European Union Aviation Safety Agency

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RESEARCH PROJECT EASA.2020.FC07

[REPORT FOR DISSEMINATION]

Market-based Measures

D11.3: Final Public Report

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SUMMARY

Problem area

The mission of the European Union Aviation Safety Agency (EASA) is to promote the highest common standards of safety and environmental protection in civil aviation. In performing this role, EASA is committed to the European strategy of 'Better Regulation' in order to improve the development, implementation and evaluation of these regulatory standards. An essential element of this strategy is the Regulatory Impact Assessment, which provides information on the consequences of taking regulatory action, and thus aids the decision-making process.

Impact assessments form an integral part of any decision-making process. The assessed impacts can cover, amongst others, environment, safety, economy, and society. The capability within the EU to assess the economic impacts of regulations is critical in identifying the optimal method to achieve future environmental objectives via various policy measures such as technology stringencies, operational restrictions, and financial measures.

In 2009, EASA took over the intellectual property rights associated with the aviation economic model 'AERO-MS' from the Dutch Government. AERO-MS is a tool that can examine the impacts of different policies intended to reduce international and domestic aviation greenhouse-gas emissions. The model is able to assess the effects of a wide range of policy measures aimed at reducing aviation emissions, including technological, operational and market-based measures.

The objective of the EASA Framework Contract EASA.2020.FC07 is to build on AERO-MS and further enhance the European modelling capability for future policy assessments in the next decade.

Description of work

This document describes the work carried out to update and enhance AERO-MS through the improvements selected by EASA for implementation. These improvements to AERO-MS are: Updating its Base Year to 2019, updating its price elasticities of demand, adding nvPM and PM to its emissions inventory, specifying its detour factors by flight stage, better aligning it with PRIMES-TREMOVE, promoting more of its variables to scenario level, including SAF and related policies in it, and improving its model security.

Results and Application

This document is the consolidated public deliverable ment for dissimination, describing deliverables D1 up to and including D10. The updated AERO-MS has been demonstrated in a Final Event at the end of the EASA Framework Contract EASA.2020.FC07. This event has been combined with a training of the updated AERO-MS to EASA, EC and Member States' staff.

The improvements incorporated into this new version of AERO-MS allow EASA and AERO-MS users to study potential policy measures, now including the use of SAF (e.g. ReFuelEU), reflecting recent 2019 aviation activities and scenario descriptions updated to the latest insights. The analysis results are produced at higher (flight stage) distance resolutions with improved detour factors. Emissions inventories have been extended with particulate matter.

CONTENTS

ABBREVIATIONS

ACRONYM	DESCRIPTION
ADS-B	Automatic Dependent Surveillance – Broadcast
AERO-MS	Aviation Emissions and Evaluation of Reduction Options Modelling System
ATEC	Aircraft Technology Model
ATK	Available Tonnes-kilometre
ATM	Air Traffic Management
ATW	Advanced Tube and Wing
BADA	Base of Aircraft Data
CAEP	Committee on Aviation Environmental Protection
CCR	CORSIA Central Registry
CIS	Commonwealth of Independent States
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
COVID-19	Coronavirus Disease 2019
CSV	Comma Separated Value
CTAG	CORSIA Tools and Analysis Group
D	Deliverable
DIP	Data Input Protocol
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
EASA	European Union Aviation Safety Agency
ECAC	European Civil Aviation Conference
EEA	European Economic Area
EIA	Energy Information Administration
ERF	Emission Reduction Factor
ETS	Emission Trading System
EU	European Union
EUROCONTROL	European Organisation for the Safety of Air Navigation
FESG	Forecast and Economic Analysis Support Group
FLEM	Flights and Emissions Model
FOI	Totalförsvarets forskningsinstitut (Swedish Defence Research Agency)
GNP	Gross National Product
GVA	Gross Value Added
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IDE	Integrated Development Environment
IFR	Instrument Flight Rules
LCC	Low-cost Carrier
LTAG	Long-term Aspirational Goal
LTF	Long-term Traffic Forecast
LTO	Landing and Take-off
MIT	Massachusetts Institute of Technology

MLAT	Multilateration
MTOW	Maximum Take-off Weight
NLR	Stichting Koninklijk Nederlands Lucht- en Ruimtevaartcentrum (Royal NLR – Netherlands Aerospace Centre)
PEM	Performance Engineering Manual
nvPM	Non-volatile Particulate Matter
O-D	Origin-Destination
PM	Particulate Matter
PRIMES	Price-induced Market Equilibrium System
RPK	Revenue Passenger Kilometres
RTK	Revenue Tonnes-kilometre
SAF	Sustainable Aviation Fuels
SAVE	Study on Aviation Economic Modelling
SC	Specific Contract
SQL	Structured Query Language
TAKS	Transport Analysis and Knowledge Systems
TFS	Traffic by Flight Stage
TREMOVE	*Policy assessment model to study effects of different transport and environment policies on emissions of transport sector*
UK	United Kingdom
UN	United Nations
US(A)	United States (of America)
VFR	Visual Flight Rules
WATS	World Air Transport Statistics
WG	Working Group

1. Introduction

1.1 Background

AERO-MS is a bespoke software developed to examine the environmental and economic impacts of a wide range of policies intended to reduce greenhouse-gas emissions from international and domestic aviation. Policies include technological, operational and market-based measures.

The objective of the EASA Framework Contract EASA.2020.FC07 (EASA and NLR (2020)) is to build on AERO-MS and further enhance the European modelling capability for future aviation policy assessments in the next decade.

This includes the capability to assess diverse aviation environmental policy options based on an accurate characterisation of the aviation industry (e.g. aircraft technology, categories of operators with their respective route networks, and capacity constraints) and the capability to interface with other databases and models.

The framework contract has been split into three distinct phases:

Under Specific Contract No 01 of this framework contract, 33 potential improvements to AERO-MS have been identified.

Under Specific Contract No 02 a selection of these potential improvements have been made and recommended to EASA for implementation. This selection process involved:

- Indentification of data requirements, including the data granularity, for the purposes of updating the AERO-MS base year and for the other potential improvements of the model;
- Compilation of a short-list of the main data sources that are available together with the associated costs to access the data;
- Identification of what data may not be available and may need to be estimated/synthesised;
- Estimation of the modelling effort of data that will be required;
- Assessing the interdependencies between proposed improvements and legacy functionalities.

The main objective of the Specific Contract No 03 of this framework contract (EASA and NLR (2022)) is to update and enhance AERO-MS through the improvements selected by EASA for implementation.

1.2 Scope

This document reports on the implementation activities of the improvements selected by EASA to update and enhance AERO-MS under Specific Contact No 03 (SC03) of the Framework Contract EASA.2020.FC07. These activities are:

- Task 1: Updating AERO-MS Base Year to 2019, with in addition extending the AERO-MS time horizon to 2070, updating the AERO-MS regionalisation, and providing a Data Input Protocol;
- Task 2: Implementing baseline scenario in AERO-MS and testing functionality of updated AERO-MS;
- Task 3: Updating AERO-MS price elasticities of demand;
- Task 4: Adding nvPM and PM to AERO-MS emissions inventory;
- Task 5: Improving AERO-MS function for data export;
- Task 6: Specifying AERO-MS detour factors by flight stage;
- Task 7: Explore aligning AERO-MS with PRIMES-TREMOVE;

- Task 8: Promoting more of ARO-MS variables to scenario level;
- Task 9: Including SAF and related policies in AERO-MS;
- Task 10: Improving AERO-MS model security.

This document describes the activities performed in these tasks.

2. Task 1: Updated Base Year from 2006 to 2019

Task 1 of Specific Contract No 03 (SC03) of the EASA Framework Contract EASA.2020.FC07 concerned the update of the AERO-MS Base Year from 2006 to 2019. In addition, it dealt with extending the AERO-MS time horizon to 2070, updating the AERO-MS regionalisation, and creating a Data Input Protocol. Chapter 2 describes the work carried out within the scope of this task:

- Identification and access to the main data sources to update the AERO-MS Base Year (Section 2.1);
- Updating the AERO-MS Base Year:
  - Processing flight data (Section 2.2);
  - Deriving demand and operations input (Section 2.3);
  - Calculating and calibrating RTK (Section 2.4);
  - Processing fleet data (Section 2.6);
  - Compilation of aircraft performance data and calibration with fleet properties (Section 2.7);
  - Deriving operating costs and revenues (Section 2.8).
- Extension of the AERO-MS time horizon (Section 2.9);
- Updating the AERO-MS regionalisation (Section 2.10);
- Preparing Data Input Protocol for AERO-MS users (Section 2.11).

2.1 Data sources and acquisition

Several datasets for updating the AERO-MS Unified Database were identified in SC02. These datasets are required to provide the necessary information for the new Base Year 2019. Table 1 lists these identified datasets that have been used in update of the database.

Table 1 Data sources

Dataset
Flightradar24
EUROCONTROL flights
ICAO-CAEP FESG traffic and fleet forecast
Cirium fleet
ICAO aircraft engine emissions databank (v.28c)
EUROCONTROL BADA4
ICAO TFS dataset
ICAO Air Carrier Fleet & Personnel dataset
ICAO Air Carrier Finances dataset
EASA Certification Noise Levels (issue 39)

Sections 2.2-2.8 describe the work done on the datasets to create the updated AERO-MS Base Year (through updating its Unified Database).

2.2 Processing flight data

Section 2.2 describes the work undertaken to process the aircraft flight data into the formats required for AERO-MS. Two sources of information have been made available for the update of the AERO-MS Unified Database to 2019:

- EUROCONTROL data with a coverage of European flights;
- Flightradar24 data with a coverage of global flights.

This section is broken into the following subsections:

- Processing of Flightradar24 data (Subsection 2.2.1);
- Processing of EUROCONTROL data (Subsection 2.2.2);
- Comparison of the two datasets for EUROCONTROL Member States (Subsection 2.2.3);
- Combining the datasets and comparing against annual totals from ICAO (Subsection 2.2.4); and
- Derivation of annualisation factors (Subsection 2.2.5).

2.2.1 Flightradar24

Flightradar24 has flight tracking information that is largely derived from ADS-B and MLAT receivers, supplemented by radar information in the US and Canada. Flightradar24 data were provided in raw comma separated value (CSV) format for four full months:

- March 2019;
- June 2019;
- September 2019;
- December 2019.

These data cover all flights globally with a separate record for each flight detailing the departure and arrival airport, aircraft tail number and equipment type, and flight number. These data were imported to an SQL Server database for further processing.

The first processing step was to aggregate the data up to airport level and assign a departure and arrival country. This step was undertaken using an airport lookup table that listed all airports and corresponding countries. The airport lookup table was initially taken from the previous Unified Database update undertaken in 2010, and additional rows were added for new airports that have opened in the intervening period. The countries and regions identified for each airport were updated to the most recent list developed for the 2019 update and documented in Section 2.10. At this point the data were also aggregated to country pair for comparison with EUROCONTROL data as reported in Section 2.2.3.

The next step was to join the operations data to the Cirium fleet data to determine how well the two datasets matched. This was done based on the aircraft tail number. Table 2 summarises the total number of flights in the Flightradar24 data in its raw format, after joining to the airport lookup, and the Cirium fleet data. There are a large number of records (about 6.3 million in the four-month sample) that do not match to the airport lookup table. These are due to missing or erroneous arrival or departure airport code (e.g. incorrect number of letters in the code, or a code that does not exist) in the Flightradar24 dataset. These records were excluded from further processing for two reasons:

- There is no other information available with which the records could be processed into the “correct” airport pair;

- The approximate annual total after excluding these flights (about 44 million) is in line with published totals from ICAO[1] for 2019, whilst the total before excluding (about 63 million) is significantly higher, suggesting that the unmatched records are erroneous, or not flights that should be included within AERO-MS. Further comparisons against the ICAO data, including at a region level, are provided in Section 2.2.4 (which presents the combined Flightradar24 and EUROCONTROL dataset after appropriate exclusions have been made).

There are a relatively small number of records in the Flightradar24 data where the departure and arrival airport are the same. These records are either taxi/intra-airport repositioning movements, or result from occasions when the aircraft ADS-B transmitter has not been updated between two flights and therefore mis-labels the destination. As the actual origin and destination of the flight are not available, these records were excluded from further processing.

Table 2 Flightradar24 total flights

	4 months	Approx. Annual (x3)
All records	~ 21 Million	63 Million
Records matching to airport lookup and departure airport not the same as arrival airport (non-erroneous)	> 14 Million	> 44 Million
Records matching Cirium fleet	~ 13 Million	> 38 Million
% of non-erroneous records with matching fleet	87%	87%

The match between the Flightradar24 operations data and the Cirium fleet data is generally good, with approximately 90% of operations matching on the aircraft tail number. This match is required to allow aggregation to the AERO-MS generic aircraft types which are used to define aircraft fuel consumption, emissions and costs. For operations that do not match, a lookup table has been developed to link the aircraft equipment type in Flightradar24 to the equivalent airframe field in the Cirium fleet dataset. The most common generic aircraft type and technology level for each airframe in the Cirium dataset was identified and this allowed the remaining Flightradar 24 operations to be mapped to a generic aircraft type based on the airframe.

2.2.2 EUROCONTROL

EUROCONTROL data originate from filed flight plans across Europe's aviation network. EUROCONTROL data were provided for the same four months as Flightradar24 data – March, June, September and December 2019. The data were also provided in raw CSV format and imported to the same SQL Server database for further processing.

The data cover flights to, from or through EUROCONTROL Member States, and include a separate record for each flight detailing the departure and arrival airport, aircraft type and tail number, operator, market segment, and departure and arrival country. EUROCONTROL registers all IFR flights within, between, to and from the EUROCONTROL Member States (there are 41 Member States and 2 comprehensive agreement states[2]). Also, flights between non-member countries are registered if they make use of EUROCONTROL airspace (overflights). It is proposed to only use the flights within, between, to and from the EUROCONTROL Member States. This is because the overflights in the EUROCONTROL data are an incomplete registration of flights between non-member countries, and are therefore better covered by Flightradar24 data.

[1] www.icao.int/annual-report-2019/Documents/ARC_2019_Air%20Transport%20Statistics.pdf
[2] www.EUROCONTROL.int/our-member-and-comprehensive-agreement-states

As with the Flightradar24 data, the EUROCONTROL data were first aggregated to airport-pair level and joined to the airport lookup table to allocate an AERO-MS departure and arrival country. Records where the departure and arrival airport were the same were excluded. In general, the EUROCONTROL data are a lot more complete than the Flightradar24 data, with only very few records having missing departure and arrival airport. These records are coded with an airport code of "ZZZZ" and represent only a small number of flights. Examination of the aircraft types used on these flights showed that they were helicopter flights and were therefore excluded from further processing. Table 3 summarises the total flights in the EUROCONTROL data at each stage of processing.

The EUROCONTROL data match well to the Cirium fleet more than 95% of records matching on the aircraft registration. As with the Flightradar 24 data, operations that did not match to the Cirium fleet based on the registration were allocated a generic aircraft type and technology level based on the stated airframe in the EUROCONTROL dataset.

Table 3 EUROCONTROL total flights

	4 months	Approx. Annual (x3)
All records	> 3 Million	> 10 Million
Records matching to airport lookup and departure airport not the same as arrival airport	> 3 Million	> 10 Million
Records matching Cirium fleet	> 3 Million	~ 10 Million
% matching fleet	96%	96%

EUROCONTROL data were also aggregated to country pair level for comparison against Flightradar24, as reported in Section 2.2.3. This was done by identifying the country of origin and destination of flights (based on the first two letters of the airport codes), and using a database with the home country of carriers.

2.2.3 Comparison of EUROCONTROL and Flightradar24

A comparison was made for the European coverage common to the EUROCONTROL and Flightradar24 data. These flights were distinghuised by:

- Domestic flights;
- International departures to EUROCONTROL Member States;
- Departures to other (non-member) countries;
- Arrivals from other (non-member) countries;
- Departures to unknown countries;
- Arrivals from unknown countries.

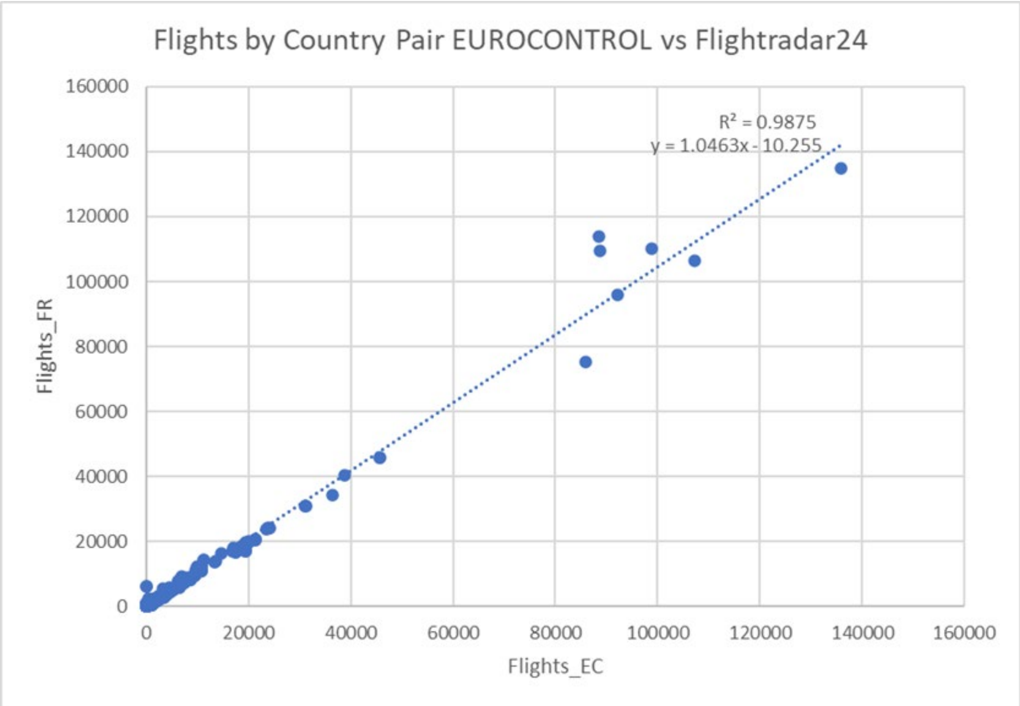
A total of approximately 3.5 Million common flights were identified. This is almost a full match with the total number of EUROCONTROL flight registrations. The remaining few percentage are overflights.

The European flights in the Flightradar24 data have been aggregated in the same way as the EUROCONTROL data for the purposes of the comparison. The main observation is that in general, the comparison is very good. The totals by route group are all less than a few precentage out. For the overall total, Flightradar24 data contain a few percent flights more than the EUROCONTROL data. It is very likely that the number of flights in Flightradar24 is higher because it includes non-commercial and general aviation. Whilst some of these flights will be included in a separate non-commercial flight type within AERO-MS, many will be filtered out. See Section 2.2.4 for further details.

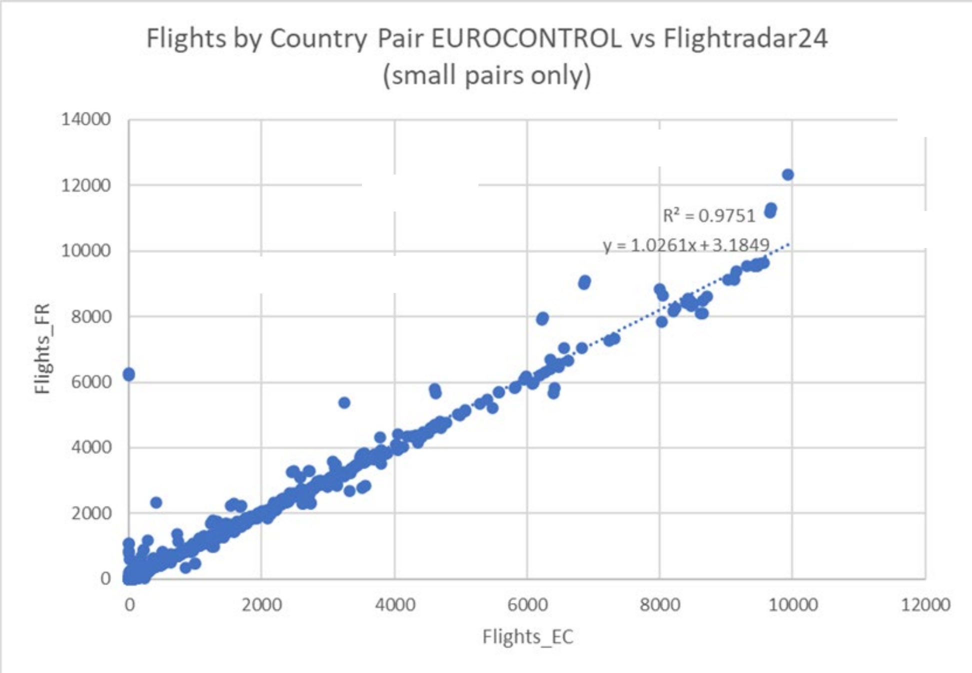
More detailed comparisons show some more significant differences. These have been analysed in more detail by looking at the differences in the number of flights by country pair. The main differences and explanations can be summarised as follows:

- The number of domestic flights for some countries is significantly higher in the EUROCONTROL data. This appears to be associated with non-passenger airports, e.g. oil platforms with helipads in the North Sea. These flights were ultimately filtered out.
- The number of domestic flights is significantly lower in the EUROCONTROL data, especially in some larger European countries. This is likely due to non-commercial and general aviation included in the Flightradar24 data, which were ultimately be filtered out.
- The number of flights between some between a few states countries on the periphery of Europe are significantly lower in the EUROCONTROL data.
- The number of departure flights from some country to EUROCONTROL Member States is significantly lower in the EUROCONTROL data. This is not related to any specific country pair, but to more non-commercial / private flights included in the Flightradar24 data, that were ultimately filtered out.

To provide further assurance that the datasets are consistent, a comparison has been made at country pair level rather than the more aggregate grouping used in Tables A1-A3. As there are approximately 4,500 unique country pairs, these have been plotted as a regression chart with the EUROCONTROL flights plotted against the Flightradar24 flights. The results are shown in Figure 1. Figure 2 shows the same information but removes country pairs with more than 10,000 flights in the EUROCONTROL data, to stop the larger country pairs dominating the regression. Overall it is clear that the regression is good, with the data giving a very strong correlation and most country pairs very close to the line of best fit. The outliers with the largest difference have been identified and these are consistent with the discrepancies identified above.



➨ **Figure 1** EUROCONTROL versus Flightradar24 by country pair – All country pairs



➨ **Figure 2** EUROCONTROL versus Flightradar24 by country pair – Less than 10,000 flights

Considering the comparison between EUROCONTROL and Flightradar24 data, Table 4 compares the key characteristics of the EUROCONTROL and Flightradar24 data.

➨ **Table 4** Comparison of key characteristics of EUROCONTROL and Flightradar24

Data source / Aspect	EUROCONTROL	Flightradar24	Remarks
Geographical coverage	O-D flights of EUROCONTROL Member States (overflights filtered out by the Team)	Worldwide O-D flights. Crowd sourced data sources, some areas have lower coverage because of lack of nearby receivers, sometimes lower quality of data (missing fields)	Comparison / quality assessment for O-D flights of EUROCONTROL Member States done
Flight coverage	Flight plans to be provided to EUROCONTROL are mandatory for commercial flights applicable to AERO-MS	All movements that carry ADS-B receivers and within ADS-B receiver field of view, incl. IFR, VFR, heli traffic and platform vehicles. Relies on ADS-B receivers by individuals and other suppliers	General good agreement for O-D flights of EUROCONTROL Member States. Specific differences can be well explained
Reliability	Established source of information	Good source of information, but data needs filtering by the Team to sort out AERO-MS qualified flights	Many (local) sources of information (receiver locations), coverage (time, geography) not always known and varying

Based on the key characteristics of the data sources, and the comparison analyses, it was decided that EUROCONTROL data would be used for O-D flights of EUROCONTROL Member States, within the AERO-MS Unified Database. This is, first of all, because EUROCONTROL is an established and centralised source of information, and only limited filtering of their data is required. Also, it is believed that taking the EUROCONTROL data on board will increase the acceptance of AERO-MS by the European Commission, especially for studies regarding Market-based Measures for traffic to, from and between EEA Member States. The Flightradar24 data were used for flights that do not have their origin and/or destination in a EUROCONTROL Member State. The Flightradar24 data were also used for missing country pairs in the EUROCONTROL data.

All in all, the conclusion is that the combined use of the available EUROCONTROL and Flightradar24 datasets ensured a good representation of global aviation traffic in 2019, which will provide a solid starting position for all future year calculations of the updated AERO-MS. The next section describes the process of combining the datasets.

2.2.4 Combining Flightradar24 and EUROCONTROL data

To prepare the inputs for AERO-MS, the next step was to combine the two datasets into a single dataset ready for aggregation to AERO-MS dimensions. This section describes the process of combining the datasets and preparing data with the correct characteristics for AERO-MS.

Flight records were selected from each dataset according to the following rules:

- For flights where the origin or destination country is a EUROCONTROL Member State, use EUROCONTROL data;
- For all other flights, use Flightradar24 data.

A separate override table was set up to allow a few specific country pairs that are missing from EUROCONTROL data to be taken from Flightradar24.

Data were aggregated to the following dimensions for the Unified Database:

- Departure airport (and corresponding AERO-MS country and region);
- Arrival airport (and corresponding AERO-MS country and region);
- AERO-MS generic aircraft type and technology level;
- AERO-MS flight type; and
- Operator region.

A world map with all airports and flights taken on-board AERO-MS is shown in Figure 3a and 3b.

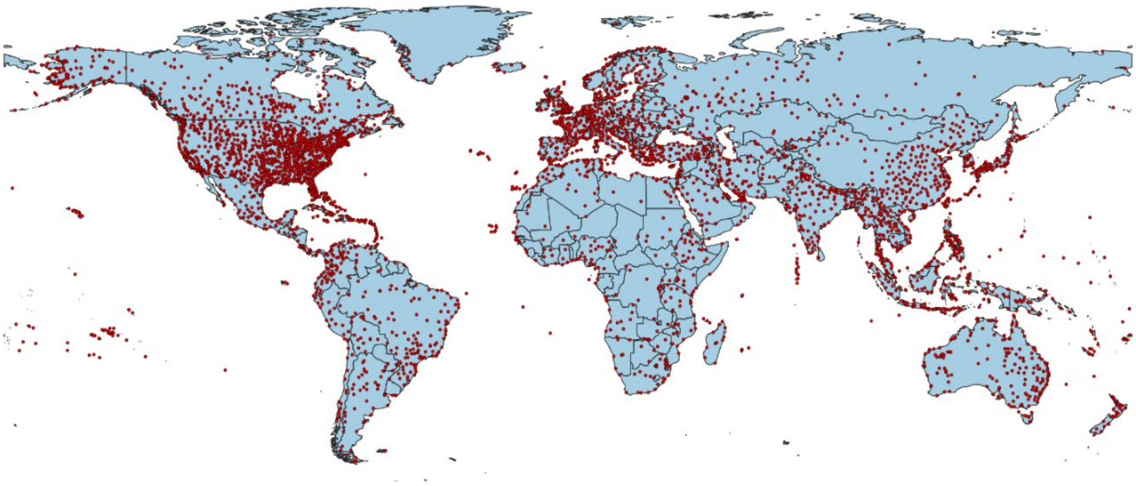


Figure 3 AERO-MS airports world map

Figure 4b AERO-MS flights map

AERO-MS generic aircraft types are based on aircraft size (number of seats), and each aircraft in the Cirium fleet database has been allocated a generic aircraft type and technology level as part of the fleet processing work reported in Section 2.6.

The AERO-MS flight types are:

- Scheduled pax – network carriers;
- Low-cost carriers and chartered – pax;
- Scheduled freight;
- Chartered – freight; and
- Non-commercial.

Flights have been allocated to the AERO-MS flight types using a combination of two fields in the Cirium fleet data – the "primary usage" and the "operator company type". Some (non-commercial) operator types have been excluded from the data. These were determined based on whether they would be exempt from CORSIA emissions regulations. Operations for small aircraft with maximum take-off weight less than 5.7 tonnes were also excluded from the operations dataset.

For records that do not match to the Cirium fleet based on aircraft registration, further consideration is required to identify whether the flight should be included in AERO-MS, and if it should be, then how to allocate a generic aircraft identifier and a flight type.

To identify whether flights should be included, the fleet data were summarised by airframe type to identify airframes which have an average maximum take-off weight of less than 5.7 tonnes. This included the majority of the non-matching operations as these were generally on small aircraft. The remaining flights were included. The remaining flights were allocated to generic aircraft type and technology level based on the stated airframe in the operations data (either from Flightradar 24 or EUROCONTROL). The most common generic aircraft type and technology level for each airframe were identified from the Cirium fleet data and this was used for the relatively small proportion of operations that did not match based on registration.

The resulting total flights and their source are shown in Table 5. It is important to note that these totals are before any calibration has been applied.

Table 5 Provisional summary of total flights

Source	4 months	Approx. Annual (x3)
Matching EUROCONTROL (to/from EUROCONTROL States)	> 3. million	> 9.5 million
Matching Flightradar24 (rest of world)	> 9.5 million	> 29 million
EUROCONTROL non-matching	~ 0.1 million	< 0.4 million
Flightradar24 non-matching	< 0.2 million	> 0.5 million
Total	**> 13 million**	**> 39.5 million**

The region of the operator was also retained in the dataset to allow the data to be aggregated to the operator region level for comparison against published ICAO Air Transport Statistics data[3] by region. The carrier region was taken from the Cirium fleet data which was not always populated. For aircraft with no region populated, the country and region were identified from the 2-letter IATA or 3-letter ICAO operator code if these fields were populated, or from the operator name. This method left about half a million flights with no operator region, out of those matching to the Cirium fleet. For these remaining flights, and also for the flights that did not match to the Cirium fleet and therefore the carrier could be identified, the operator region was set equal to the departure region of the flight. These flights combined (half a million that match to the Cirium fleet but have no operator region, plus quarter million that do not match to the Cirium fleet) represent a few percent of the total operations. However, more than half of these are in the smallest aircraft type where the Cirium dataset did not include any operator data. These flights on small aircraft are likely to be domestic and therefore the assumption that the carrier region is equal to the departure region is reasonable.

The aggregation of the operations data to carrier region for comparison against other datasets for validation is presented in Section 2.4.

2.2.5 Annualisation factors

The EUROCONTROL operations data were also used to derive annualisation factors, to allow the 4-month sample from EUROCONTROL and Flightradar24 to be annualised to represent the full year 2019. This section describes the derivation of the annualisation factors.

The Flightradar24 and EUROCONTROL data were both obtained for the same 4 months, so using annualisation factors derived from EUROCONTROL for all operations is appropriate. The factors were derived by dividing totals in the 4-month sample by the more aggregate annual 2019 EUROCONTROL operations. Separate factors were derived by flight type and for flights within the EUROCONTROL area and those to/from it. The factors are presented in Table 6.

