ENVIRONMENT

Report on

Environmental Interdependencies in Various Operating Scenarios

Deliverable of ICAO Committee on Aviation Environmental Protection (CAEP)

2025

Notes

This report was produced by ICAO Committee on Aviation Environmental Protection (CAEP) Working Group 2 on Airport and Operations during the CAEP/12 cycle. Following the review by subsidiary bodies, the ICAO Council approved the technical recommendation made by CAEP and approved the publication of this report during the 235th Session, which took place from 9 June to 4 July 2025.

Disclaimer

1. EXECUTIVE SUMMARY

During CAEP/11, WG2 conducted a global assessment on Horizontal Flight Efficiency (HFE), which was followed by a global assessment on Vertical Flight Efficiency (VFE) in CAEP/12. This previous work was mainly focused on individual flight phases and time or distance-based indicators (as operational proxies for flight efficiency) which were subsequently converted into fuel burn or CO2 emissions. This very useful data provides valuable insights to improve operational performance but gives limited insight into different operational scenarios.

In conducting this task, several operating scenarios were identified that enable the understanding of impacts from specific operational choices in the wider airspace system. These in turn may assist in better understanding the trade-offs that underly operating practices in the future, and could serve to inform possible exploration of future interdependencies in order to optimise operational performance.

This document was prepared during the CAEP/13 cycle by the Task Group O.03, Environmental Interdependencies in Various Operating Conditions. It provides analysis on eight scenarios that were highlighted by the operational stakeholders as scenarios of interest. The scenarios identified and analysed are:

- OS1: Noise abatement procedure versus emissions in the departure phase.
- OS2: Level-off vs off-track during climb to enable CCO for a departing aircraft.
- OS3: Short cut before vs. after the top of descent.
- OS4: Closed Standard Terminal Arrival Route (STAR) vs. open loop STAR (tactical intervention) procedures.
- OS5: Non-optimised descent profile and its impact on flight efficiency.
- OS6: Tactical intervention: on a descending aircraft over climbing aircraft.
- OS7: Harmonised descent speed below cross over (conversion) altitude.
- OS8: Noise analysis in the arrival phase.

2. ACRONYMS AND ABBREVIATIONS

AIP	Aeronautical Information Publication
ANS	Air Navigation Service
ANSP	Air Navigation Service Providers
ARN	Stockholm Arlanda Airport (IATA code)
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
CAEP	Committee on Aviation Environmental Protection
CANSO	Civil Air Navigation Services Organization
CAS	Controlled Airspace
CCO	Continuous Climb Operations
CDO	Continuous Descent Operations
CI	Cost Index
CO	Carbon Monoxide
CO_2	Carbon Dioxide
dB	decibels
ESGG	ICAO airport code for Gothenburg Landvetter airport, Sweden
ETOPS	Extended-range Twin-engine Operations Performance Standards
FAS	Final Approach Segment
FDR	Flight Data Recorder
FL	Flight Level
FMS	Flight Management System

HFE	Horizontal Flight Efficiency
IAP	Instrument Approach Procedure
IAS	Indicated Airspeed
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IFALPA	International Federation of Air Line Pilots’ Associations
IFR	Instrument Flight Rules
ISA	International Standard Atmosphere
ISR	Inverse Specific range [kg/NM]
KIAS	Knots of Indicated Airspeed
KPI	Key Performance Indicator
Lmax	Maximum Sound Level
MNPS	Minimum Navigation Performance Specifications
NM	Nautical Miles
NO_X	Nitrogen Oxide
OEM	Original Equipment Manufacturer
PANS-OPS	Procedures for Air Navigation Services – Aircraft Operations
PEP	Airbus Performance Engineer’s Program
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
SR	Specific Range [NM/kg]
STAR	Standard Terminal Arrival Route
TMA	Terminal Manoeuvring Areas
ToC	Top of Climb

ToD	Top of Descent
TOM	Take-off Mass
UHC	Unburned hydrocarbons
VFE	Vertical Flight Efficiency
WG	Working Group
ZFM	Zero Fuel Mass

3. TERMINOLOGY (GLOSSARY)

Disclaimer

As used in this manual, these terms have the following meanings. Where differences exist, they do not change any formal definitions in other ICAO documents.

CCO	Continuous Climb Operation (CCO) is an aircraft operating technique enabled by airspace design and facilitation by ATC, allowing for the execution of a flight profile optimised to the performance of the aircraft
CDO	Continuous Descent Operation (CDO) is an aircraft operating technique, enabled by airspace and procedure design and facilitation by ATC, in which an arriving aircraft descends continuously, to the greatest possible extent, with the flight crew employing low power/low drag, prior to the final approach segment (FAS)
Closed STARs	Provide continuous track guidance to the final approach track for an automatic transition to final approach
Open STARs	Provide track guidance to a downwind track position from which the aircraft is tactically guided (vectored) by ATC to intercept the final approach track
Interdependency	A situation where a change in Factor A results in a change to Factor B (and vice versa)
Trade-off	An interdependency where an improvement in Factor A negatively impacts Factor B

4. INTRODUCTION

During CAEP/11, WG2 conducted a global assessment on Horizontal Flight Efficiency (HFE), which was followed by a global assessment on Vertical Flight Efficiency (VFE) in CAEP/12. This previous work was mainly focused on individual flight phases and time or distance-based indicators (as operational proxies for flight efficiency) which were subsequently converted into fuel burn or CO_2 emissions. This very useful data provides valuable insights to improve operational performance but gives limited insight into different operational scenarios.

CAEP/12 agreed to WG2 Task O.03, Environmental Interdependencies in Various Operating Scenarios to determine the environmental aspects of interdependencies, e.g. between Continuous Descent Operations (CDO) and Continuous Climb Operations (CCO), HFE and VFE, noise and emissions in various operating scenarios by reviewing current available material and undertaking analysis to understand impacts and producing a report.

Ideally, from a single flight perspective, aircraft operators prefer to fly their most optimum trajectory in four dimensions (i.e., space and time, 4D). This optimal trajectory would be unconstrained and laterally and vertically optimised for meteorological conditions from the departure airport to the destination airport. This optimal trajectory would result in the minimum fuel usage for a given flight, but is seldomly flown; therefore, there is additional fuel usage compared to the ideal flight.

Multiple constraints and restrictions can influence the trajectory proposed by the Flight Planner, requested by the Operator, or instructed by ATC. Examples of such restrictions include, but are not limited to, the following:

- Geographical direction of the runways
- Meteorological conditions
- Air navigation charges
- Airspace structure and design
- Access to airspace sectors
- Traffic density
- Noise preferential routes
- Other airspace users
- Aircraft equipage (e.g. Minimum Navigation)
- Performance specifications (MNPS) requirements
- Passenger oxygen regulations for extended routes over high terrain
- Extended-range Twin-engine Operations Performance Standards (ETOPS)
- Regulations such as speed constraints
- The need to keep aircraft safely separated, etc.

Linked to this, situations commonly occur where environmental impacts are traded for one another (e.g., fuel/emissions for noise) or for other factors such as throughput.

This report contains the work approach, the considered operational scenarios, and the outcome from the analysis performed in Task O.03.

5. WORK APPROACH

There are a broad range of operational scenarios (OS) that can be analysed. Some of the OS might vary depending on the design of the airspace and the traffic density, while others might be dependent on standard operating practices in a specific region. For example, the operational challenges encountered for the traffic across the North Atlantic might differ from operational challenges encountered over Europe or the United States of America. To ensure that a broad range of OS were selected, interviews were conducted with stakeholders. The interviewed stakeholders are listed below:

- LFV – ANSP Sweden
- NATS – ANSP England
- NAV CANADA – ANSP CANADA
- CANSO – Civil Air Navigation Services Organization
- IATA – International Air Transport Association
- IFALPA – International Federation of Air Line Pilots' Association

Additionally, a survey was generated and sent to various operational organisations to reach additional stakeholders. The survey was distributed to select members of IATA, IFALPA and CANSO via their WG2 representatives with the objective of reaching a broader range of stakeholders than just those interviewed and to identify additional OS of interest. No new operational scenarios were identified but the interviews underlined the interest from the stakeholders for the selected operational scenarios. Table 1 describes the 11 operational scenarios (OS) of interest that were identified via this stakeholder outreach, both through the interviews and the survey.

Three different methodological approaches were necessary depending on the type of scenario:

- A literature survey and gathering of results from the science publication "A CO_2 versus noise trade-off study for the evaluation of current air traffic departure procedures" for OS1. The results present the trade-off between noise and fuel burn when a speed constraint is changed on a starting turn.
- The gathering of operational data from ATC and airline for OS4 and OS7, Collaboration with WG2 OEMs for analysis: OS2, OS3, OS5, OS6 and OS8.
- A literature survey and gathering of results from the Eurocontrol report "CDO/CCO Action plan" for OS2, OS3, OS4 and OS6.

