D7.4: TRADE-OFFS BETWEEN ENVIRONMENTAL IMPACT AND PERFORMANCE INDICATORS

SECURITY: PUBLIC

Lead beneficiary: UPM

Contractual Due Date: M42

Actual Submission Date: 30/06/2023 (M42)

Grant Agreement number:	875154
Project acronym:	GREAT
Project title:	GREENER AIR TRAFFIC OPERATIONS
Funding scheme:	RIA/ H2020
Start date of the project:	January 1st, 2020
Duration:	42 months
Project coordinator (organisation):	Michael Finke (DLR)
Phone:	+49 531 295-2921
E-mail:	Michael.Finke@dlr.de
Project website address:	www.project-great.eu

DOCUMENT INFORMATION

DOCUMENT NAME	D7.4 Trade-offs between environmental impact and performance indicators
VERSION	VF
VERSION DATE	30/06/2023
AUTHOR	Gustavo Alonso (UPM), Arturo Benito (UPM), Àlex Ramonjoan (PILDO), Attila Pásztor (HC), Marco Temme (DLR)
SECURITY	Public

DOCUMENT APPROVALS

	NAME	ORGANISATION	DATE
COORDINATOR	Michael Finke P/O Marco-Michael Temme	DLR	29/06/2023
WP LEADER	Gustavo Alonso	UPM	27/06/2023
OTHER (QUALITY)	Jetta Keranen	L-UP	30/06/2023

DOCUMENT HISTORY AND LIST OF AUTHORS

VERSION	DATE	MODIFICATION	NAME (ORGANISATION)
V1.0	29/05/2023	Original version	Gustavo Alonso (UPM), Arturo Benito (UPM)
V2.0	14/06/2023	Inclusion of performance indicators from D6.4	Gustavo Alonso (UPM), Arturo Benito (UPM)
V3.0	21/06/2023	Editing trade-off analysis	Àlex Ramonjoan (PILDO), Attila Pásztor (HC), Marco Temme (DLR)
V4.0	27/06/2023	Conclusions	Gustavo Alonso (UPM), Arturo Benito (UPM)
VF	30/06/2023	Validation and submission	Marco Temme (DLR), Jetta Keranen (L-UP)

DISTRIBUTION LIST

FULL NAME OR GROUP
GreAT Consortium
European Commission / CINEA
All public

EXECUTIVE SUMMARY

This report corresponds to D7.4 Report on trade-offs between environmental impact and the other performance indicators. The work reported is related to MWP7.4 ”Discussion of the trade-offs between environmental impact and performance indicators”.

WP7.4 is organized in two different tasks:

- Task 7.4.1 Correlation Analysis of Airport/Terminal Operation Performance and Environmental Impact
- Task 7.4.2 Correlation Analysis of ACC/Route Operation Performance and Environmental Impact

The information contained in this report provides a trade-off analysis between 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, and the performance indicators obtained in the work performed in previous workpackages of the project.

As it was indicated in previous reports, The GreAT Concept covers short- and long-haul operations. The long-haul part is focused on the en-route operations optimization, described in MWP3, and developed by the Chinese partners who take care of validation and environmental impact as well. This D7.4 covers the environmental impact of short-haul operation in two aerodromes: Munich with a new airspace structure for a TMA and studied by DLR, and Budapest, by HungaroControl and PildoLabs.

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 results of this report show that there is practically no need of trading-off environmental results of the new approach control procedures, as both environmental impact and performance characteristics offer positive results. It is interesting to highlight that these apparently small improvements in each individual flight, may become a non-negligible advantage when it is multiplied by the huge number of commercial flights operating every day.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Acronym	Signification
ACC	Area Control Center
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
ERF	Effective Radiative Forcing
FMS	Flight Management System
GHG	Greenhouse Gases
GTP	Global Temperature Potential
GWP	Global Warming Potential
HC	Unburnt Hydrocarbons
HFE	Horizontal Flight Efficiency
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
KPA	Key Performance Area
LCA	Life Cycle Analysis
LR	Long Range Aircraft
LTO	Landing and Take-off
RF	Radiative Forcing
SMR	Short and Medium Range Aircraft
TOD	Top of Descent
UTC	Universal Time Coordinated
VFE	Vertical Flight Efficiency

VTAS	True Air Speed
WB	Wide Body Aircraft

1. INTRODUCTION

This report corresponds to D7.4 Report on trade-offs between environmental impact and performance indicators. The work reported is related to MWP7.4 ”Discussion of the tradeoffs between environmental impact and performance indicators”.

WP7.4 is organized in two different tasks:

- Task 7.4.1 Correlation Analysis of Airport/Terminal Operation Performance and Environmental Impact
- Task 7.4.2 Correlation Analysis of ACC/Route Operation Performance and Environmental Impact

D7.4 report covers only Task 7.4.1 for the Airport/Terminal Operation referred to short-haul flights. Task 7.4.2 studying long-haul operation was developed by the Chinese partners, who have already carried out the necessary calculations and verifications.

The information included in this report has two differentiated parts. The first one establishes the indexes (Environmental indicators) to be used for quantifying the environmental impacts that have been described in the previous document D7.3 “Environmental impact assessment and green trajectories” for both DLR and HungaroControl-Pildo trajectories. The second part analyses possible trade-offs between the environmental impact improvements, achieved by the new operating procedures and other elements relevant for the performance and operation economics, like fuel consumption or flight time.

The conclusions provide a global estimation of the advantages and disadvantages of the new procedures developed by the work in the GreAT project, and the benefits of their future application, putting a final point to this Greener Air Traffic Operations endeavour.

2. ENVIRONMENTAL INDICATORS

The selection of environmental indicators is made attending to some specific characteristics:

- They represent an environmental feature relevant for the communities affected by the operations.
- They are directly dependent on the aircraft operation.
- They are quantified in a unit easy to calculate and with an homogeneous scale for internal comparisons.

As it was detailed in document D7.2 "Description of aviation emissions impact on environment", there are two types of impacts: those concentrated around the airports, mainly represented by the noise emitted by the aircraft operations and the emissions coming from the airport activity, obviously led by aircraft engine emissions, and those affecting the thermodynamic atmospheric mechanism, inducing atmospheric warming and, therefore, climatic change.

In this report, as in the majority of the scientific and technical publications, both impacts are treated separately because the spatial and temporal reach of the inductor emissions are quite different. However, some of the emitted product may be causing both types of effects, like the case of NOx, which is a strong air quality contaminant but, at the same time, intervenes in the climate change mechanism, altering the formation and destruction processes of two GHG like ozone and methane. In that case, this particular emission is included in the two impacts.

2.1. CLIMATE CHANGE

When looking at the environmental consequences of human activities, climate change is, no doubt, one of the most prominent elements to be calculated. The evaluation offers several problems, many of them still being studied because scientific certainty is far from achieving a satisfactory level of accuracy.

A first step is the separation of effects coming from natural causes and those originated by human activities. Along the history, the Earth climate has suffered many changes due to this planet geological evolution, with high temperature periods and glacial ages. However, the natural evolution moves slowly, and the dramatic changes need thousands of years to happen. However, climate changes consequence of anthropogenic activities are progressively increasing with the beginning of the XIX Century Industrial Revolution and the fast growth of the world population and its developing movements.