Table 6 Annualisation factors

Flight Type	Internal (within ECTL area)	External (to/from ECTL area)
0 Scheduled pax - network carriers	2.99	2.97
1 Scheduled freight	3.04	2.96
2 LCC and charter - pax	2.98	2.99
3 Charter - freight	3.04	2.96
4 Non-commercial	3.00	3.00

[3] www.icao.int/annual-report-2019/Documents/ARC_2019_Air%20Transport%20Statistics.pdf

The factors are all close to 3 as expected. The internal factors are used for operations where the departure and arrival region are in Europe, or North America (since a similar distribution of flights is expected throughout the year in North America to Europe). The external factors are used for operations where the departure or arrival region is in Europe but the other end is not in Europe. For all other movements where neither departure or arrival is in Europe, a factor of 3 was used. For non-commercial operations a factor of 3 was used as there are insufficient data in the EUROCONTROL data for non-commercial operations.

These factors were applied to the operations and demand data before comparison against annual totals for validation.

2.3 Processing Demand Data

2.3.1 Passenger Demand

To calculate passenger demand from the operations data, two additional inputs are required:

- Passenger load factors – these describe what proportion of the available seats are filled and are specified by country pair and flight type, predominantly from ICAO Traffic by Flight Stage (TFS) data; and
- Aircraft capacities (number of available seats) – these are specified by generic aircraft type and derived from the Cirium fleet data.

ICAO TFS data include the number of passenger seats, passenger demand and freight demand for international operations. The coverage is global and the data are provided at city pair level and include the flight operator.

These data were aggregated to country pair level to calculate passenger load factors by dividing the revenue passenger kilometres by the available seat kilometres. Records with no reported passenger demand were excluded from the calculation. The operator was used to determine the AERO-MS flight type based on those allocated in the Cirium fleet dataset for each operator.

The distribution of passenger load factors at country pair and flight type level from TFS is shown in Figure 5. This shows a sensible distribution with a peak around 80%, as would be expected. Load factors of less than 50% at the country pair level were considered to be erroneous and were removed from the dataset. However, as can be seen from the distribution, there were very few passenger load factors below 50% when the data was aggregated to country pair level.

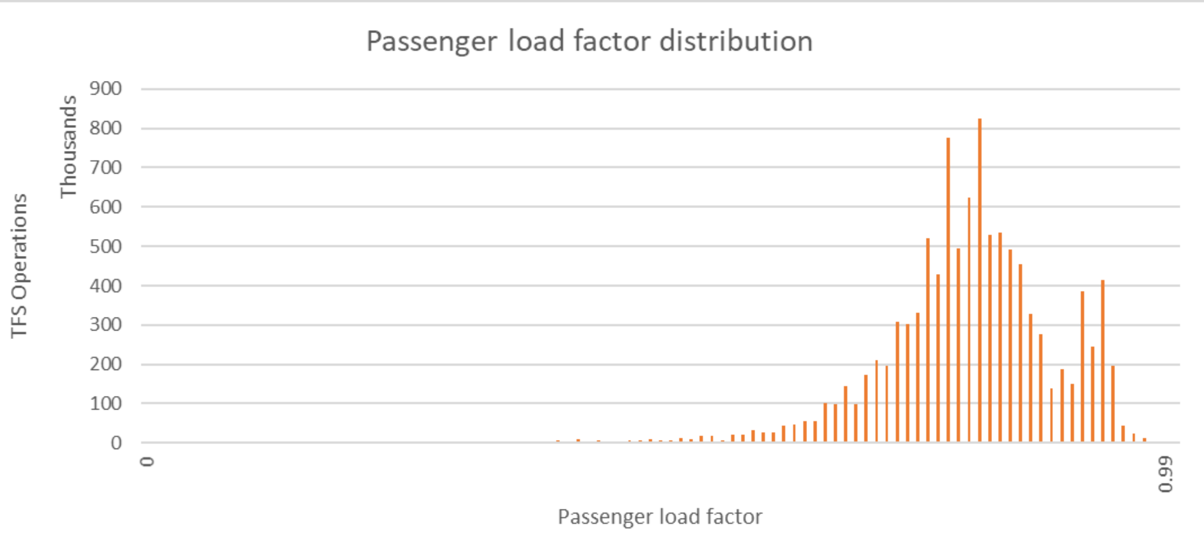


Figure 5 Passenger load factor distribution from TFS by country pair

The average load factors by flight type are shown in Table 7. As would be expected, the average load factor for low cost carriers is slightly higher than for scheduled airlines and non-commercial operations. The values compare well with the average global passenger load factor reported in the ICAO Air Transport Statistics data for 2019 of slightly over 80%.

Table 7 Average passenger load factors by flight type

Flight Type	Average load factor
Scheduled pax	0.78
LCC and charter	0.86
Non-commercial	0.76

To allow for cases where country pairs existed within the operations data but not the TFS load factor data, and for cases where the TFS load factor was not considered plausible, average load factors were calculated at the region pair level by aggregating the country pair level data and calculating an average load factor weighted by the operations on each country pair. These were also separated by AERO-MS flight type.

The TFS data only include international flights, meaning that no specific load factors are available for domestic flights. For most cases, the average load factors at the region pair level, i.e. the average load factor for flights within the region, will be appropriate to apply to the domestic market. However, there are two cases where a bespoke load factor was obtained from an alternative source:

- For domestic US and Canada, load factors were calculated from US Department of Transport T-100 data – these were around 80% for both scheduled and LCC/charter traffic.
- For domestic China (including Hong Kong, Macao and Taiwan), a similar factor was obtained from CEIC data[4]

Aircraft capacities were calculated by generic aircraft type based on the Cirium fleet dataset and weighted by the number of operations in the combined operations table described in Section 2.2.4. These are presented in **Table 8**.

Passenger demand was then calculated by applying the load factors and average capacities to the operations by airport pair, generic aircraft type and AERO-MS flight type. Passenger kilometres were also calculated by multiplying the great circle distance by the passenger demand.

Passenger demand was split into Economy and Business/First class by calculating splitting factors by generic aircraft type and flight type. The splitting factors were derived by linking the Cirium fleet data to the Flightradar24 operations, and calculating an operations weighted average number of economy class seats as a proportion of the total seats. For AERO-MS flight type 2 (low cost carriers and charter), all of the demand was assumed to be Economy class. The proportion of Economy class for scheduled network carriers is included in **Table 8**.

[4] https://www.ceicdata.com/en/china/air-passenger-load-factor

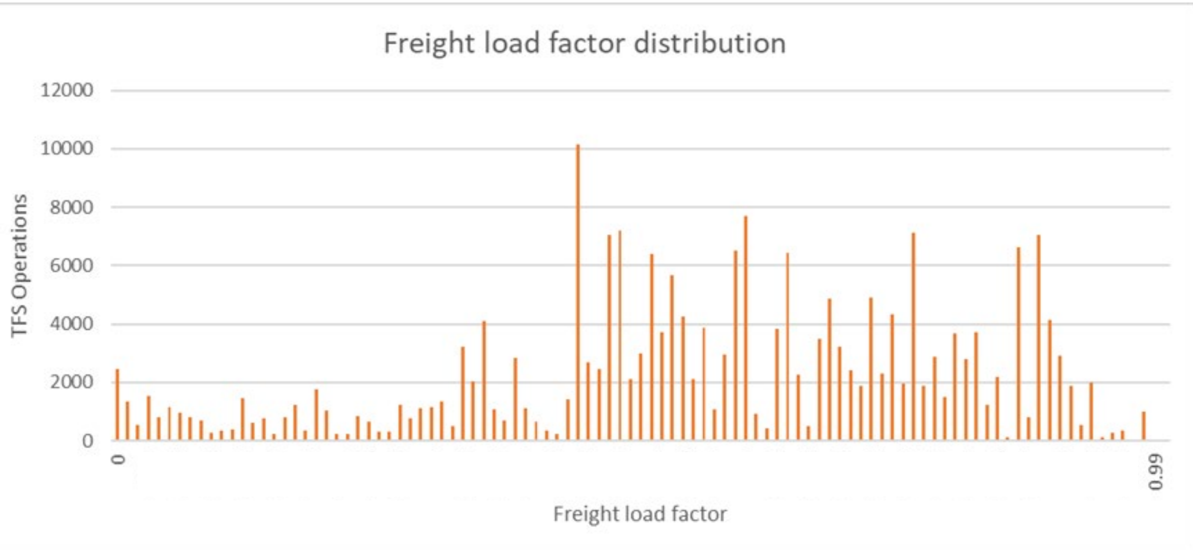
➡ **Table 8** Average seat capacity and proportion Economy class by generic aircraft type

Generic aircraft ID	Description	Average number of seats	% Scheduled network demand in Economy class
0	Short haul less than 20 seats	< 20	~ 100%
1	Short haul 20 to 50 seats	~ 50	~ 100%
2	Short haul 51 to 70 seats	~ 70	~ 95%
3	Short haul 71 to 100 seats	~ 80	~ 95%
4	Medium haul 101 to 150 seats	~ 135	~ 95%
5	Medium haul 151 to 175 seats	~ 165	~95%
6	Medium haul 176 to 235 seats	~ 190	~ 95%
7	Long haul 236 to 300 seats	~ 270	~ 85%
8	Long haul 301 to 500 seats	~ 350	~ 85%
9	Long haul more than 500 seats	~ 520	~ 85%

2.3.2 Freight Demand

Load factors for dedicated freighter operations were calculated from ICAO TFS data in a similar manner to the passenger load factors. The factors were calculated by country pair by dividing the reported revenue tonne kilometres (RTK) by the available tonne kilometres (ATK). Only operations with zero passengers reported were included in this calculation. The distribution of load factors by country pair are shown in Figure 6. These factors show a much broader distribution than the passenger load factors which is to be expected. However, load factors of less than 50% when the data are aggregated to country pair level were not considered to be plausible and these were therefore deleted from the dataset before being applied to the operations data. The operations weighted average freighter load factor once the erroneous records had been removed was roughly 70%.

A dedicated domestic US and Canada freight load factor was calculated from US DoT T-100 data as 68%.



➡ **Figure 6** Freighter load factor distribution from TFS by country pair

Load factors for belly-hold freight were also calculated from TFS data using records for passenger aircraft. This calculation was done by calculating the available belly-hold tonne kilometres (by deducting the ATK used by seats from the total ATK) and dividing the freight and mail tonne kilometres carried by passenger aircraft by this available belly ATK. The formula used was:

$$LF_{belly} = \frac{FTK + MTK}{ATK - ASK * 100kg}$$

Where FTK = freight tonne kilometres, MTK = mail tonne kilometres, ATK = available tonne kilometres, and ASK = available seat kilometres.

Due to the smaller number of operations for which this calculation is appropriate, the TFS data were aggregated to region pair level instead of country pair level to generate the belly hold-load factors. Factors were only calculated for scheduled network operations and not low-cost carrier / charter operations which are assumed to have no belly hold freight in AERO-MS. The average belly hold load factor from TFS data was less than 20%, however this includes all passenger scheduled operations including those that carry no belly-hold freight. This is appropriate because it is applied to all scheduled passenger aircraft in the AERO-MS operations database. However, during calibration of the freight demand it was found that the belly-hold load factors were too low, leading to a total freight RTK which was not as high as either the ICAO or Boeing data. These were adjusted as a calibration step to increase the total RTK.

The freighter and belly-hold load factors were applied to average capacities derived by generic aircraft type to get freight demand in units of tonnes. The Cirium fleet database did not include data on the available payload for each aircraft, so these data had to be inferred from other sources and are not readily available. Freighter capacities were derived from TFS and Transport Measures data[5]. Payload data by airframe were averaged across the datasets and allocated to representative generic aircraft types. Averages were then derived across all airframes for which data was available within each generic aircraft type. No capacity data were available for the largest generic aircraft type, so for this category, the previous AERO-MS capacity was used. A similar process, using only TFS data, was used for developing the belly hold capacities. The capacities are presented in Table 9.

Once the quantity of freight demand in tonnes had been established, freight tonne kilometres were also calculated by multiplying the great circle distance by the freight demand.

Table 9 Average freighter and belly-hold capacity by generic aircraft type (approximate values)

Generic aircraft ID	Description	Average freighter capacity (tonnes)	Average belly-hold capacity (tonnes)
0	Short haul less than 20 seats	2	0.4
1	Short haul 20 to 50 seats	4	0.5
2	Short haul 51 to 70 seats	8	0.7
3	Short haul 71 to 100 seats	9	1.7
4	Medium haul 101 to 150 seats	17	2.3
5	Medium haul 151 to 175 seats	22	3.4
6	Medium haul 176 to 235 seats	30	5.3
7	Long haul 236 to 300 seats	56	16.5
8	Long haul 301 to 500 seats	83	20.8
9	Long haul more than 500 seats	138	51.0

[5] https://www.transportmeasures.org/en/wiki/manuals/air/aircraft-types/freight-aircraft-types/

2.4 Operations and Demand Validation

2.4.1 Validation Data Sources

This section summarises the base year 2019 operations and demand, compares against other published data sources and describes the steps taken to adjust the AERO-MS data to better match the published data. The AERO-MS totals are compared primarily against to two different data sources:

- Operations, passenger demand, passenger kilometres and freight tonne kilometres from the ICAO Air Transport Statistics 2019[6]; and
- Passenger kilometres and freight tonne kilometres from the Boeing Commercial Market Outlook[7] and Boeing World Air Cargo Forecast[8].

2.4.2 Operations Validation

Table 10 presents a comparison of the commercial operations against the reported 2019 totals in the ICAO Air Transport Statistics data by ICAO carrier region. Overall the comparison is very good. During initial comparisons it was found that flights by African carriers were significantly lower in the AERO-MS data than the ICAO data. This is likely to do with poor coverage of these flights within the Flightradar24 data. The operations by African carriers were therefore uplifted which brings the total international flights close to the ICAO data. Whilst the domestic flights by African carriers appear low, it was decided that these should not be increased further due to the impact on passenger demand which can be seen in the next section.

It is important to note that:

- The allocation of carriers to regions could be different between the AERO-MS data and the ICAO data;
- The ICAO data are reported with a (small) error bound, and have limitations of its own regarding completeness and reliability;
- The definition of commercial flights is likely to be slightly different between the AERO-MS data and ICAO data; and
- The allocation of flights to carrier regions is not of primary importance to AERO-MS, it is used here only because the ICAO data are reported at that level.

Given these points, the annual comparison of operations was considered suitable to proceed to calculating passenger demand and passenger kilometres and comparing against published data.

Table 10 Comparison to 2019 annual commercial flights by ICAO operator region (percent difference to ICAO values, annual)

ICAO region	*Total*	*International*
Europe	*6%*	5%
Africa	*-23%*	2%
Middle east	*5%*	2%
Asia/Pacific	*-6%*	-6%

[6] www.icao.int/annual-report-2019/Documents/ARC_2019_Air%20Transport%20Statistics.pdf
[7] https://www.boeing.com/commercial/market/commercial-market-outlook/index.page
[8] https://www.boeing.com/resources/boeingdotcom/market/assets/downloads/Boeing_World_Air_Cargo_Forecast_2022.pdf

ICAO region	*Total*	*International*
North America	*1%*	9%
Latin America/ Caribbean	*-17%*	-1%
Total	***-2%***	**2%**

2.4.3 Passenger Demand Validation

Table 11 presents a comparison of the annual passenger demand against the reported 2019 totals in the ICAO Air Transport Statistics data by ICAO carrier region. As with total flights, the comparison is generally very good with the total demand within a few percent of all flights) as well as international flights. The international demand on African carriers is much higher than the ICAO data, despite the operations being within a few percent. The implied load factor within the ICAO data is very low for this region, and as the total demand affected is relatively small, the demand has been deemed to be appropriate to carry forward despite the difference against the ICAO data. Furthermore, the comparison of passenger kilometres against the Boeing data gives a closer match (see Section 2.4.4). Table 11 also shows North America international demand is a little high compared to the ICAO data. However, similar to the Africa difference, when comparing passenger kilometres to the Boeing data, the AERO-MS total is lower than the observed figure, highlighting the discrepancies that exist between different observed datasets.

➨ **Table 11** Comparison of 2019 annual commercial passenger demand by ICAO operator region (percent difference to ICAO values, annual)

ICAO region	**Total**	**International**
Europe	8%	4%
Africa	3%	29%
Middle east	1%	2%
Asia/Pacific	0%	-5%
North America	4%	9%
Latin America/ Caribbean	-9%	4%
Total	**3%**	**2%**

2.4.4 Passenger Kilometre Validation

Table 12 presents a comparison of the annual passenger kilometres against the reported 2019 totals in the ICAO Air Transport Statistics data by ICAO carrier region. The comparison shows a similar pattern to the passenger demand comparison, with only African carriers appearing slightly high compared to the ICAO data. Overall the total passenger kilometres are within 1% for all flights, and 2% for international flights.

➨ **Table 12** Comparison of 2019 annual commercial passenger kilometres by ICAO operator region (percent difference to ICAO values, annual)

ICAO region	**Total**	**International**
Europe	4%	3%
Africa	24%	31%
Middle east	-6%	-3%
Asia/Pacific	-6%	-1%

ICAO region	Total	International
North America	2%	6%
Latin America/ Caribbean	-5%	7%
Total	**-1%**	**2%**

Table 13 compares the AERO-MS passenger kilometres against the equivalent data published for 2019 from the Boeing Commercial Market Outlook report. These data are aggregated by departure and arrival region rather than carrier region to match the aggregation presented in the Boeing data. The regional totals are the total to and from each region, therefore the global total row is not the sum of all the regional totals because each region pair is counted twice. The last two columns show the distributions between the regions. This comparison shows a very good match between the AERO-MS and Boeing data, with all differences within 5%. Demand to and from North America and Europe are slightly lower than the Boeing figures, despite being slightly high for these regions compared to the ICAO data. Demand to and from Africa is also very close, despite being high for African carriers compared to the ICAO dataset.

➨ **Table 13** Comparison of 2019 annual commercial passenger kilometres by departure/arrival region to Boeing

To/from Region	AERO -MS distribution	Boeing distribution	% Difference
North America	22%	22%	-4%
Central America	3%	3%	0%
South America	4%	4%	2%
Europe	23%	23%	-4%
Africa	3%	3%	-2%
Middle East	**8%**	**8%**	**-3%**
South Asia	3%	3%	5%
China	12%	12%	-5%
Northeast Asia	6%	6%	3%
Southeast Asia	8%	8%	-4%
Oceania	3%	3%	3%
Rest of World	5%	5%	5%
Total			-3%

2.4.5 Freight Demand Validation

For freight demand, comparisons have been made against ICAO and Boeing data in terms of revenue tonne kilometres (RTK). The freighter and belly hold freight demand have been aggregated. In general, available data are less reliable for freight demand and it is expected that the comparisons will not be as good as for passenger demand. The global total in the ICAO data is significantly lower at 232bn compared to 265bn in the Boeing data. The AERO-MS figure lies between the ICAO and Boeing values at 243bn. Similarly, the total RTK for North American carriers is 46m in the ICAO data and 64m in the Boeing data. Due to these discrepancies, it was decided that the regional AERO-MS totals would be compared to the validation data in terms of the proportion each region contributes to the total, rather than comparing absolute numbers.

Table 14 and Table 15 show the comparison of the global AERO-MS Freight Tonne Kilometres and the proportion in each region against ICAO and Boeing published data. The tables show that the distribution of demand between carriers is generally consistent with both datasets. Where there are differences against one dataset, the AERO-MS data are closer to the other dataset. For example, against the ICAO dataset the Asia/Pacific share for AERO-MS is slightly low, whereas against the Boeing data, AERO-MS is in line with a third of the total. The North America share is higher than the ICAO data, but is much closer to the Boeing data. The absolute value of 64bn for North American carriers is within 1% of the published Boeing figure, even though it is slightly larger as a proportion of the total. As noted above, there is less confidence in the published freight demand datasets, and the AERO-MS data generally fall within the bounds of the available data, especially considering the margins of error in those data.

It is also important to note the following points, which were also relevant to the operations and passenger demand validation exercises:

- The allocation of carriers to regions could be different between the AERO-MS data and the ICAO/Boeing data;
- The ICAO data are reported with an error bound of +/-2%, and have limitations of their own regarding completeness and reliability;
- The definition of commercial flights is likely to be slightly different between the AERO-MS data and ICAO/Boeing data; and
- The allocation of flights to carrier regions is not of primary importance to AERO-MS, it is used here only because the ICAO/Boeing data are reported at that level.

Table 14 Comparison of 2019 annual freight tonne kilometres by ICAO operator region (millions, annual)

ICAO region	AERO-MS share	ICAO share
Europe	23%	24%
Africa	3%	2%
Middle East	11%	14%
Asia/Pacific	35%	38%
North America	26%	20%
Latin America/Caribbean	3%	3%

Table 15 Comparison of 2019 annual freight tonne kilometres against Boeing data (millions, annual)

	AERO-MS distribution	Boeing distribution
Africa	3%	2%
Asia Pacific	33%	33%
Europe	20%	20%
Latin America	3%	3%
Middle East	11%	13%
North America	26%	24%
Russia and Central Asia	3%	4%
South Asia	1%	1%

Table 16 presents a comparison of key global metrics and compares against the ICAO 2019 data where available. This comparison shows that the total ATK, RTK and load factors are all consistent with the ICAO data.

Table 16 Comparison of 2019 global metrics against ICAO

	% Diff	Comment/Table reference
Operations		
All Flights (m)		
Commercial operations (m)	-2%	Table 10
Passengers		
Demand (m)	3%	Table 11
Passenger km (Bn)	-1%	Table 12
RTK		
RTK Freighter (bn)		
RTK Belly-hold (bn)		
Total Freight RTK (bn)	5%	Table 14 (note Boeing reports 265 bn RTK)
Pax Tonne KM (bn)	-1%	Estimated based on passenger km and average weight per seat
Total RTK (bn)	**0%**	
ATK		
ATK Freighter (bn)		
ATK belly (bn)		
Total Freight ATK (bn)		
ATK pax (bn)		
Total ATK	**-2%**	
Avg Load Factors		
Freighter		
Belly-hold		
Total freight		IATA Air Market Analysis report states 47%
Passenger	-1%	
Overall load factor	**2%**	

2.5 Derivation of ADEM Input Files

2.5.1 Operations Files

Following the validation of the operations and demand datasets, the next step was to use this detailed dataset to produce the files required for the ADEM model within AERO-MS.

The inclusion of non-commercial operations on any aircraft with a take-off weight greater than 5.7 tonnes meant that the updated dataset included significantly more airport pairs than the previous version of AERO-MS, as there are lots of small airports used by these flights. To minimise file size and processing time, it was agreed that for the non-commercial operations, departure and arrival airports were recoded to a single airport pair for each country pair and distance band. The distance bands used were up to 500km, 500-1,000km, 1,000-2,500km and 2,500km+. The airport pair with the most operations within each country pair and distance band was used as the representative pair for all others within the same county pair and distance band. AERO-MS flight stages and airport lists were then defined using the aggregated departure and arrival airports.

Traffic indices were generated as combinations of flight stage and flight type and the operations were aggregated to this traffic index, technology level and generic aircraft type to populate the main operations input file for ADEM, *AT_Movements.*

Airports were classified as major where the total number of operations departing per year was at least 15,000. This resulted in 442 major airports.

2.5.2 Demand Files

The input passenger demand file for AERO-MS includes the passenger ticket class – First/Business, Economy and Discount.

The proportion of economy seats was calculated from the Cirium fleet dataset for each generic aircraft type and AERO-MS flight type, using the stated number of economy seats as a proportion of the total seats. This was weighted by the number of operations on each aircraft obtained from the Flightradar24 data. The proportion of Economy class was then applied to the total passenger demand to split demand between First/Business and Economy. The Discount ticket class is used only for the low-cost carrier AERO-MS flight type. So this flight type all demand was allocated to the Discount ticket class.

Passenger demand was then aggregated to traffic index and ticket class for input to AERO-MS in the file *AT_Pax_Demand*. Cargo demand was simply aggregated to traffic index for the main cargo demand file *AT_Cargo_Demand.*

2.5.3 Capacity Proportions

Although the individual carrier and country of that carrier were identified in the operations and demand database, the input operations file to AERO-MS does not include a carrier field. Instead, AERO-MS uses a set of carrier proportions to allocate operations between regions. These proportions are defined via two input files.

The first file is specified by individual traffic index and defines the proportion of capacity for each traffic index which is operated by a carrier that is either:

- From the EEA;
- From the departure region of the flight; or
- From the arrival region of the flight

These proportions were derived from the underlying database of operations based on the proportion of seat kilometres. They do not necessarily sum to 1 for each traffic index, since it is possible that a flight could be operated by a carrier which does not fit any of these criteria.

The second file is specified by region pair and defines for each region pair and flight type the proportion of capacity which is met by carriers belonging to each region which is not either EEA, departure region or arrival region, i.e. is not represented in the first file dimensioned by traffic index. This file was produced by aggregating the seat kilometres to region pair level and calculating the proportion of seat kilometres operated by carriers from each region. The EEA, departure and arrival region proportions were set to zero.

2.5.4 Surface Competition

AERO-MS has a variable which defines whether surface competition is available for each flight stage. This flag was to be 1 for flight stages where the origin and destination were in the same region and the distance was less than 400km.

2.5.5 Country level attributes

AERO-MS includes a series of country level attributes including:

- Population;
- Gross National Product (GNP) per capita;
- Imports per capita;
- Exports per capita.

These datasets were updated using World Bank World Development Indicators data for 2019.

2.6 Processing fleet data

AERO-MS is designed for evaluation of the effectiveness of measures in a future year. As aircraft types in a future year may not yet be defined, AERO-MS reverts to the concept of AERO-MS generic aircraft types, which represent groups of aircraft with similar size (number of seats), range and operational characteristics. Because aircraft production and operational life typically span several decades, historical trends in technology and sales play a significant role in the environmental and economic performance of the fleet. These trends are from historical data from the Cirium data source. Extrapolation of these trends towards the future, supported by expert judgment, guides future fleet properties. The historic and future trends are combined into technology scenarios that have the form of timelines. In this concept, AERO-MS uses observed trends of current fleet and forecast forward to predict the required fleet and its properties from the demand for transport.

The fleet data update of AERO-MS includes updating the variables that describe the historic build up (prior to 2020) of the current fleet, including operating and capital costs, transport capabilities, fuel burn and emissions properties. Variables that drive the mechanisms for fleet renewal are also reviewed and updated.

2.6.1 Databases and contents

The following data sources are used in the fleet data update process:

- Cirium aircraft registration database;
- ICAO aircraft engine emissions databank, holding fuel flow and emissions information on certified engines;
- EASA Certification Noise Levels;
- EUROCONTROL traffic, covering a 2019, 4 months traffic sample of flights through the ECAC airspace;
- Flightradar24 traffic, covering a 2019, 4 months traffic sample representing the world-wide traffic.
- In the 2009 SAVE project to update the AERO-MS data, the FOI small engine emissions database has been made available for engines that are not registered in the ICAO engine emissions database. These numbers have been used again to compare trends against those of larger engines.

EASA has provided the AERO-MS team with an excerpt from the Cirium fleet database that holds the relevant information on aircraft at a tail-number basis. This database is the prime source of information used to classify aircraft into AERO-MS generic aircraft types. The information extracted from Cirium reflects the world fleet build-up for the end of 2019 and includes both aircraft in operation and already retired aircraft. For each aircraft (tail number) the following data are relevant:

- Registration, serial number;
- Aircraft type and family;
- Number of engines;
- Engine type and family;
- Year of production;

- Primary usage;
- Status (in operation, storage, retired etc.);
- Year of retirement (if applicable);
- Number of seats (for passenger aircraft);
- Weights: max take-off, max zero fuel, max landing, max payload, max cargo volume, fuel capacity;
- Operator name, category, and country;
- Indicative market value (by mid-2022).

Supplementing the Cirium database is the ICAO emissions database holding engine certification information including fuel flow and various emissions characteristics at prescribed throttle positions typical for take-off, climb, descent and taxi. Certification is mandatory for all civil aircraft engines beyond 26.7 kN thrust. Small (-er) aircraft engines (usually associated with commuter and business aircraft) that are not registered in this database will be proxied using an older version of the FOI small engine emissions database that has been made available to update AERO-MS in the SAVE project in 2009. The nomenclature of the engines in the ICAO database is different from the one in Cirium but has a similar level of detail. Expert judgement is used to match the engines between the three data sources. For the processing of noise characteristics, the EASA Certification Noise Levels database is used and linked to the Cirium information using the most detailed available aircraft type description. Again, expert judgment is used to link the aircraft types in the tables.

2.6.2 Main data processing steps

The population of the fleet related data in the Unified Database involves several steps covering the assembly of the fleet, distribution over regions, and setting up the history of sales and scenarios on fuel consumption, emissions, depreciation and retirement. This process is split in three major steps. The first step is to check for each tail number in the Cirium database if it is part of the commercially operated fleet and eligible for the AERO-MS fleet. In the second step, the following attributes are assigned to the individual tail numbers using the Cirium database:

- AERO-MS generic aircraft type, and based on the seating arrangement;
- AERO-MS aircraft purpose: one of passenger or freighter aircraft;
- Technology band: ‘old’ or ‘current', depending on the first year of certification of the aircraft-engine combination;
- AERO-MS region based on the operator home country.

In the third step, aircraft are grouped according to the combination of AERO-MS generic aircraft type and purpose. For each group, timelines are generated that present the historic build-up of sales and technology scenarios. The following timelines are set-up:

- Sales and retirement timeline, based on active, stored or retired status, based on the build-year of each tail number;
- Fuel, emissions and noise properties, using the first build-year of the aircraft-engine combinations in Cirium and linked to the databases supplementing Cirium.

These steps are described in more detail in the remainder of this chapter, starting with the definition of the AERO-MS generic aircraft types (Section 2.6.3), describing the process to check whether a tail number in the Cirium database is eligible for AERO-MS (Sections 2.6.4 and 2.6.5). Assignment of technology age is described in Section 2.6.6. The third main step is covered by Section 2.6.7 that describes the construction of several scenarios. Differences in fleet composition between AERO-MS regions are treated in Section 2.6.8. Finally, Section 2.6.9 describes the role and choice of so-called representative aircraft for each AERO-MS generic aircraft type.

2.6.3 AERO-MS generic aircraft type definition

Within AERO-MS, aircraft are aggregated to define AERO-MS generic aircraft types that represent a group of aircraft with similar seating and similar range capabilities. The AERO-MS generic aircraft types classification is given in Table 17.

Table 17 AERO-MS generic aircraft type definition

AERO-MS aircraft	AERO-MS generic aircraft type
0	less than 20 seats (short haul)
1	20 to 50 seats (short haul)
2	51 to 70 seats (short haul)
3	71 to 100 seats (short haul)
4	101 to 150 seats (medium haul)
5	151 to 175 seats (medium haul)
6	176 to 235 seats (medium haul)
7	236 to 300 seats (long haul)
8	301 to 500 seats (medium haul)
9	501+ seats (medium haul)

The seat bands are aligned with data used and produced by ICAO-FESG. The distance band attribute, short haul, medium haul and long haul, is required to make the AERO-MS aircraft choice model functioning properly. This model predicts how the observed fleet mix operated between each airport pair (flight stages) will change if demand, operational and capital costs change.

