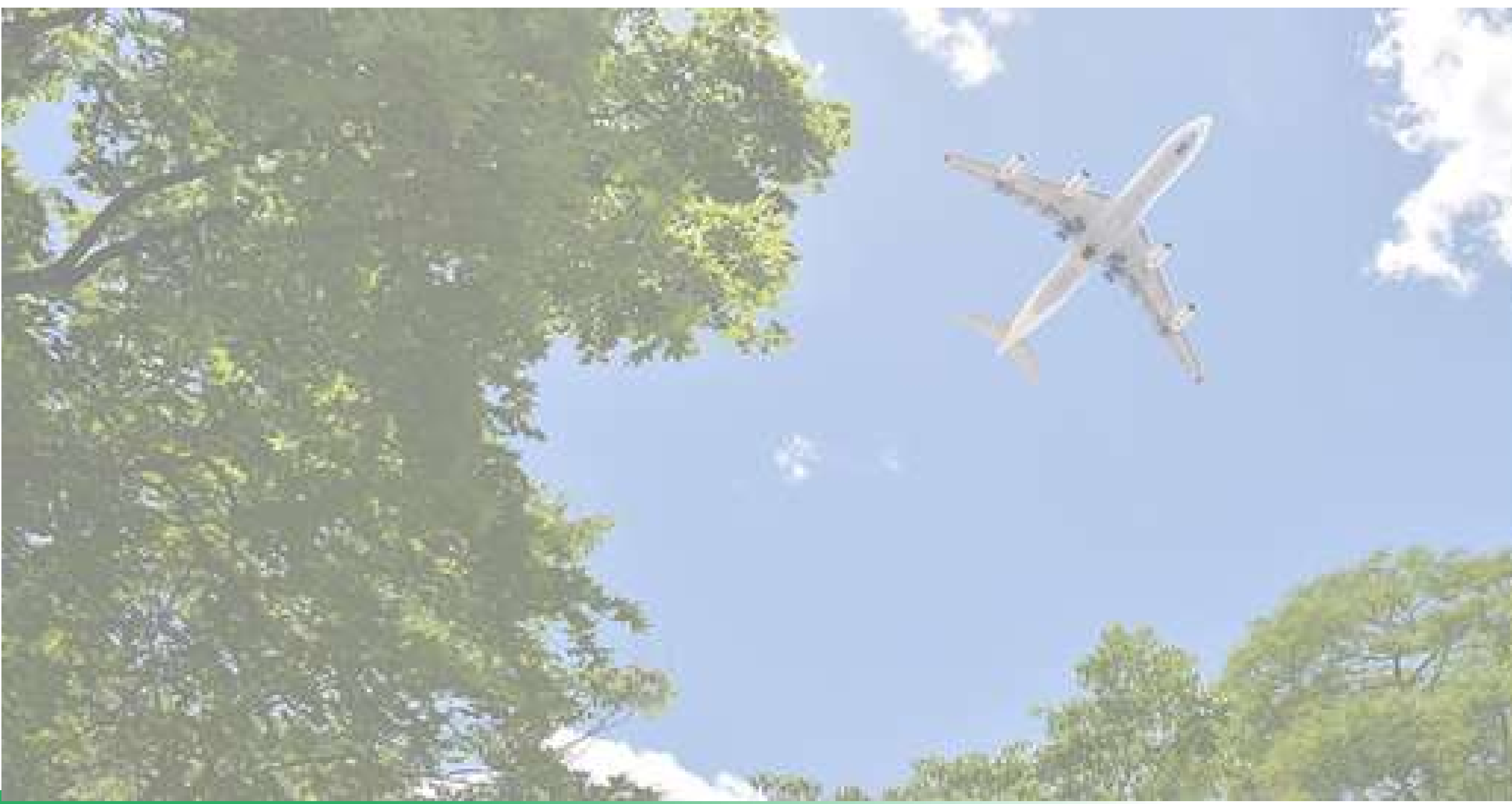

D7.3: ENVIRONMENTAL IMPACT ASSESSMENT AND GREEN TRAJECTORY SELECTION

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EXECUTIVE SUMMARY

This report corresponds to D7.3 Environmental impact assessment and green trajectory selection. The work reported is related to 'WP7.2 Development of an evaluation methodology for environmental impact' and 'WP7.3 Environmental impact assessment (EIA) of greener air traffic operation'.

WP7.2 is organized in two different tasks:

- Task 7.2.1 Environmental impact assessment indicator
- Task 7.2.2 Environmental impact assessment index system

WP7.3 is organized in three different tasks:

- Task 7.3.1 Calculation of aircraft fuel consumption and carbon emissions
- Task 7.3.2 Calculation of other climate change relevant emissions
- Task 7.3.3 Environmental impact assessment of greener long and short haul operation approaches

The information contained in this report provides a quantification of the environmental impact of trajectories developed in the work of the GreAT project, both in the local air quality aspects and in the global climate change impact effects. The report provides for a justification of what aircraft emissions, of those relevant to the environmental impact, are considered in the assessment performed within the GreAT project. In particular, the CO_2 and the NOx emissions have been evaluated with an emissions model specially designed to evaluate these emissions with the inputs provided by the previous MWPs in the GreAT project.

For the DLR exercise, the trajectories used for the environmental impact assessment correspond to the results of the validation trials executed by five Air Traffic Controllers (ATCs), (C1 - C5), testing two traffic scenarios, differing with distribution of 3D-FMS and 4D-FMS flights, where 30 and 60 corresponds respectively to 30% and 60% of the 4D-FMS air traffic operations, trying to evaluate how the "60" scenario improves the "30" one.

In the case of HC/Pildo exercise, the trajectories used for the analysis have been generated from real ADS-B data recorded in Budapest Ferenc Liszt International airport during the period in which MergeStrip was tested in the OPS room (between March 31st and April 13th). Within this period, MergeStrip was tested during three specific time slots: 0945-1130, 1545-1700 and 2030-2200 (UTC).

This report does not include environmental impact assessment results related to exercises done by Chinese partners, as it has been decided to split MWP6 in a European and a Chinese part with separate documents, as a reaction to new U.S. sanctions and the corresponding management decisions by European partners. As MWP7 is strongly depending on the output of MWP6, consequently only EU results are considered here.

The report describes the methodology that has been developed for each exercise to perform this environmental assessment, including the selection of scenarios for the evaluation, the emissions model that has been created, and the environmental impact indicators that have been used.

In terms of DLR's exercise results, overall, the 'solution' scenario "60" represents a clear improvement in terms of environmental impact with respect to the 'baseline' scenario "30",

with a reduction in CO_2 emissions between 1.1% for short to medium range (SMR) and 8.9% for long range (LR) aircraft. The improvement in NOx emissions is even larger, 2.9% for SMR and 23.1% for LR aircraft.

It is interesting to note that the reduction in the environmental impact comparing both scenarios is larger for the last generation aircraft, both in SMR with the A320 neo, and in LR with the A350-900 and B787-8, which is very promising since these aircraft will naturally and gradually replace the current fleet of previous generation(s) aircraft in the coming years.

In HC/Pildo's exercise it has been proved that the most important benefit of MergeStrip can be measured in terms of the reduction on the number of flights with low flight efficiency values:

- ✓ Horizontal Flight Efficiency (HFE), defined as the ratio between the covered distance from the Top of Descent (TOD) until the last point of the trajectory and the great circle distance between such two points.
  - The 11 flights with lowest HFE values are found in the No MergeStrip scenario.
  - 21 out of the 25 flights with lowest HFE values are found in the No MergeStrip scenario (84%).
- ✓ Vertical Flight Efficiency (VFE), defined as the ratio between the time of descent without level flight and the total time of descent.
  - The 7 flights with lowest VFE values are found in the No MergeStrip scenario.
  - 20 out of the 25 flights with lowest VFE values are found in the No MergeStrip scenario (80%).

In addition, it has been observed that the use of MergeStrip brings minor improvements in the mean values of all the analysed indicators: fuel consumption, CO2 emissions, HFE and VFE. As it is explained in the conclusions of this document, with the redesign of Budapest TMA entering into effect in January 2020, the local maximum level of efficiency was almost achieved. In this respect, the tested tool was able to make only minor improvements.

The results presented in this report, as the outcome of WP7.3 of the GreAT project, provide the necessary inputs to finalize the work in this MWP7, through the development of a trade-off mechanism between these environmental impacts and the technical and economic performance indicators that were considered in the design of the greener trajectories in previous MWPs. The results of this trade-off analysis will cover the content of WP7.4 and will be included in D7.4.

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GLOSSARY

Acronym	Signification
ARP	Aerodrome Reference Point
ATCO	Air Traffic Controller
BADA	Base of Aircraft Data
CA	Certificating Authority
EASA	European Aviation Safety Agency
EDB	Emissions Data Bank
EI	Emission Index
EIA	Environmental Impact Assessment
FMS	Flight Management System
GHG	Greenhouse Gases
GWP	Global Warming Potential
HFE	Horizontal Flight Efficiency
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
LR	Long Range Aircraft
LTO	Landing and Take-off
SMR	Short and Medium Range Aircraft
TOD	Top of Descent
UHC	Unburnt hydrocarbons
VFE	Vertical Flight Efficiency
VTAS	True Air Speed

1. INTRODUCTION

This report corresponds to D7.3 Environmental impact assessment and green trajectory selection. The work reported is related to 'WP7.2 Development of an evaluation methodology for environmental impact' and 'WP7.3 Environmental impact assessment (EIA) of greener air traffic operation'.

WP7.2 is organized in two different tasks:

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- Task 7.3.1 Calculation of aircraft fuel consumption and carbon emissions
- Task 7.3.2 Calculation of other climate change relevant emissions
- Task 7.3.3 Environmental impact assessment of greener long and short haul operation approaches

The information contained in this report provides thus a description of the methodology that has been used for the evaluation of the environmental impact of the trajectories from optimized approach procedures generated in previous MWPs of the GreAT project, and also the results of the environmental assessment of these trajectories that has been performed.

The first section of the report provides for an explanation of which aircraft emissions, among those relevant to the environmental impact, are considered in the assessment carried out under the GreAT project. The following section in this report describes the methodology that has been developed to perform this environmental assessment, including the selection of scenarios for the evaluation, the emissions model that has been created, and the environmental impact indicators that have been used. Then, the following section includes the results of the evaluation and a final section summarizes the conclusions of this study, together with the next steps of MWP7 till the end of the project.

2. CHARACTERIZATION OF EMISSIONS RELEVANT TO ENVIRONMENTAL IMPACT

The two major products of fuel combustion are carbon dioxide, CO_2 and water, H_2O. Other products of fuel combustion are nitrogen oxides, NOx, sulphur dioxide, SO_2, carbon monoxide, CO, unburnt hydrocarbons (UHC) and Soot (Figure 1). Although the amount of each emission type produced in the combustion of one ton kerosene by a modern jet engine depends on parameters such as the aircraft operating conditions, altitude, humidity, and temperature, the following figures can be taken as good approximations:

- CO_2 3.15 ton
- H_2O 1.239 ton
- NOx 6 - 20 kg
- SO_2 1 kg
- CO 0.7 - 2.5 kg
- UHC 0.1 - 0.7 kg
- Soot 0.02 kg

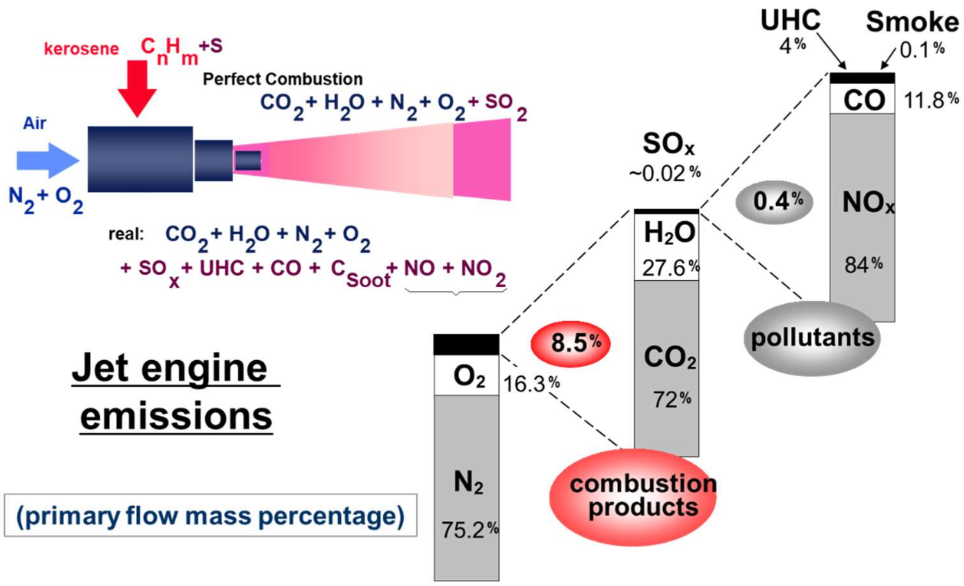


Figure 1. Jet engine emissions (Source: IPCC report).