To provide an idea of the change speed, Figure 1 shows IPCC calculation of the anthropogenic climate change evolution from year 1750, considered as the initial moment of the Industrial Revolution to our times. The effects are measured in terms of Radiative Forcing (RF), defined as an energy imbalance imposed on the climate system externally. It is computed in Watt per square metre (W/m^2) units that is the quantification system generally accepted for the instantaneous evaluation of the emissions at the moment they are injected in the atmosphere. For the global, long-term computation it is needed to add the life term of each emitted substance, once is mixed with the surrounding air, and the possible chemical reactions with the rest of the atmospheric components. Differences in particle life can be extremely large, going from a few seconds for CO to an average of 100 years for CO_2 molecules.

The different emissions are divided in those having a direct effect on atmospheric heating, called Greenhouse gases (GHG) and those having indirect effect due to their influence in the creation or destruction of GHG. The first group covers carbon dioxide (CO_2), methane (CH_4), Halocarbons and dinitrogen oxide (N_2O); the second includes carbon monoxide (CO), non-methane volatile organic compounds (NMVOC) and nitrogen oxides (NOx). In the last part of this second group, appear aerosols and precursors.

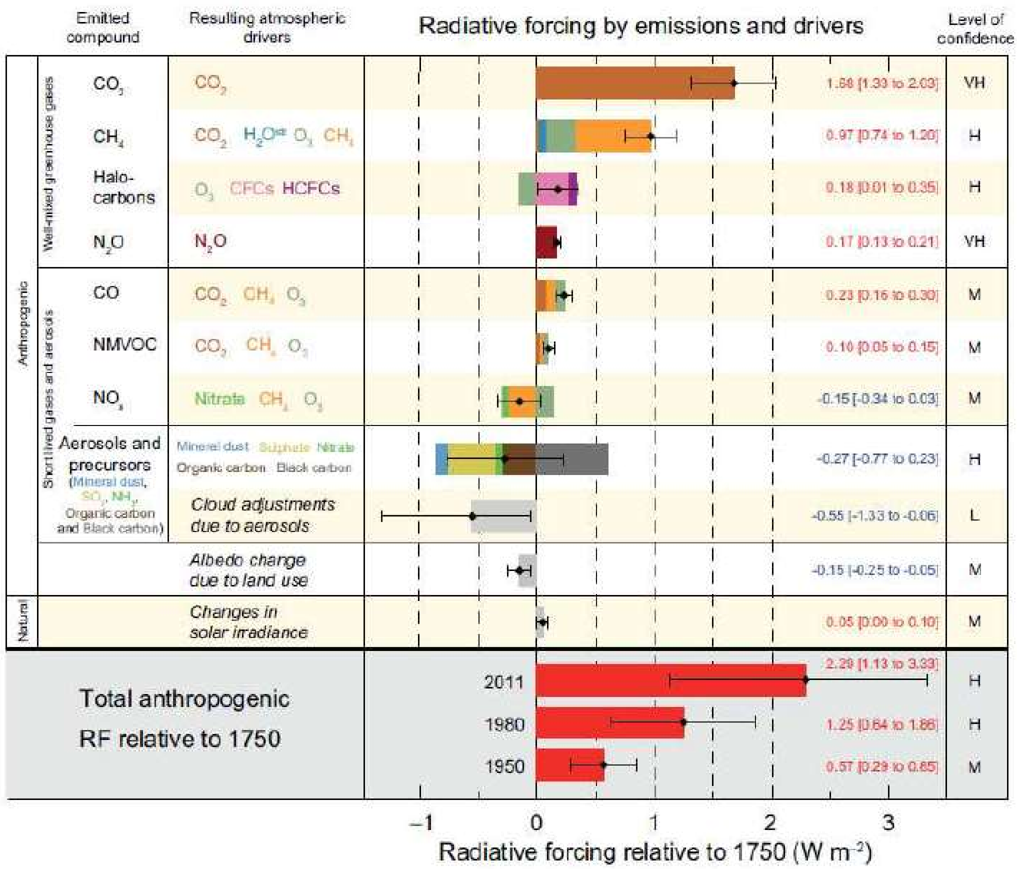

Figure 1. Radiative forcing estimates in 2011. Black lines in the center of the columns indicate estimations error margins. Letters on the right column marks the scientific confidence levels (VH very high, H high, M medium and L low) (*Source: IPCC, 2013*).

In this list of emissions, aviation produces a single GHG, CO_2, two substances in the second group, CO and NOx, and a number of aerosols (sulphate and soot) and precursors (mainly water vapour). Some of them have very little impact in the global phenomenon and the dimension of others' impact is still in discussion.

It is generally accepted that aviation impact in climate change is relatively small, with a share calculated between 4% and 6% of the total anthropogenic activities (Lee et al, 2021), but the high growth rate of the sector and the problems of reducing its emissions in a short-term period has made urgent an in-deep study of the problem and its possible solutions.

The present status of the scientific analysis of the aviation impact on climate change is described in the Section 2.1 "Investigations and results on activity 7.1.1. state-of-the-art review on aviation environmental impact", included in D7.1 "Spatial and temporal distribution characteristics of aviation emissions". A good compilation of the relative importance of each emission and related atmospheric phenomena is shown in Figure 2, in a similar format than Figure 1.

The main difference between both figures scheme is the inclusion, in the second one, of an Effective Radiative Forcing (ERF) scale. The difference between RF and ERF is the consideration of temperature at different altitudes. In the case of RF calculations, atmospheric temperature at different altitudes is fixed, while for ERF calculations rapid tropospheric adjustments are allowed and only ground temperature is fixed. At this moment, ERF is the metric receiving more scientific support.