ID	Operational Scenario	Phase of flight	Selected for analysis
OS1	Noise abatement procedure versus emissions in the departure phase	Take-off/ climb	Yes
OS2	Level-off vs. off-track deviation during climb to enable CCO for a departing aircraft	Take-off/ climb	Yes

OS3	Short cut before vs. after the top of descent	Descent/ Approach	Yes
OS4	Closed STAR vs. Open STAR procedures	Descent / Approach	Yes
OS5	Non-optimised descent profile and its impact on flight efficiency	Descent / approach	Yes
OS6	Tactical intervention: on a descending aircraft over climbing aircraft	Climb and Descent	Yes
OS7	Harmonised descent speed below cross over (conversion) altitude	Descent / Approach	Yes
OS8	Noise analysis in the arrival phase	Descent / Approach	Yes
OS9	Level (altitude) change vs off-track to ensure adequate separation between aircraft	En-route	No
OS10	Speed change vs. off track to ensure adequate separation between aircraft	En-route	No
OS11	Early arrival outside airport opening hours vs. holding	En-route /Descent	No

Table 1: scenarios of interest expressed throughout the interviews and survey. Scenarios OS1-OS8 are analysed in the report.

Due to time constraints, eight operational scenarios were selected for analysis. The selection was made based upon the level of interest from the different stakeholders. The operational scenarios that were not analysed are still listed as some interest was raised during the interviews and they might be considered for potential future analysis.

The following three scenarios (OS 9, OS 10 and OS 11) are not included in the report and the analysis. If future work is proposed on this topic, the three scenarios are described in Appendix A.

6. SCENARIOS

The following eight operational scenarios (OS) were selected for analysis:

- OS1: Noise abatement procedure versus emissions in the departure phase.

This specific operational scenario looks at the environmental aspects of noise/fuel burn interdependencies when applying speed constraints during the early departure phase. These constraints are put in place to minimise noise exposure to local communities. However, those speed constraints force the aircraft to climb in an unclean configuration thus increasing the fuel consumption and emissions.

- OS2: Level-off vs off-track during climb to enable CCO for a departing aircraft.

This specific operational scenario looks at the environmental aspects of interdependencies between the additional fuel burn caused by a level-off at different flight levels versus the additional fuel burn caused by the extension of the track performed at the cruising level.

- OS3: Short cut before vs. after the top of descent.

Based on information such as runway-in-use, wind, landing procedures, aircraft descent speed, etc., the FMS onboard the aircraft calculates an optimum descent profile together with an associated top of descent point. The FMS calculated descent profile is typically a continuous profile.

If operational conditions allow, ATCOs may instruct an aircraft with a shortcut ("direct to" instructions) during the descent phase. This specific operational scenario looks at the environmental aspects of interdependencies of the ATC shortcut intervention when given prior or after the ToD and its impact on fuel burn.

- OS4: Closed STAR vs. open STAR procedures.

This specific operational scenario looks at the environmental aspects of interdependencies between the two main different arrival procedures. The open loop STAR procedure and its accompanying ATC tactical interventions may generate a vertical flight inefficiency and in turn an increased environmental impact. The closed loop STAR on the other hand is a more efficient and predictable procedure that does not impede on the optimal descent profile of the aircraft.

- OS5: Non-optimised descent profile and its impact on flight efficiency.
  This specific operational scenario looks at the environmental interdependencies of various non-optimal descent profiles. Two typical tactical and strategical descending concepts are compared to an optimum descent profile.
- OS6: Tactical intervention: on a descending aircraft over climbing aircraft.

When an ATCO is faced with a decision concerning a potential conflict between a climbing and a descending aircraft, there is no common rule to decide on which aircraft to intervene. This specific operational scenario looks at the environmental aspects of interdependencies between the fuel burnt and related emissions of intervening on the climbing aircraft vs. on the descending aircraft.

- OS7: Harmonised descent speed below cross over (conversion) altitude.

The operational scenario of having a harmonised descent speed is an option that could potentially optimise CDO performance, save fuel for the airlines, reduce noise and emissions while increasing predictability for ATC. This specific operational scenario looks at the environmental aspects of interdependencies between airspace predictability and fuel savings against additional time flown.

- OS8: Noise analysis in the arrival phase.

While CDO operations have a great potential for reducing fuel consumption and emissions when operated from ToD, at lower altitudes the primary environmental impact, especially at or around airports, is noise. This specific scenario looks at the impact of noise and fuel when performing a CDO descent compared to an approach that includes a level segment.

The analyses presented below should be viewed as example studies to help improve understanding of the operational scenarios of interest. Due to time and resource constraints, they may be based on limited data (e.g., single set of aircraft data from a single operator or manufacturer) and the results may not be applicable in all operational scenarios and conditions. However, the methodologies and results shown provide an initial basis for assessing the trade-offs that these operational scenarios present and could inform future more detailed studies.

6.1 OS1: noise abatement procedure versus emissions in the departure phase

6.1.1 Background

The ATM procedures applied to aircraft during the departure phase of flight are commonly based on recommendations in the ICAO procedure design manual, PANS-OPS, Document 8168. However, some of these procedures are based on the performance characteristics of an older generation of aircraft and may be penalising modern, state-of-the-art aircraft. An example of such a procedure is the turn-related speed constraint applied to a Standard Instrument Departure route (SID) containing a sharp turn at lower altitudes. The speed constraint is recommended to ensure primary area containment within Controlled Airspace (CAS), as well as flyability of the nominal track. The severity of the speed constraint is dependent upon the track change of the turn, altitude, assumed meteorological conditions, maximum allowed bank angle of the aircraft in the design and flight technical tolerances. It is fair to say that the total operational performance envelope of the aircraft is seldom used, thus generating a situation where the full benefit of the aircraft performance is not used.

The effect of applying speed constraints during the early departure phase is to force the aircraft to climb in an unclean aerodynamic configuration with flaps and slats extended instead of accelerating to an optimum climb speed. This increases the overall aerodynamic drag of the aircraft and thus the fuel consumed, and CO2 emitted during the departure phase. The speed constraint is put in place as a tool to help reduce noise exposure around airports. However, the trade-off between noise versus fuel burn is an interesting one, and the study in this section presents the consequence on the trade-off when playing with the speed constraint.

6.1.2 Test case study

Gothenburg Landvetter (ICAO airport code ESGG) is a medium size airport on the west coast of Sweden. It is the second largest airport in Sweden and has an average of 220 movements per day. The airport has a 3300 m single runway, which operates as Runway 03 or 21 depending on the prevailing wind direction.

Several of the SIDs at ESGG have been designed with sharp low-altitude turns either to avoid overflying noise-sensitive areas or because the active runway direction is non-preferential for the required route. These SIDs carry a speed constraint of 210 Knots Indicated Air Speed (KIAS), which is applied until the aircraft has cleared the turn. The specific SID shown in Figure 11 is used in the study, containing a straight segment for 2.1 NM followed by a sharp right turn of 87° and then a second right turn past the waypoint GG403. A 210 KIAS speed constraint applies until the aircraft has passed waypoint GG403.

The study analyses the noise impact of the following scenario:

- Speed constraint of 205 KIAS instead of 210 KIAS
- Speed constraint of 220 KIAS instead of 210 KIAS
- Speed constraint raised to 250 KIAS when passing FL100
- Free speed

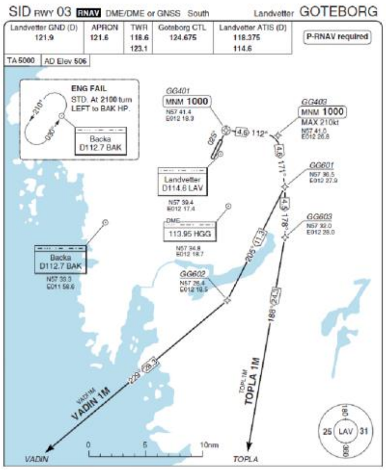

Figure 1: Published RNAV SIDs from Runway 03 at Sweden Landvetter ESGG. Copyright European Aeronautical Group (Navtech).

6.1.3 Results and analysis

Table 2 shows the computed results for the surface area of LA_{max} noise contour for 75, 70, 65 and 60 dB(A). The details of the computations and the tools used in the computation can be found in the reference study [Mitchell D., Ekstrand H]. The analysis results show that overall reducing or removing the 210 KIAS speed constraint on the SID will not affect the highest LA_{max} noise contours (75 dB(A)) but will, in general, increase the geographical area exposed to noise levels between 70dB(A) and 65 dB(A). Beyond the 65 dB(A) noise contour of a reduced speed constraint reduces the noise footprint as the aircraft is able to perform free climb in a clean configuration. Note that the free speed condition maintains the largest noise footprint throughout.

Speed restriction scenario	Surface Area of LA_{max} noise contour [km^2]			
	75 dB(A)	70 dB(A)	65 dB(A)	60 dB(A)
205 KIAS to 10 NM	7,09	14,86	31,90	74,93

210 KIAS to 10 NM (baseline)	7,09	14,99	32,04	75,01
220 KIAS to 10 NM	7,09	15,36	34,16	74,27
250 KIAS to FL100	7,09	15,09	35,49	73,08
Free Speed	7,09	15,08	42,47	93,31

Table 2: Noise results for the different scenario attached to the change in speed constraint

The trade-off between the noise and the CO_2 emitted is presented in Figure 2. It can be shown that for the baseline (green circle) and the 250 KIAS to FL 100 (green cross) scenarios, the increase in noise ranges between 2 to 5 dB(A) during initial climb depending on the position along the path (6, 10 or 14 NM). If the 210 KIAS speed constraint was removed in favour of the standard 250 KIAS at FL 100, this would result in a reduction in CO_2 of about 180 kg for a heavy-loaded A321 aircraft, according to the computation in the reference study. This equates to a fuel saving of about 60 kg per flight, but would lead to a noise increase up to 10 NM. On a year basis, with a traffic scenario of about 3500 in this particular study, this would amount to 190 tonnes of fuel and about 575 tonnes of CO_2 per year.