For the practical analysis of aircraft emissions' environmental impact, it is generally accepted that those emitted close to the airport are affecting overall the local air quality, while during the rest of the flight, emissions have an impact on global climate change. The local pollution is calculated in a volume having the airport area as the base and an altitude of 3000 ft over the runway level, simulating the typical commercial aircraft manoeuvre, as indicated in Figure 2. The complete procedure is named as Landing-Take off cycle (LTO).

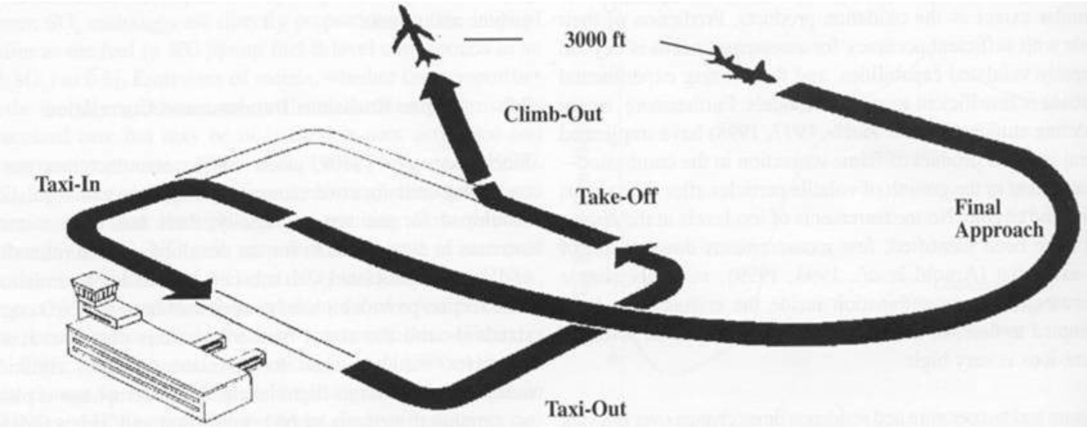


Figure 2. LTO cycle. (Source: ICAO)

At this moment, ICAO asks for local air quality emissions certification of new model jet engines of maximum thrust higher than 26.7kN, establishing limits for Smoke Number (SN), Nitrogen oxides (NOx), Unburnt Hydrocarbons (UHC), Carbon monoxide (CO) and Non-volatile Particulate Matter (nvPM) in its Annex 16, Volume II. In addition, Annex 16 Volume III sets maximum levels of Carbon dioxide emissions (CO_2) for new civil aviation models.

A detailed description of the state of the art in certification and emissions chemistry is included in the previously delivered 'D7.2 Description of aviation emissions impact on environment'.

3. METHODOLOGY

3.1. SELECTION OF SCENARIOS FOR EVALUATION

The environmental impact assessment has been performed on a set of trajectories defined in previous tasks of the GreAT project. In particular, the trajectories have been calculated according to the concept defined in MWP4, and were produced in the validation exercises performed in MWP6 (Temme et.al. 2021).

In this way, the trajectories used for the environmental impact assessment are the same that have been used for the operational efficiency, safety, capacity and human performance, in the context of the validation exercises (MWP6).

These validation exercises are reported in the document D6.3 Validation report first iteration (Kling et.al. 2022).

3.1.1. DLR TRAJECTORIES

The exercise referenced as EXE-001, "Validation of advanced controller support tools at an airport" has been used for the environmental impact assessment. This validation put the focus on a coordinated arrival-/departure flow, including automatically negotiated approach routes and target times (between the AMAN and the on-board 4D-FMS), to show the benefit of such kind of system. The used support tools will assist the controllers in handling the in- and outbound traffic with different equipment. An analysis of the traffic distribution is carried out in order to determine appropriate research horizon and measure the length of the travelled trajectories, which has also contributed to the estimation of fuel consumption reduction, prepared on the basis of OpenSky and BADA data.

The trajectories used for the environmental impact assessment correspond to the results of the validation trials executed by five air traffic controllers (ATCO), (C1 - C5), testing two traffic scenarios, differing with distribution of 3D-FMS and 4D-FMS flights, where 30 and 60 corresponds respectively to 30% and 60% of the 4D-FMS equipped aircraft. All trajectories include the portion of the flights which covers the complete distance from the 100 nm circle around the Aerodrome Reference Point (ARP) to the landing.

The environmental impact assessment therefore compares the emissions from the flights in scenario "30" with the emissions in the scenario "60", in each case for the five ATCOs (C1 to C5).

3.1.2. HUNGAROCONTROL - PILDO TRAJECTORIES

In the case of Budapest, the trajectories used for the analysis have been generated from real ADS-B data recorded in Budapest Ferenc Liszt International airport during the period in which MergeStrip was tested in the OPS room (between March 31st and April 13th). Within this period, MergeStrip was tested during three specific time slots: 0945-1130, 1545-1700 and 2030-2200 (UTC).

Two different datasets (MergeStrip vs no MergeStrip) have been generated according to the effective arrival time of each detected arrival:

- MergeStrip dataset: flights with arrival time contained within one of the MergeStrip time slots
- No MergeStrip dataset: all other flights

The flight segments to be analysed run from the Top of Descent (TOD) until 3000 ft. The last part of the descent is discarded in order to keep out of the analysis the level flight that is commonly used before the interception of the ILS.

3.2. THE EMISSIONS MODEL

The emissions for each flight have been obtained using a model that has been developed by UPM in the context of the GreAT project.

The model has been tailored to evaluate the relevant emissions from the flight trajectories format defined in previous work packages of the project. A flow diagram showing the main calculation steps of this emissions model is shown in Figure 1.

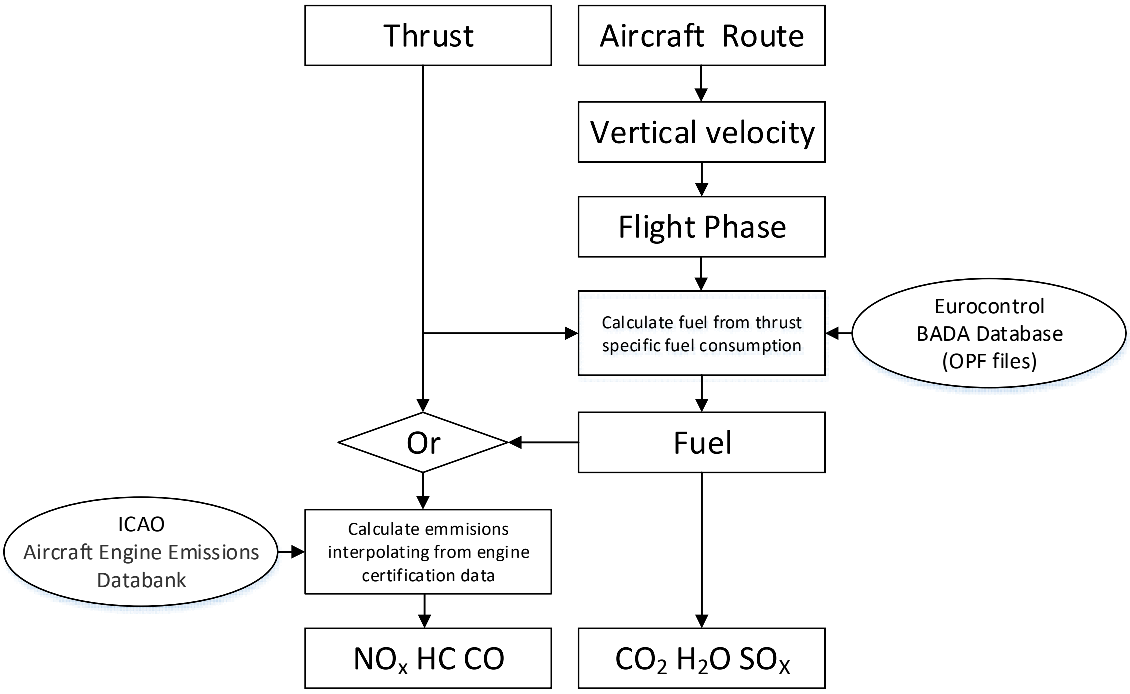


Figure 3. Flow diagram describing the main steps in the emissions model

The information which is provided for each flight is the following:

- Callsign
- Aircraft type
- Time
- Position (latitude, longitude and altitude)
- Rate of climb / descend
- Speed (VTAS)
- Heading
- Thrust level

Table 1 shows an example of the format of the input files for the environmental impact assessment, as obtained from the results of MWP3 and MWP4.

Table 1. Format of the input files for the environmental impact assessment.

Callsign	AC_Type	Time	Lat [deg]	Lon [deg]	Altitude [m]	rocd [m/s]	vtas [m/s]	hdg [deg]	Thrust [N]
AEA31QX	B738	374	47.3511623	9.827685451	6751.8	0	198.67	46.8	44378
AEA31QX	B738	375	47.3523868	9.829608223	6751.8	0	198.67	46.8	44377
AEA31QX	B738	376	47.3536113	9.831531085	6751.8	0	198.67	46.8	44377
AEA31QX	B738	377	47.3548358	9.833454036	6751.8	0	198.67	46.8	44377
AEA31QX	B738	378	47.3560603	9.835377076	6751.8	0	198.67	46.8	44377
AEA31QX	B738	379	47.3572847	9.837300205	6751.8	0	198.67	46.8	44377
AEA31QX	B738	380	47.3585091	9.839223424	6751.8	0	198.67	46.8	44377
AEA31QX	B738	381	47.3597334	9.841146732	6751.8	0	198.67	46.8	44377
AEA31QX	B738	382	47.3609577	9.843070129	6751.8	0	198.67	46.8	44376
AEA31QX	B738	383	47.362182	9.844993616	6751.8	0	198.67	46.8	44376

With this information, the model evaluates the CO_2 emissions for each time step, using the BADA version 3.16 libraries. The model also allows the calculation of the CO_2 flow in kg/min. Other emissions related to the fuel consumption, other than CO_2, such as H_2O and SOx can be also evaluated.

Following the BADA methodology, the calculation is done differently depending on whether the flight segment corresponds to cruise, ascend or descend. To determine if the segment is cruise, a parameter called "Max vertical speed" is used as a reference (so that a minimum speed does not take it out of cruise).

For the calculation of NOx, CO and HC emissions, the certified engine emissions are used. These emissions are stored in the ICAO Aircraft Engine Emissions Databank, which contains information on exhaust emissions of production aircraft engines, measured according to the procedures in ICAO Annex 16, Volume II, and where noted, certified by the States of Design of the engines according to their national regulations. The databank covers engine types which emissions are regulated, namely turbojet and turbofan engines with a static thrust greater than 26.7 kilonewtons. The information is provided by the engine manufacturers, who are solely responsible for its accuracy. The European Union Aviation Safety Agency (EASA) is hosting the databank on behalf of ICAO.

Engine manufacturers submit their data to the primary certificating authority (CA) for approval as part of the certification process. Once the data has been approved by the primary CA, manufacturers can voluntarily submit it to EASA for inclusion in the ICAO Engine Emissions Databank. The primary CA verifies that the data submitted to the databank is in conformity with the approved data from certification. EASA then checks the data format and consistency before publishing it. The Excel file with all these data, the so-called "edb-emissions-databank", is available at the EASA web page.

In order to use the emissions information in the "edb-emissions-databank", the model requires the introduction of the engine model in the input file for each flight.

For the calculation of NOx, CO, and HC, the model interpolates the four points of the "edb-emissions-databank", which provides the certified emissions at four different engine thrust levels (corresponding to the different phases of the LTO cycle).

Previously, it was necessary to create a database relating each aircraft type of each airline with the corresponding engine model, since the same aircraft type can incorporate different engine models, depending on the airline that operates the aircraft.

The information available then from the "edb-emissions-databank" is the NOx Emissions Index (EI) at the four points of the LTO cycle (corresponding to four different engine regimes:

- Take off (T/O): 100% rated engine Thrust
- Climb (C/O): 85% rated engine Thrust
- Approach (APP): rated engine 30% Thrust
- Idle (Idle): rated engine 7% Thrust

The EI provides the mass (g) of NOx per mass (kg) of burnt fuel. Combined with the Fuel Flow (mass (kg) of fuel per unit time (s)), also available in the "edb-emissions-databank", gives the NOx Flow (mass (g) of NOx per unit time (s)). This information is available at four different levels of the engine thrust. The rated engine thrust for each engine is also available in the "edb-emissions-databank".