2.6.4 Assignment of AERO-MS generic aircraft types

The first step in the fleet building process was to identify the eligible aircraft from the Cirium database, and assign a seat band (AERO-MS generic aircraft type) and purpose (cargo or passenger) to each aircraft. Another step was taken to identify aircraft eligible for fleet renewal processes based on the operator type. Commercial and non-commercial flights are both included in the traffic and emissions, but only commercial operations are part of the AERO-MS fleet renewal and aircraft choice processes. Non-commercial aviation is largely insensitive to market-based policies. The process of extracting the relevant aircraft (registrations) from the Cirium database and assigning them to the appropriate AERO-MS generic aircraft types was done in a sequence of steps:

- Exclude aircraft with a maximum take-off weight below 5.7 tonnes;
- Allocate AERO-MS generic aircraft type on the basis of Cirium quoted seating and Table 17;
- Allocate AERO-MS purpose (cargo or passenger) on the basis of Cirium "primary usage" serving the cargo and/or passenger operations;
- Identify aircraft (tail numbers) that are associated with an (airline) company that provides commercial passenger and cargo services. Mark other aircraft as non-commercial.
- Mark aircraft as available for operations ("In Service" or "Stored") or (permanently) retired from service ("Retired" or "Written-off"). From Cirium data, it is observed that many aircraft build in 2018/2019 are marked "Stored" and are not yet in operational service. However, it is expected that these will be in operation in the near future;
- Business jets (with a maximum take-off weight larger than 5.7 tonnes) are not embedded in ATEC; for these aircraft the aircraft choice mechanism that selects a best aircraft size and range for a

given demand is not applicable. The flights (mainly business jets) are included in the traffic, allocated to the general aviation type.

2.6.5 Assignment of AERO-MS generic aircraft types: filling blanks

Following the above analysis, the majority of aircraft (i.e. the operational passenger aircraft at tail-number level) have been assigned an AERO-MS generic aircraft type, purpose, technology band and commercial/non-commercial type.

Aircraft that had not been assigned an AERO-MS generic aircraft type at this point were typically aircraft that have been retired, or being used in the freighter role (not having a quoted seat capacity). These aircraft still need to be assigned to an AERO-MS generic aircraft. For this, a process is set up using the already allocated aircraft set, the operator, aircraft type and aircraft family as common keys. Unallocated aircraft were allocated an AERO-MS generic aircraft type based on, and in the following order:

- Common aircraft family (e.g. A319) and (IATA) operator;
- Common aircraft type (e.g. A319-100) and engine type (e.g. CFM56-5B5/P);
- Common aircraft type;
- Common aircraft family.

In this process, it is assumed that the operator tends to pursue fleet commonality across its network. Note that the aircraft type designation is quite detailed, whereas the aircraft family usually consists of more aircraft type members.

After completing this process, some thousand out of 55 thousand aircraft remain unallocated. Of the aircraft that were found eligible for the AERO-MS fleet renewal process, 36 thousand were “In service”, 12 thousand “Retired”, 4 thousand “In storage” and 2.5 thousand “Written off”.

2.6.6 Technology split: old and current

Aircraft operational lifespans easily exceed 20 years, and aircraft production run lifetime may be of the same order. Therefore, operating and capital running costs may vary significantly because of the differences in age and/or in technology embedded in the aircraft, even if seating arrangements are similar. As AERO-MS is a policy analysis instrument, policies might impact differently between older and current aircraft due to apparent differences in fuel burn and emissions. Therefore, AERO-MS generic aircraft type distinguishes ‘old’ and ‘current’ technology categories within each AERO-MS generic aircraft type.

To support this modelling, each aircraft tail number in the Cirium database is assigned a technology level: ‘old’ or ‘current’. This classification is based on the oldest build year of the appropriate aircraft-engine combination in the Cirium fleet. The split between ‘old’ and ‘current’ (expressed in age) is a modelling parameter that needs to be set, such that there are sufficient aircraft numbers (fleet size) in both the ‘old’ and ‘current’ groups across all AERO-MS generic aircraft types and purposes (passenger airplanes and freighters, and there must be sufficient differences in operation (fuel, capital, emissions and costs) between the two. Testing some variations in the split (15, 17 and 20 years) showed that 17 year is a reasonable number. This is a slight shift from the 15 years, as used in the 2006 AERO-MS version. Following figure shows the distribution of old and current aircraft. The average age of the current aircraft of then found to be vary between 5 and 8 years.

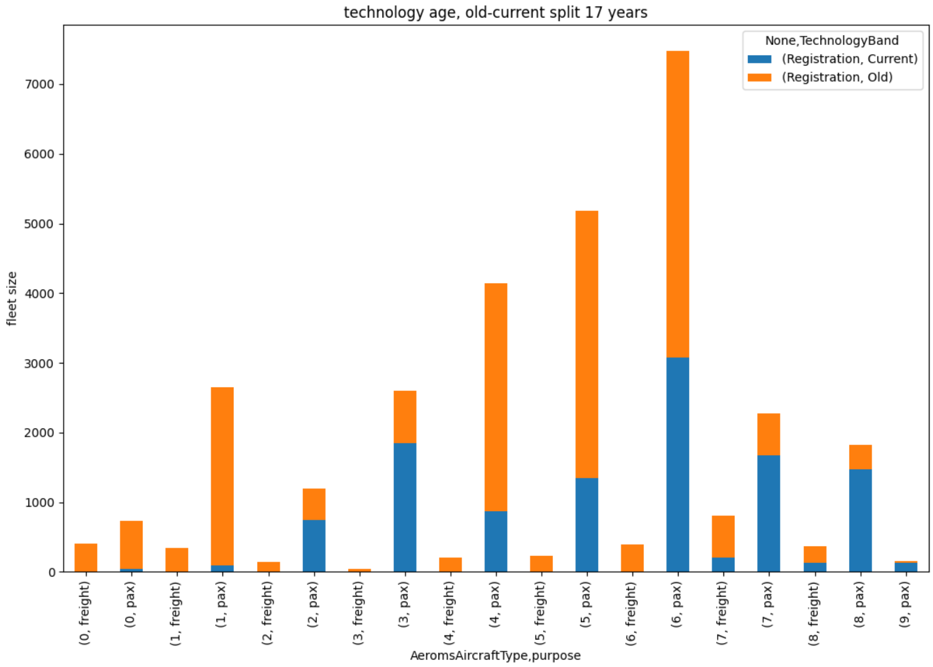


Figure 7 Old and current technology split in aircraft numbers

2.6.7 Scenarios building

Once aircraft have been assigned an AERO-MS generic aircraft type, various scenarios (timelines) embedded in the base case and describing the fleet build up and technology developments can be deducted on the basis of the records within the Cirium, emissions and noise databases. Cirium holds information on aircraft/tail-numbers over a long-time span, even if aircraft have long been retired from service. The remainder of this section discusses the relevant scenarios: the sales and retirement schemes (Section 2.6.7.1), fuel burn and emissions as well as aircraft noise parameters (Section 2.6.7.2), and aircraft new prices and depreciation rates (Section 2.6.7.3).

2.6.7.1 Sales and retirement curves

The AERO-MS fleet roll-over process as embedded in the fleet model requires to specify the historic part of the fleet build-up, consisting of a sales and a retirement curve per AERO-MS aircraft type .In AERO-MS terms, the sales curve represents the aircraft being build (and not the signing of a contract between airline and manufacturer). The process to set up these curves starts with the individual aircraft (tail numbers) as recorded in the Cirium database and being allocated an AERO-MS generic aircraft type and purpose (passenger or freight). For each AERO-MS generic aircraft type, the number of aircraft built and the proportion in active service (marked “In service” or “In storage” as opposed to “Retired” or “Written off”) are inventoried on a per year basis. These numbers are put on a timeline, see e.g. Figure 8 and Figure 9.

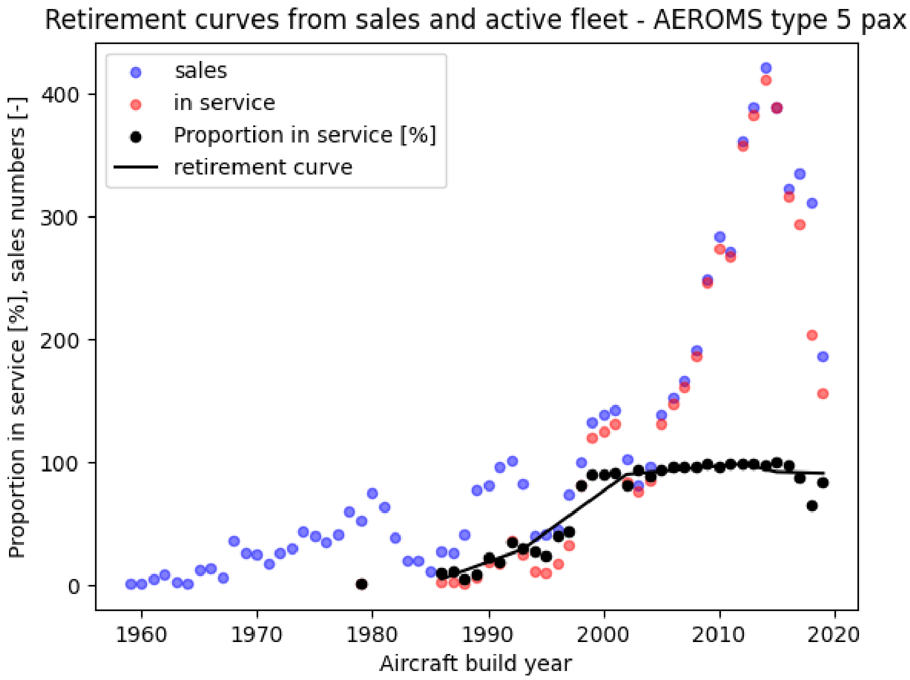


Figure 8 Retirement curve from sales and active service

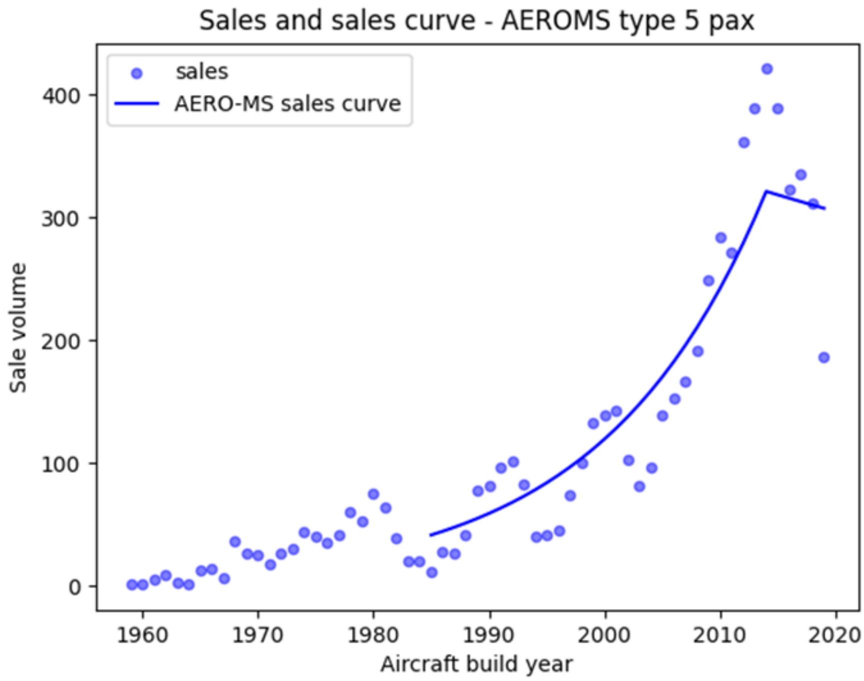


Figure 9 Sales data curve and raw data points)

For each year, there are three dots: the blue dot represents the number of aircraft being build, the red dot represents the number of aircraft actually in operation, and the black dot represents the percentage of aircraft in service (the ratio of operational and aircraft build). These data are then further processed to reduce the data to meet the AERO-MS data requirements. AERO-MS assumes a gradually declining retirement curve.

Hence, the observed retirement curve still needs some polishing: the observed series of black dots that represent the retirement process is a 2019 snapshot and may not be representative for the retirement process in other, future years. In this example, the observed curve shape shows a dip close to the year 2019. A relatively high number of aircraft built in 2018/2019 appear to be "In storage" and not yet in operation; around the year 2015, airlines keep some older aircraft longer in service than slightly younger aircraft. Also, the sales or builds (blue dots) of new aircraft show jumps if he next generation aircraft is introduced. Finally, a curve is fitted through the proportion data points and the average retirement age is calculated; see Figure 8 (black continuous line).

The retirement curves are derived from a snapshot of recent history – if the user expects changes in lifespan or the fleet-roll over process, as part of a scenario, then these curves will need user adjustment to reflect this. For the base case, the retirement curve needs to be close to the observed one; it is the only way to link the sales (and capital investments) and the actual aircraft (operations) in the fleet. If modified, either the sales (hence investments) or the fleet size (aircraft in operations) do not match the underlying traffic and fleet datasets anymore.

However, in a scenario case (i.e. future year), the introduction of new aircraft in the fleet cannot readily be predicted. Hence, alternative retirement curves are prepared based on a larger aircraft population spanning multiple AERO-MS generic aircraft types. Two retirement curves are constructed from the sales (builds) by year (blue dots) and embedded in the Task 2 scenario builds (cf. Chapter 3); one for single aisle and one for twin aisle aircraft and shown as a function of aircraft age in Figure 10 and Figure 11.

In these curves the introduction of new aircraft is less evident. It is up to the AERO-MS user to modify the retirement curve to comply with the use case scenario description, and embed the relevant variables in an AERO-MS scenario case description.

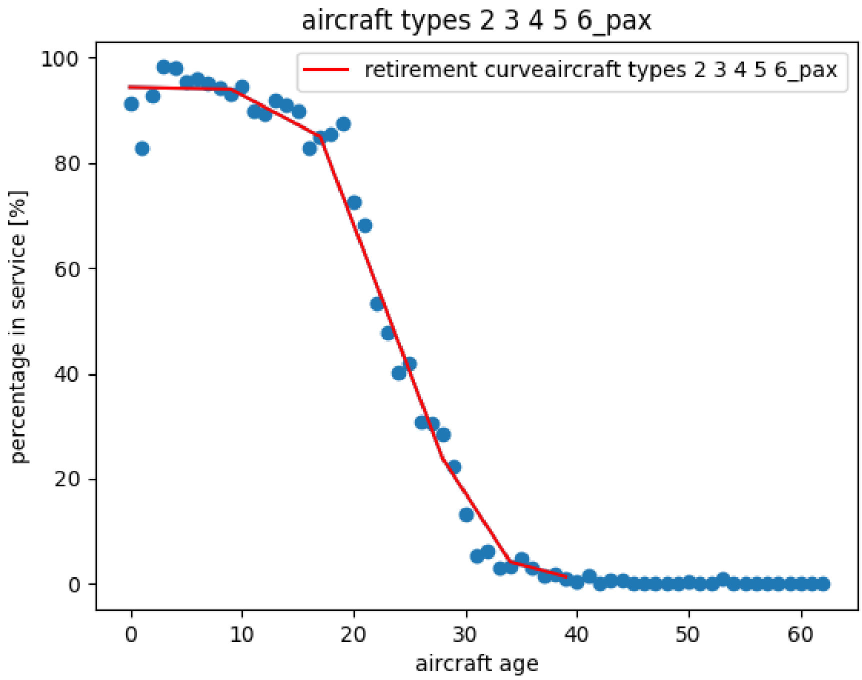


Figure 10 Narrow body aircraft retirement curve as a function of age

To model sales (aircraft builds) in AERO-MS, first a fit through the sales data points is made and this curve is then mathematically converted into the AERO-MS sales model expressed as relative sales change per year over a limited number of year intervals. There is no need to model the curve beyond the oldest aircraft in the fleet. A typical example of the "Build year" and constructed sales curve is given in Figure 8. In this particular case (passenger, AERO-MS generic aircraft type 5) a jump in sales around the year 2000 is present, reflecting the airline purchase behaviour close to the introduction of new aircraft types B738 and A320. Also observed and typically for this seat band, the number of aircraft built in 2018 and 2019 are significantly lower than in the years before, which can be attributed to the problems with the introduction of the B737Max and A320neo's. Similar observations can be made for other AERO-MS generic aircraft types (types 0, 1 and 4).

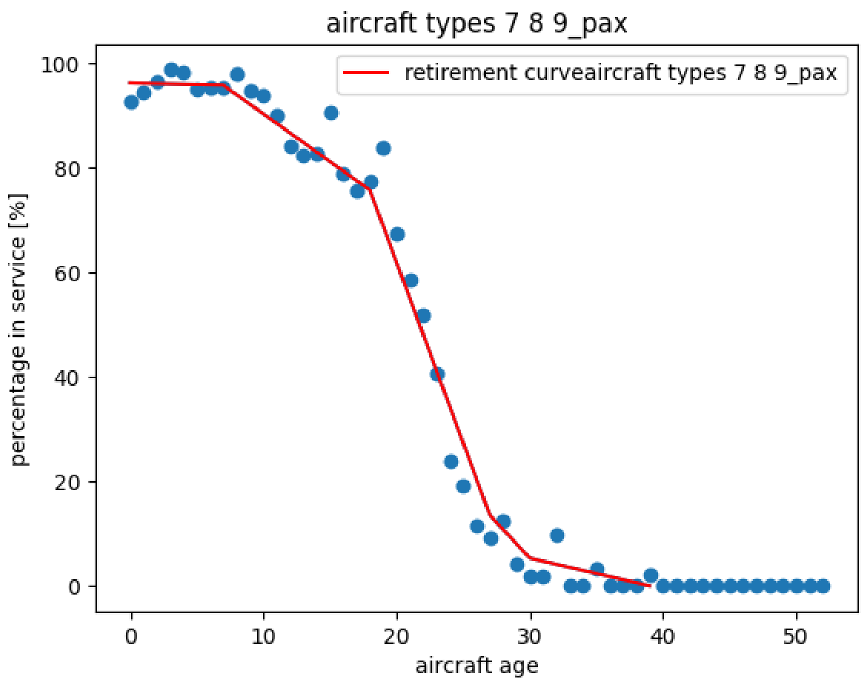


Figure 11 Wide body aircraft retirement curve

As the AERO-MS fleet model assumes a continuous sales process without knowledge of the introduction of new, future specific aircraft types and the impact on sales close of that. Hence the sales curves towards the future will need to be "polished". For the purpose of a policy evaluation in a future year, the sales curves need be extended towards the future guided by the user (through some scenario) or tuned (by AERO-MS) to match the future required fleet.

2.6.7.2 Fuel, emission and noise technology development

ATEC technology scenarios describe the changes in fuel burn and emissions (CO_2, H_2O, SO_2, HC, CO and NO_X) as a function of time. The time base of the scenarios reflects the (state-of-the-art) technology from year to year, i.e. the year of introduction (or first "Build year") of a new aircraft-engine combination. These scenarios are defined for each AERO-MS generic aircraft type and have the form of a fixed percent change per year over a limited number of time intervals.

The historic part of the scenario is based on the recorded aircraft-engine types by tail number in the Cirium database, combined with the (ICAO and FOI) engine characteristics. The climb condition is considered to be representative for the fuel burn and emissions technology, as the continuous climb condition is a certification requirement and a reasonable, best proxy to the flight conditions along a flight trajectory. For each generic AERO-MS aircraft type, one set of technology scenarios is conceived.

To construct the fuel burn scenario, and for each aircraft-engine combination, the climb fuel flow is scaled by (maximum) climb thrust (turbo-fans) or power (turbo-prop) to compensate for different sizes and thrust capabilities of aircraft within each particular AERO-MS generic aircraft type. Alongside, the first build year of any aircraft-engine combination is determined. The scaled fuel burn, the climb emission indices and the first build year are then put on a time line, as shown in Figure 12 (for the fuel burn). The first "Build year" (or "Year of Introduction") represents the "state of art" in that year. In this figure, the dots represent individual aircraft-engine types, and the dot size represents the number of aircraft-engines built (up to 2019).

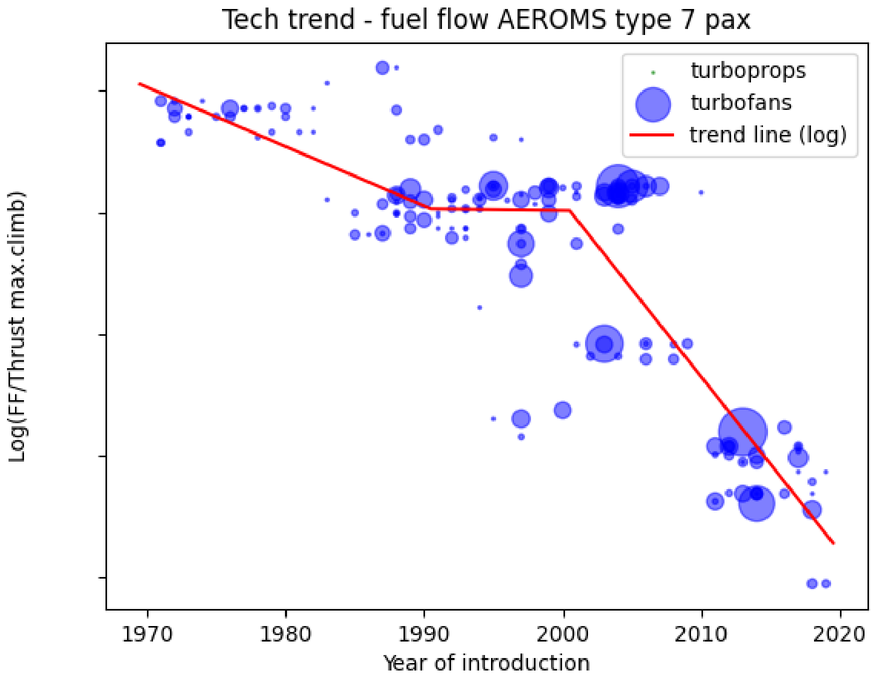


Figure 12 Fuel flow improvements over time

In this graph, the fuel burn per unit thrust is converted into its logarithmic value. This logarithmic form is a mathematical transformation allowing to transform fuel burn data into the appropriate AERO-MS variable definition: relative change in fuel burn (ΔF/F) as a function of time. As the number of time intervals in AERO-MS is limited, a best fit set of piecewise linear line segments is calculated from this set of data points. In this particular case, it can be observed that there is a technology jump in fuel burn around 2010 resulting from the introduction of a new generation of aircraft types.

As AERO-MS does only model flight trajectories, fuel consumption and emissions along the flight paths for turbo-fan powered aircraft, only the turbofan powered aircraft are taken representative of its AERO-MS generic aircraft and further processed. As turboprop aircraft are only relevant for the smallest seat band (up to 20 seats), fuel burn scenarios are based on turbofan engines and only marginally checked whether the trends in fuel burn are similar. This seems to be the case for the limited data available.

The resulting fuel burn and technology scenario in non-logarithmic form are shown below in Figure 13.

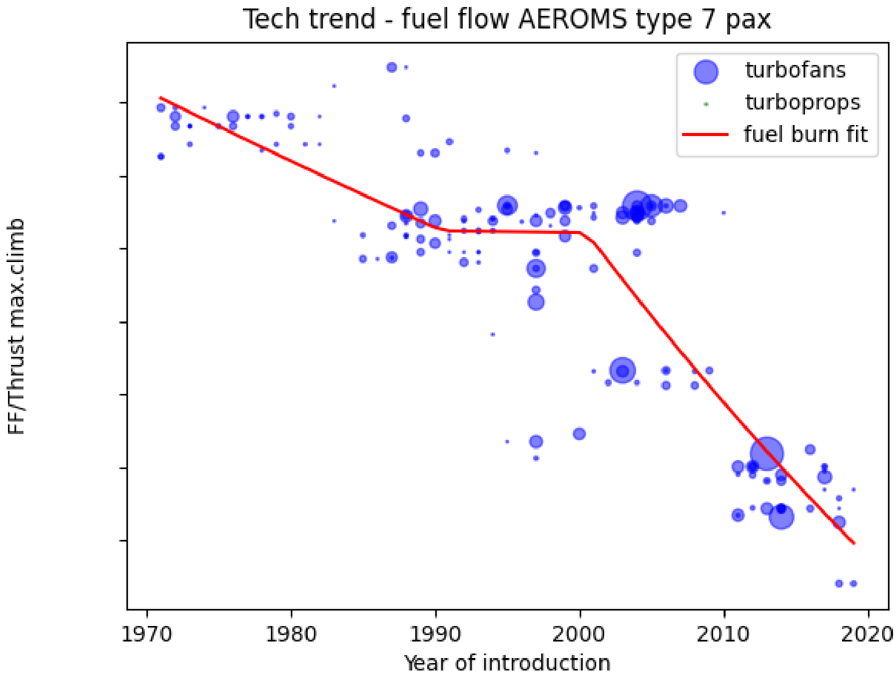


Figure 13 Fuel burn trend

The construction of emission scenarios follows the same method as the fuel burn scenario, using the relevant emission index for the climb condition from the ICAO engine emissions database.

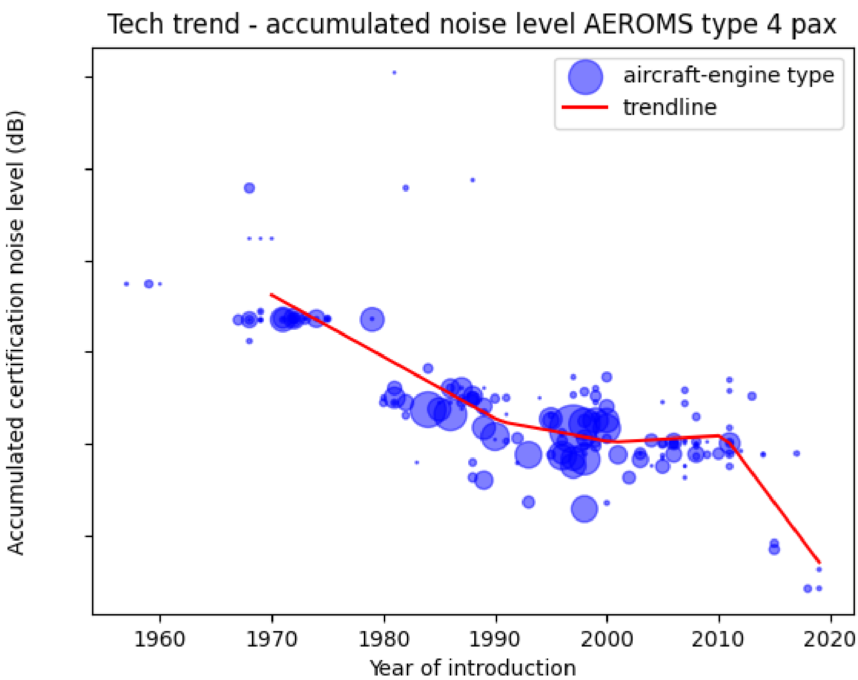


Figure 14 Certification noise improvements over time

The noise technology scenario is developed along similar lines as the fuel scenario, using the EASA recorded accumulated EPNdB per aircraft-engine type combination. The Cirium recorded aircraft-engine type combinations are linked to the EASA database. Where there is not an exact match between the datasets, expert judgement is used to make the match.

The scenario uses the (absolute, not relative) change in accumulated noise and defined for a limited number of time intervals. **Error! Reference source not found.** shows a representative result.

2.6.7.3 Aircraft new price and depreciation

AERO-MS requires depreciation rates and new prices for the calculation of capital costs. Aircraft lose value over the years after being sold to the first operator. New prices as advertised by the manufacturers should be considered as an invitation for further negotiation only. In reality, significant discounts are offered from the advertised price. In addition, one may expect a relationship between the aircraft value (or new price) and fuel consumption relative to the state of the art within a similar group of aircraft, i.e. AERO-MS generic aircraft type.

Cirium offers a value estimate for similar aircraft over a range of ages and aircraft types. These can be used to assess the depreciation and (effective) new prices. However, the recorded estimated values reflect the situation in August 2022 and reflect only aircraft in service in 2019 and before, and hence recorded values are “underestimated by 2.5 years”. For this reason, additional sources on aircraft new prices are sought to improve the estimated new prices.

Similar to the fuel and sales process, new price and depreciation rates are computed for each AERO-MS generic aircraft type. In this process, each aircraft (tail number) with an estimated value in 2022 and fuel consumption per unit thrust (at climb) is put on a timeline (grouped by aircraft-engine combination and aircraft age). The aircraft value is converted into a value per kilogramme maximum take-off weight to compensate for the differences in size. A curve fitting process was set up to reconstruct values per kilogramme as a function of time with the fuel consumption and age as independent variables, matching with the observed aircraft values. As the depreciation is expressed in a percentage change per year of a limited number of time intervals, the value is converted into a logarithmic scale. The resulting curve fitting parameters allow to estimate the loss of value from year to year and to assess the impact of fuel burn on the value and new price.

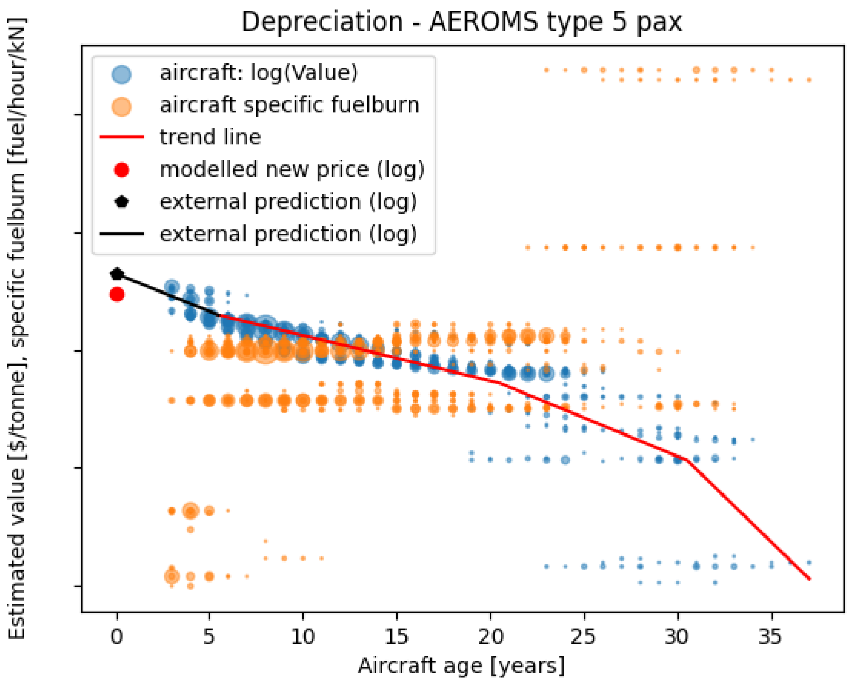


Figure 15 Aircraft new price and depreciation

A typical graph showing fuel burn parameters, values as function of aircraft age is provided in Figure 15. In this figure, the observed value of aircraft-engine combinations is represented by the blue dots (and the area the number of aircraft-engine combinations of a given age), the corresponding fuel flow per unit thrust in climb is represented by orange dots. The red line denotes the fitted curve representing value as a function of age. The impact of age and fuel burn on the value of aircraft is clearly visible from the data (graphical) patterns. A lower fuel burn suggest higher market values as does a younger age.

To correct for missing the 2.5-years for the youngest aircraft, aircraft new prices estimated from various sources (e.g. “Air Insight”) and compared to advertised new prices to obtain typical discount and selling prices per kg MTOW. These numbers are put into the figure and compared to the backward extrapolation. It shows that the extrapolation usually underpredicts the aircraft new prices, and the depreciation is revised for a better match.