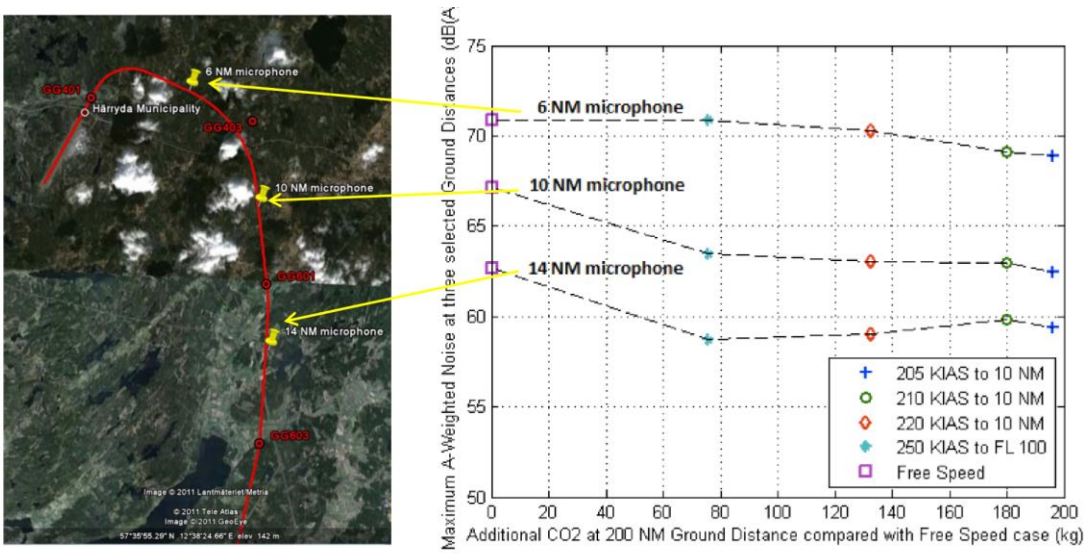

Figure 2: CO_2 vs noise trade-off analysis for the different scenarios.

6.1.4 Conclusion

The objective of minimizing the noise exposure to local communities can lead to the design of SIDs that create reduced noise disturbance but can also lead to SIDs that create additional fuel burn and emissions. The presented study demonstrates the potential interdependencies between generated noise and fuel burned on departure, in this case as a result of removing or minimizing turn-related speed constraints along SIDs.

Although using speed constraints early in the flight is a good tool to ensure that the noise emissions do not exceed the set levels, it is often set for a specific aircraft fleet. While the speed constraint remains, the aircraft fleet gets updated and newer aircraft might not need such a constrained speed to obey noise regulations. Alleviating the speed constraint could generate large fuel save while still keeping the noise emission to about the same levels. In general, the environmental benefits are to be weighed against the implications for noise exposure on the ground as well as aircraft operational capabilities. The specific benefits and trade-offs will vary by airport and aircraft type.

The speed constraint impedes the aircraft vertical profile, and enforces a steeper climb than if free speed was approved. This generates a large effect on CO_2 emissions, while mitigating noise on the ground. Another tool that is used in the trade-off noise versus emission during climb and descent phase is an extension of the horizontal track for noise abatement impact. As can be seen in the next scenario in section 6.2, this has an even larger impact on the fuel burn and CO_2 emission.

6.1.5 References

- "A CO_2 versus noise trade-off study for the evaluation of current air traffic departure procedures", Mitchell D., Ekstrand H.- First SESAR Innovation Days, 2011 - https://sesarju.eu/sites/default/files/documents/sid/2011/SID%202011-13.pdf

6.2 OS 2: level-off vs. off-track deviation during climb to enable CCO for a departing aircraft¨

6.2.1 Background

A climbing aircraft executing a CCO may be required to deviate from its preferred climb track. Stakeholder interviews indicated a large interest in understanding the impact on fuel burn, and thus the environmental impact, for the following two operational scenarios in this situation:

- allowing the climbing aircraft to climb to maintain a continuous climb profile through off-track deviation that adds track miles,
- or enforcing a level-off during the climb phase, thus interrupting the continuous climb but not adding track miles.

In order to analyse this case, the OEM partners in WG2 provided a fuel burn analysis of different operational scenarios. The scenarios were then compared to a reference trajectory and the difference in fuel burn was assessed.

The OEMs that participated in this exercise consisted of two major manufacturers. Both computed results for the scenario described below and the results obtained were very similar. Note that an average of the computed results is presented in the report.

6.2.2 Reference trajectory

The simulations were run by the OEMs for two different aircraft configurations:

- A "typical single aisle aircraft" similar to an A320 or 737 aircraft that would have a reference trajectory of 650 NM from departure airport to destination airport
- A "typical wide body aircraft", similar to a 787 or A350 that would have a 6000 NM mission from departure airport to destination airport.

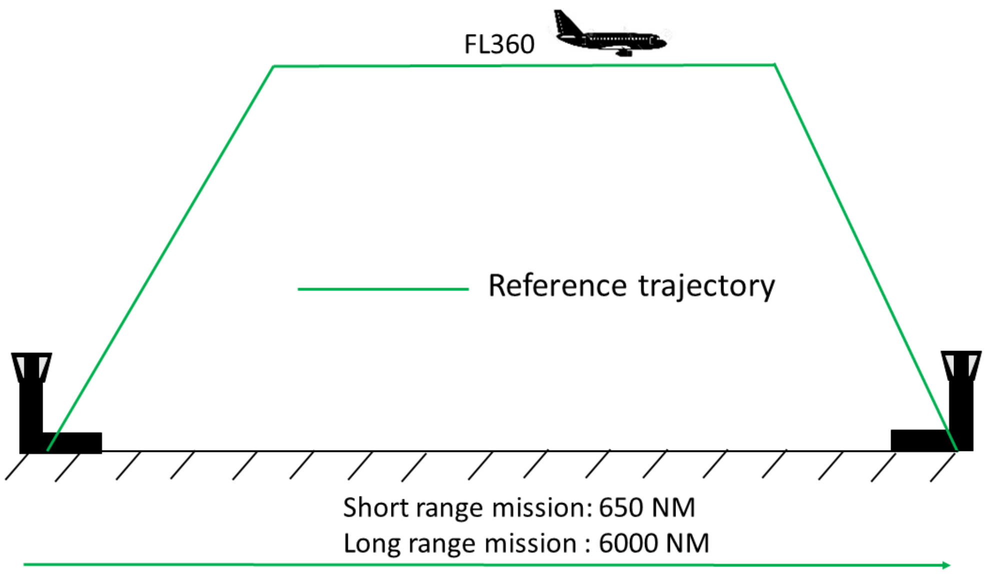

Figure 3: The reference trajectory.

The detailed assumptions for the reference trajectory are as follows:

- ISA conditions
- Zero wind
- CI = 0
- One alternate destination aerodrome 100 NM away
- Final reserve fuel = 30 min
- Contingency fuel = 5% of Trip Fuel
- Cruise Flight Level = 36 000 ft = FL360
- Given ZFM at 75% of max TOM
- Fuel from take-off to landing including a take-off and approach part
- 250 KIAS below FL100

6.2.3 Off-track deviation operational scenario

The reference trajectory is compared to a scenario where a tactical decision is taken to not affect the continuous climb of the aircraft and instead issue a tactical lateral radar vectoring of 15 NM during the climb (off-track), or to extend the cruise segment 15 NM to enable a CDO, as depicted via the dashed blue trajectory in the figure below. The delta fuel burn between the reference trajectory and the tactical decision of an off-track during climb (for CCO), or in cruise (for CDO), is then assessed.

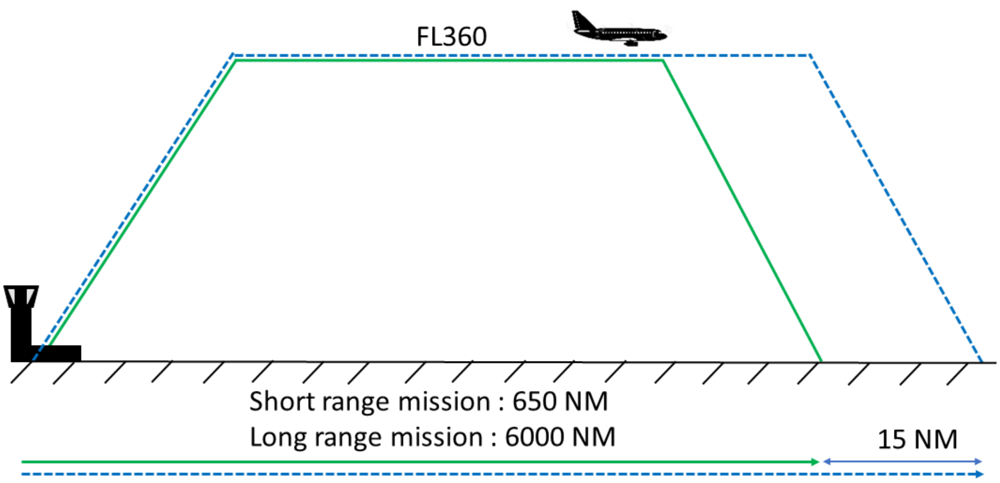

Figure 4: a 15 NM Off-track deviation operational scenario. The mission is extended by 15 NM. The climbing phase remains unchanged.