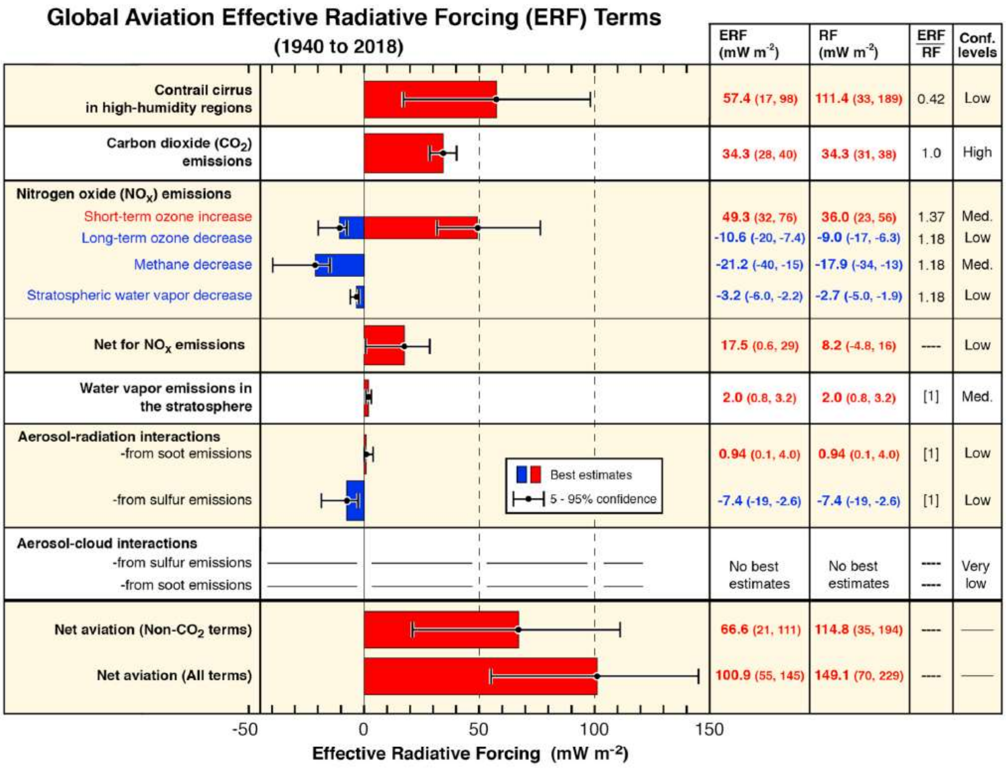

Figure 2. Global aviation impact in climate change in the 1940-2018 period. Red columns represent heating and blue ones, cooling (*Source: Lee et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment 244, 2021*).

As it can be appreciated in Figure 2, CO_2 effect is the only one receiving a high confidence level qualification, while the other important phenomena, contrails (condensation trails) cirrus cloud formation has a low rating and a corresponding high error margins in the calculations.

For the calculation of the global effect of all the emissions, IPCC developed an indicator, named Global Warming Potential (GWP) that integrated the RF of the different emissions during a pre-established period of time, taking CO_2 RF as reference and transforming the other emissions RF in their equivalent CO_2 values. In this way, the result is a single figure, dependent on the period selected. Typically, periods of 20 years for medium term and 100 years for long term are the ones most used.

Other frequently used indicator is the Global Temperature Potential (GTP) that calculates the change in temperature in a certain period to the future caused by a single emission source. This metric is useful if the main interest is the variation in Earth surface temperature and is applied to relatively short period calculations. Figure 3 shows the difference between GWP and GTP for the impact of one-time emission.

In this specific case, when the emissions to be computed are ejected at relatively low altitude, most of the atmospheric effects produced in the high atmospheric layers, like contrails formation are not present. Assuming, as shown in Figure 2, that aerosol radiation interactions are practically neutral, the two main elements to calculate are CO_2 and NOx. Considering the long life of CO_2 particles, it seems logical to select GWP_{100} as indicator, but taking into consideration that NOx effects are shorter, it is interesting to calculate GWP_{20} as well, and examine the differences between both results.

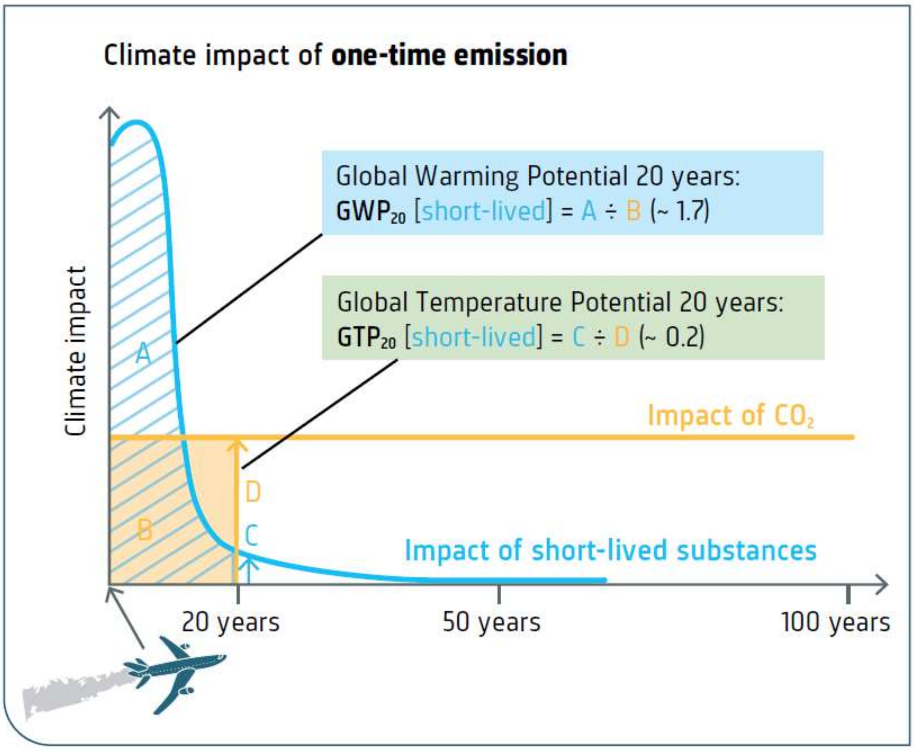

Figure 3. Comparison of the calculation of one-time emission effects in climate change using GWP_{20} and GTP_{20} (*Source: Neu: The impact of emissions from aviation on the climate. Swiss Academies communications Vol 15 nº 9. 2020).*

The calculation of GWP CO_2 equivalence for NOx is not very straightforward. NOx emissions at atmospheric altitudes below tropopause (subsonic aircraft use to fly in this area) help to form ozone (warming effect) and destroy methane (cooling effect). In addition, this methane destruction reduces ozone formation caused by methane itself (cooling effect). In addition, RF from NOx emissions changes heavily with NOx concentration in the atmosphere, which is higher in the regions with industrial activity and high air transportation concentration. Figure 4 gives a schematic idea of these processes depending on the latitude. Net RF is positive (warming effect) in all cases.

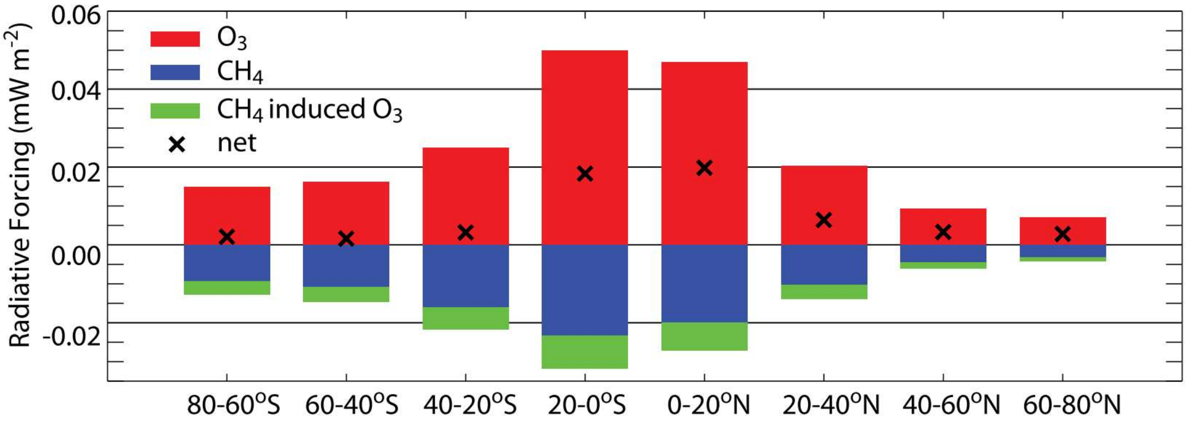

Figure 4. Response to an increase of NOx emissions by 3.8 x 10^{-4} Tg per year Variation of net global-mean RF (black cross) NOx in different latitudes. (*Source: Köhler et al. Latitudinal variation of the effect of aviation NOx emissions on atmospheric ozone and methane and related climate metrics. Atmospheric Environment 64 (2013).*

For this report, using the central European latitude as a reference and searching available sources (Holmes et al., Lammel et al., Skowron et al.) NOx values in CO_2 RF equivalent for weight unit are between 30 and 52 for GWP20 and between 7 and 25 for GWP100. The climatic effect of NOx is comparatively higher in the shorter period, as expected.