However, extrapolation of the market value to aircraft new prices process is prone to inaccuracies. To validate the aircraft new prices, a search in the public domain has been performed to find published aircraft new prices. Based on the acquired data, a new price for each aircraft type has been set, and the depreciation rate in the first 5 years adjusted. A typical example is given in Figure 15.

A special case was found in the aircraft type 9, i.e. 500+ seats. This seat band is dominated by the Airbus A380. Only one major airline is effectively purchasing new aircraft, and apparently there is a low demand for second hand aircraft. The aircraft value drops significantly faster than other aircraft types in the first few years.

In designing a future scenario, a user should check, and possibly update the depreciation rates as part of a scenario development.

2.6.8 Regionalisation and age

Although the aircraft market is a global business, AERO-MS differentiates the fleet age between countries and regions (group of similar countries). Using the Cirium operator as key, each aircraft registration in the Cirium fleet database is linked to an AERO-MS country of origin and region. The build year of each aircraft is then used to calculate the average age of the fleet by region, resulting in different fleet ages. Linking the average regional fleet age to the technology timelines will see differences in emissions as well as in responses to emission and fleet-age related policies.

2.6.9 Representative aircraft

The Flights and Emissions Model (FLEM) generates flight profiles on the basis of origin and destination airports, and aircraft performance data. Along each flight profile, fuel burn and emissions are calculated. As the fleet characteristics are not detailed enough to generate those profiles, a performance and operational dataset needs to be drafted that generates representative flight profiles (speed and altitude as a function of distance flown) for a future fleet, in conjunction with the fuel burn and emission properties determined from technology, sales and retirement scenarios.

Therefore, for each AERO-MS generic aircraft type, a so-called reference aircraft is selected to fill in missing data – typically operational data like thrust-speed schedules, empty weights, and drag and lift characteristics. The fuel flow along the trajectory, and hence take-off weight, and emissions are reflecting/scaled using properties of the future fleet as evolved from historic and future fleet build-up and fuel burn technology scenarios. For this purpose, EUROCONTROL BADA version 4 is used. The selection of a representative aircraft is based on the following criteria:

- Aircraft seats and range capabilities should reasonably fit the AERO-MS generic aircraft type;
- The propulsion technology should be representative of more recent aircraft in the fleet, since the policy analysis studies deal with a future situation;

- The aircraft performance (fuel burn and emissions) and operational characteristics (speed and altitude along the flight trajectory) should reasonably reflect common types in the associated AERO-MS generic aircraft type;
- Aircraft should be powered by turbofans, as the FLEM flight trajectory generator cannot handle turboprop like performance.
- A suitable performance and operational characteristics dataset should be available in BADA4.2, and the noise certification data in the EASA noise certification database. Likewise, engine emissions and fuel burn data should be recorded in the emissions ICAO emissions database.

Note that turboprop aircraft (in numbers) are only relevant for the AERO-MS generic aircraft type 0 (up to 20 seats), which holds many aircraft types including turbofan powered aircraft. The Team's assessment is that there will be minor implications for the flight profiles and hence location of emissions for this particular AERO-MS generic aircraft type. As AERO-MS generic aircraft holds a wide variety of aircraft, no representative aircraft can easily be identified that is most common, where the number of candidates in the BADA4.2 database is rather limited. Still a reasonable choice could be made.

2.7 Aircraft performance data

The Flights and Emissions model FLEM calculates three-dimensional flight profiles, and the associated emissions, of an aircraft flying from origin to destination. The calculated emissions are distributed across a 3D-grid. FLEM uses aviation traffic descriptions from the AERO-MS Unified (Traffic) Database, combined with the aircraft and engine characteristics from the fleet properties that are calculated by the aircraft technology model ATEC from a scenario. FLEM assesses change in fuel use and emissions as a consequence of policy options. The FLEM model also responds to a number of operational policy measures. These operational measures relate to changes in aircraft operations that affect the flight profiling, and thereby the aviation fuel use and emission levels and/or their distribution in the three-dimensional atmosphere.

FLEM combines fuel and emissions characteristics of a future generic aircraft fleet resulting from the ATEC model (by seat band and technology level) with detailed characteristics of specific reference aircraft. These reference aircraft are existing aircraft that are representative for a certain seat capacity combination, matching the relevant seat band. With the combined characteristics of each reference and generic aircraft, FLEM generates realistic flight paths between two airports and consequently calculates fuel consumption and emissions along these flight paths representative for the generic aircraft and technology level.

2.7.1 Data sources

For this purpose, FLEM holds detailed aircraft characteristics similar to aircraft Performance Engineering Manuals (PEM) and emission characteristics from the ICAO Emissions Database. PEMs however are generally no longer available, the AERO-MS team has found the BADA 4 aircraft performance model to be a suitable alternative to PEMs.

BADA 4 is a kinematic model designed for use in trajectory simulation and prediction algorithms within the domain of Air Traffic Management (ATM). The main reason for using BADA is that it has been extensively reviewed and validated by various stakeholders, including industry, and is widely used and supported by a user group to facilitate future development and enhancements.

This data deck has similar level of detail than a PEM, and has successfully been processed to update most of the FLEM input variables. However, there are notable differences in the modelling itself. BADA 4 is designed to accurately represent the kinematic behaviour of aircraft (i.e. movement as a point) and mathematically models the aircraft performance descriptors in terms of polynomes with its parameters specified per aircraft type. FLEM, by design, is a kinetic model requiring an accurate description of forces acting on the aircraft. FLEM models aircraft performance using tables (instead of polynomes) representing values in relation to combinations of parameters that span the flight envelope.

This (kinematic versus kinetic, polynomes versus tables) difference in approach to describe aircraft performance data required a calculation process. First the flight envelope in terms of speed and altitude is extracted from the BADA dataset. For various combinations of speed and altitude, the suitable parameters from the BADA dataset are retrieved and, combination with appropriate BADA algorithms, converted into the FLEM required parameters. This is followed by a next step to extract the FLEM required data and including formatting to the appropriate AERO-MS variables.

The definition of the flight envelope proved to be quite challenging, as BADA does not explicitly define this. In areas of the flight envelope where drag and fuel burn vary significantly with small changes in airspeed or weight, the choice of airspeeds spanning the flight envelope has proven crucial.

2.7.1.1 License restrictions

BADA 4.2.1 has been made available to AERO-MS with courtesy of EUROCONTROL. In concert with the BADA license agreement, all data that reference in one way or another to a BADA 4 aircraft type data have been encrypted and are not accessible to an end-user. AERO-MS is not designed and not capable to perform comparisons of individual aircraft, and its output is delivered on an aggregated generic aircraft level (seat-band and technology level). As a result, the output of AERO-MS does not relate back to any BADA 4 aircraft type.

2.7.1.2 Implementation

Using BADA 4 and the ICAO emissions databank, most FLEM variables could be populated appropriately at the required level of detail. Some variables had to be estimated from other sources e.g. Jane’s all the World Aircraft or using expert judgement. There were a few reasons for this: BADA does not contain all information required for FLEM (e.g. range at maximum payload) or does not always contain the level of detail in aircraft characteristics required by FLEM, e.g. a cruise Mach number that is dependent on weight. Where other sources of information have been used alongside BADA, these data are made consistent with BADA to allow FLEM to generate credible results.

Within FLEM, three kinds of data (or variables) can be distinguished:

- Data that are specific to an aircraft type. These data comprise specific weights e.g. maximum take-off weights, maximum fuel weight, maximum landing weight, maximum payload weight, drag and lift characteristics, fuel burn.
- Data that are related to operational flying procedures, and are aircraft-type dependent. The typical operational data are: speed at various conditions, operating altitude, range, climb rates, descent rates.
- Data holding not specific to aircraft or operations. They define various FLEM typical modelling dimensions such as grid cell sizes, altitude bands and some default settings. These are usually not critical but have been reviewed whether the values are still applicable.

There are five update methods mentioned in Table 18 which are classified as follows:

Table 18 Update methods for FLEM variables

Update method	Description
ICAO	Data are extracted/derived from ICAO emissions database. Most of the required information is directly given in the database. Information mainly involves LTO emission indices, fuel flow and pressure ratios.
Jane's	Data are extracted/derived from Jane’s All the World Aircraft. Mainly used to supplement BADA with aircraft weight, range and Mach number information.

EXPJUD	Needs expert judgement, required further investigation or interpretation of data. As FLEM was not designed around BADA data, this includes expert judgement on the use of BADA for some variables.
Calibration	A calibration between reference aircraft and aircraft fleet is required (calibration between AERO models). With this calibration a reference aircraft can accurately represent aircraft within the corresponding seat and range band.

2.7.2 Fleet and representative aircraft calibration

The FLEM model is designed to calculate flight trajectories, fuel burn and emissions for the AERO-MS generic aircraft types. The properties of these aircraft types are taken form the ATEC model. In the ATEC model the fuel burn and emissions properties have been determined based on fleet growth, fleet replacement and technology scenarios. As the selected BADA4 aircraft type representative fuel burn and emission properties do not reflect these fleet averaged generic aircraft types, FLEM holds some variables that scale the fuel burn and emission and cruise speed to between the detailed flight performance data of the reference aircraft and the ATEC fleet data.

The calibration process follows a series of steps. First the characteristics in terms of fuel use and emissions of the reference aircraft are determined for the (four) LTO thrust settings from the ICAO emissions databank. Next, the average fuel use and emissions characteristics of the 2019 aircraft fleet within each seat and technology level are determined, using the same LTO thrust settings from the ICAO emissions databank. Finally, for each of the thrust settings, the fuel and emission LTO values are determined by using a fuel burn scaling factor which turns the fuel and emission characteristics from the reference aircraft to the average aircraft for the seat and range band concerned.

In order to ensure that both the fuel and emission per unit distance and per unit time match, the cruise speed is calibrated by comparing the fleet averaged values and that of the representative aircraft.

FLEM assumes that the ground track follows the great circle. To compensate for the true track that deviates from the great circle segment, and to compensate for the wind effects, a detour factor is used. This factor has been calibrated on an airport to airport bases and further discussed in the chapter covering Task 6 (cf. Chapter 7).

2.7.3 Calibration of fuel use and emissions

The Team has compared global aviation fuel burn and CO_2 emissions in 2019 as computed by the updated AERO-MS with data from various sources. The final AERO-MS computational results are presented in

Table **19** below. A distinction is made between fuel use and emission of international aviation and domestic aviation. International aviation is defined as all flights where the airport of departure and arrival are located in a different ICAO Member State. Hence domestic aviation relates to the flights where the airport of departure and arrival are located in the same ICAO Member State. Also fuel use and emissions of commercial aviation are presented separately in order to have the proper numbers for a comparison with other sources.

Clearly commercial traffic is responsible for the vast majority of global aviation emissions (> 99%). Hence business jets and general aviation with MTOW aircraft > 5700 kg take account of less than 1% of global aviation emissions. The table also shows about 65% of global aviation fuel burn and emissions is related to international aviation and hence about 35% is related to domestic aviation.

Table 19 Global aviation fuel burn and CO_2 emissions in 2019 computed by the AERO-MS

	Fuel use [Mt]	**CO_2 emissions [Mt]**
All traffic		
International aviation	191.5	604.6
Domestic aviation	101.5	320.6
Global aviation	293.1	925.2
Of which from business jets and general aviation with MTOW aircraft > 5700 kg		
International aviation	0.5	1.5
Domestic aviation	1.1	3.4
Global aviation	1.5	4.9
Commercial traffic		
International aviation	191.0	603.1
Domestic aviation	100.5	317.2
Global aviation	291.5	920.3

Table **20** compares the global CO_2 emissions from commercial aviation in 2019, as computed by AERO-MS, with published data by international organisations. The data from these international organisations show numbers varying between 914 and 918 Mt. AERO-MS computes 920 Mt which fits very well with this range.

Also, Table **20** compares the AERO-MS computed CO_2 emissions of global international aviation in 2019 with published data from the CORSIA Central Registry (CCR). It is shown that also for global international aviation there is a close match between the AERO-MS and an international source.

Table 20 Global aviation CO2 emissions in 2019 - AERO-MS versus other sources

Source	**CO_2 emissions [Mt]**
Global commercial aviation (international plus domestic)	
IATA[9]	915
ATAG[10]	914
ICCT[11]	918
AERO-MS	920
Global international aviation	
CORSIA Central Registry (CCR)[12]	608
AERO-MS	605

[9] www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact_sheet_on_climate_change.pdf
[10] atag.org/facts-figures
[11] theicct.org/publication/co2-emissions-from-commercial-aviation-2013-2018-and-2019/
[12] www.icao.int/environmental-protection/CORSIA/Pages/CCR.aspx

The CCR data contain CO_2 emissions data for 2019 by ICAO Member State Pair. Therefore, in a next step a comparison is made between the AERO-MS and CCR by State Pair. Figure 16 compares the CO_2 emissions for the major State Pairs where according to the CCR data CO_2 emissions of international in 2019 was above 5 Mt. The results for any State Pair relate to the emissions of aircraft operations in two directions.

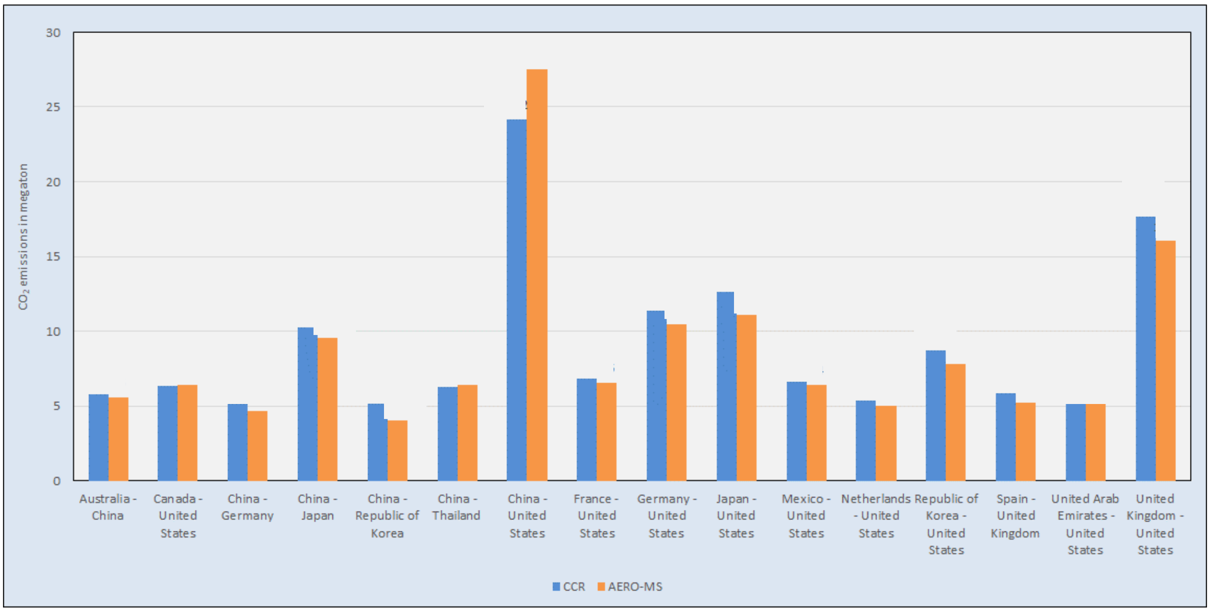


Figure 16 International aviation CO_2 emissions 2019: CCR vs AERO-MS for major State Pairs

In general, there is a good match between AERO-MS and CCR for the major State Pairs, though there are some differences. These differences have been investigated and could largely be explained

For some of the other State Pairs there are also some differences. There could be a variety of causes why there are differences between CCR (registered emissions data) and the AERO-MS (computed emissions data):

- A deviation between the number of operations in the AERO-MS database and the number of operations underlying the CCR data.
- A difference in the allocation of outermost regions to ICAO Member States between CCR and AERO-MS and thereby the exact definition which set of flights is considered as international flights.
- Transit flights, where the same aircraft is used, and whereby one flight leg is domestic and the other is international. For these transit flights, in the CCR data airlines might have attributed the fuel use/emissions of the domestic flight leg to the international emissions. This might especially an issue for ICAO Member States with a major domestic market (e.g. the USA, China).
- The AERO-MS fuel use and emissions are computed based on the characteristics of generic aircraft types (10 aircraft size classes, see Table 17) whereby a distinction is also made between two technology levels (old and current). The weighted average fuel use characteristics of any combination of a generic aircraft type and technology level are based on the fuel use characteristics of the corresponding specific aircraft types. There is however a variation in the fuel use characteristics of the corresponding specific aircraft types which is not taken into account in AERO-MS. If the average fuel use of the specific aircraft types deployed for a certain ICAO State Pair is higher compared to what is represented by the AERO-MS generic aircraft types, AERO-MS will compute a somewhat lower level of fuel use and emissions. Of course, this can also work out the other way around.

Figure 17 compares the CO_2 emissions for minor State Pairs where according to the CCR data CO_2 emissions of international aviation in 2019 were below 5 Mt. Also, in this figure the results for any State Pair relate to the emissions of aircraft operations in two directions. State Pairs for which CCR data are confidential or partly confidential (and for which the complete data are not available at the ICAO website) are excluded from the comparison. In total, the comparison in Figure 17 relates to about 4,000 State Pairs.

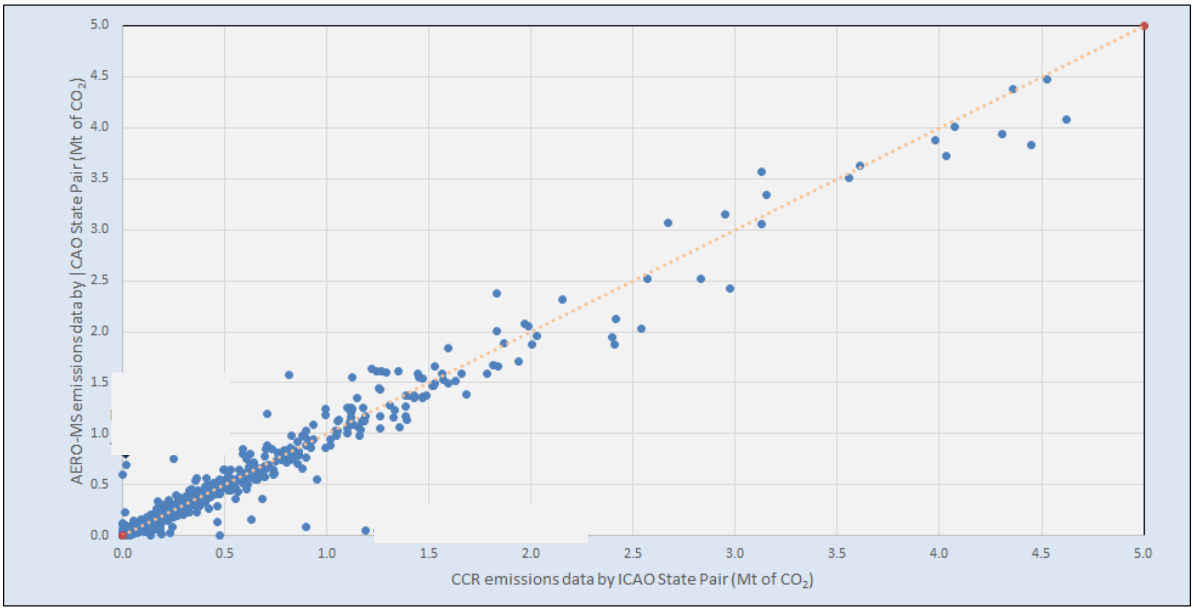


Figure 17 International aviation CO_2 emissions 2019: CCR vs AERO-MS for minor State Pairs

Also, as shown in Figure 17 there is generally a good match between AERO-MS and CCR. For some state pairs however, there is a mismatch. There can be a variety of reasons for a mismatch which are explored in detail but not reported here.

2.8 Derivation of costs and revenues

2.8.1 Data sources

The following datasets were used during the development of the airline costs and fares:

- ICAO 2019 Financial data – Financial data for each carrier that reports to ICAO. This includes a line of data on revenue, expenses, profit/loss, debt, tax and assets/liabilities for each carrier.
- ICAO 2019 Personnel data – Number of pilots, cabin crew, maintenance and ticketing personnel employed by each airline including expenditure.
- Cirium 2019 fleet dataset – Record of all aircraft as used in the derivation of the operations and demand processing.
- ICAO Regional Differences in International Airline Operating Economics (2012 and 2013[13]) – Includes a breakdown by region of scheduled passenger revenues and related costs.
- US Department of Transport 2019 Form 41 data – Categorised expenditure by American carriers, separated by aircraft type.
- Airline employee average salary information compiled by MIT using Form 41 data.

[13] More recent data do not appear to be available from ICAO

For the crude oil and kerosene prices for 2019 included in AERO-MS use is made of reported data for 2019: data from IATA[14] and US EIA[15].

It should be noted that the updated base year of AERO-MS is 2019, so although in some cases more recent data are available, it would not be appropriate to use that data for a 2019 base year model.

In general the latest ICAO 2019 datasets listed above were less complete than those used in the previous update of AERO-MS. For example, in the ICAO Personnel data there are a hundred airlines reporting a total pilot and co-pilot expenditure of around $6 bn, compared to about 190 airlines reporting a total expenditure of some $17 bn in the equivalent 2006 dataset from the previous update. For this reason there were instances where data had to be infilled either from alternative sources or by taking trends or relationships from the previous inputs. Where older data sources have been used, it is believed that alternative sources are not available. Although individual figures and examples can be found online, there are a limited number of datasets from reliable sources with the appropriate disaggregation of costs into different categories, across a range of airlines from which consistent unit costs split by geography and aircraft type can be calculated.

The cost processing described in this section relates to the unit costs per aircraft or per aircraft kilometre averaged across a wide range of operators and geographies. The unit costs are applied within AERO-MS to the volume of flights and kilometres to determine the total costs, which are then compared against published industry totals as a validation check, reported in Section 2.8.12. Table 21 shows that when these unit costs are applied, the total costs are consistent with this published data. This gives confidence in the costs despite the use of some older datasets in the derivation of those unit costs where the 2019 datasets did not have sufficient coverage.

2.8.2 Flight crew numbers and costs

Flight crew numbers were defined by generic aircraft type by mapping across the old generic aircraft types to the new types and using the numbers from the 2006 base data.

Flight crew costs were derived using the following method:

- Average flight crew costs per aircraft hour by AERO-MS region were calculated using ICAO Personnel data where these data had sufficient coverage and aircraft hours for the same airlines from the Flightradar24 operations database;
- Where the ICAO Personnel data did not have sufficient coverage the average flight crew costs per aircraft hour were taken from the 2006 data and factored up using the average salary increases from the MIT salary data;
- Average flight crew costs per aircraft hour by generic aircraft type were derived from Form 41 data;
- The distribution between aircraft types from the Form 41 data was imposed for each region whilst retaining the average cost per hour for each region derived from the ICAO Personnel data;
- Costs per aircraft hour were divided by the number of flight crew needed by aircraft type to calculate the cost per flight crew member per hour, as required for AERO-MS;
- Costs for low-cost carriers and charter AERO-MS flight type were factored down using the ratio of scheduled to low-cost carrier costs in the 2006 data, since the more recent ICAO data did not yield a plausible difference.

[14] https://www.iata.org/en/publications/economics/fuel-monitor/ and https://www.iata.org/en/iata-repository/pressroom/fact-sheets/industry-statistics/

[15] https://www.eia.gov/dnav/pet/hist/eer_epjk_pf4_rgc_dpgD.htm

2.8.3 Cabin crew numbers and costs

Cabin crew numbers are defined by generic aircraft type, technology level and AERO-MS flight type. The numbers of cabin crew required were derived by dividing the average number of seats (by aircraft type and technology level) by an assumed number of passengers per cabin crew member. For low cost carriers this value was assumed to be mandatory minimum of 50 passengers per cabin crew member. For scheduled carriers a value of 33 passengers per cabin crew member was taken from previous workings for the 2006 model, which was derived from the publication "Buying the big jets" by Paul Clarke.

Cabin crew costs were derived using the following method:

- Total expenditure on cabin crew by AERO-MS region was derived from the ICAO Finance data where data were available;
- Aircraft hours by region for the same airlines for which expenditure was reported was calculated from the Flightradar24 database;
- Expenditure per hour per cabin crew member was calculated by region by dividing by the average number of cabin crew needed by region;
- Costs for low-cost carriers and charter AERO-MS flight type were factored down using the ratio of scheduled to low-cost carrier costs in the 2006 data, since the more recent ICAO data did not yield a plausible difference.

2.8.4 Maintenance costs

Maintenance costs are defined per maintenance hour by generic aircraft type and region, and were calculated using the following method:

- Total maintenance cost per aircraft hour was calculated from Form 41 data by generic aircraft type;
- These values were divided by an assumption of 0.1 maintenance hours per aircraft hour to convert to a cost per maintenance hour;
- Regional variation indices relative to North America were derived from the 2006 base year data since the ICAO Financial and Personnel datasets did not have sufficient data to yield plausible values by region;
- The regional variation indices were applied to the Form41 values by aircraft type.

2.8.5 Interest costs

Interest rates were calculated by aggregating the total debt and total interest reported in the ICAO Financial data to AERO-MS regions and dividing the interest by the debt. Where there was insufficient data, the global average rate was used.

2.8.6 Aircraft Utilisations

Aircraft utilisations were derived using the following method:

- Aircraft hours by aircraft type, technology level and flight type were derived from the final operations dataset, using speed assumptions derived from Flightradar24 data which accounted for faster average speeds on longer flights;
- The number of aircraft by aircraft type, technology level and flight type were extracted from the Cirium fleet dataset, using only aircraft that match to operations data in the Flightradar24 or EUROCONTROL datasets (to exclude aircraft that were in the dataset but not in use during 2019);
- Utilisation was calculated by dividing the hours by the number of aircraft;

- For the smallest aircraft type 0, the Cirium fleet did not include many aircraft, so the utilisations were taken from the next smallest aircraft type;
- For some combinations of aircraft type and technology level for freighter flight types, there were no operations in the operations database, in which case an appropriate utilisation was used for an equivalent combination, for example the same aircraft type but different technology level.

2.8.7 Route navigation charges

Route navigation charges by generic aircraft type and region were calculated using the following method:

- Navigation charges in cents per passenger kilometre by region were obtained from the publication "Regional Differences in International Airline Operating Economics – ICAO" table 3-2. This is an updated version of the document used in the previous update to AERO-MS. However, the most recently available version is for 2013.
- The 2013 values were extrapolated to 2019 using the average annual change between the 2005 and 2013 values.
- The values per passenger kilometres were multiplied by the average number of passengers per operation to get to a cost per kilometre.
- Using the average MTOW by generic aircraft type as weights, the costs per kilometre were varied by generic aircraft type for each region whilst retaining the average cost per kilometre by region.

2.8.8 Landing charges

Landing charges by generic aircraft type and region were calculated using the following method:

- Landing charges in dollars per departed tonne by region were obtained from the publication "Regional Differences in International Airline Operating Economics – ICAO" table 4-3. This is an updated version of the document used in the previous update to AERO-MS. However, the most recently available version is for 2013.
- The 2013 values were extrapolated to 2019 using the average annual change between the 2005 and 2013 values.
- The values per departed tonne were multiplied by the average MTOW for each generic aircraft type to calculate average values per cycle by generic aircraft type and region as required for AERO-MS.

2.8.9 Average Stage Lengths

Average stage lengths were calculated by region pair from the operations database simply by weighting operations at the airport pair level by the great circle distance, aggregating to region pair level and dividing by the total operations for each region pair. This gives an average stage length weighted by the number of operations.

2.8.10 Fuel costs

The update of Base Year 2019 kerosene prices involves the specification of two variables:

- ACOS_CrudeOilPrice by IATA region;
- ACOS_FuelPriceFactor by IATA region.

The average crude oil price in 2019 was 65 US$ per barrel[16]. This equals 0.50 US$ per kg which is the unit of the variable ACOS_CrudeOilPrice. This price was applied to all 14 IATA Region Pairs. Regional differences of kerosene prices in 2019 are reflected by inputs for the variable ACOS_FuelPriceFactor.

The variable ACOS_FuelPriceFactor is used to convert oil prices into kerosene fuel prices. For this variable jet fuel price data from IATA[17] were analysed. IATA provides fuel price data for 5 world regions:

1. Asia & Oceania;
2. Europe & CIS;
3. Middle East and Africa;
4. North America;
5. Latin & Central America.

For each of these 5 world regions, the fuel price factor was calculated by dividing the jet fuel prices by the average crude oil price in 2019. The factor varies between 1.28 and 1.34. The 14 world regions considered in AERO-MS can be mapped to the 5 IATA world regions, which gives a factor by the 14 AERO-MS world regions.

2.8.11 Derivation of revenue and calibration

Revenues in AERO-MS are calculated by multiplying passenger fares and cargo fares by the number of passenger kilometres and mass of cargo respectively. Passenger fares are dimensioned by distance band, route group and passenger class, whilst cargo fares are dimensioned only by route group.

Passenger fares were previously derived from a combination of datasets using the following method summarised from the Study on Aviation and Economic Modelling (SAVE) Report, 2010:

- Control route group fares to match the route group average yields (cents/RPK) from the document “Regional differences in International Airline Operating Economics” and revenue of carriers as defined in the ICAO Financials data;
- Split the average yields into distance bands using the relativities from the original AERO-MS model;
- Define fares by class using data from the IATA Fare Development Report.

This method relies on the revenue by carrier from the ICAO Financial Data. However, as noted previously, the updated version of this dataset is not complete (for example, there is no passenger revenue data for any American carriers). Given the limitations of these latest data, the fares used in the 2006 base year model were initially input to a base year run of AERO-MS to test how well the revenue generated by these fares validated against observed data. This initial run yielded a good comparison against published revenue figures for 2019 which vary between approximately $830bn and $870bn. The 2006 values were therefore calibrated at the route group level to better match the ICAO data, and these fares were used in the updated version of AERO-MS.

2.8.12 Calibration of economic indicators for global airline industry 2019

The AERO-MS model DECI computes economic indicators for the airline industry. The economic indicators for the global commercial airline industry in the year 2019, as computed by the updated AERO-MS have been compared with IATA data. The results are presented in Table 21. The global airline revenues, as computed by the AERO-MS and reported by IATA, include indirect taxes. Indirect taxes

[16] www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance---june-2022---data-tables/
[17] www.iata.org/en/publications/economics/fuel-monitor/

are taxes, fees, and charges imposed by governments on the consumers of the airline industry, which are collected by airlines. The indirect taxes are included in the fare inputs of the AERO-MS and therefore also in the computed global airline revenues. Indirect taxes are also included in global airline expenses.

Direct taxes relate to taxes imposed on airlines which are generally related to airline operating profit. The operating profit reported by IATA and computed by AERO-MS both relate to the operating profit before direct taxes.

➨ **Table 21** Economic indicators global airline industry in 2019 - AERO-MS versus IATA data

Economic indicator	difference
Global airline revenues	-0.3%
Global airline expenses	-0.2%
Fuel costs	0.7%
Labour costs	-1.0%
Gross Value Added (GVA) airline industry	2.2%
Airline employment	1.2%
GVA/employee	1.0%
Operating profit	0.1%*

* This is a percentage point difference.

Table 21 shows that the economic indicators for the global airline industry in 2019, as computed by AERO-MS closely match with reported IATA data.