6.2.4 Level-off during climb operational scenario

The other possibility to operationally affect an aircraft during a climb phase is to issue a level-off. This doesn't affect the distance flown of an aircraft, but the impact on the fuel burn will differ depending on the altitude at which the level-off is issued. Therefore, two scenarios were computed by WG2, for a level-off at flight level FL80 (8000 ft/2440 m) and flight Level FL140 (14000 ft/4270 m), as shown in Figure 5.

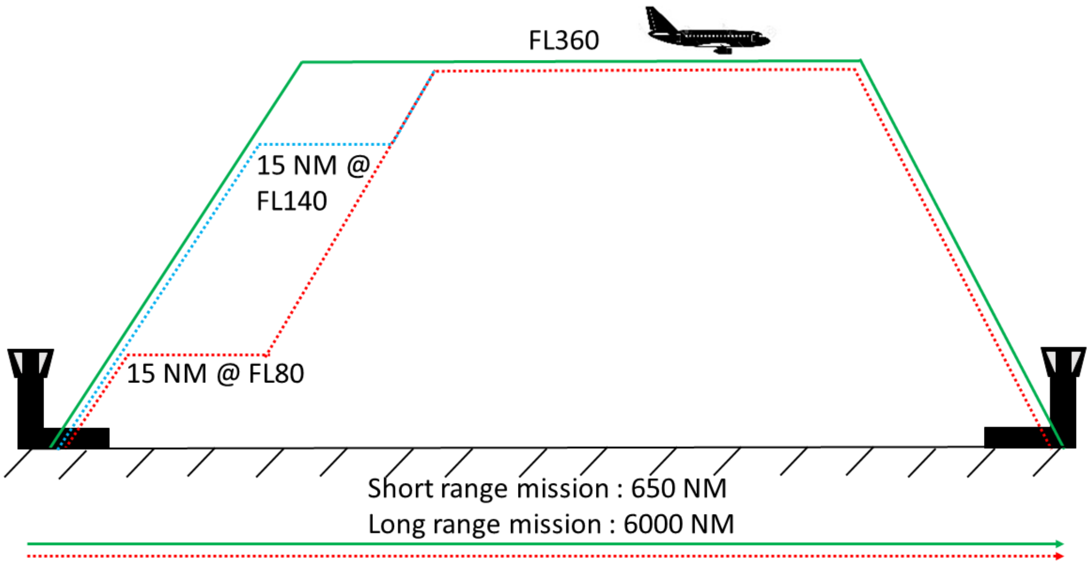

Figure 5: a 15 NM level-off during the climb phase. The climbing phase is extended, and the cruise phase reduced by 15 NM.

6.2.5 Results and analysis

Table 3 presents the delta fuel burn between the reference trajectory and the operational decisions are presented below. For the sake of the discussion in the conclusion, the delta fuel burn for a 2 NM track extension is presented in the table as well.

Operational scenario during the climb phase	Delta fuel burn ΔTF [kg] between scenarios and reference trajectory	
	Single aisle aircraft	Wide body aircraft
Off-track to enable CCO (+15 NM track extension)	66	154
Off-track to enable CCO (+2 NM track extension)	9	21
Level-off during climb at FL80 (15 NM level segment)	39	71
Level-off during climb at FL140 (15 NM level segment)	21	27

Table 3: Extra Fuel burn (ΔTF) between the baseline and the different operational scenario during the climb phase.

It can be seen that a level-off of 15 NM is more beneficial than a 15 NM off-track deviation. This is not a surprising result and can be easily explained by the fact that although an off-track of 15 NM allows the aircraft to climb continuously unaffected, it adds 15 NM to the total flown route. This extra flown distance is added to the en-route phase. The lower level-off altitude costs more fuel which is also expected, as the air is denser at lower altitudes.

6.2.6 Conclusion

The tactical choice between an off-track and a level-off is a rather complex subject with many dependencies. Note that if a tactical decision is given on a climbing aircraft, to ensure separation from another aircraft, an off-track of 15 NM is excessive in most cases. A heading adjustment to create lateral separation ultimately creates a fairly small flight path extension. Figure 6 shows that a heading difference of 15° creates a lateral separation of 5,4 NM between the original flight path and the new one, but the total extension of the cruise distance is only 1,8 NM. Rounded to 2 NM, this gives an extra fuel consumption of around 9 kg of fuel for a single aisle aircraft. Given Table 3, the 9 kg increased fuel burn from a 2 NM track extension approximates to a 3,5 NM level-off at FL80 or a 6,5 NM level-off at FL 140.

It is worth mentioning as well that an off-track deviation can, if the situation allows it (airspace capacity, traffic load etc) often be combined with a shortcut. Rather than extending the mission by 15 NM the opposite can be realised by reducing the mission length with the help of deviating the aircraft through a shortcut. If this option is available, this would be the preferred option.

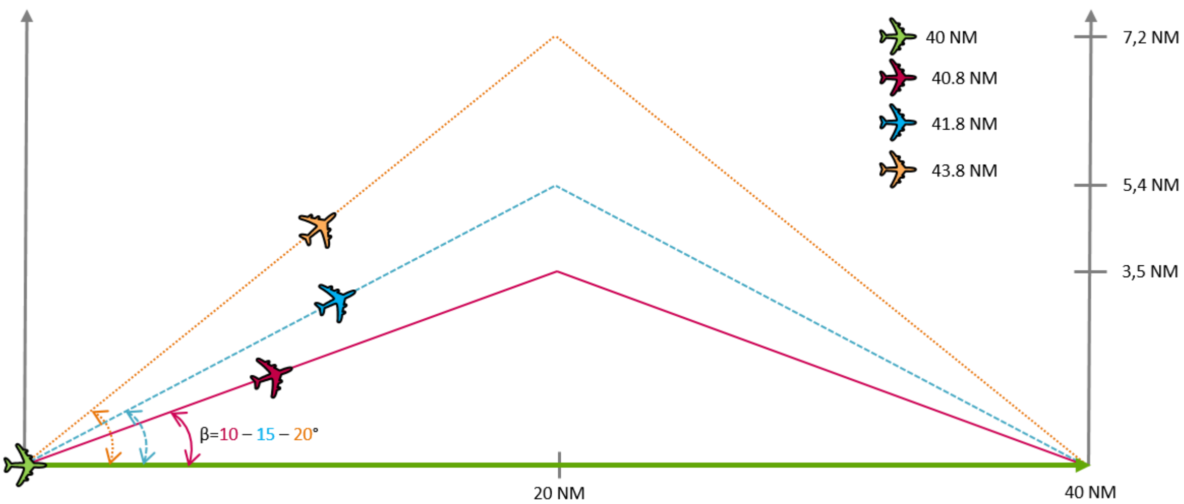

Figure 6: Track extension

6.2.7 References

- "European CCO/CDO Action plan" – Eurocontrol - https://www.eurocontrol.int/sites/default/files/2020-11/european-cco-cdo-action-plan.pdf
- Simulations performed by WG2 together with OEMs partners

6.3 OS 3: shortcut before vs. after the top of descent

6.3.1 Introduction

The start of the descent phase is defined by the Top Of Descent (ToD). An optimal ToD is computed by the Flight Management System (FMS) onboard of the aircraft. Many parameters are taken into consideration by the FMS to calculate the optimum ToD that starts an optimum continuous descent, such as:

- the Cost Index,
- the landing runway in use,
- the expected landing procedure,
- the expected descent speed,
- eventual restrictions in the airspace,
- meteorological data such as windspeed and temperature during the descent phase.

Based on the above information, the FMS calculates an optimum descent profile. Regardless of the Cost Index, the descent will happen at a near-idle thrust. When the distance to go to the landing runway is changed during the descent phase, the descent is disrupted, and the energy phase of the aircraft becomes non-optimum and needs to be addressed.

As Optimised Descent Profiles only can be flown if the exact distance to touchdown is known, a closed STAR procedure is the favoured procedure to use. A closed STAR procedure provides the Flight Crew with a defined distance to touchdown.

At airports where closed STAR approaches options are not possible, or where a tactical sequencing of the aircraft is necessary, the most appropriate solution is an open STAR procedure. Open STAR procedures provide track guidance to a downwind track position from which the aircraft is tactically guided by ATC to intercept the final approach track. Alternatively, the open STAR procedure may terminate at the entry to a TMA sector or at the merge point of two flows. Although they provide more ATC capacity than closed STARs, they also require more tactical ATC intervention. The open STAR procedure generates more uncertainty for the operator to perform an optimum descent.

The FMS assumes that the trajectory to be flown will be almost direct from the intermediate approach fix to the RWY i.e. the FMS does not know what path stretching will be applied by ATC and assumes that distance to touchdown is much shorter than might actually be the case. ATC communication is very important when the distance to the final approach is tactically modified. A clear distance to go greatly helps the operator to keep an optimum descent profile.

The closed and open STAR example procedures are shown in Figure 7 and Figure 8 respectively.