A summary of the environmental impact assessment performed in WP7.3 and reported in D7.3 is shown in Table 1. The results show the comparison both for CO_2 and NOx emissions between scenario "30" and scenario "60", showing a reduction of the emissions of both species in scenario "60".

Table 1. Summary of the environmental impact assessment reported in D7.3.

Aircraft size	CO_2	NOx
SMR	-1.1%	-2.9%
WB	-8.9%	-23.1%

The Global Warming Potential of both scenarios is shown in Tables 2 and 3, together with the individual emissions of CO_2 and NOx, in kg. The difference between scenario "30" and "60" is shown in Table 4.

Table 2. Global environmental impact index for scenario "30".

Aircraft size	**30**					
	CO_2	**NOx**	**GWP-20**		**GWP-100**	
			min	max	min	max
SMR	1470.188	2.264	1538.120	1587.936	1486.039	1526.798
WB	4110.055	8.390	4361.752	4546.330	4168.784	4319.802

Table 3. Global environmental impact index for scenario "60".

Aircraft size	60					
	CO_2	NOx	GWP-20		GWP-100	
			min	max	min	max
SMR	1454.240	2.199	1520.196	1568.564	1469.630	1509.203
WB	3744.685	6.451	3938.216	4080.139	3789.842	3905.961

Table 4. Global environmental impact index: difference between scenario "30" and "60".

Aircraft size	difference			
	GWP-20		GWP-100	
	min	max	min	max
SMR	-1.2%	-1.2%	-1.1%	-1.2%
WB	-9.7%	-10.3%	-9.1%	-9.6%

2.2. LOCAL AIR QUALITY

In addition to the CO_2 and NOx emissions calculated for each trajectory (it must be remembered that the trajectories that are considered cover the last 100 nm of each flight), the emissions of other species related to the local air quality at the airport area have also been calculated, in this case only for the portion of the trajectory below 3000 ft. The emissions that have been calculated are NOx, unburned hydrocarbons (HC) and carbon monoxide (CO). The results (in kg) for both scenarios and the comparison between them are shown in Table 5.

Table 5. Environmental impact assessment regarding local air quality.

	30			60			difference		
	NOx	**HC**	**CO**	**NOx**	**HC**	**CO**	**NOx**	**HC**	**CO**
SMR	0.486	0.088	0.845	0.418	0.099	0.591	-13.9%	12.3%	-30.1%
WB	2.129	0.221	2.706	0.906	0.023	0.652	-57.4%	-89.8%	-75.9%

In this case, as the effects are simply changing air quality in the airport proximity, there is no possibility of having a common index. It should be remembered that the airport itself may have a number of other activities affecting air quality and building different air quality scenarios. Without going into detailed particular numbers, big airports like Munich use to have NOx as the most dangerous pollutant. Therefore, NOx improvements are good news.

3. PERFORMANCE INDICATORS

3.1. FLIGHT TIME

3.1.1. DLR TRAJECTORIES

The duration of each trajectory (last 100 nm of the flight) have been determined, and the results are shown in Figure 5, for flight operated by SMR aircraft, and Figure 2, for WB aircraft. The average duration (in seconds) for each scenario and the time flight difference between scenario "30%" and "60%" are shown in Table 6.

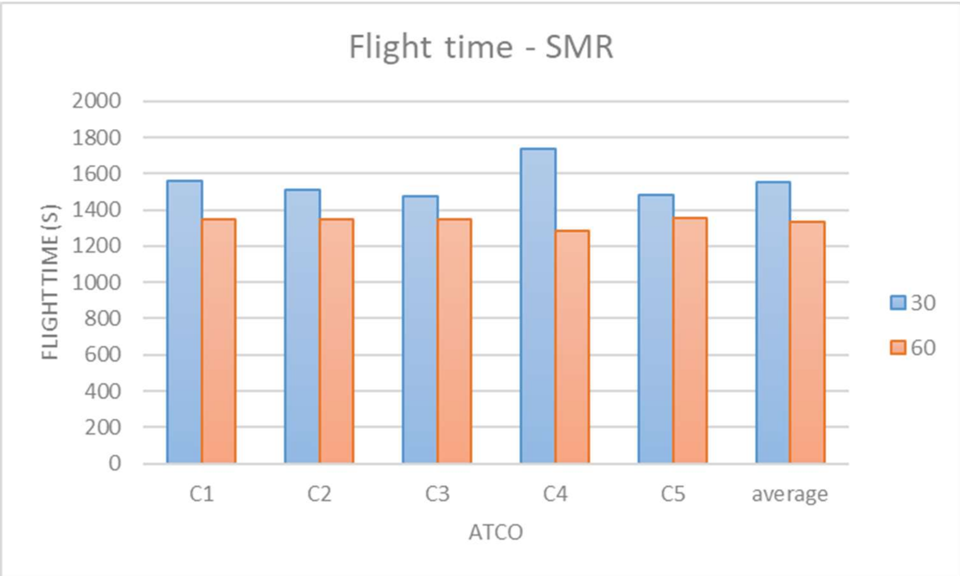

Figure 5. Flight time (in seconds) for the flights operated by SMR aircraft in both scenarios.

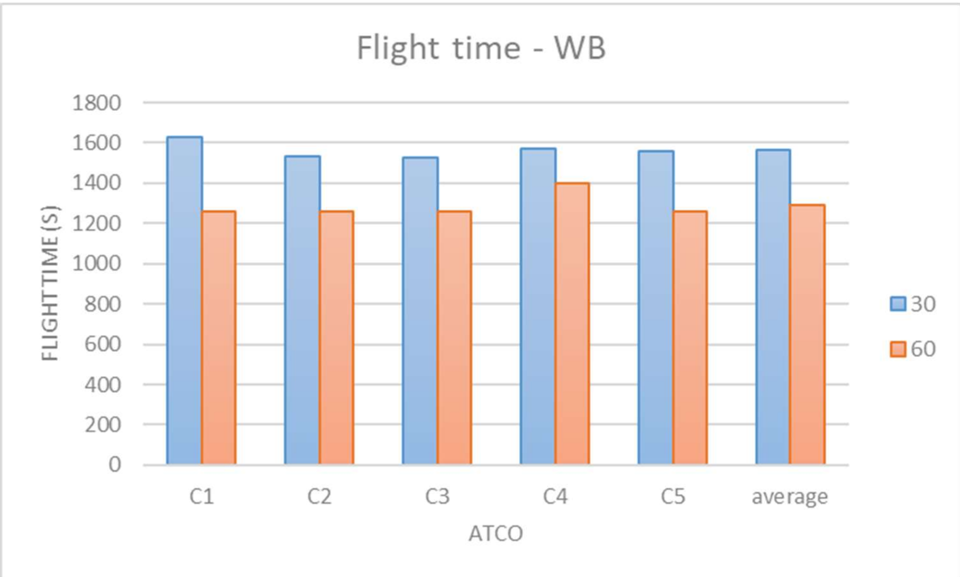

Figure 6. Flight time (in seconds) for the flights operated by WB aircraft in both scenarios.

