now scores more points than the option 'Not modelled separately / explicitly' and thereby ranks second for hindcast and forecast applications.

Appendix E.4 Incorporation in existing CO₂ emission models

Compared to the scoring metrics presented in Section 3.5.2, it has been investigated whether more emphasis on familiarity (0.75 points for methods that are ‘widely familiar’, rather than 0.5 points) and less emphasis on availability (0.25 points for methods that are available to anyone without any cost, rather than 0.5 points) influences the final result.

In this case, the score of four models scored 0.5 points (EEA EMEP, AEOLUS, EUROCONTROL AEM and NLR BeyondCO₂-tool) increases to 0.75 points. This change was however not found to affect the final (rounded) scores and associated ranking of highest- and second highest-scoring options.



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