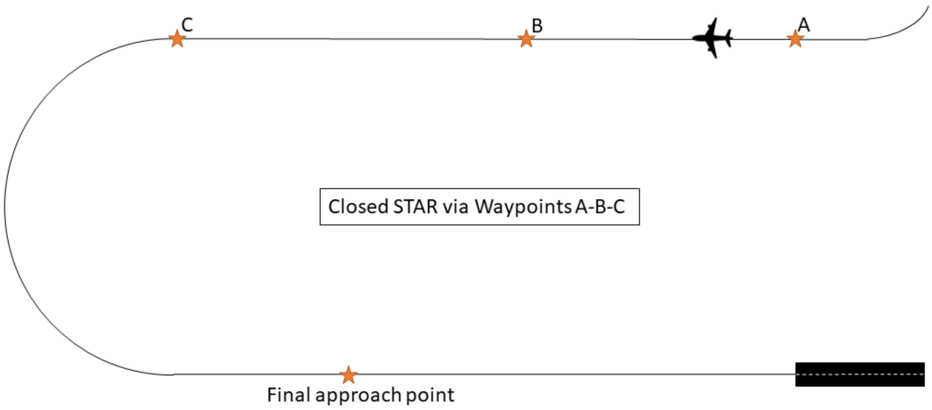

Figure 7: representation of a closed STAR procedure. The aircraft descends via waypoints A, B, C to the final approach point

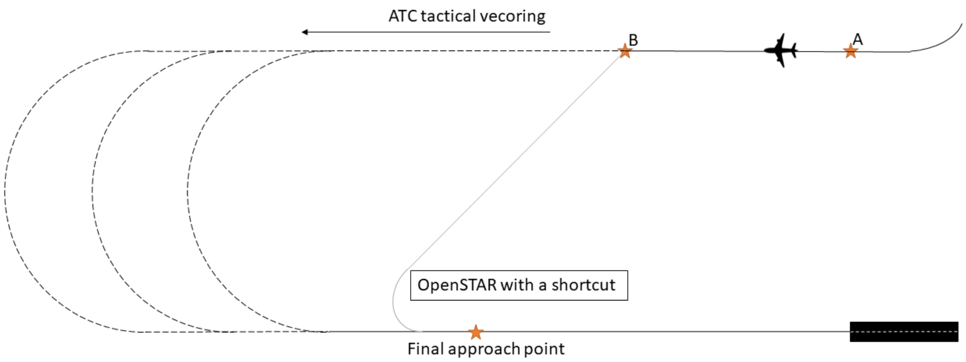

Figure 8: representation of an open STAR procedure. Past waypoint B, the ATCO provides track guidance to the final approach point. The distance to fly between B and the final approach point is not known to the pilot and might vary greatly.

ATC may intuitively assume that the shortest distance flown is always the favoured method, and when possible, try to give shortcuts to the operator. However, when it comes to the descent phase, it is important to understand the consequences of shortcuts as this may not always be beneficial from an environmental perspective.

6.3.2 Shortcut given after the ToD, during the descent phase

An ATCO may give a heading clearance to shorten the flown distance, flight time, and land earlier. In this scenario, the shortcut is offered during the optimal descent and after its ToD. Figure 9 shows a conceptualisation of the scenario. There may be multiple reasons for offering this shortcut, for example to address a sequencing or capacity need. It might also be offered simply to try to help the operators fly a shorter route and save fuel. During periods with low-density traffic, a shortcut is often offered to operators.

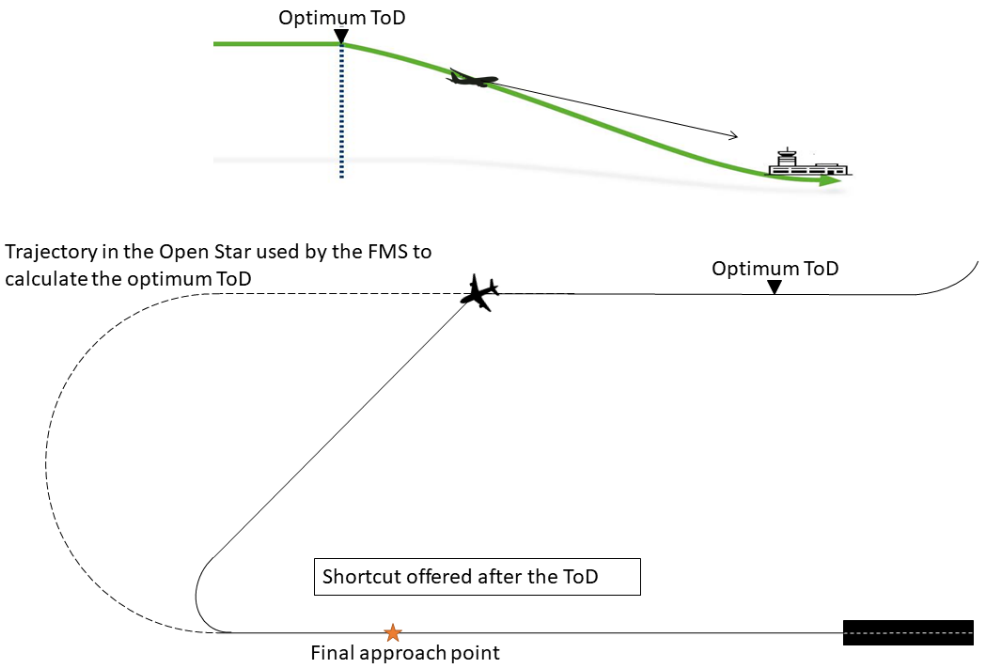

Figure 9: representation of a shortcut given during the descent phase.

6.3.3 Shortcut given before the ToD, during the cruise phase

The scenario envisages the same tactical change, but with the shortcut information being given prior to the defined ToD. The operators and FMS then have an updated distance to go that allows the FMS to schedule an earlier ToD as shown in Figure 10 and perform a continuous descent even with a shortcut.

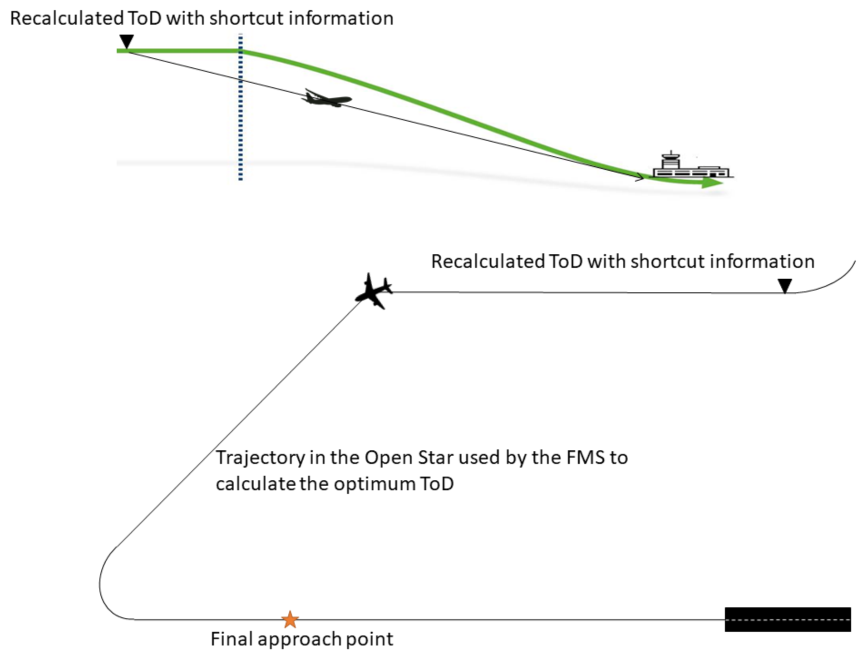

Figure 10: representation of a shortcut information given prior the ToD.

6.3.4 Results and analysis

Using a common average inverse specific range for a single-aisle aircraft in the descent phase of 2,5 kg/NM, a shortcut that allows an 8 NM shorter route will save 20 kg fuel if given during the descent phase as illustrated by the scenario in 6.3.2. The possible downside of this fuel savings is that it may create a high energy approach scenario, i.e., the aircraft has too much energy relative to the distance left to the landing runway. This energy needs to be dissipated which can be done either through a steeper descent and speed increase and/or usage of speed brakes. Whichever strategy is used can be viewed as energy wasted from a flight efficiency perspective. This could even lead to a so-called unstable approach, forcing the operator to cancel the approach and initiate a go-around.

If such a shortcut is communicated prior to setting the ToD, an updated ToD can then be calculated, and the descent phase can start earlier as illustrated by the scenario 6.3.3. The 8 NM shorter route created by the shortcut leads then to an 8 NM shorter en-route phase. Assuming a common inverse specific range for a single-aisle aircraft in the enroute phase of 5 kg/NM, in this scenario 40 kg of fuel would be saved, which is twice as much as the after-ToD shortcut scenario. Although the numeric representation of the fuel burn is simplistic in this analysis, the reasoning is sound and it is more beneficial to shorten a mission in cruise than during an optimised descent.

6.3.5 Conclusion

Giving a shortcut during the descent phase can save fuel but also has the potential to generate a non-optimum energy situation for the operators. This can be alleviated through clear communication between ATC and operators where a clear “distance to go” is issued. This will allow for the aircraft to optimally dissipate the extra energy. The analysis shows that a communicated shortcut in good time can potentially increase the fuel savings.

However, it is important to understand that often a shortcut or a heading clearance is given by ATCOs as a reactive tool to respond to a scenario happening in the vicinity of the airport, for example to address a safety or capacity need. It can be very challenging for an ATCO to communicate a shortcut prior to the ToD as such a decision might not be available at the needed time. If a shortcut is given solely to shorten the mission range in low density traffic, the importance of communicating such a shortcut ahead of the ToD should be taken into account if possible.