Table 6. Time flight difference between scenario "30%" and "60%".

Aircraft size	30	60	difference
SMR	1553	1336	-13.9%
WB	1563	1288	-17.6%

3.2. FLIGHT EFFICIENCY

3.2.1. HUNGAROCONTROL - PILDO TRAJECTORIES

The horizontal and vertical flight efficiencies (HFE and VFE respectively), computed from the TOD until an altitude of 3000 ft, have been determined for each descent trajectory. Both indicators were already introduced in D7.3. Results corresponding to HFE are shown in Figure 7.

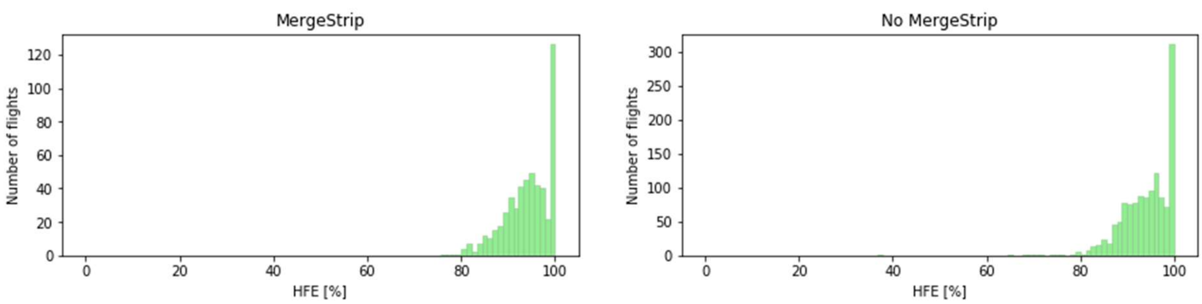

Figure 7. Horizontal Flight Efficiency [%] - Histograms

The results in terms of mean values are summarized in Table 7.

Table 7. Mean HFE per flight

Indicator	MergeStrip	No MergeStrip
HFE	94.08%	94.03%

Results corresponding to VFE are shown in Figure 8.

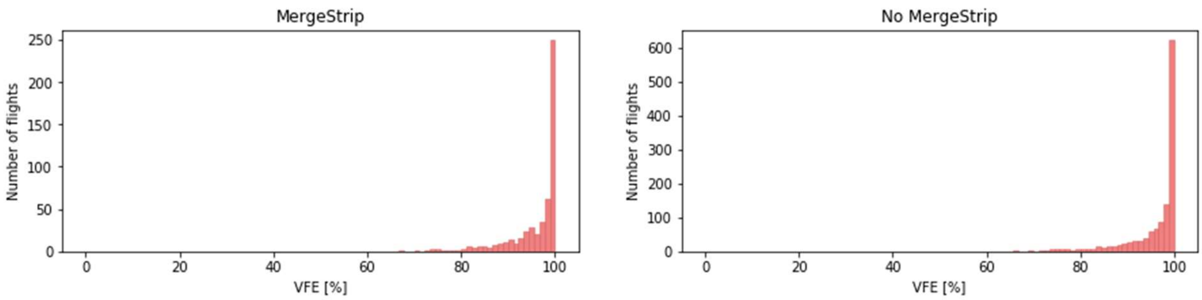

Figure 8. Vertical Flight Efficiency [%] – Histograms

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

Table 8. Mean VFE per flight

Indicator	MergeStrip	No MergeStrip
VFE	95.93%	95.81%

Table 9. Flight efficiency difference between MergeStrip and No MergeStrip scenarios

	MS	noMS	difference
HFE	94.08%	94.03%	+0.05%
VFE	95.93%	95.81%	+0.12%

3.3. OTHER PERFORMANCE INDICATORS

3.3.1. DLR TRAJECTORIES

In addition to the environmental impact characteristics, the validation of flight results included in D6.4 defines success criteria in the following KPA categories:

- Operational efficiency

The operational efficiency of an operation may include three different aspects: fuel burnt, actual flight time and actual flown distance.

The reduction in fuel burnt as a consequence of the new procedures, and the corresponding CO_2 emissions reduction was calculated in D7.3, Section 4.1.1. for short- medium range (SMR) aircraft and 4.1.2. for wide body (WB) aircraft, with summary of results in Table 6 showing reductions between 1.1 and 8.4% for SMR and 8.9 and 14.7% for WB. As a common feature of these results, newer models showed better results than older aircraft types.

Flight time results are shown with details in Section 3.1. of this document, comparing "30%" and "60%" scenarios for SMR and WB aircraft. In both cases, flight time was reduced when the new operating procedure was used more frequently (see Table 6). As in the fuel burnt comparison, the benefit was higher in the WB operation (17.6%) than in the SMR case (13.9%)

Flown distance effects were calculated in D6.4, Section 4.1.2, showing improvements for both "30%" and "60%" scenarios when compared with the baseline flown distance. A graphic resume of the results can be seen in Figure 7 from that document

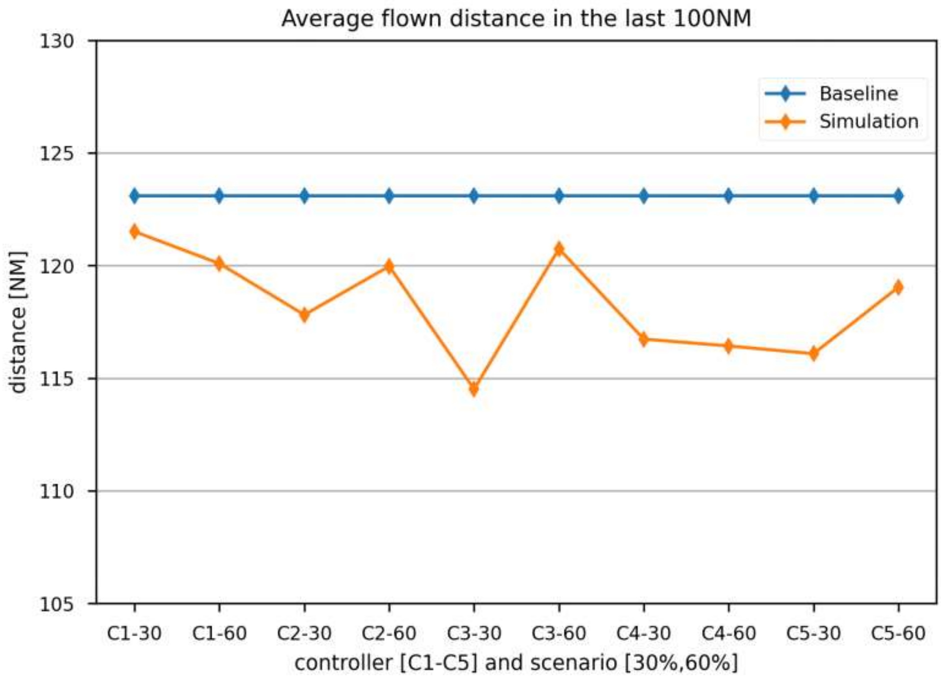

Figure 9. Flight trajectories results obtained under the simulation conditions and compared with real traffic reference values.