Tables 2 to 4 show the relevant information for each engine.

Table 2. Relevant NOx emission index (EI) from the "edb-emissions-databank".

	Airline	**aircraft**	**engine**	**NOx EI T/O (g/kg)**	**NOx EI C/O (g/kg)**	**NOx EI App (g/kg)**	**NOx EI Idle (g/kg)**
AEA	Aegean	A320	V2527-A5	26.5	22.3	8.9	4.7
DAL	Air Dolomiti	E195	CF34-10E5A1G07	20.83	16.93	8.43	3.67
AEE	Air Europa	B738	CFM56-7B26	28.8	22.5	10.8	4.7
AFR	Air France	A319	CFM56-5B5/P	21.9	18.5	8.7	3.8
AUA	Austrian	E195	CF34-10E5A1G07	20.83	16.93	8.43	3.67
BAW	British Airways	A319	V2522-A5	24.5	20.8	8.7	4.5
BAW	British Airways	A20N	CFM56-LEAP-1A26	18.77	11.16	8.67	4.63
CAI	Corendon	B738	CFM56-7B26	28.8	22.5	10.8	4.7
CTN	Croatia	DH8D	PW150A	22.1	18.1	10.1	5.6
DLA	Delta	B763	PW4060	32.8	24.7	12	4.9
ELY	El Al	B739	CFM56-7B27	30.9	23.7	11	4.8
IBE	Iberia	A319	CFM56-5B5/P	21.9	18.5	8.7	3.8
JZA	Jazz	B788	GEnx-1B67	28.56	16.26	9.29	4.3
KLM	KLM	B737	CFM56-7B22/3	17.4	14.67	8.35	3.95
DLH	Lufthansa	CRJ9	CF34-8C5B1	13.89	12.03	10.42	4.5
DLH	Lufthansa	E195	CF34-10E5A1G07	20.83	16.93	8.43	3.67
DLH	Lufthansa	A319	CFM56-5A5	24.79	19.98	8.94	4.29
DLH	Lufthansa	A320	CFM56-5B4/3	21.57	17.23	8.85	4.22
DLH	Lufthansa	A20N	PW1127G	17.76	14.18	8.85	6.55
DLH	Lufthansa	A321	V2533-A5	36.48	28.67	10.83	5.24
DLH	Lufthansa	A21N	PW1133G	25.23	18.92	9.14	6.98
DLH	Lufthansa	A346	Trent 556A2-61	44.91	32.76	11.78	6.19
DLH	Lufthansa	A359	Trent XWB-84	45.48	34.53	11.46	4.73
QTR	Qatar	A359	Trent XWB-84	45.48	34.53	11.46	4.73
THA	Thai	B77W	GE90-115B	50.34	35.98	16.5	5.19
TUI	TUI	B738	CFM56-7B27/B1	20.81	15.59	7.53	4.36
UAL	United	B764	CF6-80C2B8F	26.85	20.84	12.42	4.59
UAL	United	B772	PW4084	45	35.5	12	4.4
UAL	United	B788	GEnx-1B70	34.06	18.48	9.63	4.37
VLG	Vueling	A320	CFM56-5B4/3	21.57	17.23	8.85	4.22

Table 3. Relevant Fuel Flow from the "edb-emissions-databank".

	Airline	aircraft	engine	Fuel Flow T/O (kg/sec)	Fuel Flow C/O (kg/sec)	Fuel Flow App (kg/sec)	Fuel Flow Idle (kg/sec)
AEA	Aegean	A320	V2527-A5	1.053	0.88	0.319	0.128
DAL	Air Dolomiti	E195	CF34-10E5A1G07	0.866	0.714	0.237	0.087
AEE	Air Europa	B738	CFM56-7B26	1.221	0.999	0.338	0.113
AFR	Air France	A319	CFM56-5B5/P	0.891	0.742	0.26	0.094
AUA	Austrian	E195	CF34-10E5A1G07	0.866	0.714	0.237	0.087
BAW	British Airways	A319	V2522-A5	0.971	0.817	0.311	0.118
BAW	British Airways	A20N	CFM56-LEAP-1A26	0.855	0.705	0.242	0.088
CAI	Corendon	B738	CFM56-7B26	1.221	0.999	0.338	0.113
CTN	Croatia	DH8D	PW150A	0.69	0.58	0.21	0.07
DLA	Delta	B763	PW4060	2.647	2.085	0.703	0.213
ELY	El Al	B739	CFM56-7B27	1.284	1.043	0.349	0.116
IBE	Iberia	A319	CFM56-5B5/P	0.891	0.742	0.26	0.094
JZA	Jazz	B788	GEnx-1B67	2.368	1.94	0.625	0.203
KLM	KLM	B737	CFM56-7B22/3	1.004	0.832	0.291	0.099
DLH	Lufthansa	CRJ9	CF34-8C5B1	0.606	0.497	0.171	0.063
DLH	Lufthansa	E195	CF34-10E5A1G07	0.866	0.714	0.237	0.087
DLH	Lufthansa	A319	CFM56-5A5	0.972	0.799	0.276	0.098
DLH	Lufthansa	A320	CFM56-5B4/3	1.142	0.939	0.316	0.102
DLH	Lufthansa	A20N	PW1127G	0.8004	0.6613	0.2322	0.0897
DLH	Lufthansa	A321	V2533-A5	1.426	1.1447	0.3901	0.1363
DLH	Lufthansa	A21N	PW1133G	1.0230	0.8385	0.2783	0.0988
DLH	Lufthansa	A346	Trent 556A2-61	2.24	1.83	0.62	0.23
DLH	Lufthansa	A359	Trent XWB-84	2.819	2.306	0.801	0.291
QTR	Qatar	A359	Trent XWB-84	2.819	2.306	0.801	0.291
THA	Thai	B77W	GE90-115B	4.69	3.67	1.13	0.38
TUI	TUI	B738	CFM56-7B27/B1	1.265	1.033	0.351	0.115
UAL	United	B764	CF6-80C2B8F	2.583	2.106	0.685	0.205
UAL	United	B772	PW4084	3.411	2.689	0.875	0.242
UAL	United	B788	GEnx-1B70	2.494	2.037	0.65	0.208
VLG	Vueling	A320	CFM56-5B4/3	1.142	0.939	0.316	0.102

Table 4. Relevant NOx Flow derived from data in the "edb-emissions-databank".

	Airline	aircraft	engine	NOx Flow T/O (g/sec)	NOx Flow C/O (g/sec)	NOx Flow App (g/sec)	NOx Flow Idle (g/sec)	Rated Thrust (kN)
AEA	Aegean	A320	V2527-A5	27.9045	19.6240	2.8391	0.6016	111.2
DAL	Air Dolomiti	E195	CF34-10E5A1G07	18.0388	12.0880	1.9979	0.3193	83.7
AEE	Air Europa	B738	CFM56-7B26	35.1648	22.4775	3.6504	0.5311	116.99
AFR	Air France	A319	CFM56-5B5/P	19.5129	13.7270	2.2620	0.3572	97.89
AUA	Austrian	E195	CF34-10E5A1G07	18.0388	12.0880	1.9979	0.3193	83.7
BAW	British Airways	A319	V2522-A5	23.7895	16.9936	2.7057	0.5310	102.66
BAW	British Airways	A20N	CFM56-LEAP-1A26	16.0484	7.8678	2.0981	0.4074	120.6
CAI	Corendon	B738	CFM56-7B26	35.1648	22.4775	3.6504	0.5311	116.99

CTN	Croatia	DH8D	PW150A	15.2490	10.4980	2.1210	0.3920	97.72
DLA	Delta	B763	PW4060	86.8216	51.4995	8.4360	1.0437	266.9
ELY	El Al	B739	CFM56-7B27	39.6756	24.7191	3.8390	0.5568	121.44
IBE	Iberia	A319	CFM56-5B5/P	19.5129	13.7270	2.2620	0.3572	97.89
JZA	Jazz	B788	GEnx-1B67	67.6301	31.5444	5.8063	0.8729	308.7
KLM	KLM	B737	CFM56-7B22/3	17.4696	12.2054	2.4299	0.3911	101
DLH	Lufthansa	CRJ9	CF34-8C5B1	8.4173	5.9789	1.7818	0.2835	56.35
DLH	Lufthansa	E195	CF34-10E5A1G07	18.0388	12.0880	1.9979	0.3193	83.7
DLH	Lufthansa	A319	CFM56-5A5	24.0959	15.9640	2.4674	0.4204	104.53
DLH	Lufthansa	A320	CFM56-5B4/3	24.6329	16.1790	2.7966	0.4304	120.1
DLH	Lufthansa	A20N	PW1127G	14.2154	9.3767	2.0549	0.5878	120.44
DLH	Lufthansa	A321	V2533-A5	52.0205	32.8185	4.2248	0.7142	140.56
DLH	Lufthansa	A21N	PW1133G	25.8095	15.8652	2.5440	0.6895	147.28
DLH	Lufthansa	A346	Trent 556A2-61	100.5984	59.9508	7.3036	1.4237	261.5
DLH	Lufthansa	A359	Trent XWB-84	128.2081	79.6262	9.1795	1.3764	379
QTR	Qatar	A359	Trent XWB-84	128.2081	79.6262	9.1795	1.3764	379
THA	Thai	B77W	GE90-115B	236.0946	132.0466	18.6450	1.9722	513.9
TUI	TUI	B738	CFM56-7B27/B1	26.3247	16.1045	2.6430	0.5014	121.44
UAL	United	B764	CF6-80C2B8F	69.3536	43.8890	8.5077	0.9410	267
UAL	United	B772	PW4084	153.4950	95.4595	10.5000	1.0648	369.6
UAL	United	B788	GEnx-1B70	84.9456	37.6438	6.2595	0.9090	321.6
VLG	Vueling	A320	CFM56-5B4/3	24.6329	16.1790	2.7966	0.4304	120.1

The model has been implemented in MATLAB. An illustration of the landing screen of the program is shown in Figure 4.

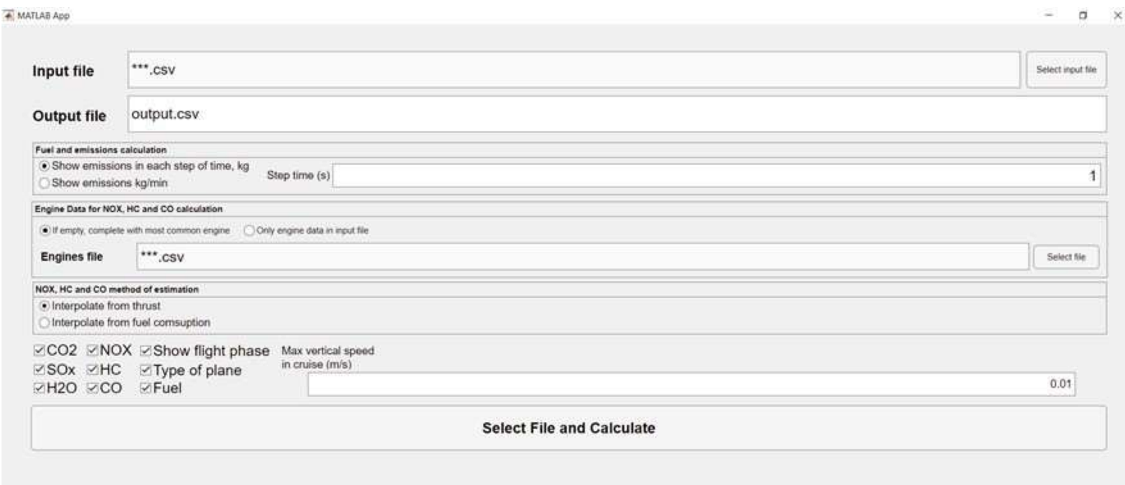


Figure 4. Landing screen of the MATLAB tool implementing the emissions calculation model.

3.3. ENVIRONMENTAL IMPACT ASSESSMENT INDICATORS

According to the European Environmental Agency, air pollutants may be categorised as primary or secondary (EEA, 2021). Primary pollutants are directly emitted to the atmosphere, whereas secondary pollutants are formed in the atmosphere from precursor gases through chemical reactions and microphysical processes. Air pollutants may have a natural, anthropogenic, or mixed origin, depending on their sources or the sources of their precursors. A detailed description of all those pollutants was presented in the D7.2 report.

Key primary air pollutants include particulate matter (PM), black carbon (BC), sulphur oxides (SOx), nitrogen oxides (NOx), ammonia (NH), carbon monoxide (CO), methane (CH), non-methane volatile organic compounds (NMVOCs), including benzene, and certain metals and polycyclic aromatic hydrocarbons, including benzo[a]pyrene (BaP).