Regarding the calibration of global airline expenses, the Team has first looked at the different variable cost components considered in AERO-MS, which are based on detailed unit cost input. In a second step the remaining costs (in the AERO-MS referred to as volume related costs) were specified as a closing entry to end up with a reasonable total operating costs and profitability level for the global airline industry.

2.9 Extending AERO-MS time horizon

AERO-MS calculations for future years start from the calculated results for the base year. In the SAVE version of AERO-MS the maximum number of years to look into the future from the base year onwards was 50. The base year in the SAVE version of AERO-MS was 2006 and hence AERO-MS calculations for future years could be made for the period up to 2056. For the updated version of AERO-MS the requirement is to be able to make calculations for future years up to 2070. With the new base year of 2019, this is 51 years from the base year onwards. The extension of the AERO-MS time horizon required a number of actions:

- It had to be ensured that the AERO-MS models and the AERO-MS shell do not have hard-coded data with respect to the base year (presently 2006) or the time horizon (presently 2056). The AERO-MS source code has been meticulously checked on this. No hard-coded data regarding the base year or the time horizon were found in the AERO-shell. However, the ADEM model required to make a small change in order to facilitate calculations to be made for 2070.
- New baseline scenarios have to be implemented in AERO-MS reflecting the expected future developments of the global aviation industry. The implementation of these baseline scenarios has been part of Task 2 (cf. Chapter 3).

The above implies that, with the base year updated to 2019, the maximum time horizon of AERO-MS is extended to 2070. In order to make use of this extended time horizon, new baseline scenarios are implemented, including a scenario for the year 2070.

2.10 Updating AERO-MS regionalisation

As a first step in the update of the regionalisation, the country dimension in AERO-MS has been updated. For this, the most recent list of countries of CAEP was used. A number of adjustments were made to the list of countries in the existing, 2006 Base Year of AERO-MS, e.g. separating South Sudan from Sudan, constitutional reform of Caribbean Netherlands. This resulted in an updated list of 249 countries in the updated AERO-MS, whereas in the previous AERO-MS version 245 countries were included.

The updated regionalisation in AERO-MS considers 14 world regions. Compared to the regionalisation in the AERO-MS version with Base Year 2006, a number of changes were made:

- The region EEA[18] is now considered instead of EU. This is because the two most important EU directives to regulate European aviation greenhouse-gas emissions (EU Emissions Trading System and REFuelEU Aviation directives) have EEA relevance.
- Following Brexit, the UK is not part of the EU/EEA anymore, and is now included in the region "ECAC (non-EEA)";
- The definitions of AERO-MS regions are made in such a way that they can be mapped to the ICAO regions and to the CAEP regions used in the Long-term Traffic Forecast (LTF).

The updated regionalisation in AERO-MS is presented in Figure 18.

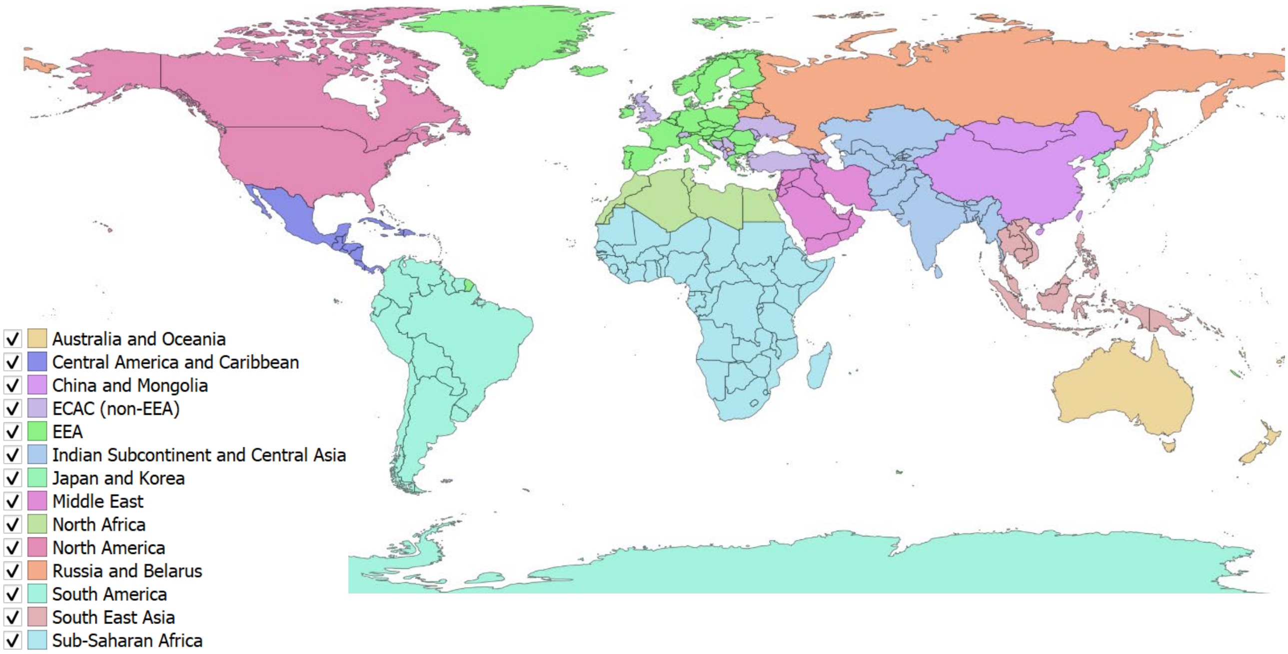


Figure 18 Regionalisation in AERO-MS

A list of the updated AERO-MS regions and mapping to ICAO and CAEP LTF regions is presented in

Table 22.

Table 22 Updated AERO-MS regions and mapping to ICAO and CAEP LTF regions

[18] EEA is EU27 plus Norway, Iceland and Liechtenstein

<table>
<tr><th>AERO-MS Regions</th><th>ICAO Regions</th><th>CAEP LTF Regions</th></tr>
<tr><td>1. North America</td><td>1. North America</td><td>1. North America</td></tr>
<tr><td>2. Central America and Caribbean</td><td rowspan="2">2. Latin America / Caribbean</td><td>2. Central America / Caribbean</td></tr>
<tr><td>3. South America</td><td>3. South America</td></tr>
<tr><td>4. ECAC (non-EEA)</td><td rowspan="3">3. Europe</td><td rowspan="3">4. Europe</td></tr>
<tr><td>5. EEA</td></tr>
<tr><td>6. Russia and Belarus</td></tr>
<tr><td>7. North Africa</td><td rowspan="2">4. Africa</td><td>5. North Africa</td></tr>
<tr><td>8. Sub-Saharan Africa</td><td>6. Sub Saharan Africa</td></tr>
<tr><td>9. Middle East</td><td>5. Middle East</td><td>7. Middle East</td></tr>
<tr><td>10. Indian Subcontinent and Central Asia</td><td rowspan="5">6. Asia / Pacific</td><td>8. South West Asia</td></tr>
<tr><td>11. China and Mongolia</td><td>9. China</td></tr>
<tr><td>12. Japan and Korea</td><td>10. North Asia</td></tr>
<tr><td>13. South East Asia</td><td rowspan="2">11. Pacific South East Asia</td></tr>
<tr><td>14. Australia and Oceania</td></tr>
</table>

The latest CAEP long-term traffic forecast considers 51 route groups (41 with respect to international aviation and 10 with respect to domestic aviation) with routes between/within the 11 CAEP LTF Regions. Because the 11 CAEP LTF regions can be mapped to the 14 AERO-MS regions, the 196 region pairs considered in AERO-MS can also be mapped to the 51 CAEP LTF route groups.

2.11 Data Input Protocol

The Data Input Protocol (DIP) for AERO-MS users summarises the process required to update the AERO-MS base case data guiding a user to specify their own traffic. This process reflects the processing undertaken by the Team in Task 1; users of AERO-MS who would like to use their own dataset (i.e. compile their own Base Year), would essentially replicate this work. This protocol summarises the steps required to translate external datasets into AERO-MS input files and calibration activities. As these datasets can be from different sources and built for different purposes, the DIP focuses on data requirements and on the steps to be taken, rather than on detailing actual data conversions.

2.11.1 Prerequisites

The AERO-MS suite as delivered to EASA consists of two separate packages:

1. A package with the compiled AERO-MS system. This is the part to be used for actual analyses by the end users. End users can only use the package if they have obtained a (user) license key. By default, much of the input data are encrypted. Sensitive input data (e.g. BADA data) are not accessible by any means to the end-user.

2. A package with the source code, underlying data and compiled system. This is stored at EASA and forms the basis for any future development of the system. This package also contains the programs to generate license keys for end users and developers.

To update the baseline, access to the source code and underlying unencrypted data is required. By default, end-users do not have that code and associated data. These data are not available in the user interface nor accessible in the underlying data structures. For an update of the base data, EASA needs to facilitate access to the source code and data. Sensitive AERO-MS data are encrypted in the model, and these data can only be modified if the user has an appropriate (administrator) license that allows decryption, to be granted through EASA.

This administrator license key is also needed for compilation and data encryption to produce a new version of the model for end-users. EASA is provided with a separate package which includes the license key generator for both the administrator and end-user roles. For the purpose of compilation of new data, the model holds dedicated scripts in the main directory to compile a new base case dataset. Running these scripts requires an MS-Visual integrated development environment (IDE) from Microsoft and running on Windows 10 or Windows 11. The protection of data to end-users is further discussed in task 10 (cf. Chapter 11).

2.11.2 Data sources

Starting point of an update of the AERO-MS base case is a collection of datasets that have a world-wide description of air traffic, fleets and the (costs and emission) properties for a given base year. To populate the relevant data sets, the data sources should cover:

- Aircraft fleet: an inventory of present and past aircraft by tail number at least denoting the number of seats, build year, year of withdrawal form active service and engine type, and an indication of present value on the market; the aircraft fleet should also encompass detailed engine information allowing to be linked to fuel burn and emission characteristics;
- Flight operations: number of flights between an airport pair, indicating aircraft type and operator (type);
- Financial data describing several capital and operational costs components with sufficient detail to be linked to the type of operator, and with geographical differentiation;
- Geographical and aeronautical information on airports and countries.

The selected datasets should have sufficient detail to allow discrimination between several types of operations, e.g. low costs carriers vs. full service carriers, passenger versus cargo operations, typical seat capabilities, and differences between geographical regions. The fleet data source should not only cover the aircraft in service, but also aircraft that have been retired in order to facilitate the calculation of retirement and sales data, and the fuel burn and emissions technology scenarios. The process of how such external sources have been used in the present update is described at length in this document. The data sources for this project are listed in Table 1.

Additional data sources are needed for supporting information e.g. engine emissions data. For the development of scenarios, several additional datasets or information sources are required that describe current and future economic and geographical properties related to background development, e.g. country GDP and population. These supporting data sources are typically found in the public domain. Beyond the bare minimum of data sources, additional, supporting information might help to improve, validate or calibrate various data, in particular on the estimates on transport volumes and translates this into demand for transport, i.e. passenger and freight volume flows.

For an update of the detailed aircraft performance for specific aircraft (in the FLEM model), additional information is required at BADA 4 depth of detail. For the emissions properties the ICAO emissions database is required. For smaller aircraft with engines that are not registered in the ICAO emissions database, in particular for aircraft up to 20 seats, proprietary information might be needed.

2.11.3 Data structures

The above-mentioned datasets need to be processed in order to make them consistent, fitting the format and requirements of AERO-MS, and transfer them into the AERO-MS dataset structure and formats.

AERO-MS consists of several models that are exchanging information through the Unified Database structure, and the source code reflects this approach. The source code is distributed over several sub directories, one for each model (ACOS, ADEM, ATEC, DECI, FLEM and the framework that connects these models). The dataset structure is aligned with the individual models. For each model, in the source code directory, a sub directory called "DATA" is present that holds the data for the base case. This "DATA" directory may consist of several subdirectories, and holds the model variables. Each variable is stored in a separate file in *.csv format. This format is easily accessible using a text editor or excel spreadsheet, or an access database. Note that the separator is a "|" (rather than a comma). Each file holds exactly one variable and related information: caption, description, dimensions and its values. The filename relates to the variable name, e.g. the file "AT_City_Latitude.csv" holds the variable "AT_City_Latitude".

There are two basic types of variables defined in the model:

- Variables holding data that are independent of other variables, e.g. containing the latitudes of an (ordered) list of airports. E.g. opening AT_City_Latitude.csv under the ADEM>Data>city sub directory yields using MS-Excel:

Airport	Airport (Label)	AT_City_Latitude
0	#ACX XINGYI	25.1564
1	#AEB BAISE	23.7167
2	#AVA HUANG GUO SHU	33.5479
…	…	…
4529	ZYYK	40.5425

- Variables that link (map) one variable to another using one or more indices or holding some value linking to another table. E.g. ADEM>Data>city>AT_Country.csv links the airport to a country using two indices; the column Airport refers to the position in the AT_City_Latitude and the AT_Country to the position in table CountryAttrib.csv. And the great circle distance between airports of a flight stage (AT_Greatcirvle_Distance in file ADEM>Data>city>AT_Greatcricle_Distance.csv) that is coupled to the index of the Flight Stage.

Airport	AT_Country
0	45
1	45
2	45
3	13
4	3
5	118
6	182
7	30

Flight Stage	AT_Greatcircle_Distance
0	1920.45
1	1957.81
2	1937.42
3	585.696
4	869.405
5	885.963

Data values might have one or more dimensions. From the LandingCharges.csv file in the ACOS>Data>imp_nlr9 directory, e.g. a landing charge depends on the IATA region, the aircraft seat band and the aircraft technology level. The last column holds the value, and the other columns indicate the independent variables.

IATA Region	IATA Region (Label)	Technology Level	Technology Level (Label)	Aircraft Type	Aircraft Type (Label)	LandingCharges
0	North America	0	Old	0	Short haul less than 20 seats	149
1	Central America and Caribbean	0	Old	0	Short haul less than 20 seats	98

5	Russia and Belarus	1	Current	4	Medium haul 101 to 150 seats	1180
6	North Africa	1	Current	4	Medium haul 101 to 150 seats	647

2.11.4 AERO-MS information structures

In building a new input dataset representing the base case, there is a logical order in re-populating the csv files that together represent the base case.

Many variables have one or more dimensions in common, and these relationships need to be inventoried first. Dimensions for all variables can be extracted from the header in each *.csv file or from the graphical user interface. The first step is to find those variables that are independent of other variables. Those variables form the foundations of other variables. In many cases, other variables then refer to these base variables using an index.

These dimensions are not only described in the file header of the *.csv file but are also apparent through the AERO-MS user interface by using the Data Inspect option, selecting the “Assumption”, “Input” or “Update” option in the “Variable Filter” to select the input variables, and then finding the dimension in the properties tab, as shown in Figure 19.

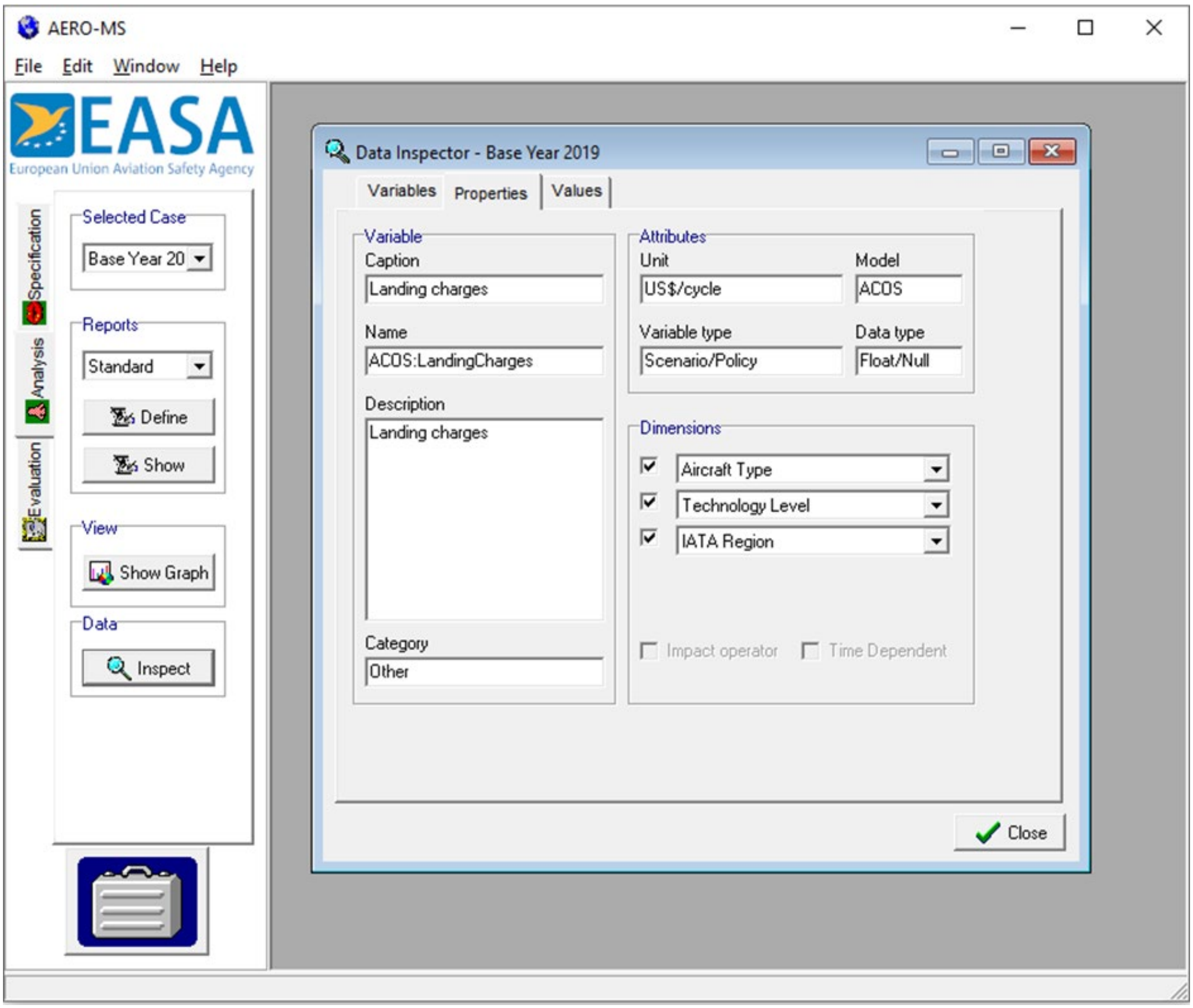


Figure 19 User interface: dimenions panel

Some of the dimensions may be flexible in size between AERO-MS updates because they need to reflect the observed world, e.g. the description of traffic and airports. The size will vary between updates, and so will the number of rows in the table. Other dimensions have a fixed size because they are the result of modelling choices, typical examples are the number of seat-bands, technology levels, and operator types. In the latter case, it is sufficient to only update the last table column with the values and leave the other columns intact.

Once the data structure is clear, the individual *.csv files can be updated with new values. Starting with the independent, base variables and then populate those variables that are dependent on others that have been assigned already in an earlier step. This step can be iterated until all variables have been assigned new values.

2.11.5 Preparing a traffic database

When building a new AERO-MS Unified Database, the starting point is usually the description of the external source traffic. This traffic should be expressed in arrival and departure airports, the number of flights, the operator and aircraft type. The aircraft type (preferably a tail number) serves to classify the flight into a seat-band and technology level and a provides a link to an external fleet database. The operator serves as a proxy to identify flight type; distinguishing commercial and non-commercial flights, full service versus and charter or low-costs, scheduled and non-scheduled, passenger and cargo flight, and the home country, as costs and policy options and impacts vary between them. The traffic should be representative for a full year, cover commercial operations and have world-wide coverage.

The second step is to compile fleet properties from the aircraft and operators, observed in the traffic and fleet inventory, and link those to the AERO-MS fleet model. AERO-MS distinguishes fleet and traffic properties by splitting both the fleet and flights into seat bands (based on seating capacity), its primary function (passenger aircraft or freighter) and technology level.

Each operation in the traffic need to be linked to an appropriate aircraft-engine combination. For this the aircraft tail number or the combination of aircraft type and operator may act as a guide. This aircraft-engine combination is used to classify the aircraft operated on each flight according to the seat-bands and technology levels, using seating capacity of the airframe and the certification year of aircraft-engine combination from the fleet database.

This classification forms the basis for estimating the operating and capital cost components, new prices, fuel burn and emissions properties. These variables describe properties of the traffic and fleet and vary according to the classifications (dimensions) of the fleet and traffic.

From the traffic, the demand, in terms of passenger and freight volume flows between airports can be estimated based on the seat capacities and the payload factors of the aircraft being operated. This demand can then be linked to the countries and its properties e.g. population and GDP.

For each generic aircraft type a representative aircraft is selected for which performance and operational data are available in order to generate flight trajectories (and fuel burn and emissions) between airports. The performance data are supplementary to the generic fuel burn and emissions characteristics that can be derived from the fleet by seat-band and technology level. In order to compile new aircraft performance data, a few steps need to be taken:

- Select an aircraft type that best reflects the aircraft within a seat-band and for which performance data is available;
- For the selected aircraft, define the independent variables, basically the altitude, speed and weights that span a flight envelope;
- Compile the various aircraft performance and operations, e.g. lift, drag, thrust, fuel burn that may vary throughout the flight envelope;
- Make the aircraft performance representative for the part of the fleet, i.e. at seat-band level by through calibration.

2.11.6 Internal calibration aspects

Once all variables have been updated where necessary, a key activity is to align various models (and their variables) internally, and to check the inputs to AERO-MS and outputs of AERO-MS base case against available external sources. This process can be split into two main steps:

- Make the AERO-MS models internally consistent;
- Compare the AERO-MS base run outputs against external data and adjust where necessary.

Calibration itself is reported in Task 2 (cf. Chapter 3), this paragraph focuses on the protocol to make the model internally consistent. Starting point is the traffic that is compiled for the ADEM model, the fleet data that are compiled for the ATEC model, and the FLEM detailed performance data for a representative aircraft. These properties are further split into seat bands and technology levels. The calibration is then performed in a series of steps:

- Scaling factors on the fuel burn, emissions, cruise speed translate the representative aircraft values into the performance of the fleet average values by seat-band. For this purpose, the engine data and throttle settings in ICAO engine emissions database are used. The scaling factors themselves can be judged to reflect on the choice of the aircraft that is considered representative for the relevant fleet.
- The demand in terms of passenger and freight is derived from traffic, fleet and external data sources. To ensure a good alignment between fleet and traffic, calculation and checking the utilisation (flying hours per airframe per year) is key. The obtained utilisations can be checked against external data sources.
- The outputs of an AERO-MS base run hold many outputs in terms of transport parameters, e.g. passenger kilometres, cost components, revenues, fuel burn and emissions. These can all be partially checked against external sources from IATA, ICAO, EC and others.

3. Task 2: Baseline scenario and testing

3.1 Implementing baseline scenario in updated AERO-MS

The main capability of AERO-MS is to assess the impacts of a range of potential policy options to reduce aviation emissions. AERO-MS computes the effects of policy options relative to a baseline future development without policy options in place (baseline scenario).

A baseline scenario is a statement of future circumstances that are exogenous to the policy options, but which potentially affect the analysis of the impacts of policy options. In AERO-MS a baseline scenario is defined in terms of a coherent set of AERO-MS scenario variables. A baseline scenario in AERO-MS should satisfy the following requirements.

- A baseline scenario should be consistent in itself. Developments in different fields are sometimes interdependent, which implies the need to link the predictions on individual variables in a baseline scenario;
- A baseline scenario should cover the total range of potential future developments of relevance for the air transport sector;
- A baseline scenario description must be formulated in such a way that it can be made operational by means of the available AERO-MS scenario variables.

A baseline scenario is defined for a future year to be selected by the AERO-MS user. This allows AERO-MS to produce a "snapshot" of effects for the air transport sector for the selected forecast year. A baseline scenario run for any forecast year requires a separate, scenario specification file.

As part of Task 2 a baseline scenario has been implemented for four future years (2028, 2038, 2050, and 2070) in the updated and enhanced AERO-MS. Because the basis for the baseline scenario is the CAEP13 Mid Growth traffic forecast the scenarios are abbreviated as CAEP13 Mid 2028, CAEP13 Mid 2038, CAEP13 Mid 2050 and CAEP13 Mid 2070. The main baseline scenario developments included in the baseline scenarios relate to:

- Air transport demand;
- Aircraft technology and operational improvements;
- Operating costs, fares and airline profitability.

3.1.1 Air transport demand

As part of the CAEP/13 cycle, an air traffic demand forecast has been made for the period up to 2050. Also, an extension of the forecast was made for the period 2050-2070. The forecast is related to both passenger and cargo demand. Thereby low, mid and high growth forecasts have been defined. As indicated above, the mid growth forecast is implemented in AERO-MS.

For passenger demand, an annual growth percentage in passenger km is defined by CAEP for 51 route groups. These route groups cover global air transport, with 41 route groups related to international air transport and 10 route groups to domestic air transport. The annual growth percentages are defined for the periods 2018-2028[19], 2028-2038 and 2038-2050. The mid forecast assumes an average global growth in passenger demand of 2.1%, 4.0% and 4.0% per annum for these 3 periods respectively (with variations in growth across route groups). The lower growth for the period 2018-2028 is clearly related to the impacts of COVID-19 on the global aviation industry. The data for the period 2050-2070

[19] The CAEP13 forecast takes 2018 as the base year. In the updated AERO-MS 2019 is the base year

are defined with less granularity. The average global growth in air transport passenger demand in this period, as assessed in the CAEP13 cycle, is 3.2% per annum.

Each of the 113,514 airport pairs in the updated AERO-MS is linked to one of the 51 CAEP route groups, and hence each airport pair takes on board the passenger demand growth of the applicable route group. In the CAEP13 mid growth baseline scenario a growth rate for any route group applies to scheduled and non-scheduled traffic of both network and low-cost carriers.

The CAEP/13 traffic forecast also contains cargo demand forecast. This forecast is defined in terms of an annual growth percentage in cargo tonne-km. These annual growth percentages are defined separately for the flights departing from 6 ICAO regions[20], whereby also a distinction is made between international and domestic traffic.

The mid forecast assumes an average global growth in cargo demand of 3.1%, 3.5% and 2.9% per annum for the periods 2018-2028, 2028-2038 and 2038-2050 respectively. The growth percentage for the period 2018-2028 reflects that cargo demand was much less affected by COVID-19 compared to passenger demand. Also, the cargo demand growth for the period 2050-2070 is defined with less granularity, whereby the average global growth in cargo demand in this period is forecast to 3.3% per annum.

3.1.2 Aircraft technology and operational improvements

Regarding aircraft technology the main issue is the assumed autonomous fuel efficiency improvement of aircraft. In AERO-MS, the fuel efficiency improvement is specified in terms of the yearly fuel burn reduction of new aircraft: that is, the fuel burn of aircraft produced in year X relative to that of aircraft produced in year X-1. These improvements can be separately specified for the 10 AERO-MS generic aircraft types. For the CAEP13 mid growth baseline scenario implemented in AERO-MS, the LTAG Advanced Tube and Wing (ATW) medium technology scenario is adopted[21]. This technology scenario specifies technology improvements for different aircraft categories[22]. For each aircraft category an annual fuel efficiency improvement is specified for the periods 2019-2030, 2030-2040 and 2040-2050. For the period 2050-2070 the upper fuel burn bound for far future years is adopted, which basically assumes a stand-still in fuel efficiency improvement of new aircraft for this period.

For each of the AERO-MS generic aircraft types the distribution across the 5 LTAG aircraft categories is assessed based on the Cirium fleet database. Based on that, and using the LTAG ATW data, the average annual fuel efficiency improvement per AERO-MS generic aircraft type is assessed for the periods 2019-2030, 2030-2040 and 2040-2050. These data are included as part of the CAEP13 baseline scenario specifications in AERO-MS.

Operational improvements are generally a result of higher ATM efficiency. CAEP13 considers two operational improvement scenarios: a moderate and high operational improvement scenario. In line with the CORSIA Tools and Analysis Group (CTAG) of CAEP Working Group 4 (WG4), the CAEP13 baseline scenario with the high operational variant is selected for implementation in AERO-MS. These operational improvements are specified for the 51 CAEP route groups for the years 2028, 2038, 2050 and 2070. In the AERO-MS baseline scenario these improvements are implemented by a reduction in detour factors.

3.1.3 Operating costs, fares and airline profitability

The main uncertainty with respect to the development of operating costs into the future is related to the development of kerosene price for airlines. Within CAEP13 the future kerosene price is forecast

[20] See also Section 2.10 of this report.

[21] Source: www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM3.pdf

[22] A distinction is made between Turboprop (TP), Business Jet (BJ), Regional Jet (RJ), Single Aisle (SA) and Twin Aisle (TA)

to 3 US$ per gallon. This is about one third higher compared to the average global kerosene price which was observed in 2019. For the CAEP13 baseline scenario for all future years, it is assumed that the kerosene price is 3 US$ per gallon. With respect to most of the other direct operating cost categories in AERO-MS (e.g. en route costs, landing costs, maintenance costs) unit costs in real terms are assumed not to change.

As a final step in the scenario development procedure, the Team adopted the levels of volume related costs in such a way that reasonable levels of profitability are computed for all carrier regions.

3.2 AERO-MS computational results for CAEP13 Mid baseline scenario

The main effects of the CAEP13 Mid baseline scenario, as computed by AERO-MS, are presented in Table 23. The table relates to the global aviation industry including both domestic and international aviation. The table presents results for the scenario years 2028, 2038, 2050 and 2070 together with the results for the updated AERO-MS Base Year 2019. The effects are presented in both absolute terms and in terms of the annual % change for the periods 2019-2028, 2028-2038, 2038-2050 and 2050-2070. Table 23 includes results related to:

- Air transport demand and aircraft operations;
- Effects on airlines;
- Aircraft fleet;
- Fuel and emissions;
- Operating efficiency.

According to the CAEP13 Mid demand growth baseline scenario there is a significant increase in demand for air transport services over the coming decades. For the year 2050 total Revenue Tonne Km (RTK) is forecast to go up to 2,911 billion tonne km (+178% relative to the level of demand in 2019). For the year 2070 the forecast level of demand is 5,462 billion RTK (+422% relative to the level of demand in 2019).

In order to serve the future levels of demand the number of flights and aircraft km also very significantly increase over time according to the CAEP13 Mid baseline scenario. Also, the global aircraft fleet size for commercial aviation significantly increases. For 2070 the fleet size is computed to over 106 thousand aircraft (+314% relative to the fleet size in 2019).