- Capacity

An increase of airport capacity was not considered as a GreAT project target, but the two scenario simulations allow to compare the number of arrivals allowed by each one of them for the different controllers. That was calculated in D6.4 section 4.1.5. In all cases, the scenario with more frequent use of the new procedures was able to manage a higher number of arrivals, independently of who was the controller on duty. These results can be seen in figure 8, taken from the D6.4 document.

- Human performance

In order to calibrate different aspects of the new procedure use by the controllers, standardized questionnaires with a double iteration were used. The results are widely discussed in D6.4 section 4.1.4. and covers workload, situation awareness, usability, and trust. The conclusion was that the levels of each one of those conditions were within acceptable limits.

- Safety

The analysis of this basic KPA is included in D6.4 section 4.1.3. The assessment was made in two different ways: an objective approach, adding up the number of separation infringements extracted from the simulation log, and a subjective qualification from ATCO perspective through debriefing and questionnaires. Results showed that procedures and system functions were safe in normal situations, covered by the exercise.

- Cost Effectiveness

This KPA has two different approaches. On one side, the cost variation for the operator due to the changes that the new procedures cause to its flight operation. On the other, possible modifications on the ATCO productivity.

From the airline's point of view, flight cost might be changed by a variation in fuel consumption or in flying time. The fuel consumption with the new procedures is reduced in every case included in this study, as it is shown in D7.3, section 4.1. Also, flight time diminishes, according to the figures that appear in the section 3.1. of this document. With this information, it can be concluded that airlines will spend less if operating under the new procedures.

With respect to ATCO productivity, no direct calculation was made in D6.4., but from the figures of increasing capacity and the different workload simulations and questionnaires it seems likely that the new procedures might induce a slight improvement in this factor.

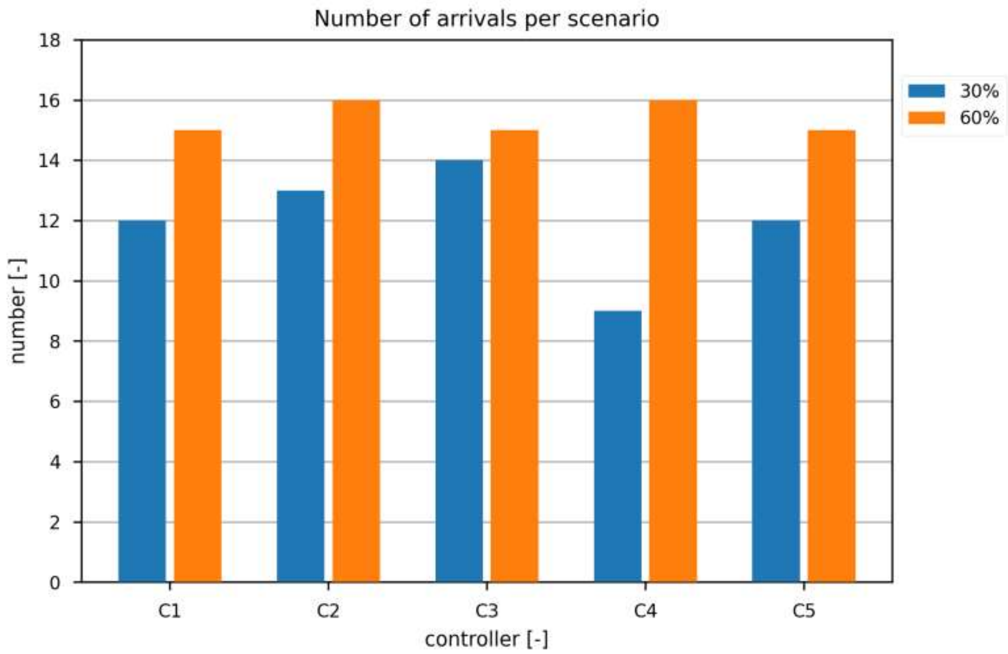

Figure 10. Capacity assessment from validation trials.

3.3.2. HUNGAROCONTROL - PILDO TRAJECTORIES

Apart from the environmental impact characteristics, the validation of the new developments covered the following KPA categories:

- Capacity

The number of arrivals were evaluated for real time simulations (RTS). Further to the participating ATCOs' feedbacks, MergeStrip with its what-if function is not there to increase capacity. To put it differently, the planner controller needs the capacity to actively interact with the what-if function, probe waypoints and speed values, which cannot happen when the number of arrivals is high in the TMA. As it will be further explained in Section 4.3.3 of D6.4, Budapest TMA traffic is still below the pre-COVID level, and also below what was expected for 2023. During the execution of the shadow mode exercise, the traffic level was far below the maximum capacity of the airport in terms of number of arrivals per unit of time. For this reason, no relevant capacity-related conclusions could be extracted from this validation exercise. Capacity related statements can be found under Section 4.2.4 of D6.4.

- Human performance

Human performance was analyzed in depth, which can be found in Section 4.3.1 of D6.4. Similarly to DLR's experiment, the fields examined were workload, situational awareness, usability and trust in both the real time simulation and shadow mode validation phases. The newly developed what-if function proved well in the two simulation trails, it added a new dimension where ATCOs have to interact actively with the system and probe different waypoints or speed values to see how that effects the arrival sequence. The 'What-if' function's usefulness and usability was further confirmed in the shadow mode validation. Apart from this function, two others were tested in shadow mode, i.e. the Improved ETA and the new recommender functionality. Unfortunately, the system was relatively unstable to properly test the ETA calculation. Yet it seemed that the ETA algorithm was more advanced than the one in the current MergeStrip and did not take only into account the current speed, but also other characteristics (e.g. arrivals will slow down). However, the new recommender functionality did not live up to the expectations, as the suggestions seemed unjustified and inconsistent most of the time.

- Safety

The analysis of this basic KPA is included in D6.4 Section 4.2.2. Separate assessments were made during the real time simulation and the shadow mode validation. The means of verification were questionnaires and post validation workshop. it can be stated that the developments proved well in simulator environment, however, for live operations, a more robust system is needed.

- Cost Effectiveness

With respect to ATCO productivity, no direct calculation was made in D6.4. However, from over the shoulder observations and certain ATCOs comments, it can be stated that the developments enabled the handling of more traffic during a certain period of time.

4. TRADE-OFF ANALYSIS

Air traffic has been subject to an everlasting optimization process in recent years. This has mostly been related to the aspects of safety and efficiency, but fuel consumption and thus also pollutant emissions have also been continuously improved in the past years. It is therefore not surprising that even with the use of new technologies and processes, only small and incremental improvements are still possible. This also applies in particular to kerosene consumption. Thus, it must always be considered a success if a few litres of fuel and carbon dioxide can be saved in a specific flight phase through new measures.