Key secondary air pollutants are PM, ozone (O_3), NO and several oxidised volatile organic compounds (VOCs). Key precursor gases for secondary PM are sulphur dioxide (SO_2), NO, NH and VOCs. These pollutants and their precursor gases can be of both natural and anthropogenic origin including: burning of fossil fuels in electricity generation, transport, industry and households; industrial processes and solvent use, for example in the chemical and mining industries; agriculture; waste treatment; natural sources, including volcanic eruptions, windblown dust, sea-salt spray and emissions of volatile organic compounds from plants.

The main difference of aviation and other emitters is the place where pollutants are injected in the atmosphere. Aviation is the only source emitting in a wide space, from the ground surface to the high atmospheric layers, close to the tropopause, the altitude of which depends on the geographic coordinates of the flight. The effects of the low altitude emissions are integrated with those of the other sources affecting local air quality, while high altitude emissions are more influential in the atmospheric dynamics and the climate change.

For the case of the local air quality, Table 5 provides an idea of the relative importance of the different transportation mode emissions in the European air quality, evaluating the comparative participation of their five more important elements in the total European emissions, including all type of sources.

As it is shown in Table 5, transportation is particularly important in nitrogen oxides, with 57.4% of the total emissions, where aviation represents 4.5% a much higher participation than any other of the other pollutants. Its effects are harmful because induces photochemical reactions, acid rain and toxicity. In addition, it increases the ozone creation that has oxidant and climate warming potential.

Carbon monoxide is a powerful toxic, but when emitted in the open air, as it is the case of the engine exhaust, has a very short average life, because it combines with the air oxygen and derives into CO_2. Unburnt hydrocarbons (included in Volatile Organic compounds in Table 5) are toxic, as well, in addition of causing odour problems, as sulphur. Most of the emitted sulphur is in the shape of SO_2 and dilutes very fast in open air. Finally, small PM2.5 particles are causing breathing problems and lungs deterioration. They have a sizeable average life although emitted in the open air are dispersed very fast.

Other particles not mentioned in the table are soot or visible carbon particles, that appear in the form of smoke. This was the first aviation pollutant emission studied in the 60's, as it was visible from long distance and that creates a problem to the military aircraft. With combustion chamber technology progress, it has practically disappeared, although when emitted in altitude, its particles may help to generate condensation trails (contrails) a powerful atmospheric warming element.

Table 5. Main local air quality pollutants in Europe (Source: European Environmental Agency)

LOCAL AIR QUALITY EMISSIONS (EUROPE)

					NON-TRANSPORT	
NOx	32.9%	0.9%	19.1%	4.5%	NOx	42.6%
CO	26.6%	0.2%	2.3%	0.7%	CO	70.2%
SOx	0.1%	0.0%	20.9%	0.5%	SOx	78.5%
VOLATILE ORGANIC COMPOUNDS	15.4%	0.14%	2.52%	0.40%	VOLATILE ORGANIC COMPOUNDS	81.54%
FINE PARTICLES (PM2.5)	14.2%	0.4%	11.4%	0.6%	FINE PARTICLES (PM2.5)	73.4%

In % of total emissions | source: European Environment Agency, 2013

When discussing climate change, the only greenhouse gas (GHG) emitted by jet engines is carbon dioxide, a product of the perfect fuel combustion and not dangerous for breathing in the concentration of a typical airport. CO_2 emissions are now the first objective of the carbon footprint reduction of the industry, which has adopted the "Net Zero carbon emissions" target for the year 2050. As CO_2 is a product of the perfect fuel combustion, its elimination needs not only improving fuel efficiency but also replacing fossil-origin kerosene by new Sustainable Aviation Fuels (SAF) or new disruptive technologies like electricity or hydrogen fed powerplants.

The different nitrogen oxides emitted by aviation, commonly identified as NOx emissions, are not greenhouse gases, because N_2O, that is a GHG, is not emitted by jet engines. However, when NOx is injected in the high levels of the atmosphere, it produces a dual effect creating ozone and destroying methane, both GHG. The resultant of both effects increases atmospheric warming.

Other emissions have a minor impact on climate change. Water vapour itself has a small warming effect. Direct sulphate depends on the sulphur content of the kerosene, that is regulated by fuel specifications, and direct soot is a consequence of the combustor efficiency, being reduced as the fuel and the air mix improves its quality.

The formation of condensation trails (usually mentioned as contrails) is more complex because depends on the physical conditions of the atmospheric region where the flight is being performed. A detailed analysis of the present situation of the scientific knowledge in this area was presented in the Deliverable D7.1 [Reference?]. The incertitude levels continue being very high.

With respect to the emissions during the different flight phases, in standard atmospheric conditions, they depend on the engine regime. Schematically, they can be described as:

- Low thrust period during aircraft taxi in and out: high amount of CO and UHC
- Moderate thrust period during descent and approach: sizeable amount of CO and UHC, small amount of NOx
- Mid thrust period during cruise: small amount of CO and UHC, sizeable amount of NOx
- High thrust period during climb: High amount of NOx
- Very high thrust period during take-off and initial climb: High amount of NOx and soot

The established ICAO certification procedure covers all these phases and measure engine emissions in the test cell for new engines. The relationship between certificated values and actual values is contingent upon how much the actual operation is similar to the certification procedure.

With respect to climate change impact at low flight altitudes, CO_2 and NOx are the most relevant factors. At cruise altitudes, contrails effects should be added to those two elements.

3.3.1. BUDAPEST SCENARIO SPECIFICS

The approach used to quantify the benefits of MergeStrip in terms of environment impact is slightly different than the one used in the previous analysis. The following 4 indicators are assessed:

- **Fuel consumption**, modeled using BADA version 4.1
- **CO_2 emissions**, modeled using BADA version 4.1
- **Horizontal flight efficiency (HFE)**, defined as the ratio between the covered distance from the TOD until the last point of the trajectory and the great circle distance between such two points.
- **Vertical flight efficiency (VFE)**, defined as the ratio between the time of descent without level flight and the total time of descent. If no level flights occur from the TOD until 3000ft, the VFE is 100%.

The differences on the used approach lay in the origin of the trajectories to be analyzed. In the case of Budapest, all trajectories have been generated taking real ADS-B data as input, so an accurate modeling of the thrust (which is required to evaluate indicators such as NOx) is not feasible.

Since the main objective of MergeStrip is to help ATCOs to sequence the arrivals, thus reducing the need to apply non-efficient procedures at a late stage of the approach, two very important indicators are the HFE and the VFE. For this reason, both indicators have been included in this analysis. Furthermore, a direct relation exists between fuel consumption and both HFE and VFE.

- **HFE:** the distance of the most direct route from the TOD to the airport is always equal to the great circle distance between these two points. If the aircraft follows this direct route, its HFE is the maximum achievable (100%). Any deviation from this direct route (e.g. due to vectoring or the execution of a holding pattern) carries an increase of the distance to be flown and, as a consequence, an increase of the fuel consumption.
- **VFE:** when an aircraft interrupts the descent to execute a level flight, both the thrust and the fuel flow increase. This effect can be observed in the example of Figure 5. As a consequence, the higher is the VFE, the lower are the fuel consumption and CO2 emissions for a specific flight.

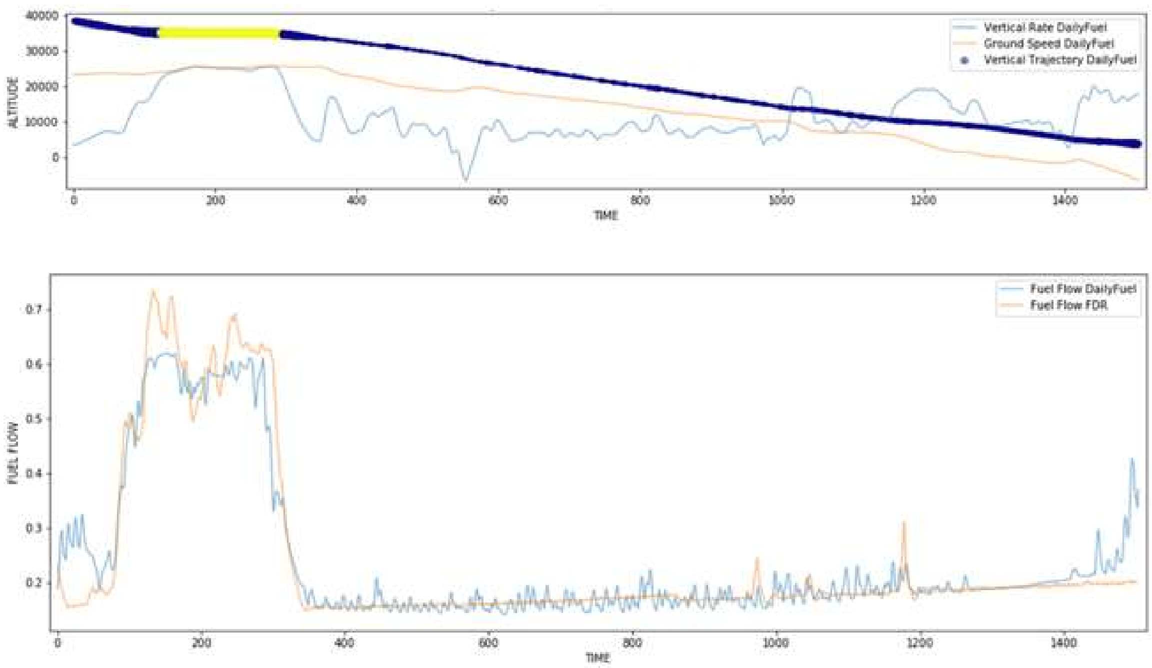


Figure 5. Impact of a level flight in the fuel flow profile

For the exposed reasons, both HFE and VFE are considered to be relevant indicators for this environmental impact assessment. In addition, while the conclusions drafted from the analysis of fuel consumption and CO_2 emissions can be biased by the aircraft model which is dominant in one specific scenario, this is not the case when analyzing and comparing flight efficiencies. As a result, it is considered that the most suitable indicators to assess the benefit of MergeStrip are the aforementioned flight efficiencies.

4. RESULTS

The following results have been postprocessed for the most commonly used aircraft at European airports, and also worldwide, the short and medium range aircraft, or single aisle aircraft (SMR). In particular, for the flights that are included in this exercise, the A320 / B737 types are considered, including the last generation A320 neo.

These aircraft represent a large percentage of the movements at European airports.

The results are also presented for another very relevant aircraft group from the point of view of their emissions: the wide bodies, or long-range aircraft (LR). These aircraft are used by airlines in long range routes, responsible of a large majority of the CO_2 emissions for flights departing an EU airport (Alonso et al, 2014). The trajectories that have been considered for this assessment include the A340-600, B777-200, B777-300ER, and also the last generation A350-900 and B787-8.

4.1. DLR TRAJECTORIES

4.1.1. SHORT AND MEDIUM RANGE AIRCRAFT

CO_2 EMISSIONS

The calculated CO_2 emissions of Short and Medium Range aircraft are shown in Figure 4. The results are presented comparing, for each of the five air traffic controllers (ATCO), the average CO_2 emissions of all flights (operated with this aircraft category) in scenario "30" with those of scenario "60". For most of the ATCOs, the scenario "60" represents an improvement in terms of CO_2 emissions, compared to scenario "60".

Figure 5 also shows the comparison of the average CO_2 emissions of the flights under the control of the five ATCOs. Overall, the scenario "60" represents a reduction of the CO_2 emissions of 1.1% for the approach phase covering the last 100 nm of flight compared to scenario "30".

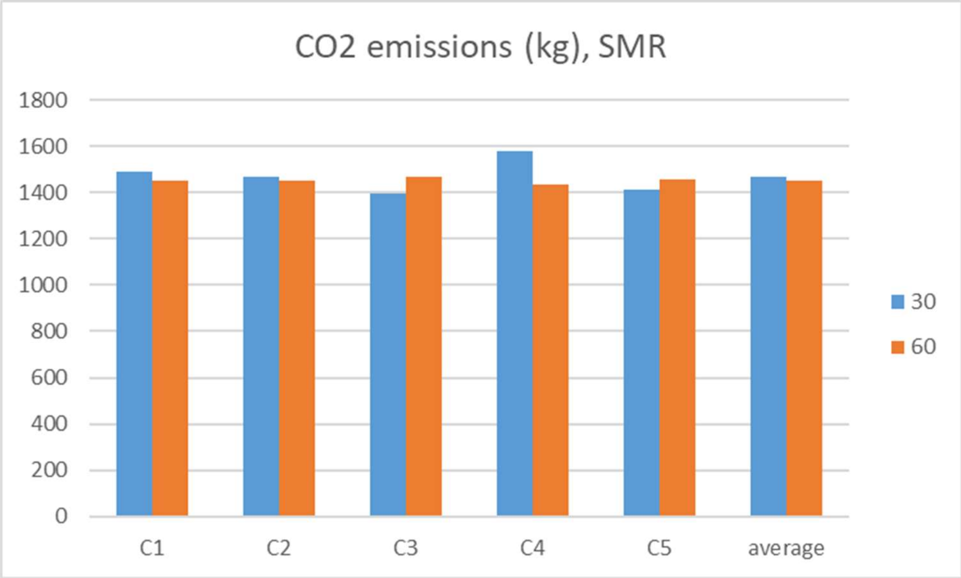


Figure 6. CO_2 emissions for SMR aircraft.