While offering shortcuts may save fuel and time, the potential of putting the aircraft into a high energy state needs to be considered. A study of operations at Charles de Gaulle airport during COVID noted that although the traffic went down by 90%, the unstable or atypical approaches (approaches with a too high energy state) increased by 50% due to trajectory shortenings [Jarry et al.]

6.3.6 References

- https://skybrary.aero/shortcuts-and-unstable-approaches-skyclip
- “Flight safety during Covid-19: A study of Charles de Gaulle airport atypical energy approaches", G. Jarry, D. Delahaye, E. Feron, Transportation Research Interdisciplinary perspectives, https://doi.org/10.1016/j.trip.2021.100327

6.4 OS 4: closed STAR vs. open STAR procedure (tactical intervention)

6.4.1 Background

As explained above, there are a number of STAR procedures available to transition from the en-route structure to final approach in the terminal area. The different procedures can be divided into two main categories:

- Open path procedure - where ATC tactically clears the aircraft for descent with the help of radar vectoring to intercept the final approach segment, see Figure 8.
- Closed path procedure – the aircraft follows a series of waypoints and possible restrictions to safely descend to the final approach segment, see Figure 7.

The impact of tactical intervention on the fuel burn and on the efficiency of the descent phase was raised during the different interviews conducted. With closed path procedures, the FMS has information about the distance to go, as the whole procedure is defined. With open path the ATC interventions make the horizontal profile less predictable and may result in either an extension or a shortening of horizontal profiles, that may create inefficient level segments thus affecting fuel burn and noise.

Analysis performed during the ALBATROS SESAR project is presented below that underlines the vertical inefficiency linked to an Open STAR procedure and the correlation between the fuel burn and the ATC clearances in these procedures.

6.4.2 Method

The analysis has been performed using the Novair Fuel Management Information System, containing FDR data for all flights performed by Novair between 2019-2021. In addition to the FDR parameters, so called “Delta Burn” values are available for each flight, indicating the vertical, lateral, and total efficiency during the approach phase of the flight. The Delta Burn values are calculated by comparing the actual fuel consumption of each flight with the calculated fuel consumption of a theoretically optimal flight under the same flight conditions. The actual fuel burn is calculated based on the FDR data for the flight and the fuel consumption of the optimal flight is calculated using the Airbus Performance Engineer’s Program (PEP) based on actual conditions for the flight and Cost Index (CI) 0 (minimum fuel usage).

ATC clearance data was received from LFV for all Novair flights in the period 2019-2021. The clearance data was imported into the Novair Fuel Management Information System, making it possible to analyse it together with the FDR data and Delta Burn values for the flights.

6.4.3 Results and analysis

This section presents the results of the method applied on arrivals to the Stockholm Arlanda airport (ESSA), for the 2019-2021 period. The results presented summarised a total of 823 flights in total, all from the airline Novair. Table 4below summarises the landing procedures used for the different flights.

The procedures typically used for landing aircraft at Stockholm Arlanda are as followed:

- Open STAR procedure with one or more clearances: that is the most common use way of directing flight to the runway. During high density traffic heading clearances are used to guide the traffic into final approach. Table 4 shows how often clearances were given to the flights landing to ESSA for the analysed flights. It can be seen that on average four to seven clearances are given to arriving aircraft.
- Open STAR procedure with no heading clearance: If the traffic density is low, flights are cleared directly to a waypoint typically runway inbound and are cleared for approach from there. This allows for a rather light load on ATCOs, and a short flightpath.
- Closed STAR loop procedures: At ESSA, RNP-AR procedures are in place and when used allow for an unhindered landing operation where pilots can optimally plan the flight trajectory to the final approach segment.

Airport: ESSA	Average delta burn vertical	Average descent distance	Average time in level flight from ToD	Delta distance compared to the shortest route	Number of flights
OPEN STAR procedure with one or more heading clearances	54 kg	133NM	60 sec	10.5 NM	582
OPEN STAR procedure with no heading clearances	30 kg	127 NM	22 sec	3,7 NM	194
CLOSED STAR procedure	30 kg	123 NM	5 sec	5 NM	47

Table 4: Comparison between flights arriving via the different procedures available at ESSA (Stockholm Arlanda, 2019-2021).

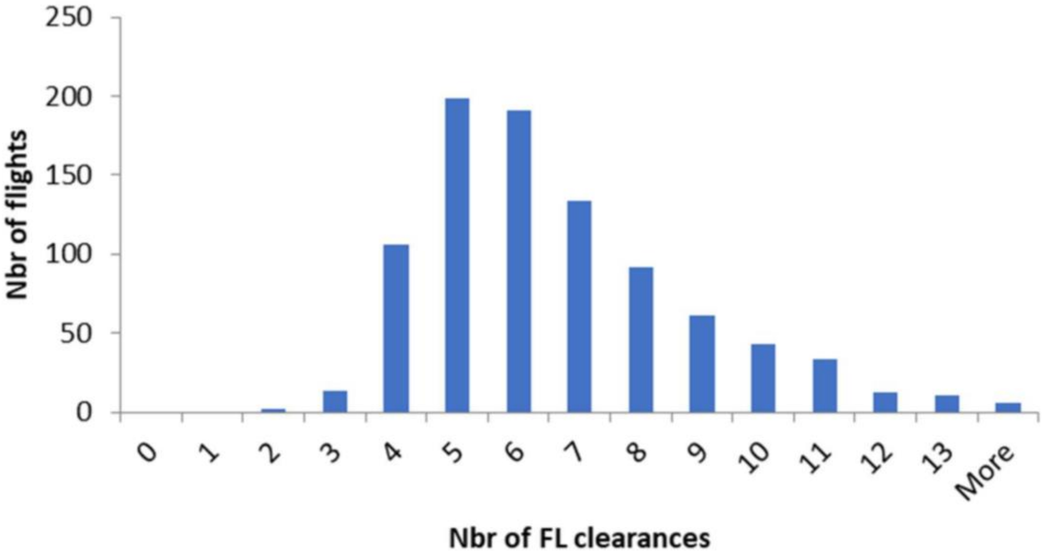

Figure 11: Frequency of ATC clearances per landing flight (Stockholm Arlanda, 2019-2021).

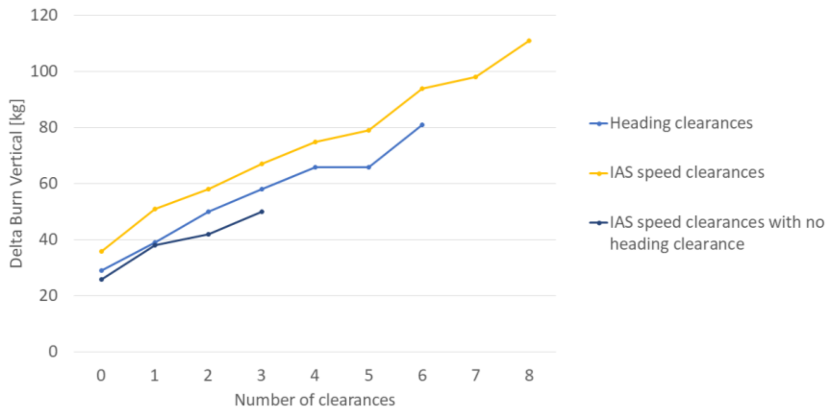

Figure 12: ATC clearances sorted by category against average delta burn (Stockholm Arlanda, 2019-2021).

When a closed STAR procedure is followed, the contact with the ATCOs is limited and few to no clearances are issued. However, when an Open STAR procedure is in place, the ATCO in position interacts with the pilot to issue clearances, from heading to speed or altitude clearances. Figure 11 shows the histogram of clearances for analysed arrivals into Stockholm Arlanda. A large number of flights gets between four to seven eight clearances.

Figure 12 presents the behaviour of the average delta vertical fuel burn compared to the number of clearances issued by ATC. The average delta vertical fuel burn is calculated as the difference between an actual flight and the vertical fuel burn from the reference optimal trajectory computed in the Airbus program PEP.

The different clearance categories are plotted in Figure 12. A strong correlation is visible between increased number of the various clearances and decreased vertical efficiency. This is to be expected but the correlation appears to be quite linear. For example, if looking at heading clearances in Figure 12, a large number of heading clearances in an Open STAR procedure probably indicates a longer route than one flown with less clearances issued.

6.4.4 Conclusion

This case study indicates that the use of open STAR procedures should be avoided if vertical profile optimization is of importance. During periods of low traffic, it has been shown that Open STAR procedure can be efficiently used from a fuel burn perspective by clearing a plane into a waypoint typically inbound, thus limiting the impact of the ATCO on the optimised descent set by the FMS onboard. This method is however subject to having a low-density traffic to safely direct traffic in such a way. Closed STAR procedures offer the predictability to fly an optimum descent profile during both low and high traffic density. For illustration, for closed STAR procedures into Stockholm Arlanda the average excess fuel due to vertical efficiency is reduced by 24 kg in the SESAR study.

If Open STARs are used and vectoring is used to tactically control traffic flows, ATC may facilitate an optimised vertical profile by providing regular and accurate “distance to go” information to the Flight Crew, whenever possible, so that a descent profile without inefficient level segments can be executed to the extent possible. Even with no level segments, the Open path option may create a non-optimal descent unless the “distance to go” information is given before the descent is initiated.