4.1. DLR PROCEDURES

A trade-off analysis is performed to compare the evolution of the environmental impact indicators and the performance indicators. It is found that in general both types of indicators improve in scenario "60%" with respect to scenario "30%", although with different intensities, as it can be seen in Tables 7 and 8, and Figures 9 and 10.

Table 10. Trade-off between environmental and performance indicators.

Aircraft size	**Climate change emissions**		**Local air quality emissions**			**Performance**
	CO_2	**NOx**	**NOx**	**HC**	**CO**	**Flight time**
SMR	-1.1%	-2.9%	-13.9%	12.3%	-30.1%	-13.9%
WB	-8.9%	-23.1%	-57.4%	-89.8%	-75.9%	-17.6%

The application of the GreAT airspace is about the separation of aircraft that can use differently optimized approaches due to their technical equipment. Due to the spatial separation, the airspace may well become tighter at times, which always means increased concentration and thus also workload for controllers. This can be compensated for with the help of support systems, but these systems must be developed, tested, introduced and, of course, later maintained for operational use.

The separation of approach flows leads to two effects that can have a negative impact on pollutant emissions. Technically well-equipped aircraft are given the opportunity in the GreAT airspace to approach the final almost directly and land at a negotiated target time. This allows near-direct routing to the threshold and the ability to optimize the approach profile aircraft type individually. Conventional approaching aircraft, on the other hand, would have to accept a slightly longer approach route due to the airspace, which means that part of the route optimization is lost. It is therefore clear that with a higher proportion of technically well-equipped aircraft, the benefit will increase disproportionately.

Departure routes have proven to be the second challenge. Due to the more complex approach procedures, the space in which departures can be guided is somewhat reduced. This means a slightly longer flight path for some departure directions, which also means that some of the route optimization of the approaches is lost again. However, this is extremely dependent on the airport under consideration, as different boundary conditions apply across the board. For example, the alignment of the runways, the location of other neighboring airports, aircraft noise restrictions and the use of restricted military areas always have a considerable influence on the routing and thus on the optimization possibilities of the airspace.

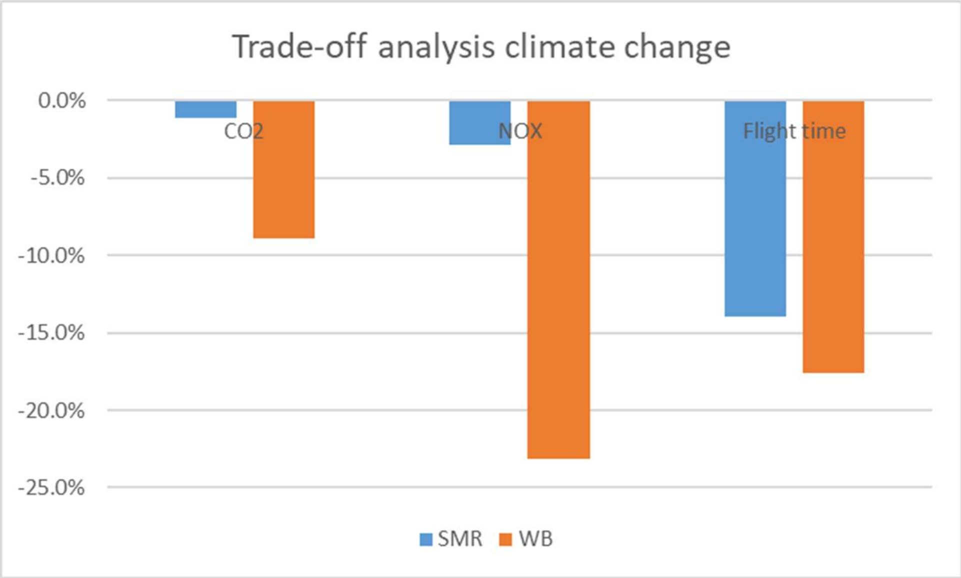

Figure 11. Trade-off analysis between climate change emissions and flight time. Difference between scenarios "30%" and "60%".

It also shows that WB aircraft could contribute significantly more to CO_2 reduction than SMR. However, at most major commercial airports, WB only have a share of 20-30% of total traffic, which can increase to a share of up to 50% only at individual airports and only at special times. This therefore reduces the maximum amount of CO_2 that can be achieved at an airport by converting to GreAT airspace in operational use.

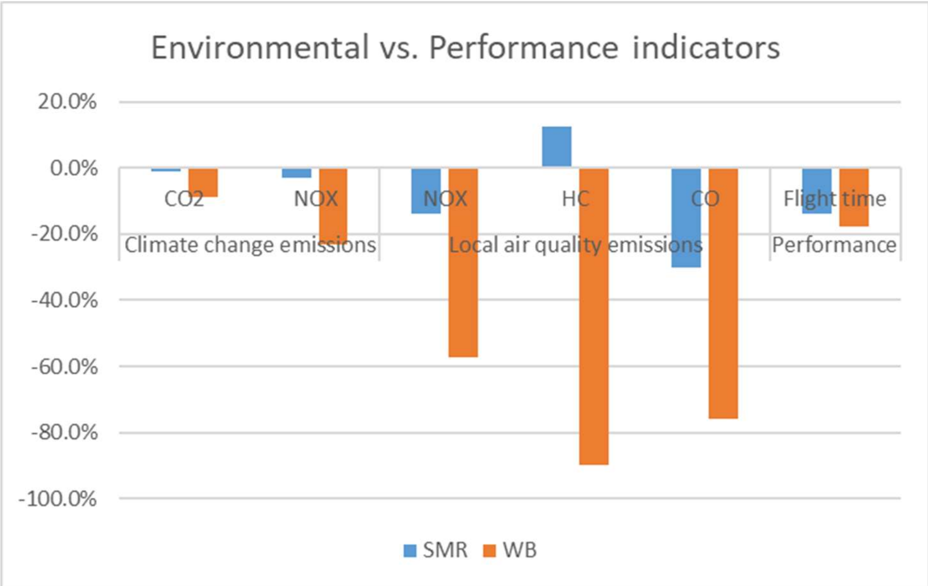

Figure 12. Trade-off analysis between climate change and local air quality emissions and flight time. Difference between SMR and WB aircraft.

Closer analysis of the validation results also revealed that not all aircraft types would benefit equally from the new procedures. Together, this means that for efficient and successful implementation of GreAT airspace, as many aircraft as possible would have to be equipped with 4D FMS by their airlines, but at the same time the investment costs for WB aircraft will be significantly more worthwhile.

The immediate environment of an airport also benefits differently from the global climate, for example, it has been shown that CO_2 emissions can be reduced with the new techniques, but local aircraft-related HC pollution in the vicinity of an airport could increase by a few percent depending on the equipment level of the typical local traffic mix (Figure 12).

Table 11. Trade-off between environmental and performance indicators.