This difference is much larger when only the new models in this aircraft category are considered, i.e. the A320 neo aircraft (Figure 6). In this case, the reduction in CO_2 emissions is found in flights under the control of the five ATCOs, and overall in average the improvement in CO_2 emissions is 8.4% comparing both scenarios.

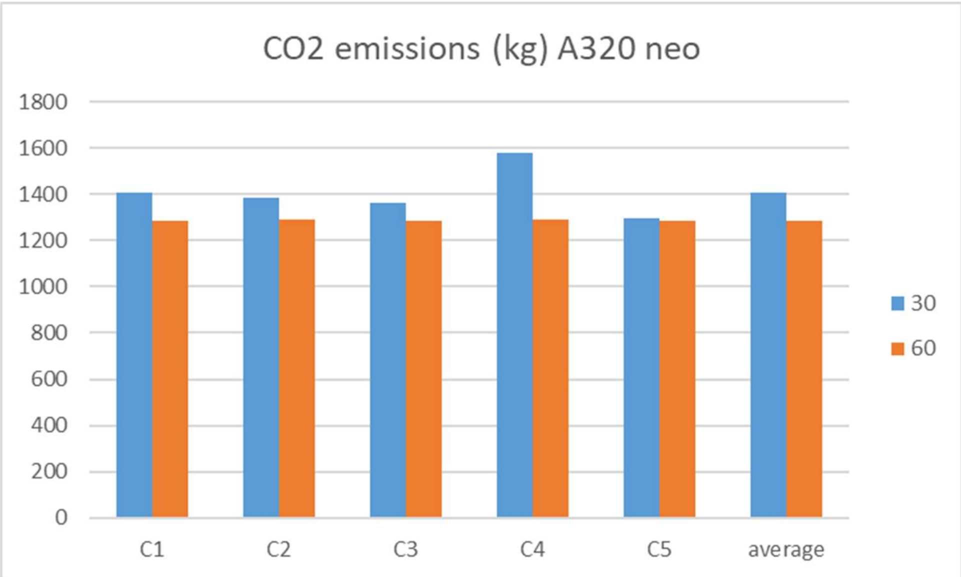


Figure 7. CO_2 emissions for A320 neo aircraft.

The more efficient engine in the A320 neo and other newest generation aircraft, compared to the A320 ceo, seem to be more sensible to improvements in the trajectories from the environmental perspective, not only in terms of fuel efficiency (associated to the CO_2 emissions), but also in terms of the thrust levels required (associated to the NOx emissions).
As it will be shown in the following section, the same effect is observed in the case of the modern widebodies by comparison to the older models, and for the same reasons.

NOx EMISSIONS

The NOx emissions of Short and Medium Range aircraft are shown in Figure 7. Like in the previous cases, the results are presented comparing, for each of the five air traffic controllers (ATCOs), the average NOx emissions of all flights (operated with this aircraft category) in scenario "30" with those of scenario "60". For most of the ATCOs, the scenario "60" represents an improvement in terms of NOx emissions, compared to scenario "60".

Figure 7 also shows the comparison of the average NOx emissions of the flights under the control of the five ATCOs. Overall, the scenario "60" represents a reduction of the NOx emissions of 2.9% compared to scenario "30", a larger difference than in the case of CO_2.

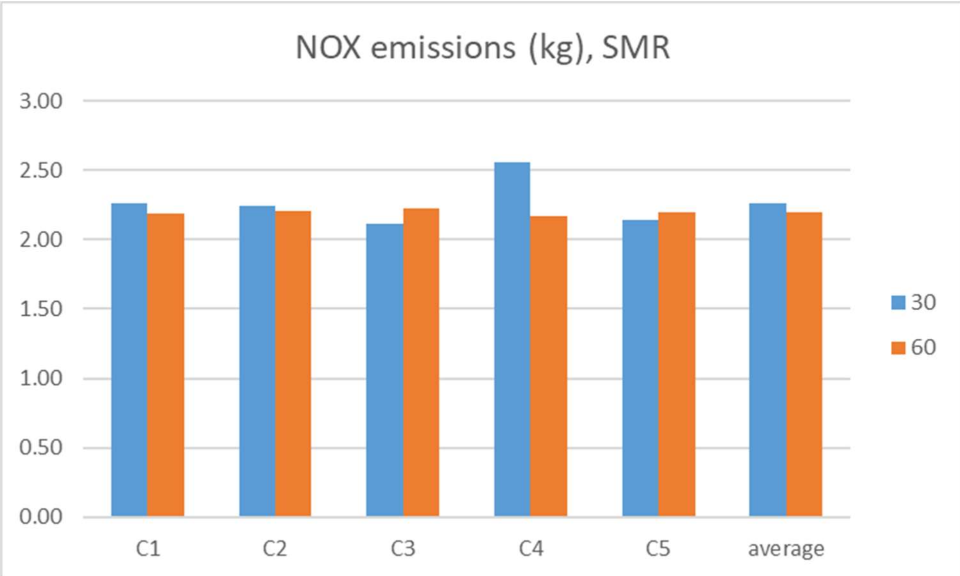


Figure 8. NOx emissions for SMR aircraft.

Also, in this case, this difference is much larger when only the new models in this aircraft category are considered, i.e. the A320 neo aircraft (Figure 8). In this case, the reduction in NOx emissions is found in flights under the control of the five ATCOs, and overall in average the improvement in NOx emissions is 11.0% comparing both scenarios.

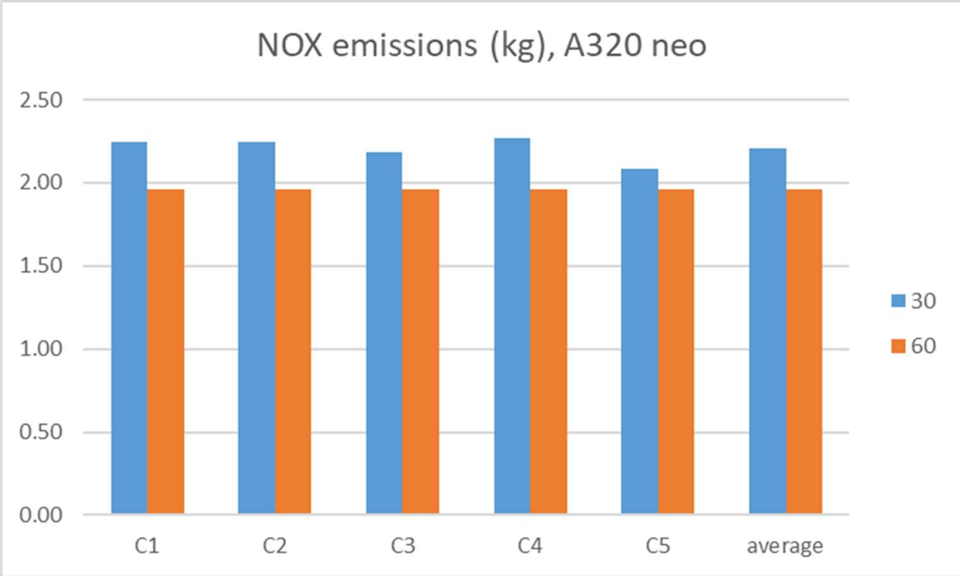


Figure 9. NOx emissions for A320 neo aircraft.

4.1.2. WIDE BODY AIRCRAFT

CO_2 EMISSIONS

The CO_2 emissions of Wide Body, or Long Range (LR) aircraft are shown in Figure 9. Here again the results are presented comparing, for each of the five air traffic controllers (ATCOs), the average CO_2 emissions of all flights (operated with this aircraft category) in scenario "30" with those of scenario "60". For all five ATCOs, the scenario "60" represents an improvement in terms of CO_2 emissions, compared to scenario "60".

Figure 9 also shows the comparison of the average CO_2 emissions of the flights under the control of the five ATCOs. Overall, the scenario "60" represents a reduction of the CO_2 emissions of 8.9% compared to scenario "30".

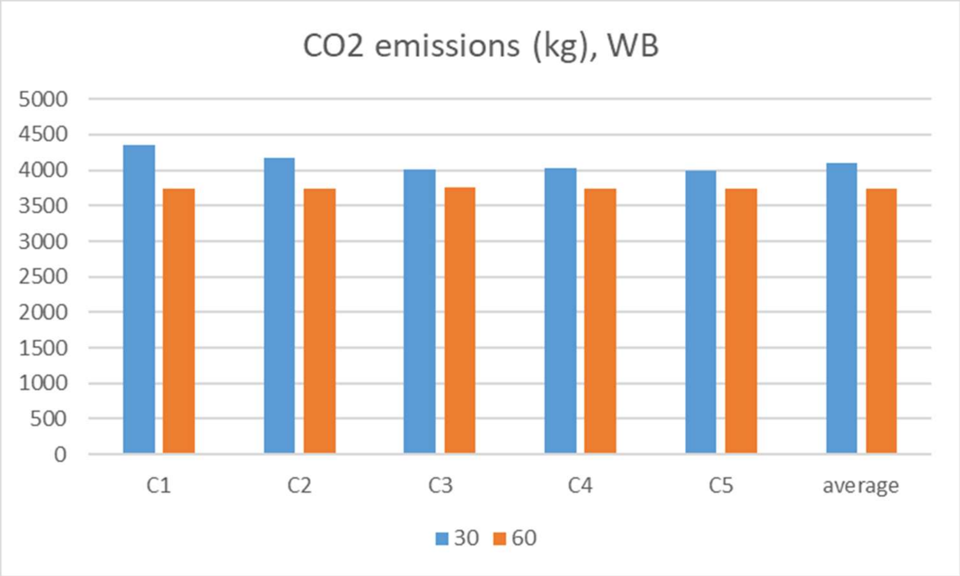


Figure 10. CO_2 emissions for LR aircraft.

This difference is much larger when only the new models in this aircraft category are considered, i.e. the A350-900 and B787-8 aircraft (Figure 10). In this case, the reduction in CO_2 emissions is found in flights under the control of the five ATCOs, and overall, in average, the improvement in CO_2 emissions is 23.1% comparing both scenarios.

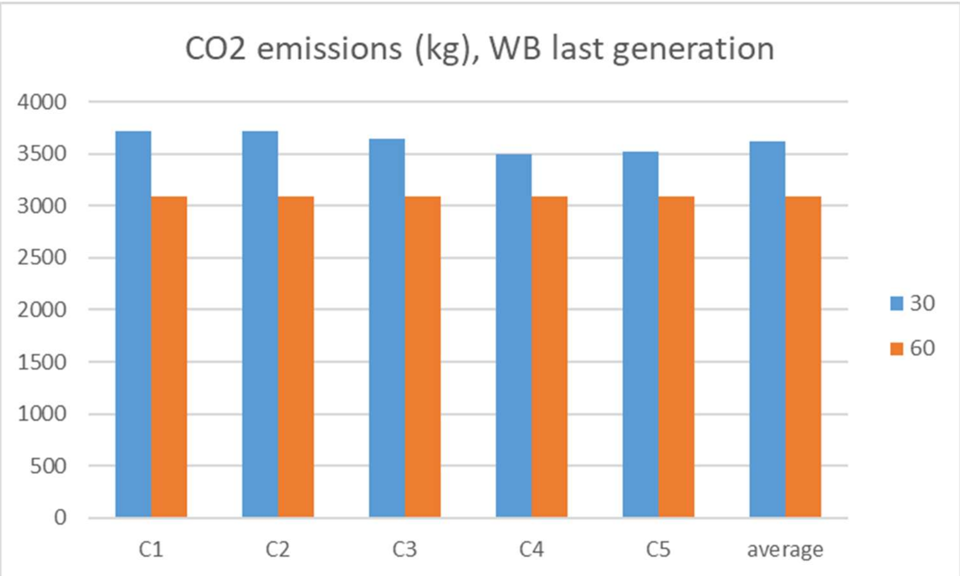


Figure 11. CO_2 emissions for LR aircraft, last generation.