Table 23 AERO-MS results for CAEP13 Mid baseline scenario for the years 2028, 2038, 2050 and 2070

Effect	Unit	Base Year 2019	Baseline scenario results (absolute)				Average annual % change			
			CAEP13 Mid 2028	CAEP13 Mid 2038	CAEP13 Mid 2050	CAEP13 Mid 2070	2019-2028	2028-2038	2038-2050	2050-2070
Air transport demand and aircraft operations										
Passenger demand - scheduled network carriers										
a. First/business	billion pax-km pa	627	764	1,123	1,803	3,347	2.2%	3.9%	4.0%	3.1%
b. Economy	billion pax-km pa	5,599	6,794	10,017	15,954	29,673	2.2%	4.0%	4.0%	3.2%
c. Total scheduled network carriers	billion pax-km pa	6,226	7,558	11,140	17,757	33,020	2.2%	4.0%	4.0%	3.2%
Passenger demand - LCC and non-scheduled	billion pax-km pa	2,382	2,841	4,168	6,680	12,574	2.0%	3.9%	4.0%	3.2%
Total passenger demand	billion pax-km pa	8,608	10,399	15,307	24,436	45,594	2.1%	3.9%	4.0%	3.2%
Cargo demand	billion tonne-km pa	243	320	453	628	1,204	3.1%	3.5%	2.8%	3.3%
Revenue tonne-Km (RTK)	billion RTK pa	1,047	1,291	1,883	2,911	5,462	2.4%	3.8%	3.7%	3.2%
Available tonne-Km (ATK)	billion ATK pa	1,494	1,833	2,657	4,171	7,654	2.3%	3.8%	3.8%	3.1%
Flights	million	38	46	64	96	169	2.4%	3.3%	3.5%	2.8%
Aircraft km	billion ac-km pa	60	72	99	151	266	2.1%	3.3%	3.6%	2.9%
Effects on airlines										
Direct operating costs	billion 2019 US $	436	577	759	1,138	1,926	3.2%	2.8%	3.4%	2.7%
Total operating costs	billion 2019 US $	827	1,098	1,463	2,259	4,085	3.2%	2.9%	3.7%	3.0%
Total operating revenues	billion 2019 US $	870	1,138	1,524	2,353	4,284	3.0%	3.0%	3.7%	3.0%
Total operating result*	% of revenues	5.0%	3.5%	4.0%	4.0%	4.7%	n.a.	n.a.	n.a.	n.a.
Airlines related employment	1000 employees	2,935	3,471	4,752	7,477	14,211	1.9%	3.2%	3.8%	3.3%
Aircraft fleet										
Commercial fleet size	number of aircraft	25,822	31,605	42,425	61,684	106,788	2.3%	3.0%	3.2%	2.8%
Fuel consumption and emissions										
Fuel use	billion kg pa	293	321	395	526	827	1.0%	2.1%	2.4%	2.3%
CO_2 emissions	billion kg pa	925	1,012	1,247	1,662	2,610	1.0%	2.1%	2.4%	2.3%
NO_x emissions	billion kg pa	3.2	3.7	5.0	7.1	11.4	1.7%	3.2%	2.9%	2.4%
PM emissions	million kg pa	68.3	66.2	73.1	93.7	147.2	-0.3%	1.0%	2.1%	2.3%
PM emissions LTO cycle	million kg pa	42.1	45.3	51.2	64.8	97.9	0.8%	1.2%	2.0%	2.1%
Operating efficiency										
Direct operating costs / RTK	US$/tonne-km	0.42	0.45	0.40	0.39	0.35	0.8%	-1.0%	-0.3%	-0.5%
Total oparting cost / RTK	US$/tonne-km	0.79	0.85	0.78	0.78	0.75	0.8%	-0.9%	0.0%	-0.2%
Fuel / RTK	kg/tonne-km	0.28	0.25	0.21	0.18	0.15	-1.3%	-1.7%	-1.2%	-0.9%
Fuel / ATK	kg/tonne-km	0.20	0.17	0.15	0.13	0.11	-1.3%	-1.6%	-1.4%	-0.8%
RTK / ATK	factor	0.70	0.70	0.71	0.70	0.71	0.1%	0.1%	-0.1%	0.1%
RTK / aircraft-km	tonne-km/ac-km	17.58	17.97	18.97	19.26	20.54	0.2%	0.5%	0.1%	0.3%
Revenues / RTK	US$/tonne-km	0.83	0.88	0.81	0.81	0.78	0.6%	-0.8%	0.0%	-0.2%
Fuel / aircraft-km	kg/ac-km	4.92	4.46	3.98	3.48	3.11	-1.1%	-1.1%	-1.1%	-0.6%

* Total operating result is presented as a % of operating revenues for the base year and the baseline scenarios.

The CAEP13 Mid baseline scenario shows a clear increase in fuel use and CO_2 emissions of global aviation. CO_2 emissions are forecasted to go up to 1,012 Mt in 2028 (+9% relative to 2019), 1,247 Mt in 2038 (+35% relative to 2019), 1,662 Mt in 2050 (+80% relative to 2019) and 2,610 Mt in 2070 (+182% relative to 2019).

As described in Section 3.1, the CAEP13 Mid baseline scenario includes aircraft technology and operational improvements. These improvements result in fuel efficiency improvements. This is reflected by the average fuel per ATK for global aviation. In 2019 the average fuel use per ATK for global aviation was 0.20 kg per ATK. As a result of aircraft technology and operational improvements this is forecasted to come down to 0.13 kg per RTK in 2050 (-36% relative to 2019). For the year 2070 fuel use per ATK for global aviation for the CAEP13 Mid baseline scenario is computed to 0.11 kg per ATK (-45% relative to 2019).

3.3 Testing of policies

A number of policies have been defined in order to test the functionality of the updated AERO-MS. These policies are merely defined for the purpose of testing the updated AERO-MS and do not reflect actual policies which are currently discussed internationally.

The following policy tests are defined:

- A global fuel taxation of 0.50 US$ per kg of fuel (FuelTax 0.50US$_pkg);
- A global CO_2 taxation of 50 US$ per ton of CO_2 (CO2Tax 50US$_pt);
- A global passenger ticket and cargo taxation of 10% (Ticket+CargoTax 10%).

The impacts of the policy tests are presented relative to the CAEP13 Mid baseline scenario for the years 2028 and 2038 in Table 24 and Table 25 respectively.

The 10% taxation shows a reduction in passenger demand of about 6% relative to the CAEP13 Mid baseline scenario for both 2028 and 2038. This impact on demand directly follows from the updated price elasticities of demand (see Task 3 described in Chapter 4). Clearly first/business class passengers are less price sensitive and hence the impact on demand for these passengers is less (-1.7% in both 2028 and 2038). The impact on demand for passengers served by low-cost carriers on the other hand is significantly higher (-8% in 2028 and -7.6% in 2038).

The cost increases for airlines brought about by a fuel taxation of 0.50 US$ per kg are higher compared to the 10% ticket taxation policy. The total costs per RTK go up by about 15%. The higher cost increase for the fuel taxation also implies a higher impact on demand. Table 3.2 shows that in 2028 the impact on demand in terms of RTK is -9.7% for the global fuel taxation versus -5.7% for the 10% ticket and cargo taxation.

The cost increases for airlines brought about by a global CO_2 taxation of 50 US$ per ton are lower compared to the 10% ticket taxation policy. The total costs per RTK go up by about 5%. Table 24 shows that in 2028 the impact on demand in terms of RTK is -3.4% for a global CO_2 taxation of 50 US$ per ton.

The cost increase per RTK of both a global fuel taxation and a global CO_2 taxation reduces over time. This is because the fuel use per RTK reduces over time and hence a taxation per unit of fuel or CO_2 emissions results in a declining cost impact per RTK over time. As a result, the demand impact of both a global fuel taxation and a global CO_2 taxation also diminishes over time.

The impact of the 10% ticket taxation policy on fuel use and CO_2 emissions is fully related to demand reduction and the related decline in the number or aircraft operations. The ticket taxation does not give an incentive for airlines to improve the fuel efficiency of the fleet. This is reflected by the impact on the fuel use per RTK which in case of the 10% ticket taxation policy slightly goes up relative to CAEP13 Mid baseline scenario.

For both the global fuel taxation and global CO_2 taxation the impact on fuel use and CO_2 emissions partly follows from demand reduction. In case of a fuel taxation or CO_2 taxation there is a price incentive for the use of more fuel efficient aircraft. This is referred to as the supply side response. AERO-MS takes into account the following supply side responses:

- New aircraft technology shift: change in purchase behaviour of airlines towards (available) environmentally more efficient new aircraft;
- Accelerated fleet renewal: replacing the older part of the fleet earlier than in the situation without a fuel/CO_2 taxation, based on financial considerations of airlines;
- New aircraft capacity shift: adjustment of mission capabilities to allow for more efficient aircraft operation in view of anticipated fuel/CO_2 taxation impacts on transport flows.

Table 24 shows that the reduction in fuel use and CO_2 emissions resulting from the global fuel taxation is 11.1% in 2028. The global fuel taxation also results in a reduction of the fuel use per ATK by 2.3% in 2028. This reduction reflects the impacts of the supply side responses. Though a global fuel taxation triggers supply side responses the larger part of the reduction in fuel use and CO_2 emissions is related to a reduction in demand.

The pattern of impacts for a global CO_2 taxation is very similar to the pattern of impacts of a global fuel taxation. The main difference between the two policy test is the taxation level, and related level of cost increases. This taxation level in case of the global fuel taxation of 0.50 US$ per kg is roughly 3 times as high compared to the global CO_2 taxation of 50 US$ per ton of CO_2. In other words, a global CO_2 taxation of *150* US$ per ton of CO_2 would have very comparable impacts as the global fuel taxation of 0.50 US$ per kg.

Because the percentage impact on demand of both a global fuel taxation and a global CO_2 taxation reduces over time, also the percentage impact on fuel use and CO_2 emissions of these policies tend to reduce over time. This whereas the percentage impact on fuel use and CO_2 emissions of a ticket taxation remains constant (i.e. -5.5% impact in both 2028 and 2038; cf. Table 25).

All in all, the policy tests show results with general patterns which are consistent with the results of earlier versions of AERO-MS. Moreover, the impact on passenger demand is in line with the updated price elasticities of demand (see Task 3 in Section 3.4). Most importantly, compared to earlier versions of AERO-MS, the policy tests with the updated AERO-MS are made against the background of updated CAEP baseline scenarios which start from the updated base year 2019. A comparison between the results of the updated version of the AERO-MS and the SAVE version of the model is provided in Section 3.4 below.

Table 24 Impacts of policy tests relative to CAEP13 Mid baseline scenario for the year 2028

Effect	Unit	Baseline scenario: CAEP13 Mid 2028	Policy tests results (absolute)			Policy tests impacts (% change relative to baseline scenario)		
			FuelTax 0.50US$_pkg	CO2Tax 50US$_pt	Ticket+CargoTax 10%	FuelTax 0.50US$_pkg	CO2Tax 50US$_pt	Ticket+CargoTax 10%
Air transport demand and aircraft operations								
Passenger demand - scheduled network carriers								
a. First/business	billion pax-km pa	764	744	758	752	-2.7%	-0.9%	-1.7%
b. Economy	billion pax-km pa	6,794	6,234	6,602	6,402	-8.2%	-2.8%	-5.8%
c. Total scheduled network carriers	billion pax-km pa	7,558	6,978	7,359	7,153	-7.7%	-2.6%	-5.4%
Passenger demand - LCC and non-scheduled	billion pax-km pa	2,841	2,382	2,672	2,615	-16.2%	-6.0%	-8.0%
Total passenger demand	billion pax-km pa	10,399	9,360	10,031	9,768	-10.0%	-3.5%	-6.1%
Cargo demand	billion tonne-km pa	320	292	310	306	-8.8%	-3.0%	-4.5%
Revenue tonne-Km (RTK)	billion RTK pa	1,291	1,166	1,247	1,218	-9.7%	-3.4%	-5.7%
Available tonne-Km (ATK)	billion ATK pa	1,833	1,667	1,775	1,737	-9.1%	-3.2%	-5.3%
Flights	million	46	42	45	43	-9.4%	-3.3%	-6.2%
Aircraft km	billion ac-km pa	72	65	69	68	-9.2%	-3.3%	-5.8%
Effects on airlines								
Direct operating costs	billion 2019 US $	577	664	606	638	14.9%	4.9%	10.5%
Total operating costs	billion 2019 US $	1,098	1,147	1,114	1,129	4.5%	1.4%	2.9%
Total operating revenues	billion 2019 US $	1,138	1,180	1,152	1,163	3.7%	1.2%	2.2%
Total operating result*	% of revenues	3.5%	2.8%	3.3%	2.9%	n.a.	n.a.	n.a.
Airlines related employment	1000 employees	3,471	3,182	3,370	3,273	-8.3%	-2.9%	-5.7%
Aircraft fleet								
Commercial fleet size	number of aircraft	31,605	28,727	30,573	29,802	-9.1%	-3.3%	-5.7%
Revenues for governments								
Revenue from taxation**	billion 2019 US $	n.a.	143	49	106	n.a.	n.a.	n.a.
Fuel consumption and emissions aviation sector								
Fuel use	billion kg pa	321	285	308	303	-11.1%	-3.9%	-5.5%
CO_2 emissions	billion kg pa	1,012	900	972	957	-11.1%	-3.9%	-5.5%
NO_x emissions	billion kg pa	3.7	3.2	3.5	3.5	-12.0%	-4.3%	-4.9%
PM emissions	million kg pa	66.2	56.4	62.8	62.8	-14.9%	-5.2%	-5.1%
PM emissions LTO cycle	million kg pa	45.3	38.9	43.0	42.9	-14.1%	-5.0%	-5.2%
Operating efficiency commercial aviation								
Direct operating costs / RTK	US$/tonne-km	0.45	0.57	0.49	0.52	27.3%	8.6%	17.2%
Total oparting cost / RTK	US$/tonne-km	0.85	0.98	0.89	0.93	15.7%	5.0%	9.0%
Fuel / RTK	kg/tonne-km	0.25	0.24	0.25	0.25	-1.6%	-0.5%	0.2%
Fuel / ATK	kg/tonne-km	0.17	0.17	0.17	0.17	-2.3%	-0.8%	-0.2%
RTK / ATK	factor	0.70	0.70	0.70	0.70	-0.7%	-0.2%	-0.4%
RTK / aircraft-km	tonne-km/ac-km	17.97	17.88	17.94	17.99	-0.5%	-0.2%	0.1%
Revenues / RTK	US$/tonne-km	0.88	1.01	0.92	0.96	14.9%	4.8%	8.4%
Fuel / aircraft-km	kg/ac-km	4.46	4.37	4.43	4.48	-2.1%	-0.7%	0.3%

* Total operating result is presented as a % of operating revenues for the baseline scenario and the policy cases.
** For policy cases this impact is presented in absolute terms (and thus not as a % change relative to the scenario case).

Table 25 Impacts of policy tests relative to CAEP13 Mid baseline scenario for the year 2038

Effect	Unit	Baseline scenario: CAEP13 Mid 2038	Policy tests results (absolute)			Policy tests impacts (% change relative to baseline scenario)		
			FuelTax 0.50US$_pkg	CO2Tax 50US$_pt	Ticket+CargoTax 10%	FuelTax 0.50US$_pkg	CO2Tax 50US$_pt	Ticket+CargoTax 10%
Air transport demand and aircraft operations								
Passenger demand - scheduled network carriers								
a. First/business	billion pax-km pa	1,123	1,095	1,114	1,104	-2.5%	-0.8%	-1.7%
b. Economy	billion pax-km pa	10,017	9,257	9,758	9,442	-7.6%	-2.6%	-5.7%
c. Total scheduled network carriers	billion pax-km pa	11,140	10,352	10,871	10,547	-7.1%	-2.4%	-5.3%
Passenger demand - LCC and non-scheduled	billion pax-km pa	4,168	3,544	3,938	3,849	-15.0%	-5.5%	-7.6%
Total passenger demand	billion pax-km pa	15,307	13,896	14,809	14,396	-9.2%	-3.3%	-6.0%
Cargo demand	billion tonne-km pa	453	416	440	433	-8.2%	-2.8%	-4.5%
Revenue tonne-Km (RTK)	billion RTK pa	1,883	1,714	1,823	1,777	-9.0%	-3.2%	-5.6%
Available tonne-Km (ATK)	billion ATK pa	2,657	2,427	2,576	2,518	-8.7%	-3.1%	-5.2%
Flights	million	64	58	62	60	-8.5%	-2.9%	-6.1%
Aircraft km	billion ac-km pa	99	91	96	94	-8.3%	-2.9%	-5.7%
Effects on airlines								
Direct operating costs	billion 2019 US $	759	867	794	841	14.2%	4.6%	10.9%
Total operating costs	billion 2019 US $	1,463	1,526	1,483	1,507	4.3%	1.3%	3.0%
Total operating revenues	billion 2019 US $	1,524	1,579	1,542	1,560	3.6%	1.2%	2.3%
Total operating result*	% of revenues	4.0%	3.3%	3.8%	3.4%	n.a.	n.a.	n.a.
Airlines related employment	1000 employees	4,752	4,390	4,626	4,485	-7.6%	-2.6%	-5.6%
Aircraft fleet								
Commercial fleet size	number of aircraft	42,425	38,925	41,168	39,998	-8.2%	-3.0%	-5.7%
Revenues for governments								
Revenue from taxation**	billion 2019 US $	n.a.	176	60	142	n.a.	n.a.	n.a.
Fuel consumption and emissions aviation sector								
Fuel use	billion kg pa	395	353	380	373	-10.6%	-3.8%	-5.5%
CO_2 emissions	billion kg pa	1,247	1,114	1,199	1,178	-10.6%	-3.8%	-5.5%
NO_x emissions	billion kg pa	5.0	4.4	4.8	4.8	-12.0%	-4.4%	-5.1%
PM emissions	million kg pa	73.1	62.6	69.0	69.0	-14.4%	-5.7%	-5.6%
PM emissions LTO cycle	million kg pa	51.2	44.1	48.3	48.3	-14.0%	-5.6%	-5.8%
Operating efficiency commercial aviation								
Direct operating costs / RTK	US$/tonne-km	0.40	0.51	0.44	0.47	25.5%	8.0%	17.4%
Total oparting cost / RTK	US$/tonne-km	0.78	0.89	0.81	0.85	14.6%	4.6%	9.1%
Fuel / RTK	kg/tonne-km	0.21	0.21	0.21	0.21	-1.8%	-0.7%	0.1%
Fuel / ATK	kg/tonne-km	0.15	0.15	0.15	0.15	-2.1%	-0.8%	-0.3%
RTK / ATK	factor	0.71	0.71	0.71	0.71	-0.3%	-0.1%	-0.4%
RTK / aircraft-km	tonne-km/ac-km	18.97	18.82	18.92	18.99	-0.8%	-0.2%	0.1%
Revenues / RTK	US$/tonne-km	0.81	0.92	0.85	0.88	13.8%	4.5%	8.4%
Fuel / aircraft-km	kg/ac-km	3.98	3.88	3.94	3.99	-2.5%	-0.9%	0.2%

* Total operating result is presented as a % of operating revenues for the baseline scenario and the policy cases.
** For policy cases this impact is presented in absolute terms (and thus not as a % change relative to the scenario case).

3.4 Comparison of results with SAVE version of AERO-MS

Results of the updated AERO-MS have been compared with the SAVE version of AERO-MS. This version of AERO-MS was developed in 2009 and had Base Year data for 2006. More information on the results of the SAVE project can be found on the EASA website.[23]

A comparison is made for:

- The Base Year results for 2006 (SAVE) versus the updated results for 2019 providing information on the growth in aviation demand, airline operating costs and revenues and fuel use and emissions over this period;
- The baseline scenario results for 2026 (SAVE) versus the results for 2028 (current version of AERO-MS);
- The percentage impact of a global fuel taxation of 0.50 US$ per kg relative to the baseline scenarios.

The comparison is presented in Table 26.

The comparison of the Base Year results indicates the strong growth of global aviation passenger demand over the period 20006-2019 (annual growth of 4.8%), with the highest annual growth for passenger demand from Low Cost Carriers (LCC) and non-scheduled traffic (8.4%) The annual growth for cargo demand was less (3.3%). This results in an annual growth in Revenue Tonnes Kilometre (RTK) of 4.5%.

According to the Base Year data in the two AERO-MS versions, the annual growth in fuel use and CO_2 emissions of the global aviation industry was 3.5% per annum over the period 2006-2019. The fuel per RTK efficiency improvement was 1% per year over the 13-year period.

In the SAVE version of AERO-MS the Mid Growth forecast of CAEP8 for the years 2016, 2026 and 2036 were implemented. In Table 27 a comparison is made between the SAVE results for the CAEP8 M 2026 baseline scenario and the CAEP13 Mid 2028 baseline scenario implemented in the current version of AERO-MS.

The CAEP forecast for 2026 made as part of the SAVE project (implemented in the model in 2009) shows higher levels of aviation demand and fuel use and emissions compared to the most recent CAEP forecast for 2028. Clearly this is related to the impacts of COVID-19, which has very seriously affected the growth path of the global aviation industry. The forecast of the fuel efficiency for the global aviation industry however is still very comparable between the two baseline scenarios (0.24 kg fuel per RTK for CAEP8 M 2026 versus 0.25 kg fuel per RTK for CAEP13 Mid 2028).

Finally, the impacts of a global fuel taxation of 0.50 US$ per kg computed by the SAVE version and current version of AERO-MS are compared. Table 26 shows a larger impact on overall passenger demand in the current version compared to the SAVE version. This mainly reflects the difference in price elasticities of demand in both model versions (i.e. in the SAVE version the elasticities from a report produced by Intervistas – see also under Task 3 – were not yet implemented). Because of the larger impact on demand also the impact on fuel use and CO_2 emissions is larger in the current version of AERO-MS. The impact on fuel per RTK, which reflects the incentive of a fuel taxation to switch to more fuel-efficient aircraft, is very comparable between the two model versions (1.8% improvement in the SAVE version versus 1.6% improvement in the current version).

[23] https://www.easa.europa.eu/en/document-library/research-reports/easa2009op15

Table 26 Comparison of results updated AERO-MS with the previous, SAVE version

Effect	Unit	Base Year results			Baseline scenario results		Impacts of FuelTax 0.50US$_pkg	
		Base Year 2006 (SAVE)	Base Year 2019	Annual % change (2006-2019)	CAEP8 M 2026 (SAVE)	CAEP13 Mid 2028	% impacts relative to CAEP8 M 2026 (SAVE)	% impacts relative to CAEP13 Mid 2028
Air transport demand and aircraft operations								
Pax demand - scheduled network carriers								
a. First/business	billion pax-km pa	357	627	4.4%	976	764	-2.1%	-2.7%
b. Economy	billion pax-km pa	3470	5,599	3.7%	9419	6,794	-7.0%	-8.2%
c. Total scheduled network carriers	billion pax-km pa	3827	6,226	3.8%	10395	7,558	-6.6%	-7.7%
Pax demand - LCC and non-scheduled	billion pax-km pa	831	2,382	8.4%	1676	2,841	-21.7%	-16.2%
Total passenger demand	billion pax-km pa	4658	8,608	4.8%	12072	10,399	-8.7%	-10.0%
Cargo demand	billion tonne-km pa	159	243	3.3%	509	320	-9.3%	-8.8%
Revenue tonne-Km (RTK)	billion RTK pa	594	1,047	4.5%	1636	1,291	-8.9%	-9.7%
Aircraft km	billion ac-km pa	42	60	2.8%	93	72	-10.3%	-9.2%
Effects on airlines								
Total operating costs	billion US $**	486	827	4.2%	1403	1,098	4.6%	4.5%
Total operating revenues	billion US$**	502	870	4.3%	1453	1,138	4.1%	3.7%
Total operating result*	% of revenues	3.1%	5.0%	n.a.	3.4%	3.5%	2.9%	2.8%
Fuel consumption and emissions aviation sector								
Fuel use	billion kg pa	189	293	3.5%	397	321	-10.5%	-11.1%
CO_2 emissions	billion kg pa	595	925	3.5%	1255	1,012	-10.5%	-11.1%
Operating efficiency commercial aviation								
Total oparting cost / RTK	US$/tonne-km**	0.82	0.79	-0.3%	0.86	0.85	14.8%	15.7%
Fuel / RTK	kg/tonne-km	0.32	0.28	-1.0%	0.24	0.25	-1.8%	-1.6%

* Total operating result is presented as a % of operating revenues for the baseline scenario and the policy cases.

** In the SAVE version of the AERO-MS financial outputs are in US$2006, in the updated verson these are US2019, hence % changes from 2006 to 2019 are in nominal terms.

4. Task 3: Updated price elasticities of demand

Task 3 involved reviewing and updating the price elasticities of demand used in AERO-MS. These values determine how sensitive passenger demand is to changes in fares. This chapter describes the steps undertaken and the changes made to the methodology.

4.1 Review of existing elasticities

The elasticities used in AERO-MS were derived from a report produced by Intervistas on behalf of IATA in 2007 – *Estimating Air Travel Demand Elasticities*. This report recommended some headline elasticities for different types on interventions (route/market level, national level and pan-National level), a range of geographical multipliers and a short haul adjustment factor. The values from the report were used to produce elasticities for AERO-MS using the following method:

- Use the pan-National value of -0.65[24] from the Intervistas report as a starting point, since most testing in AERO-MS is for policies that apply at a pan-National level;
- AERO-MS region pairs were mapped to one of the geographic markets from the Intervistas report and the regional adjustments from the Intervistas report were applied to get an average elasticity by AERO-MS region pair;
- The short-haul multiplier from the Intervistas report was applied to AERO-MS region pairs with an average flight time of less than 2 hours;
- Using the proportions of business and leisure passengers for each AERO-MS region pair, the region pair average value was adjusted for each purpose whilst maintaining a differential of 0.7 between the business and leisure elasticities.

This approach yielded values which varied significantly between different region pairs for the same purpose, simply because one region pair had a larger share of one purpose over another. Some elasticities for certain region pairs were also very high (e.g. stronger than -0.5 for Intra Europe business and up to -1.52 for intra-Europe leisure) and it was found during policy testing that the elasticities yielded demand impacts which were considered to be implausibly high in some cases.

4.2 Update of elasticities

A desktop study was undertaken to identify any new research available that could be used in place of the Intervistas report as the source of the underlying elasticities data. However, no suitable alternative research with sufficient coverage has been carried out since the Intervistas study, so it was decided that the Intervistas report remained the most appropriate source. As part of the ICAO Report on the Feasibility of a Long Term Aspirational Goal (LTAG) for International Civil Aviation CO_2 emission reductions, undertaken in 2022, Appendix M1[25] includes a literature review (Section 6.4) which references the Intervistas report, referred to as the Air Travel Demand Study, when considering elasticities. No alternative studies were identified as part of the

[24] . This value is slightly different to the published figure of -0.6 in the InterVistas study. This is because the Intervistas study elasticities are defined slightly different than elasticities in AERO-MS. In the InterVistas study an elasticity value of -1 means that a price increase of 10% results in a demand reduction of 10% (because the elasticity is multiplicative). In AERO-MS an elasticity value of -1 implies that a price increase of 10% results in a demand reduction of 9.1% (because the elasticitiy is applied as a power function). A base value of -0.65 in the AERO-MS has the same effect (1.1^-0.65-1=-6.0%) compared to a value of -0.6 according to the InterVistas definition of a price elasticity of demand (0.1*-0.6=-6.0%)

[25] https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM1.pdf

literature review, suggesting that the LTAG task group came to the same conclusion regarding the lack of more recent studies to provide the required passenger demand elasticities.

However, the method of using the data from the report to produce elasticities for AERO-MS was revised. The revised process is:

- Use the pan-National value of -0.65[23] from the Intervistas report as a starting point, since most testing in AERO-MS is for policies that apply at a pan-National level;
- Use global business and leisure shares and a differential of 0.6 to obtain global business and leisure elasticities of -0.19 (business) and -0.79 (leisure) – this differential is slightly lower than the 0.7 used in the previous method, but remains in line with evidence and ensures that the business elasticity is not implausibly low;
- For each region pair, apply the Intervistas regional multiplier to both the leisure and business elasticities;
- Calculate the proportion of passenger demand by AERO-MS region pair which has a flight time of less than 2 hours;
- For each AERO-MS region pair, apply the short haul multiplier multiplied by the proportion of demand with a flight time less than 2 hours.

This method produces a more consistent set of elasticities which have less variation for a given purpose. The intra Europe elasticities are very similar to values used in the UK National Air Passenger Model[26]. The values are also lower overall. The values are actually input to AERO-MS by region pair but there are too many region pairs to present individually. The new values have considerably less variation and are in general lower, especially for business.

In addition to updating the elasticities, the purpose to class mapping (ADEM variable PurToClass.csv) was also reviewed and updated. This file specifies the proportion of business and leisure demand for each ticket class and therefore impacts the overall sensitivity of demand to changes in fare. The proportion of business travellers in Economy class was considered to be too high and not consistent with an overall business proportion of approximately 10-15%. The purpose to class mapping was therefore adjusted by factoring the previously established business/leisure split in Economy class such that approximately 10-15% of all air travel was by business purpose.

Following the update to the elasticity values and the purpose to class mapping, the impacts of the changes were assessed by running a 10% ticket tax test which effectively increased fares by 10%. The impacts of this test using both the old elasticities and mappings, and new values are presented in

Table **27**. The impact on first/business class demand is significantly smaller due to the lower elasticities, and the fact that the business/leisure split has not been changed for this ticket class. For Economy passengers, the impact is a slight increase in sensitivity because there is now a higher share of leisure passengers, despite the lower elasticities. For low-cost carriers, all demand is assumed to be leisure, so the impact is reduced in line with the reduction in the elasticities. Overall, the impact is a slight reduction in sensitivity to -6.1% in response to a 10% increase in fare. This represents an overall elasticity of -0.66[27], which is very close to the overall elasticity of -0.65 used as the starting point from the Intervistas report.

Table 27 Impact of 10% ticket tax test using old and new elasticities and purpose to class mappings

[26] Econometric Models to Estimate Demand Elasticities for the National Air Passenger Demand Model, DfT, 2022 assets.publishing.service.gov.uk/media/6235a5378fa8f540edba36f5/econometric-models-to-estimate-demand-elasticities-for-the-national-air-passenger-demand-model.pdf

[27] Elasticity = ln(1-0.061)/ln(1+0.1)

IATA Region	Demand impact: old elasticities and purpose shares	Demand impact: new elasticities and purpose shares
Network carriers - first/business	-3.3%	-1.7%
Network carriers - economy	-5.3%	-5.8%
Total network carriers	-5.1%	-5.3%
LCC and non-scheduled	-10.0%	-8.0%
All passengers - all carriers	-6.5%	-6.1%

5. Task 4: Adding Particulate Matter emissions

This task extends the current set of AERO-MS emissions, CO_2, H_2O, CO, NO_x, C_xH_y and SO_2 with volatile and non-volatile particulate matter (PM). This chapter describes the activities performed, the choice for a modelling approach and data sources, and the required changes to the various models and framework.

Particulate Matter is the term used to describe particles with an aerodynamic diameter of 10 micrometres or less. Most PM emitted from aircraft engines are fine particles with an aerodynamic diameter of 2.5 micrometres or less (PM2.5). PM emitted from gas turbines is formed during a complex combustion process that, due to the conditions in the combustion chamber and the (lossy) composition of jet fuel, lead to partially incomplete oxidation and secondary formation from other types of combustion products. Hence, PM is a combination of solid and liquid particles of varying sizes and composition.

Since decades, epidemiological evidence indicates that fine particles impact human health and cause contamination of soil and food. More recently, soot or black carbon particles have also been shown to contribute to climate impacts.