6.4.5 References

- “SESAR ALBATROSS Report Part 1 “ - https://sesar.eu/sites/default/files/documents/solution/SolALBATROSS-RAD%20Demo%20Report%20TRL6.pdf
- “European CCO/CDO Action plan” – Eurocontrol - https://www.eurocontrol.int/sites/default/files/2020-11/european-cco-cdo-action-plan.pdf

6.5 OS 5: non-optimised descent profile and its impact on flight efficiency

6.5.1 Introduction

Ideally an aircraft should stay at cruise altitude where fuel burn is optimal until reaching the ToD corresponding to the start of a descent at idle thrust. From a fuel burn minimisation perspective, this is the most efficient way to descend.

A descending aircraft executing a CDO may be required to deviate from its preferred descent profile. A non-optimum descending phase can take many different forms, considering the impact of different parameters such as airspace structure, weather, ATC/pilot communications, etc. The stakeholder outreach identified a few cases of interest, which are detailed below. The OEM partners in WG2 provided a fuel burn analysis of those different operational scenarios. The scenarios were then compared to a reference trajectory and the difference in fuel burn was assessed. The reference trajectory is the same as the previous operational scenario, detailed in section 6.2.2.

The OEMs that participated in this exercise consisted of two major manufacturers. Both computed results for the scenario described below and the results obtained were very similar. Note that an average of the computed results is presented in the report.

6.5.2 Early descent scenario due to strategic or tactical decisions

This operational scenario simulates a descent being initiated 15 NM prior to the optimum ToD. The aircraft then initiates a non-optimum descent to FL 80 followed by a level-off at FL 80 at an IAS speed of 250 KIAS over a distance of 15 NM. Thereafter, the aircraft re-intercepts the reference trajectory. The Early descent scenario as well as the reference trajectory (described in 6.2.2) is shown in Figure 13. The delta fuel burn between the reference trajectory and the early descent scenario is then assessed.

This operational scenario is a common scenario when entering high-density airspace. The scenario can either be tactical, where ATC instructs the aircraft to descend to lower non-optimum altitudes, for example to avoid traffic or weather. But the non-optimum descent profile can also be initiated for strategic reasons, for example when a speed and altitude constraint is enforced at the TMA entry waypoint.

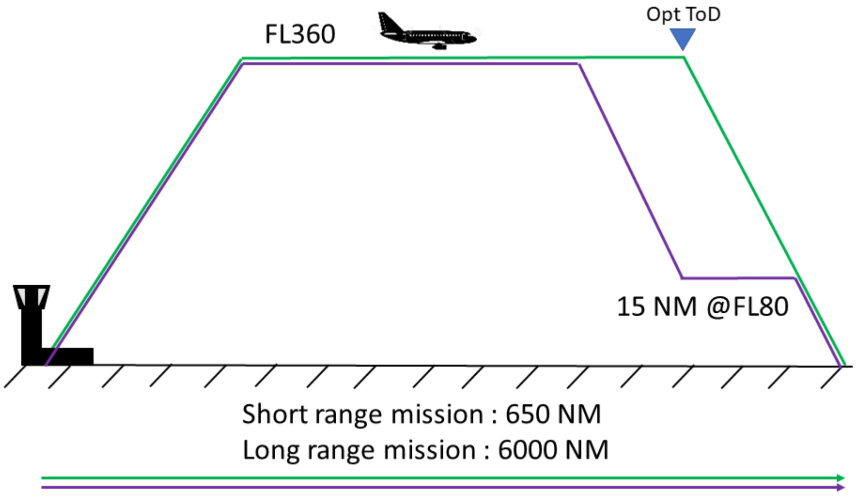

Figure 13: Early descent scenario.

6.5.3 Level-off during descent leading to a track extension scenario

Another scenario of interest to the operational stakeholders was an operational scenario where an optimum descent profile is interrupted by a level-off track extension. The aircraft leaves the en-route phase at what the FMS views as the optimum ToD. An optimum descent profile is then initiated but interrupted by a tactical level-off that leads to a track extension of 15 NM. Thereafter the glide slope is re-intercepted. The impact on the fuel burn will differ depending on the altitude at which the level-off is issued. Therefore, two scenarios were computed by WG2, for flight level FL80 (8000 ft/2440 m) and flight Level FL140 (14000 ft / 4270 m), as shown in Figure 14.

This scenario is common during an Open STAR procedure. In such a procedure, the uncertainty around the distance to go makes it difficult for the operators to perform a continuous descent. When ATC intervenes during an Open STAR procedure, for safety or capacity reasons for example, this often results in inefficient level-off segments.

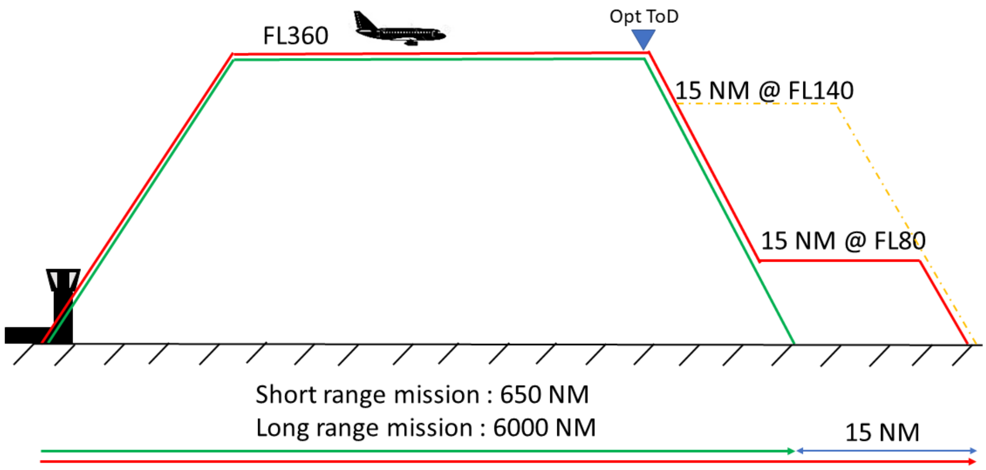

Figure 14: Level-off during descent

6.5.4 Results and analysis

The delta fuel burn between the reference trajectory and the operational decisions are presented in Table 5.

Operational scenario during descent phase	Delta fuel burn ΔTF [kg] between scenarios and reference trajectory	
	Single-aisle aircraft	Wide body aircraft
Early descent for tactical or strategic reasons (15 NM level segment)	41	94
Level-off during descent at FL80 (+15 NM track extension)	106	250
Level-off during climb at FL140 (+15 NM track extension)	98	218

Table 5: Extra Fuel burn (ΔTF) between the baseline and the different operational scenario during the descent phase.

The results indicate clearly that the operational changes to the optimal descent have an impact on fuel consumption. It is of no surprise that extending the mission by 15 NM has a greater impact on the fuel consumption. There is also an observed correlation between the level-off altitude and the extra fuel burned. The analysis emphasises as well that a level-off at a lower flight level costs more fuel than at a higher level, which was shown as well in section 6.2.5.

As mentioned previously, the reasons for a non-optimum descent are many and varied, but can mostly be sorted into two categories, strategic or tactical. Tactical reasons for not performing a continuous descent operation may involve for example safety, airspace capacity, or weather. The ATCO must then use the tools in their possession to safely separate and sequence aircraft. This can generate extra fuel burn, and possibly add track miles to the mission.

When the optimum descent is not performed due to fixed constraints in the airspace, this may be for strategic reasons. An example of strategic interventions in the descent phase are altitude constraints in the STAR structure or in the TMA airspace. These strategic interventions in the latter part of the flight often are associated with additional fuel usage as shown by the analysis of the early descent scenario above in 6.5.2. The extra fuel associated with the strategic decision is added to the mission fuel. This has an impact on the fuel burn during the whole mission as the weight of the aircraft gets heavier for the whole mission.

6.5.5 Conclusion

The two non-optimal descent scenarios analysed above show extra fuel burn compared to the reference trajectory. An important conclusion is that if a deviation is deemed necessary leading to a level-off and an extension of the mission, the extra flown distance should be minimised and if possible, absorbed at the highest altitude possible.

The analysis presented here highlight only two possible scenarios that could happen during a descent phase and disrupt an optimum descent. The purpose is not to weigh them against each other. Rather, the intent is to emphasise the importance of performing a continuous descent operation to the greatest extent possible. To highlight the benefit, a 2018 Eurocontrol study (https://www.eurocontrol.int/concept/continuous-climb-and-descent-operations) shows that in Europe the potential savings from optimising CCO and CDO are up to 340,000 tonnes fuel/year, (1.1M tonnes CO2/150M EUR) and that the potential fuel saving benefits from CDO are around ten times those from CCO. Although reaching a full CDO potential might not be fully realisable due to safety reason for example, striving to extend the use of continuous descent operations is viewed as highly desirable from an environmental perspective.

6.5.6 References

- "European CCO/CDO Action plan" – Eurocontrol - https://www.eurocontrol.int/sites/default/files/2020-11/european-cco-cdo-action-plan.pdf
- Simulations performed by WG2 together with OEMs

6.6 OS 6: tactical intervention: on a descending aircraft over climbing aircraft

6.6.1 Background

When ATCOs are faced with the decision of how to separate climbing / descending traffic, via level-offs or track extensions, there are different solutions depending on the individual circumstances and local conditions. One method of tactical intervention may be instructions to provide vertical separation or horizontal separation by using either shortcuts ("direct to" instructions) or track extensions. Shortcuts without any level-offs may be considered the most efficient intervention. If a shortcut to a climbing aircraft, or a track extension to a descending aircraft, does not solve the conflict, as the ATCO did not anticipate the conflict in advance, then it is likely that one or both aircraft in the conflict situation have to be levelled off.