NOx EMISSIONS

The NOx emissions of Long Range aircraft are shown in Figure 11. Like in the previous cases, the results are presented comparing, for each of the five ATCOs, the average NOx emissions of all flights (operated with this aircraft category) in scenario "30" with those of scenario "60". For all five ATCOs, the scenario "60" represents an improvement in terms of NOx emissions, compared to scenario "60".

Figure 11 also shows the comparison of the average NOx emissions of the flights under the control of the five ATCOs. Overall, the scenario "60" represents a reduction of the NOx emissions of 14.7% compared to scenario "30", a larger difference than in the case of CO_2.

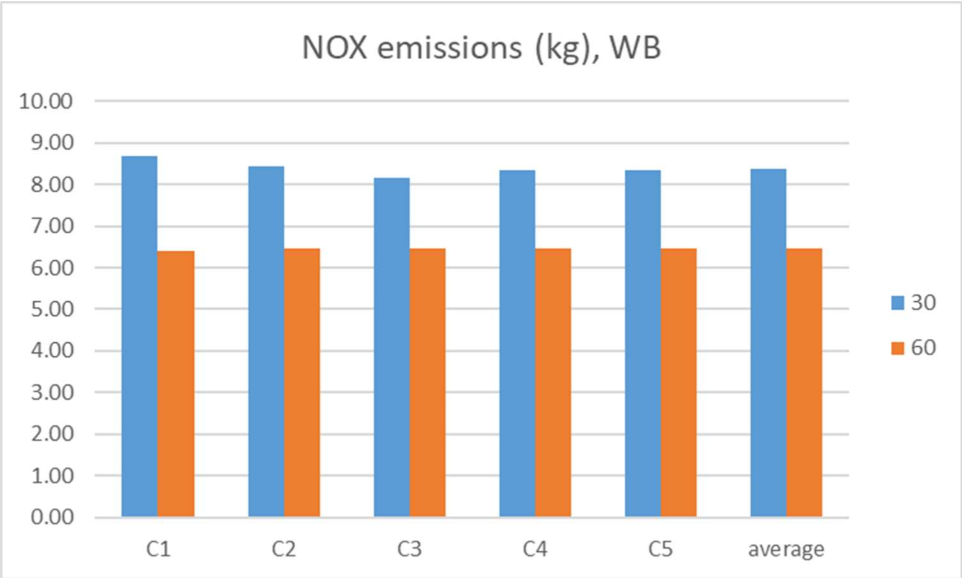


Figure 12. NOx emissions for LR aircraft.

Also, in this case, this difference is much larger when only the new models in this aircraft category are considered, i.e., the A350-900 and B787-8 aircraft (Figure 12). In this case, the reduction in NOx emissions is found in flights under the control of the five ATCOs, and overall, in average, the improvement in NOx emissions is 50.6% comparing both scenarios.

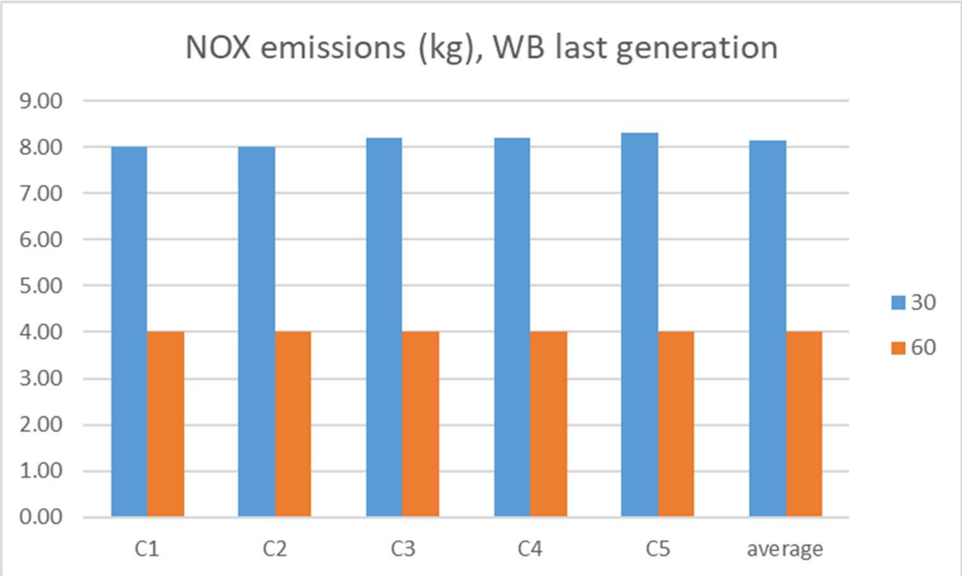


Figure 13. NOx emissions for LR aircraft, last generation.

All these results are summarized in Table 6, where the general improvement in terms of both CO_2 and NOx emissions comparing the two scenarios that are being analysed can be appreciated. Overall, the scenario "60" represents a clear improvement in terms of environmental impact with respect to the scenario "30", with a reduction in CO_2 emissions between 1.1% for SMR and 8.9% for LR aircraft. The improvement in NOx emissions is even larger, 2.9% for SMR and 23.1% for LR aircraft.

Table 6. Summary of results: CO_2 and NOx emissions improvements.

aircraft category		CO_2	NOx
all aircraft	SMR	-1.1%	-2.9%
	LR	-8.9%	-23.1%
last generation	SMR	-8.4%	-11.0%
	LR	-14.7%	-50.6%

These results are very promising and represent a good achievement of the GreAT project. Obviously, and considering that the scenarios in this exercise are only related to descent trajectories, the improvements have to be seen as a contribution to a more ambitious greener ATM that would consider all the segments of a flight.
Since the emissions associated to the descent are relatively small compared to the total emissions produced during the whole flight, the climate impact is limited, but this does not mean that the savings that can be acomplished with greener trajectories are irrelevant.
The improvements affect not only the contribution of the emissions to the climate change, but also the local air quality at the airport area.
The detailed environmental assessment, together with a trade-off analysis between the environmental assesssment indicators and other operational performance indicators will be presented in the report D7.4, the last deliverable of MWP7.

4.2. BUDAPEST SCENARIO

4.2.1. DATA

The different type of trajectories used in the analysis are quantified in Table 7.

Table 7. Number of trajectories used for the MergeStrip analysis

Total number of trajectories	**1819**
Trajectories with fuel estimation	**1060**
MergeStrip trajectories	**534**
No MergeStrip trajectories	**1285**
MergeStrip trajectories with fuel estimation	**302**
No MergeStrip trajectories with fuel estimation	**758**

The exported data used to generate these results does not include the aircraft model, so no separate analysis for SMR and LR is done in this part of the study.

4.2.2. FUEL CONSUMPTION

Figure 14 shows the comparison between the scenarios under study in terms of fuel consumption per flight.

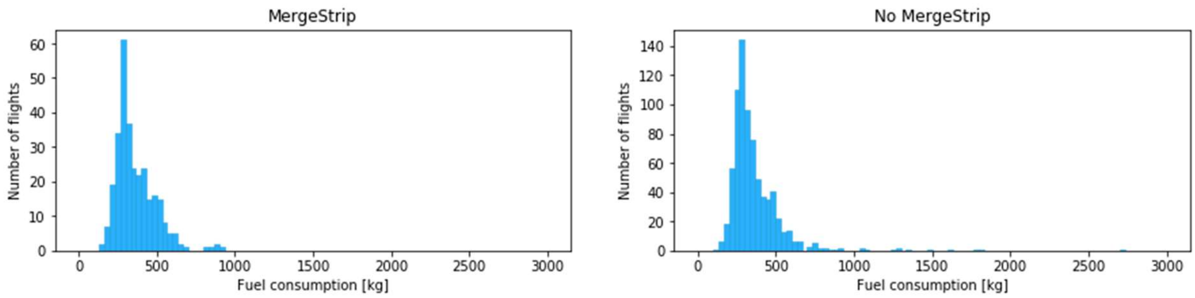


Figure 14. Fuel consumption [kg] - Histograms

The results in terms of mean values are summarized in Table 8.

Table 8. Mean fuel consumption per flight

Indicator	**MergeStrip**	**No MergeStrip**
Fuel consumption	361.26 kg	364.24 kg

4.2.2.1 OUTLIER ANALYSIS

Flights with the highest fuel consumption values can be identified as outliers by representing the results using boxplots. Aiming at identifying under which scenario we obtain the highest fuel consumption values, one boxplot per scenario is presented below.

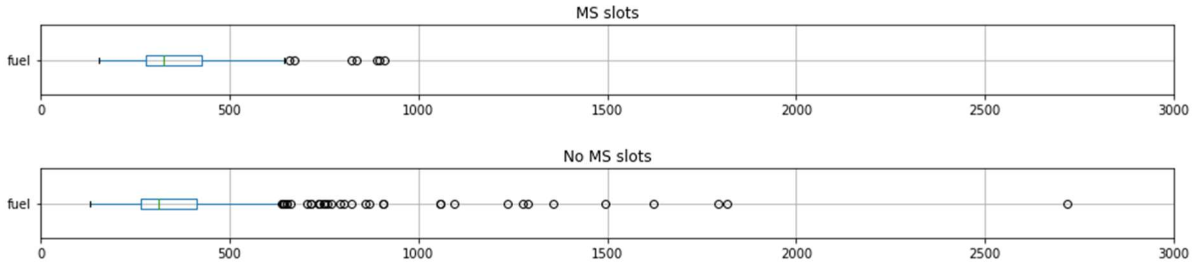


Figure 15. Fuel consumption [kg] – Boxplots

The 12 flights with highest fuel consumption values are included in the No MergeStrip scenario.

4.2.3. CO_2 EMISSIONS

CO_2 emissions are linearly dependent on the fuel consumption by a factor of 3.15 (Section 2). For this reason, the comparison of results for the case of CO_2 emissions has exactly the same shape than the one presented for the fuel consumption.

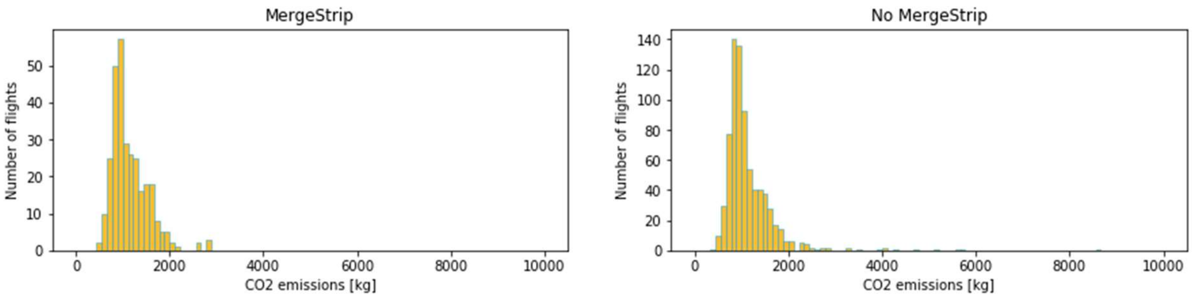


Figure 16. CO_2 emissions [kg] - Histograms

The results in terms of mean values are summarized in Table 9.

Table 9. Mean CO_2 emissions per flight

Indicator	MergeStrip	No MergeStrip
CO_2 emissions	1137.93 kg	1147.36 kg

4.2.4. HORIZONTAL FLIGHT EFFICIENCY

The HFE is defined as the *ratio between the covered distance from the TOD until the last point of the trajectory and the great circle distance between such two points*.

Figure 17 shows the comparison between the scenarios under study in terms of HFE per flight.

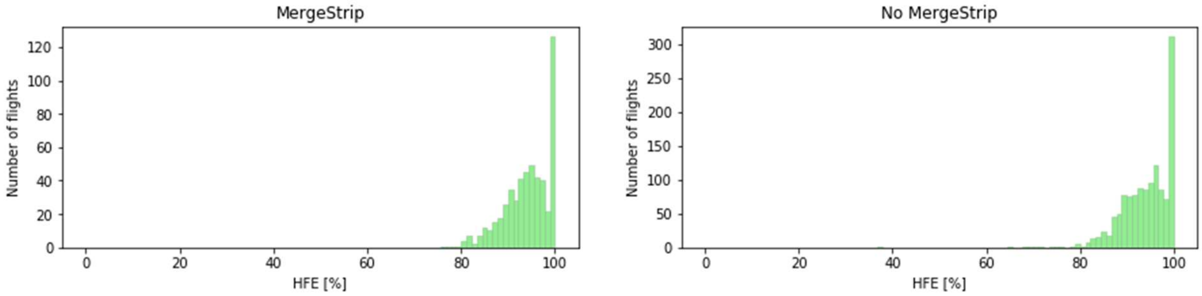


Figure 17. Horizontal Flight Efficiency [%] - Histograms

The results in terms of mean values are summarized in Table 10.