Aircraft size	difference				
	GWP-20		GWP-100		Performance
	min	max	min	max	Flight time
SMR	-1.2%	-1.2%	-1.1%	-1.2%	-13.9%
WB	-9.7%	-10.3%	-9.1%	-9.6%	-17.6%

All in all, it is clear that the potential for reducing climate-damaging emissions exists and that this potential could be exploited by separating traffic flows. Based on the current trials, it is reasonable to assume that it is currently more worthwhile to focus on new approach routing of WB aircraft, as there appears to be more potential for emission reduction. Of course, it should be considered that aircraft of other weight classes are not disadvantaged by this. However, the exact magnitude of this potential depends on many local and traffic factors that general statements on the climate effectiveness of individual measures are hard to make.

4.2. BUDAPEST SCENARIO

A trade-off analysis is performed to compare the evolution of CO_2 emissions (the only environmental impact indicator assessed in Budapest scenario) and the performance indicators. It is found that in general both types of indicators slightly improve in the "MergeStrip" scenario with respect to the "No MergeStrip" scenario, as it can be seen in Table 12 and Figure 13.

Table 12. Trade-off between environmental and performance indicators.

Climate change emissions		Performance	
CO_2 [kg]	**CO_2 [%]**	**HFE**	**VFE**
-9.43	-0.82%	+0.05%	+0.12%

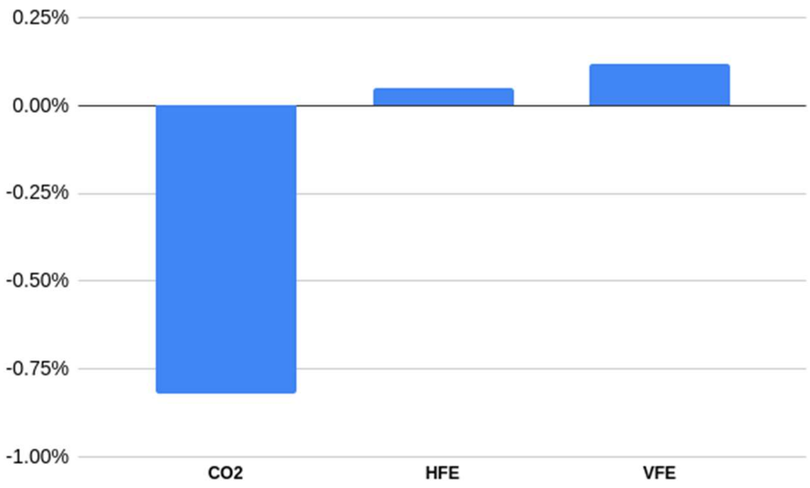

Figure 13. Trade-off analysis between CO_2 and flight efficiencies (HFE/VFE)

5. CONCLUSIONS

The information contained in this report provides a trade-off analysis between 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, and the performance indicators obtained in the work performed in previous work packages of the project.

In addition to the environmental impact features, the validation of flight results includes validation in the KPA categories, established in the project document D6.4.

5.1. DLR PROCEDURES

The analysis of the two scenarios contemplated in a two independent parallel runway system like Munich airport shows a clear advantage of the scenario "60" with respect to the scenario "30", both in climate change emissions and in those products affecting the local air quality, with the only exception of SMR HC emissions. At the same time, the average flight time for the last 100 nm flight trajectory was lower as well.

It is worthwhile to note that improvements are much greater in the case of widebody (WB) aircraft that for the short-medium range (SMR) in all the three studied categories (climate change, local air quality and flight time).

The five studied KPAs (operational efficiency, capacity, cost effectiveness, human performance and safety) show clear improvements in the first three, while working levels for controllers are within acceptable limits, and procedures and system functions affecting safety were safe in normal procedures, covered by the validation exercise.

5.2. HUNGAROCONTROL – PILDO PROCEDURES

The new approaches in Budapest, using the MergeStrip scenario show an average slight reduction of CO_2 (-0.82%) at the same time that increase the flights efficiency both in the horizontal (+0.05%) and the vertical (+0.12%) trajectories. In this exercise, CO_2 was the only emission that has been studied.

With respect to the different KPA associated to this project, no relevant conclusions could be obtained, mainly due to the relatively low level of traffic below the pre-COVID situation, but, during the simulations, it seems that MergeStrip might allow handling a higher number of flights, without human factors and safety conditions deterioration.

5.3. FINAL COMMENTS

The results of this report show that there is virtually no need to trade-off environmental results of the new approach control procedures, as both the environmental impact and the performance characteristics offer positive results. It is interesting to highlight that these apparently small improvements in each individual flight, may become a non-negligible advantage when it is multiplied by the huge number of daily commercial flights.

A final reference to the problems that the traffic alterations caused by COVID and other international conditions have induced in the working conditions during the GreAT project working period. As it was noted in the previous sections, they have limited the conclusions of some of the studied project elements.

6. REFERENCES

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

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

GreAT. Validation report European Consortium (Final Iteration). D6.4 (June 2023).

GreAT. Spatial and temporal distribution characteristics of aviation emissions. D7.1 (June 2021).

GreAT. Environmental impact assessment and green trajectory selection. D7.3 (May 2023).

Holmes C. D., Tang Q., Prather M. J. Uncertainties in climate assessment for the case of aviation NO. PNAS, 108. (July 2011).

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

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

Volume III, Aeroplane CO2 Emissions 1st ed. Montreal (2017).

International Panel on Climatic Change (IPCC). Climate change 2013. The Physical Science Basis. Cambridge University Press (2013).

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

Jungbluth N. and Meili C. Aviation and climate change: Best practice for calculation of the global warming potential. International Journal of LCA. (August 2018).

Jungbluth N. and Meili C. Recommendations for calculation of the global warming potential of aviation including the radiative forcing index. International Journal of LCA. (November 2018).

Köhler M. O., Rädel G., Shine K. P., Rogers H. L., Pyle J. A. Latitudinal variation of the effect of aviation NOx emissions on atmospheric ozone and methane and related climate metrics. Atmospheric Environment 64. (2013).

Klöwer M., Allen M. R., Lee D. S., Proud S. R., Gallaher L., Skowron A.: Quantifying aviation’s contribution to global warming. Environmental Research Letters 16. (2021).

Lammel G., Grassl H. Greenhouse effect of NOx. Environmental Science and Pollution Research. (July 1995).

Lee D. S., Fahey D. W., Skowron A., Allen M. R., Burkhardt U., Chen Q., Doherty S. J., Freeman S., Forster P. M., Fluglestvedt J., Gettelman A., De León R. R., Lim, L. L., Lund M. T., Millar R. J., Owen, B., Penner J. E., Piari G., Prather M. J., Sausen R., Wilcox L. J. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment 244 (2021).

Neu U. The impact of emissions from aviation on the climate. Swiss Academies communications Vol. 15 nº 9 (2020).

Skowron A., Lee D. S., Hurley J. Aviation NOx Global Warming Potential. TAC-2 Proceedings. Aachen and Maastricht. (June 2009).

Skowron A., Lee D. S., De León R. R. Variation of radiative forcing and global warming potentials from regional aviation NOx emissions. Atmospheric Environment 104. (2015).

Sustainable Aviation. Inter-dependencies between emissions of CO2, NOx & noise from aviation. Policy Discussion Paper. (2017).