5.1 Activity breakdown

One of the functionalities of AERO-MS is to compute aviation emissions and the distribution in the world's atmosphere. This task extends the current set of emissions (CO_2, H_2O, CO, NO_x, C_xH_y, SO_2) with volatile and non-volatile particulate matter (PM). The following activities have been undertaken:

- A desk top study to investigate the state-of-the-art PM modelling with an eye to the purpose and capabilities of AERO-MS;
- Inventory of the modelling options, requirements and data availability; selection of the preferred PM modelling approach;
- Investigation into required framework and software changes, associated update of data and other AERO-MS data enhancements. Adding PM as one additional emission to AERO-MS involves changes in the software environment at several places:
  - ➢ The user interface (and framework) needs to offer user options to define a PM emissions scenario (timeline) that defines a future state of the art PM emissions;
  - ➢ The user interface (and framework) needs to offer the user access to the resulting, calculated PM values that are internally stored as results by flight stage (airport pairs), by aircraft seat-band and technology level, as world-spanning 3-dimenensional grid. These outputs can further be aggregated or summed, allowing to compare policies, fleet properties, and flight trajectories, and allow aggregation into inventories by countries, regions, altitude bands etc.;
  - ➢ Investigation of the models that need updates to include PM and find the "best places" to include the PM related algorithms and variables, including the links to the user interface. For this purpose, the fleet properties and the underlying technology scenario (ATEC), the representative aircraft data (FLEM) and several calibration factors need extension to accommodate PM;
  - ➢ Population of the PM related variables with data relevant for the fleet and traffic. Update and adjust the software source code;
  - ➢ Testing the updated models and ensure internal consistency. Partially tests have been done in this task; overall testing is done in Task 2.
- Update AERO-MS and commit the software and data changes to the software repository.

5.2 PM modelling selection

Since decades PM emissions have drawn attention in the technical world because of the epidemiological and climate concerns. Following these concerns, PM emissions have been studied in various ICAO/CAEP cycles as early as 2010, leading to setting ICAO Standards for PM emissions certification in the 14th cycle, and embedded in Annex 16, Volume II. The standards apply for turbofan/turbojet engines >26.7 kN. The certification process involves running the engine on a test bed at 4 specific thrust settings. Relevant certification data are stored in the publicly available ICAO engine emissions database, but is limited to engines of aircraft in production. Engines out of production but still in service do not have to be certified.

For those aircraft engines for which no PM engine certification data is available, ICAO has published (Doc.9889) a reasonably robust relationship between the SN and nvPM mass concentrations. Doc9889 also holds an estimation method (FOA3.0) for volatile PM based on fuel organics and sulphur content. However, these methods are intended to be used only for emission inventory purposes within the vicinity of airports.

Nevertheless, the CAEP process has not (yet) defined a robust algorithm that allows to predict the PM emissions along a full aircraft flight trajectory that includes cruise and for operating conditions throughout the aircraft flight envelope.

Also noted: over the years, and well before a new PM standard settings has been initiated, there have been many different approaches to calculate PM, usually based on Smoke numbers as no PM certification data were yet at hand. Smoke numbers are determined in the ICAO engine certification process for a long time and also cover aircraft that are out of production. Smoke Numbers are a quantity measure of the particles that mainly consist of carbon and are visible to the human eye. PM have a similar composition but are much smaller and not visible.

As a consequence, as AERO-MS is focused on full flights and most of the time spent in flights is at higher altitudes and speed, there is currently still no agreed and robust algorithm to calculate PM along a full flight trajectory. As a fallback, the Boeing-2 method has been selected to calculate the PM along a flight trajectory using the certified PM data in the ICAO Emissions Database. This model has the advantage that it considers the data recorded in the ICAO engine database (holding measured PM values), the operational conditions along a flight trajectory, and elementary gas turbine theory. However, Boeing-2 leaves room for interpretation, and varying implementation according to the type of emissions. The interpretation covers two aspects: the effect of pressures on the emissions downstream of the combustion chamber and how to interpolate (linear, logarithmic and variants thereof) between the different throttle settings for which emission data are measured. The typical thrust settings in cruise do not nicely align with the thrust conditions for takeoff, climb, approach and taxi. And, the modern engines adopt different concepts of burning fuel; among them lean burn and rich burn that might warrant different ways of interpolation.

Here Boeing-2 variant for the unburnt hydrocarbons is used as this is believed to be the closest to the PM formation. In broad lines, the Boeing-2 method converts engine fuel flow at a given speed and altitude to an equivalent fuel flow at static (zero altitude, zero speed) conditions assuming equal temperature at turbine entry. It is then assumed that for the same turbine entry temperature, PM production per unit of fuel (the emissions index) is the same. This equivalent fuel flow is then used to interpolate between the fuel flows and PM emission indices as recorded in the ICAO engine emissions database that holds data for static conditions. As such, the characteristics of the engine are broadly taken into account. The interpolated PM value is then scaled back to the operating conditions by correction through turbine entry pressures. Note that the combination of temperature and pressures, this is also a proxy for the air density. Air density is an indicator for clustering of many small particles into fewer, larger particles. Finally, the emission index is translated into actual PM emissions using the actual fuel flow.

5.3 Implementation

The implementation of PM required changes to the software and data variables of the ATEC and FLEM models as well as the framework user interface and data handling.

The framework definitions are extended in such a way that all input, scenario and policy variables that have a dimension "emission" in their definition, now accommodate PM alongside other emissions. Additional changes have been made to allow user access to the related data variables in the user-interface and allowing transferring and aggregation of data between models. As a result, the user interface (and framework) has access to the resulting, calculated PM values, stored by flight stage (airport pairs), by aircraft seat-band and technology level, and PM values stored in a world-spanning 3-dimenensional grid. The framework allows PM outputs to be aggregated or summed, allowing to compare policies, fleet properties, and flight trajectories, and allow aggregation into inventories by countries, regions, altitude bands etc.

The interface also holds a facility to build scenarios. One of the options is to build technology scenarios for emissions that represent the state-of-the art as a function of time (future years) by aircraft seat-band. This technology scenario can now hold PM emissions as well.

ATEC describes the fleet properties (by seat-band and technology level) that are derived from the historic fleet build-up (base case) and future (scenario) trends in engine technologies. The ATEC software code and data have been extended with PM and involved several tasks:

- Extending software source code and (emission) data structures to include PM;
- Gather PM related data from the engine ICAO emissions database for all aircraft in the Cirium fleet;
- Set up a historic timeline of aircraft-engine combinations with the PM values. This activity is similar to that for other emissions types. For most aircraft that are in operation today, PM values are available. However, for the oldest aircraft in the fleet, no PM certification values exist. Instead it is explored if Smoke Numbers (SN) and the conversion to PM using the FOA4 method can be used as a proxy. This appeared not a reliable way, but at the same time did not really affect the PM scenario development;
- Recalibrate the detailed aircraft engine data to match the aircraft in seat-band covering the default ICAO engine certification thrust settings.

The FLEM model takes the results of ATEC and the traffic database and converts the fleet properties and origin destination into a 3-dimensional flight trajectory. FLEM actually calculates the emissions along a flight trajectory and the software code has been extended to calculate PM as a function of fuel flow, speed and altitude in a similar way as other emissions. This includes the outputs and emissions aggregations.

The fleet properties, the underlying technology scenario (ATEC), the representative aircraft data (FLEM) and several calibration factors have been redone to accommodate PM.

6. Task 5: Improved function for data export

The main purpose of Task 5 is to improve the AERO-MS function for data reporting and export. This allows for an easier access to data for side-/post-processing, and for easier producing detailed output tables as especially required by the EC. As part of Task 5 the Team:

1. Modified the model DECI whereby output variables are now created with available tonne kilometres (ATK) by flight stage (i.e. flight stages in AERO-MS reflect airport pairs). This allows the AERO-MS user to show load factors at country level. The computation of Revenue Tonne Km (RTK) by flight stage was already included in the computed by DECI.
2. Improved the AERO-MS reporting and export function, whereby the user is now able to export output variables by flight stage to a single excel file.

The new ATK related output variables are comparable to the RTK related output variables by flight stage. This offers the option to calculate load factors at any level (e.g. for all flights departing from a certain EU country). For the computation of ATK by flight stages 3 new output variables are created. These relate to:

- The available seat km by flight stage for operations of scheduled network carriers;
- The available seat km by flight stage for scheduled operations of LCC and charter operations;
- The available freight capacity by flight stage (both in the belly hold of passenger aircraft and of freighters.

The AERO-MS reporting and export function has greatly improved. It is now possible in the AERO-MS user interface to create a custom report to export any subset of variables which are dimensioned by flight stage. During the training of AERO-MS it will be shown how this is done.

Furthermore, the speed by which aggregations are made by the Interface is greatly improved. This by implementing a more efficient aggregation method which was not yet available when the first version of AERO-MS was developed. This allows users to quickly aggregate flight stage data to for example country pair.

Moreover, a new dimension in AERO-MS has been implemented: ICAO Member State. All 249 countries in the updated AERO-MS are allocated to one of the 193 ICAO Member States. The implementation of the new dimension ICAO Member State allows for the quick reporting of CO_2 emissions by ICAO Member State Pair. This can support CORSIA related analysis because offset requirements under CORSIA are valid for a sub-selection of ICAO Member State Pairs.

7. Task 6: Specification of detour factors by flight stage

Task 6 was to specify in AERO-MS detour factors by flight stage[28]. This improvement allows for a more accurate computation of fuel use at a disaggregated level.

In FLEM the detour factor is used to simulate detours resulting from the fact that great circles are not always flown by aircraft. Detour factors reflect the relative difference between great circle distances and actual flight distances. In AERO-MS the detour factors have an impact on the fuel use in cruise phase of the flight and consequently on aircraft take-off weights.

The variable FLEM_DetourFactor in the AERO-MS module FLEM contains the detour factors. In the 2006 version of AERO-MS, the variable was dimensioned by region pair and aircraft type. Within a region pair, flight distances can significantly vary however and detour factors are especially different for very short distances (i.e. short distances imply higher detour factors). Therefore, as part of Task 6 the dimension of the variable FLEM_DetourFactor has been changed from region pair to flight stage (whereby the dimension aircraft type has become redundant).

The main steps to implement this improvement in AERO-MS, as part of Task 6, were:

- Change the dimensions of the variable DetourFactor in FLEM;
- Change the code of other AERO-MS modules (DECI and ACOS) where the variable DetourFactor is used;

With regard to ACOS, calculations using the detour factor variable are performed in a loop over region pairs. These calculations relate to the computation of en route navigation costs. Here the use of flight stage specific values is not relevant. Therefore, in ACOS the 'old' DetourFactor with dimension region pair is computed based on the new DetourFactor with dimension flight stage. A weighted average DetourFactor per region pair determined in AERO-MS is computed based on the following steps:

1. Variable $ADEM\_AT\_Movements_{tr,\ at,\ tl}$, is aggregate from traffic line (tr) to flight stage and aggregate over aircraft type (at) and technology level (tl). This gives the temporary variable $AT\_Movements_{fs}$;
2. Aircraft km per flight stage with the detour factor by flight stage are calculated by: $ADEM\_AT\_Movements_{fs}$ * $ADEM\_AT\_Greatcircle\_Distance_{fs}$ * $FLEM\_DetourFactor_{fs}$;
3. Aircraft km per flight stage without detour factor are calculated by: $ADEM\_AT\_Movements_{fs}$ * $ADEM\_AT\_Greatcircle\_Distance_{fs}$;
4. Results per flight stage from Steps 2 and 3 are aggregated to region pair, and the totals of Step 2 per region pair are divided by the totals of Step 3 by region pair. This gives the weighted average DetourFactor by region pair which is used in ACOS.

On the basis of CAEP and EUROCONTROL data regarding the relationship between flight distance and detour factor, as part of Task 6 a set of detour factors was assessed for the 113,514 flight stages in the updated AERO-MS. For this, use was made of the updated variable ADEM_ AT_Greatcircle_Distance which provides the great circle distance for each of the flight stages. The detour factors were further fine-tuned as part of the calibration of the CO_2 emissions computational results for the new Base Year 2019 in task 1.

[28] Each flight stage represents a connection between two airports. In fact, flight stages in AERO-MS reflect airport pairs.

Figure 20 below presents the relationship between flight distance and detour factor as included in AERO-MS.

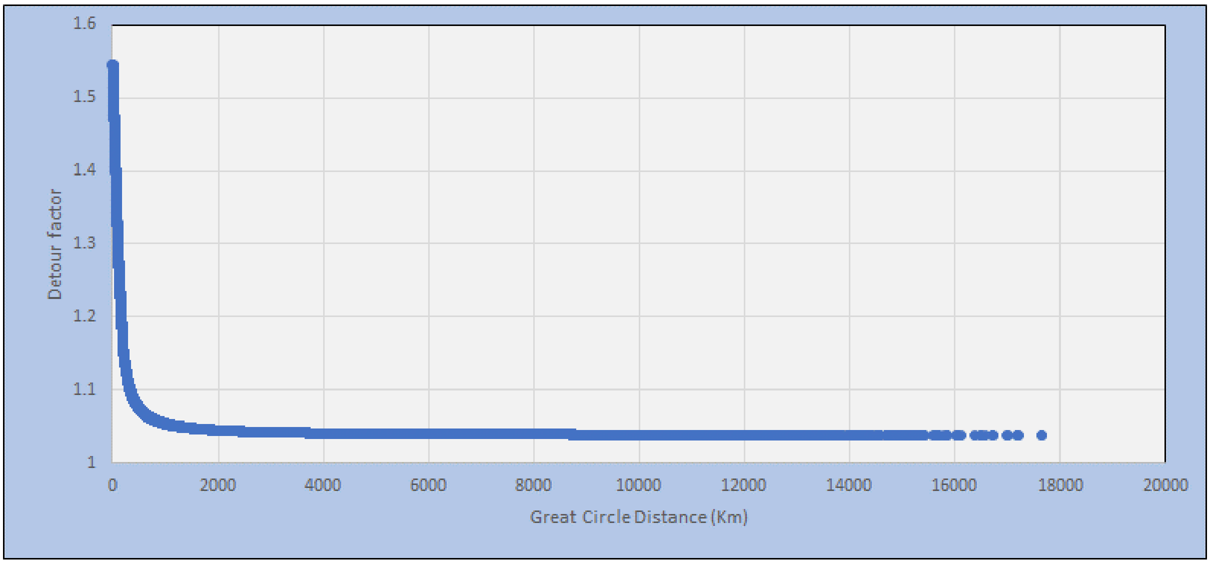


Figure 20 Flight distance versus detour factor in AERO-MS

8. Task 7: Better alignment with PRIMES-TREMOVE

8.1 Introduction

This task is to better align AERO-MS with PRIMES-TREMOVE. A better alignment will improve impact assessments made for the EC. PRIMES-TREMOVE is widely used by the EC, and therefore aligning AERO-MS with PRIMES-TREMOVE could lead to more interest in the use of AERO-MS for air transport studies in relation to for example the implementation of the Fit-for-55 Package.

The EU Reference Scenario is the EC's main baseline scenario for European transport, energy use and greenhouse-gas emissions, which provides policy-makers a reference situation against which they can assess policy proposals. The EU Reference Scenario is developed using a modelling framework whereby the EU transport system is modelled in PRIMES-TREMOVE. In order to prepare AERO-MS for use in future EC impact assessments in the field of aviation, there is great merit in developing procedures to include the aviation part of the EU Reference Scenario in AERO-MS and to establish further linkages between PRIMES-TREMOVE and AERO-MS.

As part of this task the Team has discussed the alignment of PRIMES-TREMOVE and AERO-MS for modelling the aviation part of the EU Reference Scenario and potential linkages between the models with representatives of DG-MOVE.

The result of this task in described is the following sections:

1. Short description of the PRIMES-TREMOVE model;
2. Differences, similarities and complementarity of AERO-MS and PRIMES-TREMOVE;
3. Implementing the EU Reference scenario in AERO-MS.

8.2 Short description of the PRIMES-TREMOVE model

PRIMES-TREMOVE is part of a larger modelling system, referred to as the PRIMES model. The PRIMES model is a comprehensive energy system model that provides a detailed analysis of the EU's energy and industry sectors which are included in the EU ETS. PRIMES includes the electricity, gas, oil, and renewable energy sectors, as well as their supply chains and demand-side components. The model takes into account the policy and regulatory framework, as well as the economic, environmental, and technological factors that influence the energy system. The model also provides a comprehensive analysis of the interactions between the energy and transport sectors in the EU. This allows policymakers to develop policies and strategies that take into account the interdependencies between these two critical sectors and their impact on the environment, the economy, and society as a whole.

The PRIMES-TREMOVE model is the part of the overall PRIMES model that focuses on the transport sector in the EU. It provides a detailed analysis of the demand for transport, the fleet, and the infrastructure required to support transport activities. The model also takes into account the environmental and economic impacts of transport activities, as well as the policy and regulatory framework that affects the sector.

The PRIMES-TREMOVE model is used by the EC for policy formulation. Model projections include the transport demand by the transport mode including aviation. The model includes passenger demand for European aviation. Also, the model takes into account technologies and fuels, including conventional and alternative types of fuel. Energy demand and greenhouse gases are an important output of the model.

PRIMES-TREMOVE can show how policies and trends in the field of transport, including aviation, contribute to economy wide trends in energy use and emissions. Using data disaggregated by Member State, the model can show differentiated trends across Member States. PRIMES-TREMOVE can be used to model different types of policy measures in the aviation sector. Examples are taxes on fuels, ETS for aviation and blending mandates for Sustainable Aviation Fuels (SAFs).

The TREMOVE model includes passenger demand data for European aviation. Passenger demand data are split out by EU Member State. Also, data for EEA Member States which are not an EU Member (Norway and Iceland) and EU candidate countries are included. Finally, the model includes data for the UK, but after Brexit there are no requirements for the UK anymore to deliver data, and hence these data are less up to date.

8.3 Differences, similarities and complementarity of PRIMES-TREMOVE and AERO-MS

The differences and similarities between PRIMES-TREMOVE and AERO-MS have been assessed. For this the Team has had an interaction with staff members of DG MOVE by which PRIMES-TREMOVE is used frequently for impact assessment studies.

The comparison between PRIMES-TREMOVE and AERO-MS focuses on aspects regarding aviation, which is basically the area where both models overlap.

A first clear difference between the PRIMES-TREMOVE and AERO-MS is that the latter model only covers the aviation sector, whereas PRIMES-TREMOVE is a multi-modal transport model which also covers the energy sector in the EU.

For aviation the geographical scope of both models also very clearly differs. PRIMES-TREMOVE covers flights departing from a set of European countries (EU27, Norway, Iceland, the UK and EU candidate countries) whereas AERO-MS covers global flights. Furthermore, AERO-MS has a much higher granularity with model data for about 113,000 separate airport pairs. PRIMES-TREMOVE on the other hand operates on the level of countries, with per country a distinction between Intra European flights and extra European flights and a distinction between distance bands.

Another difference between the two models is that AERO-MS considers both air transport passenger and freight demand whereas PRIMES-TREMOVE only includes air transport passenger demand.

For PRIMES-TREMOVE the main outputs for the air transport sector relate to passenger demand, energy demand and emissions (CO_2, NO_x and PM). AERO-MS has a wider range of outputs for the air transport sector. The main outputs relate to:

- Number of flight operations and aircraft km;
- Pax and freight demand;
- Airline costs and revenues;
- Fuel use; and
- Emissions (CO_2, NO_x, H_20, SO_2, C_xH_y, CO and PM).

Both models consider demand responses to a policy induced increase in ticket prices. These policies can for example be the inclusion of aviation in the EU ETS, CORSIA, a fuel or ticket taxation or fuel price increases due to a SAF blending mandate.

Regarding the inclusion of aviation in the EU ETS, AERO-MS uses the EU ETS allowances prices as an input. This because the marginal abatement costs for CO_2 emission reduction in the aviation sector are lower compared to other sectors included in the EU ETS, which implies that the aviation sector will be a price taker. PRIMES-TREMOVE however is part of the larger PRIMES model which takes into account all sectors included in the EU ETS. Using marginal abatement costs in all economic sectors included in the EU ETS, PRIMES outputs the EU ETS allowances price. This is then an input for the aviation module in PRIMES-TREMOVE but can also be used as an input to the AERO-MS.

Table 28 shows a summary of the comparison between the two models.

Table 28 Comparison between PRIMES-TREMOVE and AERO-MS regarding aviation

	PRIMES-TREMOVE	AERO-MS
Overall scope		
Non-transport sectors	Energy sector in EU	None
Transport sectors	All transport modes in EU	Only aviation
Aviation scope		
Geographical coverage	Flights departing from EU27+NO+IS+UK+EU candidate countries	All global flights
Level of detail	Intra EU and extra EU total per country and distance band	About 113.000 airport pairs
Passengers/freight	Passengers	Passenger and freight
Main outputs for aviation	Pax demand, energy, emissions	Number of flight operations and aircraft km, pax and freight demand, airline costs and revenues, fuel use, emissions
Demand response to a policy induced increase in ticket prices	Yes	Yes
EU ETS allowances prices	Output (from the overall PRIMES model)	Input

From the comparison it follows that both PRIMES-TREMOVE and AERO-MS can be used for impact assessment of various aviation related EU policies (i.e. EU ETS, fuel taxation, use of renewable aviation fuels). PRIMES-TREMOVE is suitable for aviation policy assessments where linkages with other EU economic sectors are relevant (e.g. EU ETS for aviation in relation to EU ETS for other economic sectors). AERO-MS on the other hand is more suitable for aviation policy assessments where linkages with global aviation policies are relevant (e.g. EU ETS for aviation in relation to CORSIA).

8.4 Implementing the EU Reference scenario in AERO-MS

The EU Reference Scenario is regularly updated whereby the updated scenario is implemented in the PRIMES-TREMOVE. A procedure has been developed how to, based on PRIMES TREMOVE data, include the aviation part of the EU Reference Scenario in AERO-MS. The implementation of the EU Reference Scenario in both models provides a common starting point for aviation policy impact assessments.

Outputs of PRIMES-TREMOVE in relation to European aviation are made available in a spreadsheet with a fix format. The main outputs are:

- Passenger demand in billion pax km (Gpkm);
- Energy demand in thousand ton of oil equivalent (ktoe);
- CO_2 emissions in kilo-tonne (ktons).

These outputs are dimensioned by:

- Country (EU27+NO+IS+UK+EU candidate countries);
- Domestic and International intra-EU versus International extra-EU;
- Distance band (<500km; 500-1,000km; 1,000-1,500km; 1,500-2,000km; and >2,000km);

- 5-year intervals.

Other relevant PRIMES-TREMOVE outputs are:

- International oil price in € per barrel per 5-year interval;
- EU ETS carbon price in € per tonne CO_2 per 5-year interval;
- Share of biofuels as a % of total energy consumption per country and 5-year interval.

The following steps need to be taken for implementing the EU Reference Scenario, reflected by the PRIMES-TREMOVE aviation data, in AERO-MS:

- Specify growth in passenger demand;
- Specify crude oil and carbon price;
- Specify growth in energy demand and CO_2 emissions.

8.4.1 Specify growth in passenger demand

In AERO-MS a baseline scenario is specified for a specific year. Typically, a baseline scenario input file is made for years with a 10-year interval. Furthermore, it is noted that the Base Year in AERO-MS is updated to 2019. The inputs for the Base Year 2019 are fixed, well calibrated and cannot be modified by the AERO-MS model user.

In AERO-MS there are two ways to forecast/specify the growth in global aviation passenger demand. The first is to input variables related to growth in GNP, population and export. AERO-MS then works out the growth in demand using elasticities. The second option for the AERO-MS user to take on board the growth in passenger demand from an outside source and input that to the AERO-MS model. This in order to model a specific future situation for the global aviation industry against which the impacts of greenhouse-gas emission reduction policies can be assessed. Clearly when taking on board the growth in passenger demand from PRIMES-TREMOVE in AERO-MS this second option is adopted.

For this second option AERO-MS can make use of the scenario variables PaxAutoGrowth_FS. This variable is dimensioned by:

- Flight stage;
- Movement type.

Each flight stage represents a connection between two airports (airport pair). The dimension movement type makes a distinction between passenger demand for:

- Scheduled flight operations of network carriers;
- Flight operations of low-cost carriers and charter operations.

In order to input the PRIMES-TREMOVE passenger demand data into AERO-MS, they first need to be translated into an average annual growth percentage between the AERO-MS base year (2019) and the forecast year for which an AERO-MS baseline scenario is specified (e.g. 2050). These growth percentages can be simply computed based on the absolute numbers in the PRIMES-TREMOVE data. The resulting annual passenger demand growth percentages (dimensioned country, intra EU versus extra EU and distance band) then have to be assigned to the appropriate AERO-MS flight stages. This can be done as follows:

- For each flight stage the airport of departure and arrival is known (AERO-MS variables AT_City_of_Departure and AT_City_of_Arrival), and for each airport the country is known (AERO-MS variable AT_Country);
- For each flight stage the great circle distance is known (AERO-MS variable AT_Greatcircle_Distance).

The PRIMES-TREMOVE data do not distinguish between the passenger demand growth for network carriers and low-cost carriers. Over the last decades however, passenger demand growth for low-cost carriers for the intra-EU market has been significantly higher compared to network carriers. This has resulted in a steadily increase of low-cost carrier market share. The AERO-MS variable PaxAutoGrowth_FS allows to specify different values by movement type, and thereby assume a continued higher growth in passenger demand for low-cost carriers.

In some studies[29], where PRIMES-TREMOVE data have been implemented in AERO-MS, after consultation with the EC, growth in passenger demand for the two movement types where specified differently. This was done in such a way that the overall growth in passenger demand still matches the PRIMES-TREMOVE data.

AERO-MS also needs input for the growth in air transport cargo demand (AERO-MS variable CgoAutoGrowth_FS). These data are not provided by PRIMES-TREMOVE and need to be based on a different source.

8.4.2 Specify oil and carbon price

As part of any AERO-MS baseline scenario the user can specify changes in unit cost for various variable airport operating cost categories. The main one is the specification of the expected development of the international oil price. For this the scenario variable CrudeOilPrice is available. This variable expresses the crude oil price in terms of US$ per kg. For any future year the forecasted change of the crude oil price relative to the Base Year 2019 can be specified. In the case of the implementation of the EU Reference scenario in AERO-MS, this change can be based on the PRIMES-TREMOVE data.

In relation to the carbon price, it needs to be assessed whether the carbon price reflects the price which is related to existing policies. If so, these existing policies need to be reflected in the AERO-MS baseline scenario. This baseline scenario is then available in AERO-MS as a reference scenario to assess the impacts of additional greenhouse-gas emission reduction policies Hence if the carbon price included in the PRIMES-TREMOVE data reflects existing polices, it needs to be included in the EU Reference scenario implemented in AERO-MS.

8.4.3 Specify growth in energy demand and CO_2 emissions

The growth in energy demand and CO_2 emission resulting from an AERO-MS baseline scenario is one of the main computational results. There are a number of AERO-MS scenario variables available to the AERO-MS user which affect the computational results. These are:

- FuelUseFactorChgFunc: Fuel use efficiency improvement over time in terms of a percentage improvement of new aircraft relative to previous year;
- DetourFactor: Ratio between actual flight distance and Great Circle Distance.

The AERO-MS scenario variable FuelUseFactorChgFunc is dimensioned by AERO-MS generic aircraft type and by year. For each aircraft type, a fuel use efficiency improvement function can be specified (use of dimension year). This AERO-MS variable is typically used to implement technology improvement scenarios defined by CAEP/WG3. For implementing the EU Reference Scenario in AERO-MS this variable is also to be used. The user can assess the fuel use efficiency improvement included in the EU Reference Scenario by comparing the growth in passenger demand and the growth in energy demand. Typically, the EU Reference Scenario shows a lower growth in energy demand reflecting a fuel use efficiency improvement, which can be reflected when implementing the EU Reference Scenario in AERO-MS.

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[29] For example, the study for the EC on the taxation of the air transport sector: taxation-customs.ec.europa.eu/system/files/2021-07/Aviation-Taxation-Report.pdf

The AERO-MS scenario variable FuelUseFactorChgFunc does not allow to reflect specific fuel use efficiency improvements in different geographical markets (e.g. flights to/from a specific EU Member State). In case the PRIMES-TREMOVE data for the EU Reference Scenario show differences between the fuel efficiency improvements for different geographical markets, in AERO-MS this can be reflected by the variable DetourFactor. This AERO-MS variable is typically used to implement operational improvement scenarios defined by CAEP/WG3. As part of Task 6 (cf. Chapter 7), the scenario variable DetourFactor is dimensioned by flight stage (airport pair). By this the user can specify operational improvements for each airport pair separately using the information on the country of departure and arrival for each airport pair (AERO-MS variables AT_City_of_Departure, AT_City_of_Arrival and AT_Country – see above).

Finally, the impact on CO_2 emissions of biofuels being introduced as part of the EU Reference Scenario can be included in AERO-MS by using the new variable implemented as part of Task 9 (variable SAF_CO2_reductionfactor; cf. Chapter 10).

8.5 Conclusions and recommendations

The main conclusions from Task 7 are:

- There are clear differences and similarities between PRIMES-TREMOVE and AERO-MS. The PRIMES-TREMOVE model is a multi-modal transport model which also covers the energy sector in the EU. For aviation PRIMES-TREMOVE covers passenger demand data for European aviation. AERO-MS is involved with aviation only, but has global coverage for both passenger and freight demand. Moreover, AERO-MS contains a greater level of detail for aviation (about 113,000 airport pairs);
- AERO-MS can be aligned with PRIMES-TREMOVE by implementing the EU Reference Scenario in AERO-MS. Procedures to do so have been developed as part of Task 7;
- PRIMES-TREMOVE is part of the larger PRIMES model which takes into account all sectors included in EU ETS. Using marginal abatement costs in all economic sectors included in EU ETS, PRIMES outputs the EU ETS allowances price. This is then an input for the aviation module in PRIMES-TREMOVE but can also be used as an input to AERO-MS;
- Both PRIMES-TREMOVE and AERO-MS can be used for impact assessment of various aviation related EU policies (i.e. EU ETS, ReFuelEU aviation, fuel taxation). PRIMES-TREMOVE is suitable for aviation policy assessments where linkages with other EU economic sectors are relevant. AERO-MS on the other hand is suitable for aviation policy assessments where linkages with global aviation policies are relevant.

Recommendations are:

- Use the PRIMES-TREMOVE model and AERO-MS in conjunction to assess the impacts of European policies to reduce aviation emissions. This because these policies (e.g. EU ETS, ReFuelEU aviation) have interlinkages with other modes of transport and other economic sectors in Europe, and with policies to address aviation emissions globally (e.g. CORSIA).
- Implement the most recent version of the EU Reference scenario in AERO-MS. This would make AERO-MS ready to be applied for impact assessments of European policies (e.g. ReFuelEU aviation). Also, it would make AERO-MS ready to be applied for the European Aviation Environmental Report 2025.

9. Task 8: Promotion of variables to scenario level

This task investigates whether to promote some variables that hold assumptions with fixed values to scenario variables where values vary with time. The investigation shows that some related observed data appear to change over time. In consultation with EASA some variables have been modified to allow changes as part of a scenario. This task has been relatively small.