Table 10. Mean HFE per flight

Indicator	MergeStrip	No MergeStrip
HFE	94.08%	94.03%

4.2.4.1 OUTLIER ANALYSIS

Flights with the lowest HFE values can be identified as outliers by representing the results using boxplots. Aiming at identifying under which scenario we obtain the lowest HFE values, one boxplot per scenario is presented below.

Figure 18. Horizontal Flight Efficiency [%] – Boxplots

It can be observed that most of the bigger HFE outliers correspond to arrivals which take place in the No MergeStrip scenario.

callsign	horizontal_efficiency	is_mergestrip
EXS1CW	36.9791	0
EXS84GV	65.458	0
THY5TS	68.4719	0
BCS76K	69.4394	0
WZZ89	70.3911	0
SWR5NH	71.5797	0
LOT5CH	71.7807	0
MSC2914	73.7446	0
AUA721	73.8772	0
EWG76ZV	74.4708	0
MSR751	74.9958	0
WZZ203	75.9726	1
ASL35B	76.5833	0
THY6RN	76.8244	1
WZZ662	78.2253	1
AUA721	78.2364	0
ASL53Q	78.2589	0
AUA713	79.1511	0
BBG442	79.2431	0
WZZ0436	79.2982	1
AUA713	79.4922	0
WZZ85Y	79.5906	0
THY5TS	79.7814	0
BCS5867	79.925	0
EXS4UA	80.2723	0

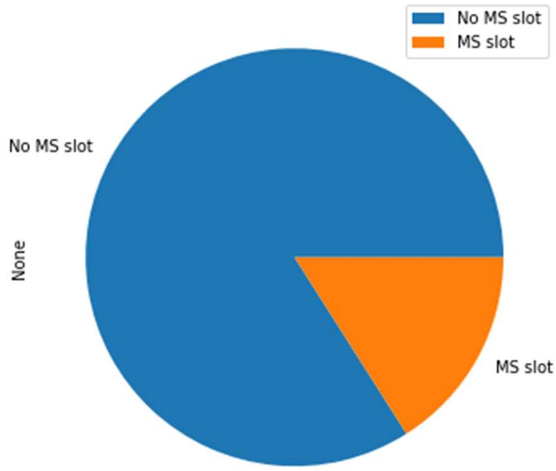


Figure 19. List of the 25 flights with lowest HFE values

The arrival with the lowest HFE value took place on 4th of April.

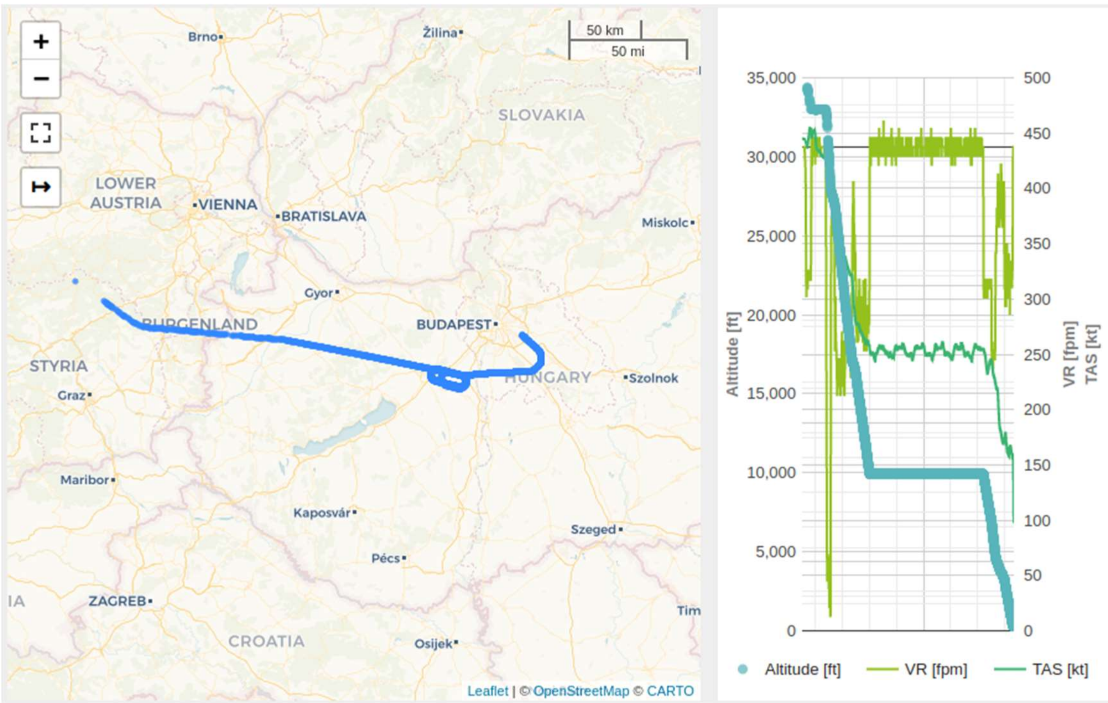


Figure 20. Data from flight with lowest HFE value

As it can be seen in Figure 21, the presence of multiple repetitions of a holding pattern is the cause of the abnormally low HFE value.

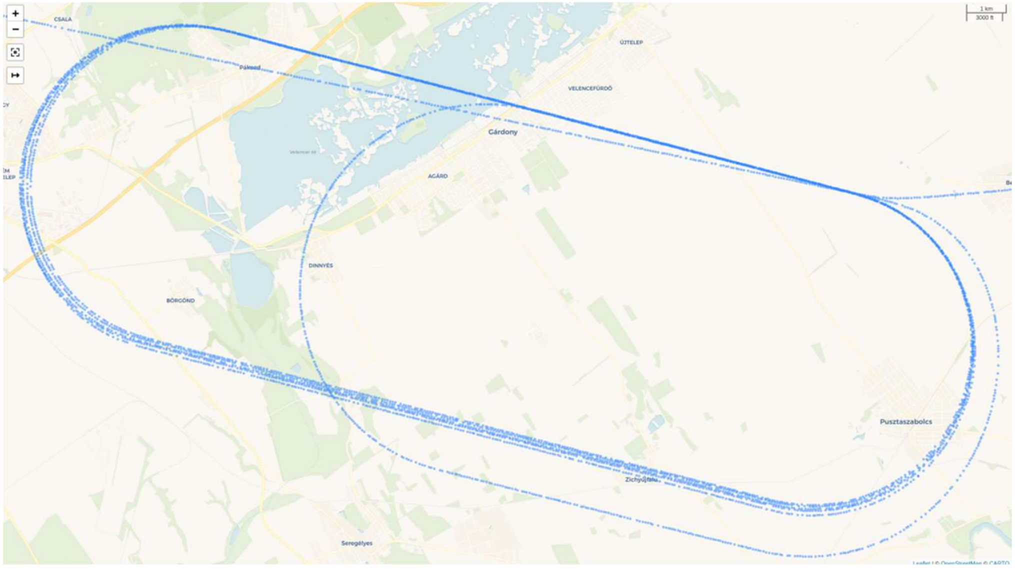


Figure 21. Holding pattern repeated by the flight with lowest HFE value

The following pictures show the 2D trajectories of the other 4 flights with lowest HFE values.

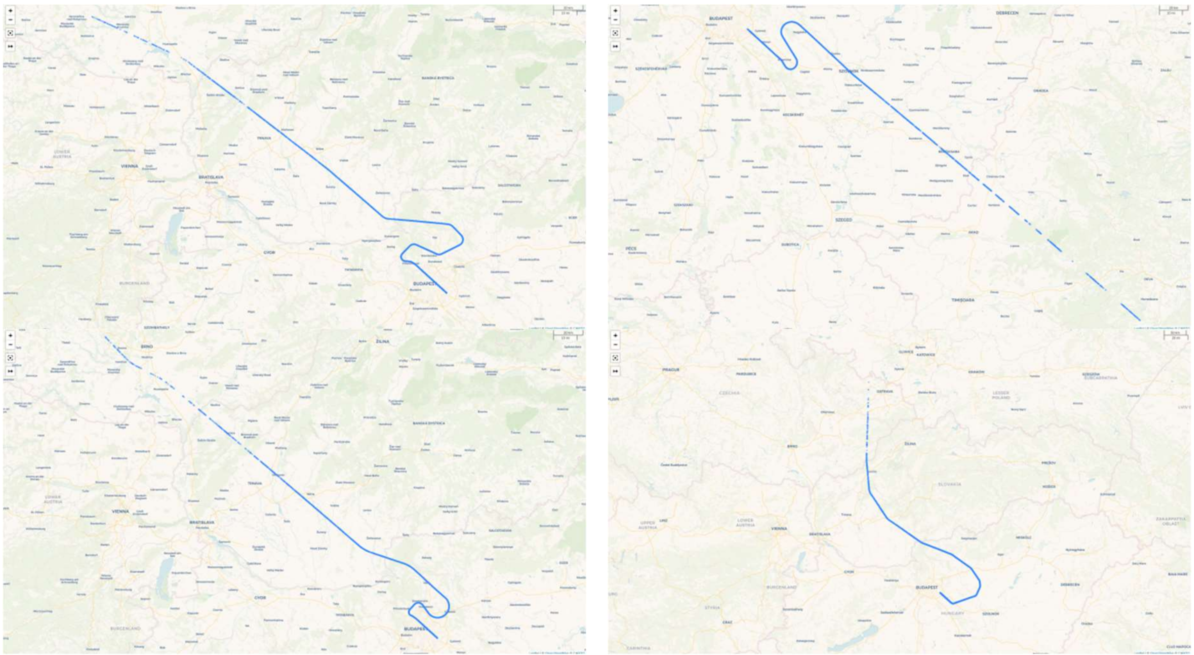


Figure 22. 2D trajectories of flights with low HFE

4.2.5. VERTICAL FLIGHT EFFICIENCY

The VFE is defined as *the ratio between the time of descent without level flight and the total time of descent*. If no level flights occur from the TOD until 3000ft, the VFE is 100%.

Figure 23 shows the comparison between the scenarios under study in terms of VFE per flight.

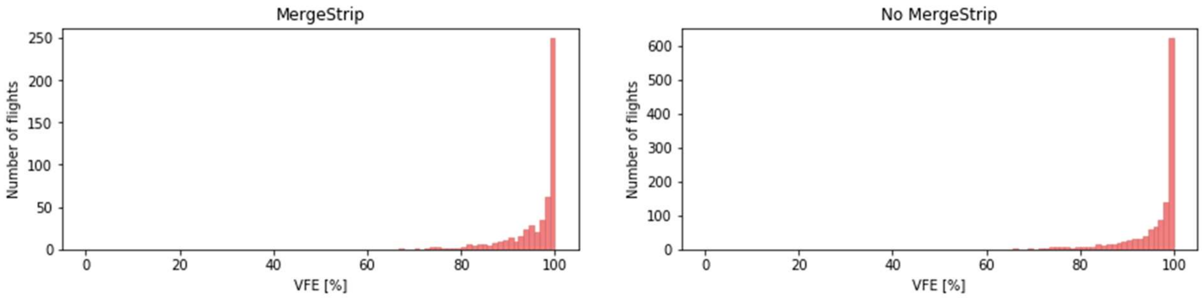


Figure 23. Vertical Flight Efficiency [%] – Histograms

The results in terms of mean values are summarized in Table 11.

Table 11. Mean VFE per flight

Indicator	MergeStrip	No MergeStrip
VFE	95.93%	95.81%

4.2.5.1 OUTLIER ANALYSIS

Flights with the lowest VFE values can be identified as outliers by representing the results using boxplots. Aiming at identifying under which scenario we obtain the lowest VFE values, one boxplot per scenario is presented below.

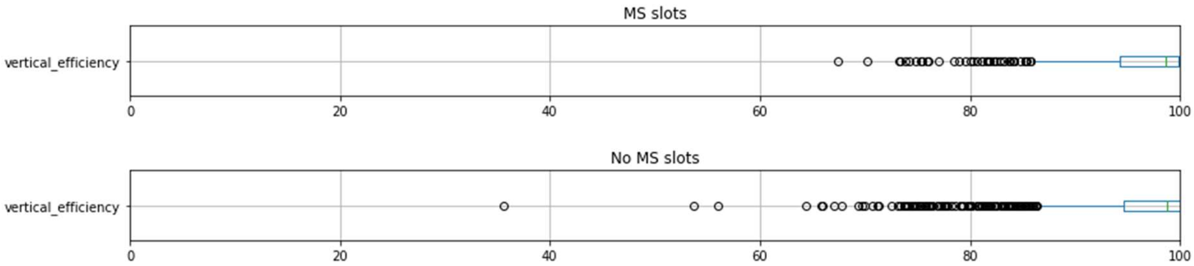


Figure 24. Vertical Flight Efficiency [%] – Boxplots

It can be observed that most of the bigger VFE outliers correspond to arrivals which take place in the No MergeStrip scenario.

	callsign	vertical_efficiency	is_mergestrip
689	EXS1CW	35.5528	0
431	FPO4268	53.7217	0
291	BAW870	55.9793	0
1618	EWG5AP	64.4291	0
432	WZZ87LU	65.896	0
1936	EWG76ZV	65.9529	0
1669	KLM1979	67.043	0
1603	WZZ43SS	67.4603	1
1092	EZS87GB	67.8308	0
1019	CSH869	69.3503	0
604	KLM21E	69.7662	0
1484	IBE32AM	69.9234	0
1880	DIOBB	70.2363	1
1408	RYR7	70.7207	0
688	KLM1979	71.1735	0
932	EZY49PU	71.3004	0
1756	UAE6H	72.4987	0
881	DUKE22	73.1569	0
1262	RYR7	73.2298	1
539	EXS4UA	73.34	0
1194	KON9001	73.3813	1
1496	BEL6PR	73.742	0
731	EWG4FX	73.7982	0
493	WZZ49	73.8167	1
345	BAW68H	73.8682	0

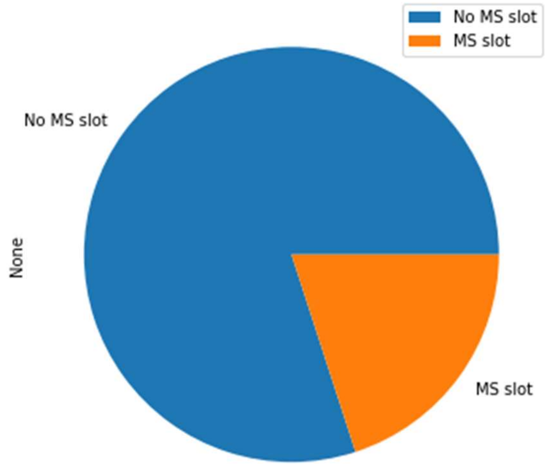
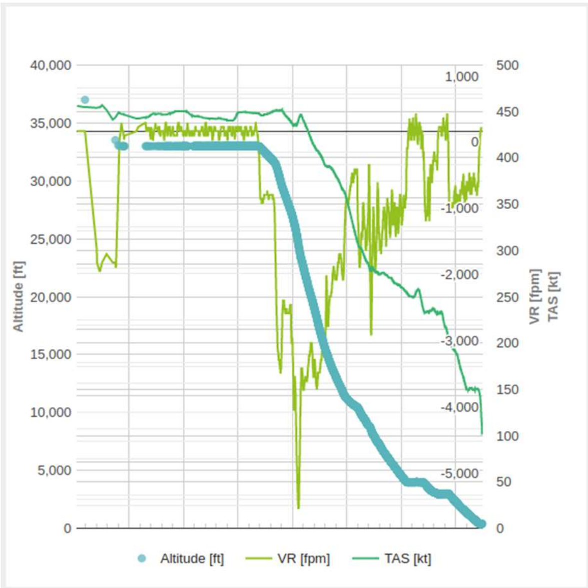
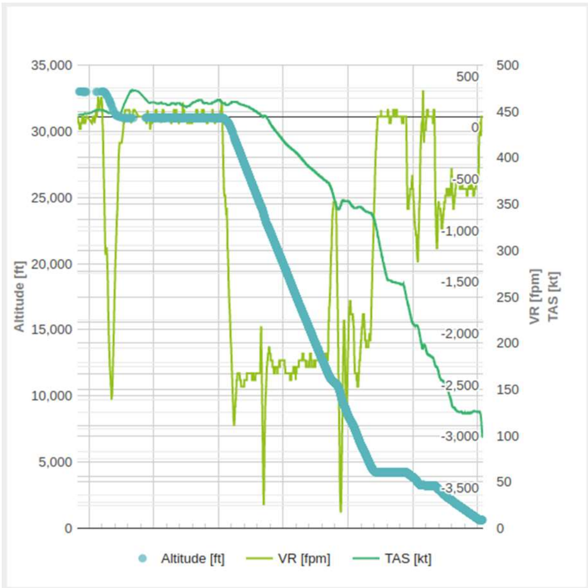


Figure 25. List of the 25 flights with lowest VFE values

The arrival with the lowest VFE value took place on 4th of April (see Figure 20).

The following pictures show the vertical profiles of the other 4 flights with lowest VFE values.





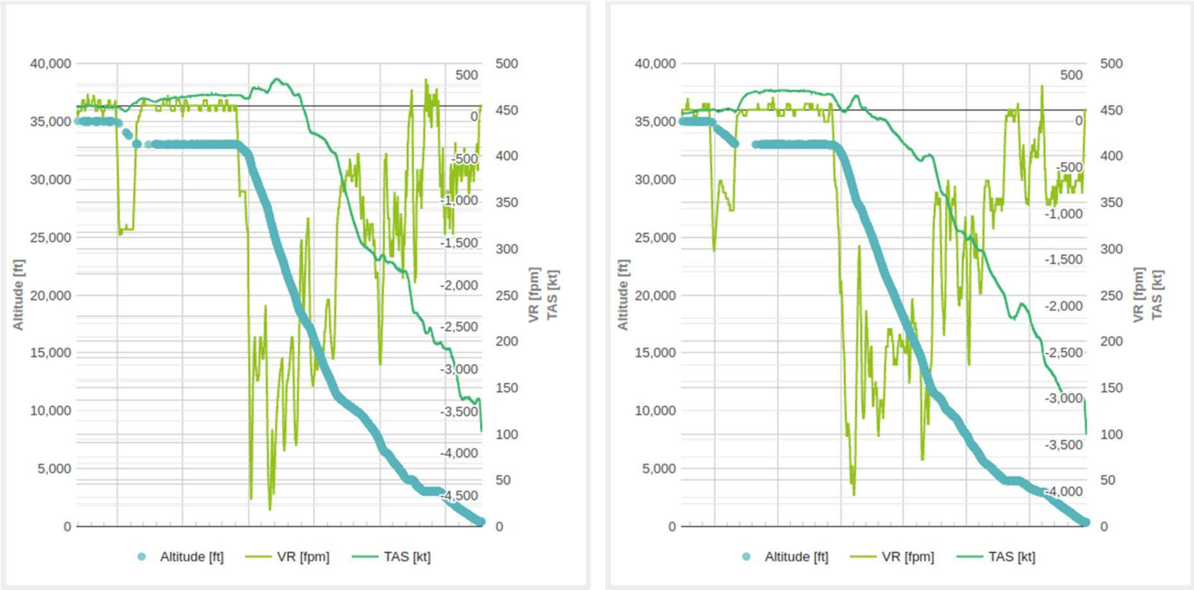


Figure 26. Vertical profiles of flights with low VFE

5. CONCLUSIONS AND NEXT STEPS

The information contained in this report provides a quantification of the environmental impact of the trajectories developed in the work of the GreAT project, both in the local air quality aspects and in the global climate change impact effects. In particular, the CO_2 and the NOx emissions have been calculated with an emissions model specially designed to evaluate these emissions with the trajectory inputs provided by the previous MWPs in the GreAT project.

5.1. DLR TRAJECTORIES

The trajectories used for the environmental impact assessment correspond to the results of the validation trials executed by five air traffic controllers (C1 - C5). These trials were testing two future traffic scenarios, differing with distribution of 3D-FMS and 4D-FMS flights, where 30 and 60 corresponds respectively to 30% and 60% 4D-FMS equipped aircraft, which are able to fly undisturbed continuous descent approaches.

Overall, the 'solution' scenario "60" represents a clear improvement in terms of environmental impact with respect to the 'reference' scenario "30", with a reduction in CO_2 emissions between 1.1% for SMR and 8.9% for LR aircraft. The improvement in NOx emissions is even larger, 2.9% or SMR and 23.1% for LR aircraft.

It is interesting to note that the reduction in the environmental impact comparing both scenarios is larger for the last generation aircraft, both in SMR with the A320 neo, and in LR with the A350-900 and B787-8, which is very promising since these aircraft will naturally and gradually replace the current fleet of previous generation(s) aircraft in the coming years.

5.2. HUNGAROCONTROL – PILDO TRAJECTORIES

The trajectories used for the analysis have been generated from real ADS-B data recorded in Budapest Ferenc Liszt International airport during the period in which MergeStrip was tested in the OPS room (between March 31st and April 13th). Within this period, MergeStrip was tested during three specific time slots: 0945-1130, 1545-1700 and 2030-2200 (UTC).

Minor improvements have been observed in terms of mean fuel consumption, CO2 emissions and horizontal and vertical flight efficiency.

Table 12. Measured benefits of MergeStrip

Indicator	MergeStrip	No MergeStrip	MS benefit
Fuel consumption	361.26 kg	364.24 kg	**-2.98 kg**
CO2 emissions	1137.93 kg	1147.36 kg	**-9.43 kg**
HFE	94.08%	94.03%	**+0.05%**
VFE	95.93%	95.81%	**+0.12%**

The most important benefit of MergeStrip can be measured in terms of the reduction on the number of very low efficient flights:

- ✓ The 11 flights with lowest HFE values are found in the No MergeStrip scenario.
- ✓ 21 out of the 25 flights with lowest HFE values are found in the No MergeStrip scenario (84%).
- ✓ The 7 flights with lowest VFE values are found in the No MergeStrip scenario.

- ✓ 20 out of the 25 flights with lowest VFE values are found in the No MergeStrip scenario (80%).

These results have to be put into context as there were several factors influencing this shadow-mode validation, and which were beyond the control of project partners.

It has to be mentioned that with the redesign of Budapest TMA entering into effect in January 2020, the local maximum level of efficiency has been achieved. In this respect, the tested tool was able to make only minor improvements.

Furthermore, given the fact, that Budapest TMA traffic is still below the pre-COVID level, and also below what was expected for 2023. Finally, as a consequence of the war in Ukraine, the number and occurrence of TRAs have increased significantly, and these TRAs hinder aircrafts to fly the optimal vertical profile. In this context, even this minor improvement development can be considered a very important one.

5.3. FINAL COMMENTS

The results presented in this report, as the outcome of WP7.3 of the GreAT project, provide the necessary inputs to finalize the work in this MWP7, through the development of a trade-off mechanism between these climatic environmental impacts, measured in terms of Global Warming Potential (GWP) and the technical and economic performance indicators that were considered in the design of the greener trajectories in previous MWPs. The results of this trade-off analysis will cover the content of WP7.4 and will be included in the coming D7.4 report to be delivered by June 2023.

6. REFERENCES

Alonso G., A. Benito, A., Lonza, L., Kousoulidou, M. Investigations on the distribution of air transport traffic and CO_2 emissions within the European Union. Journal of Air Transport Management, 36 (2014).

Base of Aircraft Data (BADA) v3.16. EUROCONTROL.

Benito A. and Alonso G. Energy efficiency in Air Transportation. Elsevier Butterworth-Heinemann, Oxford, UK (2018).

Chati Y S, Balakrishnan H. Analysis of aircraft fuel burn and emissions in the landing and take-off cycle using operational data. International Conference on Research in Air Transportation (2014).

European Environmental Agency. Air pollution. Copenhagen (2021).

Hileman J. Fuel composition & aircraft emissions. CAAFI Biennial General Meeting (2018).

International Civil Aviation Organisation (ICAO). Annex 16 Environmental Protection

Volume II, Aircraft Engine Emissions 4th ed. Amendment 10. Montreal, Canada (2021).

Volume III, Aeroplane CO_2 Emissions 1st ed. Montreal (2017).

International Panel on Climate Change (IPCC). Aviation and the Global Atmosphere. Cambridge University Press (1999).

Kling, F., A. Pásztor, T. Mühlhausen, À. Ramonjoan, R. Abdellaoui, H. Boumann, N. Ahrenhold, I. Stasicka, L. Tyburzy and M.-M. Temme. GreAT Validation Report - European Consortium. D6.3. Greener Air Traffic Operations (GreAT) D6.3. HungaroControl, Budapest, Hungary (2022).

Lee, D. S., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C. N., Lim, L. L., Owen, B., Sausen, R. Aviation and global climate change in the 21st century. Atmospheric Environment 43 (2009).

Temme, M.-M., M. Kleinert, R. Abdellaoui, M. Finke, I. Gerdes, M. Schaper, F. Kling, B. Nagy, T. Boldogh, Z. Eszes, Z. Molnár, A. B. Pásztor, H. Haoliang, O. Ohneiser and A. Ramonjoan. Environmental-friendly airspace structuring and traffic sequencing. Greener Air Traffic Operations (GreAT) D4.1. German Aerospace Center (DLR). Braunschweig, Germany (2021).