9.1 Introduction

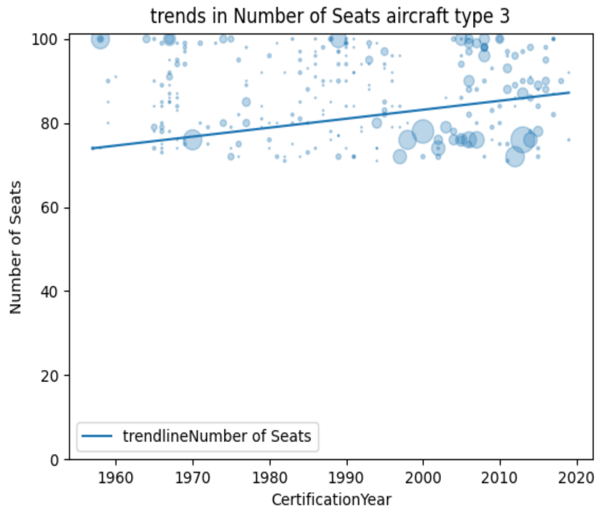
The values of some AERO-MS variables are fixed throughout the model and will not vary with time, even if calculations are made as part of a scenario in a future year. Some of these variables appear to have changed over time if looking back in time. E.g. some aircraft have seen the number of seats increased over the years and aircraft ranges have increased as new variants have come to the market. This implies that, over time, aircraft types might slowly “outgrow” their original AERO-MS seat-band and haul designation. Also, if a production runs over a long-time span, an aircraft type may both be present in the old and current technology levels. Such observations, and having fixed values within AERO-MS, may become significant as these might impact some outputs and assessments. Therefore, this task was to investigate what variables change significantly over time while the model assumes them constant.

Important to note is that the original AERO-MS seat classification did have multiple generic aircraft types with the same seat range but different ranges (hauls). Also, seat band boundaries were such that the same aircraft type could occur in different generic aircraft types just because the seating arrangement varied between operators, or its range has increased because of additional fuel capabilities. This blurred the development of fuel burn scenario. In this version of AERO-MS seat band and haul combinations have been revised. Now this is far less of a concern as seat-band and haul classifications do not overlap.

9.2 Selection process

For this purpose, a list of variables that hold assumptions and inputs (having fixed values) is compiled. These variables are then reviewed whether they are meaningful for outputs while not covered (indirectly) in a scenario. If so, it is checked whether there is historic data readily available in the data sources. From this list, it shows that most of these data concern aircraft specific data. Aircraft types (and within the same seat band) show trends in weights, freight and seat capacities, whereas AERO-MS assumed them constant. Traffic volume, demand, costs, fuel burn and emissions developments are all covered (well enough) by scenarios. Also, impact of aircraft weights is implicitly covered by fuel burn scenarios. However, there is a historic trend in the number of seats and the cargo weights within a seat-band. And many outputs from AERO-MS report transport related values with reference to passenger-kilometers, or tonne-kilometers that affect interpretations. One example is a comparison on the basis of costs per passenger-kilometer versus costs per aircraft kilometer.

To illustrate this process, the trends in two representative seat-bands in the seats are visualised. Each unique combination of aircraft-engine-seating is inventoried from the Cirium data base and the first production year and the number of aircraft (with the same engine and seating) produced. To discover potential trends, timelines are compiled on the basis of aircraft seat-bands. In these graphs, each individual data point that represents a unique aircraft-engine-seating combination. The size of the datapoint is the number of aircraft built with that with that unique combination. The x-axis denotes the first build year of that unique combination, the y-axis denotes the number of seats. A trendline is then calculated allowing for a single kink to identify potential trend breaks. From this representation is clear that there is a trend apparent in the number of seats.



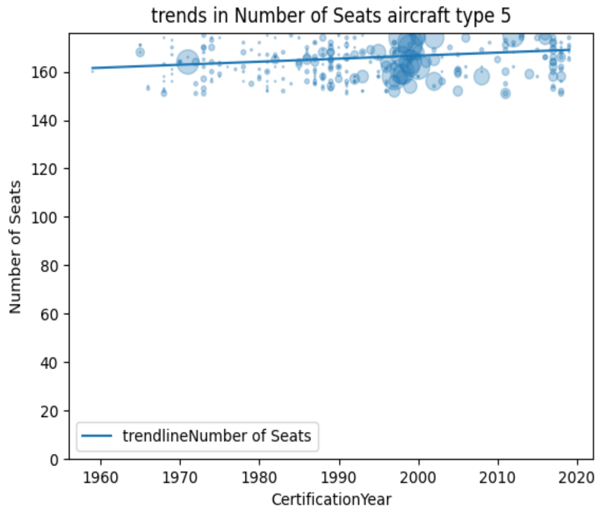


Figure 21 Assumption variables having trends

9.3 Proposed candidates and implementation

From this process, a few key variables are proposed to be promoted from assumption to scenario type: the number of seats and the cargo capacity of passenger aircraft. Within a seat-band, these appear to show a trend over a longer period of time. To implement these variables some changes had to be made to the source code and variable definitions. The table below shows the newly introduced scenarios variables with description and dimension.

Table 29 Candidate scenario variables

Variable	description	dimension
AIMS_AveSeats	Average number of seats for each aircraft type	[Aircraft type]
AIMS_PaxAcCargoAd	Adjustment for Cargo Carried on Pax Aircraft	[Aircraft type]

10. Task 9: Impacts of SAF and related policies included

Task 9 is to include impacts of Sustainable Aviation Fuel (SAF) in the form of drop-in fuels. These types of fuel resemble conventional kerosene in their specification and combustion properties and therefore require no or minor modifications to existing aircraft. The chemical composition is close to kerosene in terms of hydrocarbons but have fewer contaminations and lower aromatic content.

The production pathways and distribution of SAF are very different to kerosene and come with much higher costs. There are likely to be major impacts on costs of operations, and changes on the fuels market are limited if not supported by market-based measures.

This task describes how drop-in SAF is embedded in AERO-MS including the potential supporting pricing policies and economic driven responses of the stakeholders.

In an early stage it was decided, in consultation with EASA, not to consider alternative propulsion systems (like electric power, fuel cells and hydrogen). These kinds of systems are still in a research phase and no aircraft types have been readied for certification, production or in service. As of today, it is rendered impossible to predict the physical, performance and operational aircraft characteristics. Views on the market chances of such aircraft and the required supporting (fuel) infrastructure are at very early stage. AERO-MS is focussed at market-based measures where stakeholder respond to changes in costs and supporting policies in economic competition and a fleet roll-over process. Many of the characteristics that are relevant to AERO-MS like range, seating, production rates, market adaptation, costs of acquisition and operation, year of introduction and how alternative propulsion will replace or compete with the existing aircraft is unclear and the supporting policies are not known.

The remainder of this chapter will elaborate on the modelling aspects of drop-in SAF.

10.1 Impact of drop-in fuels

Drop-in SAFs will be introduced into operations at a larger scale in the near future and will complement fossil fuels as a prime energy source. There are notable differences between SAF and fossil kerosene relevant to AERO-MS and policy making:

- Sources: SAF has many different production pathways, leading to different costs of production and available quantities;
- Pricing: due to the production pathways of SAF, fuel prices will naturally be higher than for fossil kerosene. Higher fuel prices will lead to higher costs and likely higher ticket prices. This will lead to lower demand and fewer flights and hence reduce CO_2 emissions;
- Availability: The production volumes of the different kinds of SAF will be limited in the coming years. Availability at airports may vary significantly between airports, countries and regions. Mandates and supporting policies may vary accordingly;
- CO_2 reduction properties: There are many different production pathways of drop-in SAFs with different ways (and properties) to recover CO_2 from the atmosphere.

The introduction of SAF into AERO-MS covers two areas:

- Demand impact: Higher SAF prices will reduce CO_2 emissions through higher costs and higher ticket prices that in turn dampen demand. Operators may seek ways such as fleet renewal or adapting the fleet mix on particular routes to mitigate those higher fuel costs.
- Reduction of net CO_2 emissions: As SAF will have approximately similar chemical and combustion properties the CO_2 emissions (at the engine exhaust) per unit fuel will be approximately be the same. The CO_2 savings

(expressed in an Emission Reduction Factor (ERF)) will result from the production pathway and attributed to the airports.

- It is assumed that drop-in SAF can be blended with fossil fuels.

Drop-in Sustainable Aviation Fuels are ‘designed’ with a focus on CO_2 reduction but are not identical to fossil kerosene. Fossil fuel have quite a lossy specification, but in general, and depending on the SAF type, SAFs have:

- Lower aromatic and lower sulphur content: this tend to reduce PM if the blending ratio is significant (typically beyond 20%);
- Slightly different chemical C-H composition resulting in a marginal increase in H_2O emissions, a marginal decrease in CO_2 emissions at the engine exhaust and slight changes in NOx production, fuel burn and fuel weight.

These aspects are minor, and very much depending on the SAF chemical composition and therefore not taken on board AERO-MS. However, if needed, these effects can be included as a post-processing step through appropriate design and application of report and/or scorecards embedded in AERO-MS.

10.2 Implementation of SAF

SAF is introduced into AERO-MS in the form of a policy that facilitates mandatory application and competition based on costs differences. The policy comprises a few variables:

- Effective Emission Reduction Factor (ERF) that considers the blending ratio between SAF and fossil fuel;
- Fuel price change of the blended fuel, modelled through the fuel tax option;
- Life Cycle CO_2 emissions per flight stage that calculates that savings in CO_2;
- A measure year where the SAF policy is put into effect. This measure year is set somewhere between the base year 2019 and the scenario year where the policy is being evaluated. A longer elapsed time between introduction of the policy and the year of evaluation will allow airlines to better adapt the fleet to the fuel price changes.

The net CO_2 differences between SAF and fossil fuel is modelled by introducing the (effective) Emission Reduction Factor (ERF). This ERF is an input to AERO-MS and is quite flexible in many respects:

- It can represent different types of SAF and even future types of SAF that are not yet defined;
- SAF can be blended with standard kerosene and the effective ERF computed from the blending ratio and the pure SAF ERF value. The blending ratio is flexible. A mandatory blending ratio could be a part of a policy.
- The blending ratio and ERF (the types of SAF) can be set at the airport level or at the airport pair level for one or more airports (pairs). At airport level, SAF is applicable for all flights from the airport, selecting the airport pair level targets specific routes. Given the large number of individual airports, the user may opt to specify the inputs at a higher aggregation level, e.g. country (pair) level, depending on the scope and policy needs;
- The resulting CO_2 savings are stored at the airport (pair) level. These CO_2 savings can be translated into the required SAF production volumes at various aggregation levels: airport, country or region.

Important to note is that other CO_2 reduction policies such as EU-ETS or CORSIA are also modelled through a fuel tax. Modelling price (differences) across different policies using the same fuel tax as an input parameter allows them to be combined with SAF. Within AERO-MS, a fuel tax is a rather detailed parameter for policy making, tried and tested throughout the model with respect to geographical detail and proper stakeholder responses. Stakeholders will react to higher fuel prices in the exactly same way as to the introduction of a fuel tax. As part of a calculation, AERO-MS will inventory the CO_2 savings at airport level (which can be aggregated into at country or region level by the user in the user interface).

10.2.1 SAF pricing level and responses

The price of SAF is expected to be higher than the price of kerosene, but the actual fuel price paid by the airlines will also dependent on the blending of SAF with standard kerosene. In a SAF policy study, the price of a specific SAF type, the blending ratios and availability at airports are conceived at input preparation, the SAF production volume will be a result of a policy study. Variations at input will establish a relationship between SAF prices and required production volume. The actual price will be unknown to a large degree because of many factors outside of aviation sector. Therefore, policy makers will usually cover a wider range of fuel prices and blending ratios in a study to assess the effects onto, and responses of stakeholders.

10.2.2 Airport infrastructure

Application of a SAF policy considers stakeholder responses where airlines have options to change the fleet mix and number of flights to take advantage of policies or regain market shares. AERO-MS assumes that the airport can accommodate such changes and provide the appropriate infrastructure.

10.3 User case application

A sketch of how to handle SAF policy in AERO-MS follows. Fuel prices can be quite flexible, so it is common to prepare a number of variants of a SAF policy with different combinations of prices, SAF types, blending ratios (if not mandatory) and airport application. For each policy:

- First, the pure SAF fuel property needs to be defined in terms of an Emission Reduction Factor and a price for a unit of SAF should be determined;
- Second, the airport (if all flights from an airport are targeted for SAF) or pairs of airports (if specific routes are targeted for SAF) where some type of SAF policies will be applied must be selected;
- Third, for each airport (or pair of airports) where SAF is used, the blending ratio with standard kerosene needs to be considered. Again, this is typically a choice by the policy analysts.

These three parameters already represent many options, especially the choice of airports. These choices can be simplified by selecting all airports within a country or an IATA region such as EU, as AERO-MS can disaggregate regions and countries to individual airports.

In the fourth step, these data need to be combined to provide the proper inputs at airport, airport pair level (or aggregations from that). The following variables need to be defined and set in a policy:

- SAF lifecycle CO_2 emission reduction factor (under Technical/Operational policies);
- Fuel tax by flight stage (under Financial policies);
- Measure Year.

This can be achieved through the AERO-MS user interface with or without the help of a spreadsheet program. An example spreadsheet is provided in the supporting training material, where results from various policy runs are copied from the AERO-MS user interface to the spreadsheet for the next step. This step comprises to compute the effective ERF and fuel price difference of SAF and fossil fuel using the blending ratio. The fuel tax is then computed as the price difference between default kerosene and the blend. If SAF is to combined with another form of pricing policy, the fuel tax is then increased accordingly.

After the policy has been evaluated using AERO-MS, the SAF volume can be computed from the CO_2 emissions savings and the pure SAF ERF. In Task 2 (cf. Chapter 3), an example application case of SAF has been included.

10.4 Impacts of SAF test-case: ReFuelEU Aviation

10.4.1 Assumptions adopted for ReFuelEU Aviation analysis

In October 2023, the ReFuelEU Aviation initiative was adopted by the EU Council[30]. For flights departing from airports in the European Economic Area (EU27+Norway+Iceland+Liechtenstein) fuel suppliers are bound to the following blending mandates for Sustainable Aviation Fuels (SAF):

- 2% SAF in 2025;
- 6% SAF in 2030;
- 20% SAF in 2035;
- 34% SAF in 2040;
- 42% SAF in 2045; and
- 70% SAF in 2050.

As part of Task 9 model changes have been implemented in the updated AERO-MS to assess the impacts of SAF. This in order to show the analysis capabilities of AERO-MS in relation to SAF, a realistic test-case has been defined to assess the impacts of ReFuelEU Aviation for European aviation in the years 2028 and 2038.

For the test-case policy specifications and assumptions had to be specified. These are related to:

1. The blending mandate of SAFs;
2. The expected mix of different types of SAFs;
3. The Emission Reduction Factors (ERF) for the fuel mix;
4. Price trajectories for different types of SAFs;
5. Price of EU ETS allowances and CORSIA offsets.

(1) Blending mandate of SAFs

The blending mandates for the year 2028 are based on interpolation of the blending mandates for the years 2025 and 2030 and is 4.4%. Similarly, the blending mandate for the year 2038 is assessed to 28.4%.

(2) The expected mix of different types of SAFs.

The expected mix of different types of SAFs is taken from a study published by the EU[31]. For both 2028 and 2038 this mix is presented in Table 30.

[30] Council adopts RefuelEU aviation initiative:

[31] Study supporting the impact assessment of the ReFuelEU Aviation initiative

Table 30 Expected mix of different types of SAFs used under ReFuelEU Aviation in 2028 and 2038

Type of SAF	2028	2038
HVO/HEFA	1.3%	2.7%
Fischer Tropsch	0.0%	8.0%
Alcohol to jet	1.5%	6.6%
Imports biokerosene	0.7%	3.3%
Synthetic fuels	0.9%	7.7%
Total SAF	**4.4%**	**28.4%**

(3) The Emission Reduction Factors (ERF) for the fuel mix

The emission reduction of SAFs is based on Life cycle emissions factors (LS_f). For each type of SAF, an LS_f is defined in an ICAO document[32]. Based on the LS_f for the different types of SAFs used under ReFuelEU Aviation (see Table 30) an ERF can be computed for the fuel mix in 2028 and 2038. The ERF expresses the percentage CO_2 emission reduction from the use of a fuel mix (including both fossil fuels and SAFs) relative to the CO_2 emissions resulting from the use of fossil fuels only[33].

The ERF for the fuel mix in 2028 and 2038 is computed to 3.0% and 23.7% respectively.

(4) Price trajectories for different types of SAFs

A recent study of PwC includes price trajectories for different types of SAFs[34]. Two policy scenarios are taken into account including the ReFuelEU Aviation policy scenario. For this policy scenario the price trajectories are:

HVO/HEFA;	From 1,500 US$ per ton in 2025 to 1,400 US$ per ton in 2040
Fischer Tropsch and Alcohol to jet	From 1,800 US$ per ton in 2025 to 1,600 US$ per ton in 2040
Synthetic fuels	From 3,200 US$ per ton in 2025 to 1,800 US$ per ton in 2040

Based on these price trajectories, and taking into account the SAF mix (see Table 30) an average price of SAF has been assessed for 2028 and 2038. For the imported biokerosene an average of the prices for HVO/HEFA and Fischer Tropsch/Alcohol to jet is assumed.

The computed average price of SAFs is 1,850 US$ per ton in 2028 and 1,700 US$ per ton in 2038.

(5) Price of EU ETS allowances and CORSIA offsets

Under the EU ETS regulation, SAFs are assumed to have zero CO_2 emissions[35]. This implies that the use of SAFs under ReFuelEU Aviation reduces the number of allowances to be surrendered for intra EEA flights which are subject to the EU ETS. This also implies that for intra EEA flights the costs impacts of SAF have to take into account the reduced costs for surrendering allowances. To assess these reduced costs, a future price for EU ETS

[32] CORSIA eligible fuels document

[33] ERF = 1 – LCfuel mix/LC, where LCfuel mix is the lifecycle emissions value of the fuel mix and LC is the baseline lifecycle emissions value for conventional jet fuel, equal to 89 gCO2e/MJ

[34] PwC study - Real costs of green aviation

[35] The EU ETS Directive 2003/87/EC states: "The emission factor for biomass shall be zero"

needs to be taken on board. For this analysis the Team took on board an allowance price of US$ 80 and US$ 120 per tonne of CO_2 for respectively 2028 and 2038.

Extra EEA flights (i.e. flights departing from airports in the EEA with a destination outside the EEA), are subject to CORSIA. Under CORSIA, the use of SAFs reduces the offset obligation. This implies that for extra EEA flights the costs impacts of SAF have to take into account the reduced costs for CORSIA offsets. For this expected CORSIA prices which are forecast to rise to about 14 US$ per tonne of CO_2 in 2035[36] were taken.

Table 31 presents the costs for the fuel mix (fossil fuels and SAFs) in 2028 and 2038 for both intra EEA and extra EEA flights. These costs take into account the savings in EU ETS and CORSIA costs related to the use of SAFs following from ReFuelEU Aviation. Table 31 also includes the price for fossil fuel included in the baseline scenario which is based on the CAEP13 assumption of a future average price of 3 US$ per gallon of kerosene for the global aviation industry (see also Section 3.1 of this report). Based on that the net additional costs for the fuel mix in case of ReFuelEU Aviation are also presented in Table 31. These net additional costs have been used to assess the impact of ReFuelEU Aviation with the updated AERO-MS.

The table shows that the net price per tonne of fuel for extra EEA flights is higher compared to the net price for intra EEA flights. This follows from the higher allowances price for the EU ETS (applicable to intra EEU flights) compared to the expected CORSIA offset price (applicable to extra EEU flights).

Table 31 Net price per tonne of fuel for fuel mix in 2028 and 2038 in US$2019 per tonne of fuel

	2028	2038
Net price per tonne of fuel for fuel mix*		
Baseline scenario	848	848
ReFuelEU Aviation - Intra EEA flights	881	984
ReFuelEU Aviation - Extra EEA flights	892	1078
Additional price per tonne of fuel relative to baseline scenario		
ReFuelEU Aviation - Intra EEA flights	33	136
ReFuelEU Aviation - Extra EEA flights	44	230

* The net prices include the reduction of CO_2 costs related to the EU ETS and CORSIA

10.4.2 ReFuelEU Aviation impacts computed by AERO-MS

The impacts of ReFuelEU Aviation are presented for all EEA related routes. This includes:

- Intra EEA routes (subject to the SAF blending mandate in 2 directions);
- Extra EEA routes departing from the EEA (subject to the SAF blending mandate);
- Extra EEA routes arriving in the EEA (not subject to the SAF blending mandate).

Though the extra EEA routes arriving in the EEA are not subject to the SAF blending mandate, these flights are affected because price increases, following from the higher costs of SAFs, are assessed based on a return ticket basis. This implies demand on these routes is also affected. The impacts of ReFuelEU Aviation for 2028 and 2038 are presented in

[36] Currently CORSIA only runs until 2035. For this analysis we have assumed CORSIA is still in place in 2038

Table **32** and Table 33 respectively. The main observations from these tables are:

- Impacts on demand are very limited in 2028 (-0.7% impact on RTK) but are more significant in 2038 (-3.1% impact on RTK). The higher impact in 2038 clearly follows from the more stringent blending mandate and the related higher net price per tonne of fuel for the fuel mix (see Table 31).
- The total demand for SAF resulting from ReFuelEU Aviation is computed to 15 Mt in 2038 (up from 2 Mt in 2028).
- ReFuelEU Aviation brings about CO_2 emission reduction which follows from the lower carbon intensity of SAFs and from a reduction within the aviation sector. The latter follows from passing on the higher costs of SAFs into higher ticket prices.
- For 2028 the overall CO_2 emission reduction is around 6 Mt. Around 4 Mt is related to the lower carbon intensity of SAFs (contribution of 70% to overall CO_2 emission reduction) and around 2 Mt is related to a CO_2 emission reduction within the aviation sector (contribution of 30% to overall CO_2 emission reduction).
- For 2038 the overall CO_2 emission reduction is around 49 Mt. Around 38 Mt is related to the lower carbon intensity of SAFs (contribution of 78% to overall CO_2 emission reduction) and around 11 Mt is related to a CO_2 emission reduction within the aviation sector (contribution of 22% to overall CO_2 emission reduction).

As a result of the ReFuelEU Aviation test-case a number of conclusions and remarks can be made. These are:

- The updated AERO-MS, and the model updates made as part of Task 9 (cf. Chapter 10), can be used to assess the impacts of SAF policies.
- AERO-MS is able to assess the combined impact on CO_2 emission resulting from the lower Life Cycle CO_2 emissions of SAFs and the reduction within the aviation sector. The latter is often not quantified in analyses, but the ReFuelEU Aviation test-case shows it is not insignificant.
- AERO-MS can be used to forecast the demand for SAFs resulting from ReFuelEU Aviation or any other SAF policy.
- The ReFuelEU Aviation test-case shows the ability of the updated AERO-MS to assess the impact of regional policies in addition to the ability to analyse the impacts of global policies.
- There are relations of SAF policies with other policies like EU ETS and CORSIA. AERO-MS can also be used to assess the impact on demand (and the resulting reduction of emissions within the aviation sector) of a package of policies.
- In a more elaborate analysis of ReFuelEU Aviation, impacts could be split out between intra and extra EEA routes. Also, AERO-MS allows impacts to be shown per EEA Member State.
- In this test-case the impacts of ReFuelEU Aviation are presented relative to the CAEP13 mid growth scenario. Similarly, the impacts could be shown relative to a European baseline scenario (e.g. EU Reference scenario).

Table 32 Impacts of ReFuelEU Aviation relative to CAEP13 Mid baseline scenario 2028 - scope flights departing from and arriving at airports in the EEA

	Unit	Baseline scenario: CAEP13 Mid 2028	ReFuelEU Aviation 2028	% change relative to baseline scenario ReFuelEU Aviation 2028
Aircraft operations				
Flights	million	9.8	9.8	-0.7%
Aircraft km	billion ac-km pa	16.4	16.3	-0.7%
Passenger and cargo demand				
Passenger-km - scheduled network carriers	billion pax-km	1,616	1,609	-0.4%
Passenger-km - LCC and non-scheduled	billion pax-km	980	968	-1.3%
Total passenger demand	billion pax-km	2,596	2,576	-0.8%
Cargo tonne-km	billion tonne-km	77	76	-0.5%
Revenue tonne-Km (RTK)	billion RTK pa	319	317	-0.7%
Available tonne-Km (ATK)	billion ATK pa	443	440	-0.6%
Fuel use and emissions				
Fuel use (fossil fuel plus SAF)	billion kg pa	76	76	-0.8%
Use of SAF	billion kg pa	0	2	n.a.
CO_2 emissions (direct emissions)	billion kg pa	241	239	-0.8%
SAF Life Cycle CO_2 emissions reduction	billion kg pa	0	4	n.a.
CO_2 emissions (net emissions)	billion kg pa	241	235	-2.6%
CO_2 emission reduction				
Contribution of lower SAF Life Cycle CO_2 emissions	%	n.a.	70%	n.a.
Contribution of reduction within aviation sector	%	n.a.	30%	n.a.

Table 33 Impacts of ReFuelEU Aviation relative to CAEP13 Mid baseline scenario 2038 - scope flights departing from and arriving at airports in the EEA

	Unit	Baseline scenario: CAEP13 Mid 2038	ReFuelEU Aviation 2038	% change relative to baseline scenario ReFuelEU Aviation 2038
Aircraft operations				
Flights	million	12.3	12.0	-2.8%
Aircraft km	billion ac-km pa	20.8	20.2	-2.9%
Passenger and cargo demand				
Passenger-km - scheduled network carriers	billion pax-km	2,182	2,138	-2.0%
Passenger-km - LCC and non-scheduled	billion pax-km	1,315	1,243	-5.5%
Total passenger demand	billion pax-km	3,497	3,381	-3.3%
Cargo tonne-km	billion tonne-km	99	97	-2.3%
Revenue tonne-Km (RTK)	billion RTK pa	426	413	-3.1%
Available tonne-Km (ATK)	billion ATK pa	585	567	-3.0%
Fuel consumption and emissions				
Fuel use (fossil fuel plus SAF)	billion kg pa	88	84	-3.9%
Use of SAF	billion kg pa	0	15	n.a.
CO_2 emissions (direct emissions)	billion kg pa	277	266	-3.9%
SAF Life Cycle CO_2 emissions reduction	billion kg pa	0	38	n.a.
CO_2 emissions (net emissions)	billion kg pa	277	228	-17.7%
CO_2 emission reduction				
Contribution of lower SAF Life Cycle CO_2 emissions	%	n.a.	78%	n.a.
Contribution of reduction within aviation sector	%	n.a.	22%	n.a.

11. Task 10: Improved model security

Task 10 was to improve the AERO-MS model security, and in particular, to establish a better protection against unauthorised access to AERO-MS data. This includes protecting the base year data where EASA-licensed data are used.

In a first step an analysis was made of the model security of the SAVE version of AERO-MS. The main security issues identified were:

1. AERO-MS is provided to the end user for a specific project without any software technical licensing procedure. Thereby there is no end date for the access the end user has to the AERO-MS;
2. All input data, including data which were based on EASA licensed data, were available in easily readable formats to AERO-MS end users;
3. Source code and the compiled AERO-MS system are included in one package delivered to EASA.

This analysis was shared with EASA on the technical meeting in May 2023, and it was agreed to, as part of Task 10, to take the following steps.

1. Develop an AERO-MS license manager to create licence files. This allows EASA to control who has access to AERO-MS for which period of time;
2. Develop a tool to encrypt/decrypt data files, as part of the AERO-MS compilation tool. This ensures sensitive input data are omitted from the AERO-MS database and cannot be accessed by end users;
3. Split the source code and compiled AERO-MS system in various packages to be delivered to EASA and ensure the compiled AERO-MS system can be run separately.

The AERO-MS license manager is an executable which is delivered together with AERO-MS. A valid user license key has to be included in the license manager in order to make AERO-MS runs.

An admin license key has been provided to EASA. This enables EASA to generate user license keys. Keys are encrypted. The user keys include encrypted information on the name of licensee, the expiration date and how to decrypt AERO-MS data. Also, additional admin keys can be generated for other EASA staff members. Admin keys also provides encrypted information to generate user keys. Instructions how to use the AERO-MS license manager are included in a separate document provided to EASA.

Also, AERO-MS includes instructions for users how to activate AERO-MS with the use of a user license key provided by EASA. These instructions are included in the file "README - Instruction how to activate the AERO-MS using the license manager.pdf".

The tool to encrypt/decrypt data files has been developed and is included in the AERO-MS compilation tool. When the AERO-MS models are compiled, all AERO-MS input data are encrypted. When a run is made, only data which are earmarked as non-sensitive are included in the AERO-MS database which can be inspected with the AERO-MS interface. As part of Task 10, sensitive input data have been identified. These are mainly FLEM input variables for which BADA data are used. These variables are omitted from the AERO-MS database.

Finally, the source code and compiled AERO-MS system are now fully separated. These will be delivered in two packages to EASA. AERO-MS end users only need the compiled AERO-MS system, which also includes the AERO-MS license manager, to make runs and use the AERO-MS for specific analyses. The source code of AERO-MS can be achieved by EASA, and is available for possible future projects in which the AERO-MS is updated and/or enhanced.

12. Conclusion

This document reported on the implementation activities of the improvements selected by EASA to update and enhance AERO-MS under Specific Contact No 03 (SC03) of the Framework Contract EASA.2020.FC07. These updates and enhancements were implemented into AERO-MS by the Team (consisting of Royal NLR and its subcontractors DLR, SYSTRA and TAKS) in nine tasks:

- Task 1 updated the AERO-MS baseline data. The baseline case is now based on 2019 data. This task included exploration and harmonisation of external data sources on passenger and freight demand, flight movements, fleet and costs as well as making these data suitable for AERO-MS;
- Task 3 updated price elasticities of demand in AERO-MS. The Intervistas price elasticities embedded in AERO-MS have been re-interpreted and revised to bring them in line with other, more recent studies that have more local (airport) focus;
- Task 4 added non-volatile and volatile Particulate Matter to the AERO-MS emissions technical scenario's, fleet properties and emissions inventory modelling;
- Task 5 enhanced the AERO-MS data export functions. Data, especially for those variables with a large data volume, can now be more conveniently handled and exported by the user;
- Task 6 increased the detour factors detailing down to airport pairs (flight stages) instead of ICAO regions. The detour factors are now calibrated using fuel burn data;
- Task 7 explored how to align AERO-MS with PRIMES-TREMOVE. Consultation with the PRIMES-TRIMOVE developers resulted in an outline how the models could benefit from each other;
- Task 8 promoted selected assumption variables to scenario. Some assumption variables, while having fixed values, appear to be changing slowly over time and are significant to some outputs. These variables have been identified and promoted to scenario variables yielding more consistent results and allowing for more flexibility;
- Task 9 explored and implemented drop-in Sustainable Alternative Fuels (SAF) as a policy in AERO-MS. SAF properties and mandates can be specified in detail down to airport and airport pair levels. The implementation of SAF considers a price increase and an emission reduction factor, and can be combined with any other policies;
- Task 10 implemented encryption to make sensitive data in AERO-MS inaccessible. A user-license key is now required to operate the model. Access to data for the purpose of updating the base year requires a separate master license key.

All these implemented updates and enhancements to AERO-MS were successfully tested in Task 2. More specifically, this task implemented a baseline scenario and performed testing. The work involved the calibration of traffic volumes, fuel use and emissions for 2019 (i.e. the base case), the implementation of the CAEP13 Mid Outlook scenario, and the testing of AERO-MS built-in policies;

Finally, the updated AERO-MS will be demonstrated in a Final Event at the end of the EASA Framework Contract EASA.2020.FC07. This event will be combined with a training of the updated AERO-MS to EASA, EC and Member States' staff.

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