6.6.2 Method

To understand the impact on the fuel burn, the fuel burn differential [Reference: European CCO/CDO Action Plan] is presented in Figure 15

Figure 15 between optimum and sub-optimum flight levels for two aircraft representatives of single-aisle and wide-body aircraft. The fuel burn differential is showed as the inverse specific range differential, which is the amount of fuel burn per unit of flown distance.

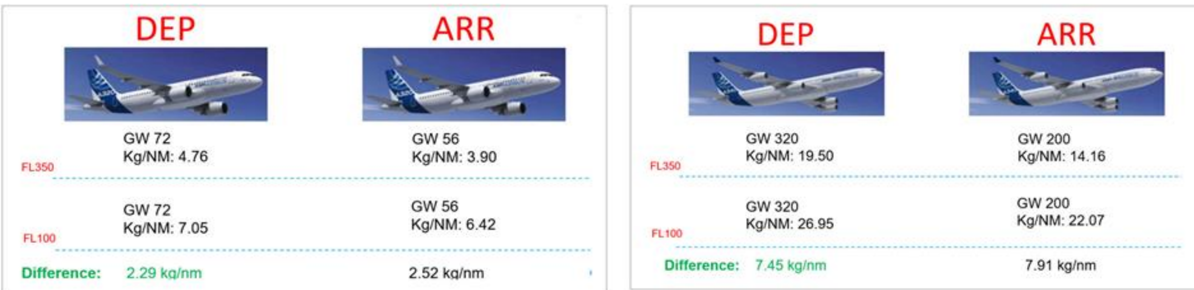

Figure 15: inverse Specific Range differential between cruise (FL 350) and F L100 for departure (DEP) and arrival (ARR) for two different aircraft types: a typical single-aisle aircraft type (left side) and typical wide-body aircraft (right side)

In Figure 16, the results from the OEMs analysis detailed above are presented as well. The fuel burn differential between the reference trajectory and a 15 NM level-off at FL80 was presented above in section 6.2.5 and is presented in Figure 16 by the dashed red line. For the descent phase, the fuel burn differential between the reference trajectory and a 15 NM level-off at FL 80 was presented above in section 6.5.4 and is presented in Figure 16 by the purple line.

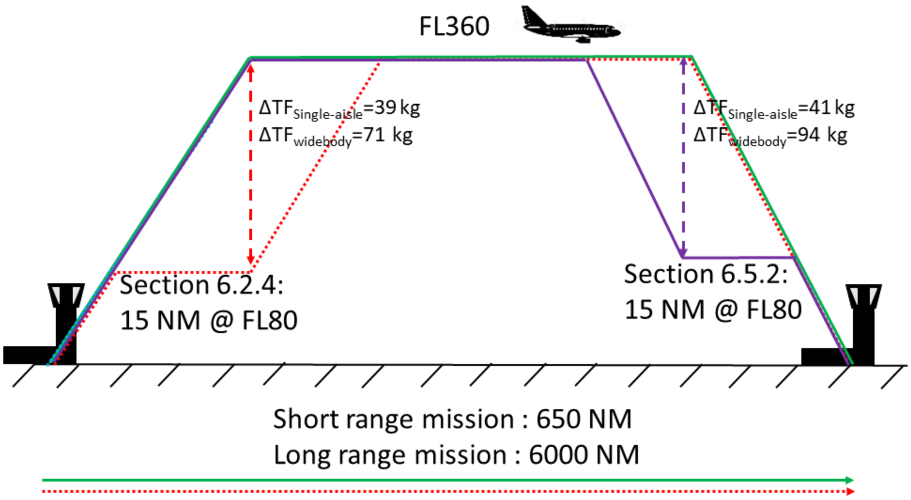

Figure 16: OEMs analysis of fuel burn differential between the reference trajectory and level-off in climb (red dash line) and a level-off in descent (purple line).

6.6.3 Results and analysis

Figure 15 shows the inverse specific range (ISR) for a climbing aircraft for a level off at an optimum and non-optimum flight level, both in the climbing phase as well in the descent phase. As mentioned previously, if a level-off is executed at a non-optimum flight level during a descend or a climb and the range of the mission is unaffected, the distance flown at the non-optimum level replaces the same distance in cruise.

If a level-off is executed in the climb phase at FL 100, a single-aisle aircraft burns 2,29 kg/NM more fuel than flying at FL 350 (optimum flight level). For a level-off of 15 NM that represents an extra 34,3 kg (2,29*15) consumed in the climb phase by flying at a non-optimum flight level.

However, following the same method, using Figure 15, if a level-off is executed at FL 100 during the descent phase, a single-aisle aircraft consumes 2,52 kg/NM more fuel than flying at FL350. For a level-off of 15 NM that represents an extra 37,8 kg (2,52*15) consumed in the descent phase by flying at a non-optimum flight level.

So, when an ATCO is faced between the decision of levelling-off a climbing or a descending aircraft, this analysis shows that it will cost 34.3kg of extra fuel to level-off a climbing aircraft, while it will cost 37,8 kg extra fuel to level-off the descending aircraft. It will thus cost 3,4 extra kg of fuel if choosing to level-off the descending over the climbing aircraft. This differential in fuel burn gets larger when looking at a wide-body aircraft, where the extra fuel burn consumed for a level-off of 15 NM at FL100 sums to around 7 kg according to Figure 15.

These results are corroborated by the analysis performed by the OEMs. A summary of the delta fuel burns from the computations performed with the OEMs can be found in Table 6. The extra fuel burn for a level-off at FL80 in the departure phase is about 39 kg for a single-aisle aircraft while it is 41 kg in the descending phase. It therefore costs 2 kg more to level-off a descending aircraft than a departing one. For a wide-body aircraft, the difference is bigger and comes to 23 kg (94 kg instead of 71 kg see Figure 16 and Table 6).

Operational scenario during the climb phase	Delta fuel burn ΔTF [kg] between scenarios and reference trajectory	
	Single aisle aircraft	Wide body aircraft
Level-off during climb at FL80 (15 NM level segment)	39	71
Level-off during descent at FL80 (15 NM level segment)	41	94

Table 6: Delta fuel burn numbers from the computations performed together with the OEMs for a 15 NM level-off in climb vs in descent.

Further, medium to long haul operations are typically associated with a vertical profile in the en-route phase including step climbs. The final cruise altitude is therefore higher than the initial cruise one, a detail that does not appear in the studies above. The ISR is lower at higher altitude, which is the reason why airlines strive to fly as high as possible. So, the differential ISR between the optimum altitude and a non-optimum flight level becomes even larger during the descent phase.

6.6.4 Conclusion

When an ATCO is faced with a decision concerning a potential conflict between a climbing and a descending aircraft, and where a level-off should occur, multiple factors (aircraft types, traffic flow situation, etc.) come into play, as a 'one size fits all' solution is not available. When asked whether ATC should prioritise the flight profile of a climbing aircraft or a descending aircraft, as a tactical option in a one for one comparison, Flight Crew will almost unilaterally respond that the climbing aircraft should always be prioritised as it is heavier and therefore has a higher fuel burn and therefore, CO_2 emissions. Current practices reinforce this thinking.

However, the results of the analysis demonstrate that the fuel burn differential between levelling off at optimum and sub-optimum flight levels, for heavier and lighter aircraft, is a more important factor to take into consideration, rather than the actual weight of the aircraft. The scenarios above have showed that taking an aircraft out of its optimum continuous descent profile generates a larger fuel burn penalty than disrupting the climbing aircraft.

It should be reiterated that the objective of this analysis is not to make recommendations for ATC CONOPS or a proposal for updating aircraft operator instructions in the OM. The objective is to provide a basis for further discussion and analysis of the factors that may influence the optimisation of fuel burn in climb and descent.

6.6.5 References

- "European CCO/CDO Action plan" – Eurocontrol - https://www.eurocontrol.int/sites/default/files/2020-11/european-cco-cdo-action-plan.pdf
- Simulations performed by WG2 together with OEMs

6.7 OS 7: harmonised descent speed below cross over (conversion) altitude

6.7.1 Background

One of the main parameters that affects the descent profile and in turn the aircraft fuel burn is the speed at which the aircraft descends. Ideally, an aircraft should stay at cruise altitude where fuel burn is optimum until reaching the ToD corresponding to the start of a descent at idle thrust. This is the most efficient way to descend to minimise fuel consumption. Leaving the cruise altitude before this ToD will lead to a non-optimum decent profile requiring thrust from the engine that leads to extra fuel consumption. Likewise, leaving cruise after the optimum ToD will lead to an increased speed of descent and thus a steeper descent angle. Extra drag will be required to shed the excess energy during the descent phase or an unstable approach and subsequent go-around may occur, thus leading to an even higher fuel penalty.

In current operations, the intended descent speed is not communicated by the airspace user to the ground through the flight plan, and thus the ATCOs are not aware of the amount of energy that needs to be dissipated by the aircraft. Furthermore, in high traffic periods, tactical intervention from ATC might be needed to accommodate the flow of arriving aircraft with different descent and approach speeds.

To optimise CDO performance, a good practice would be to define a harmonised descent speed in the local AIP (Aeronautical Information Publication). A harmonised descent speed is based on the principle that all descending civil aircraft operating under Instrument Flight Rules (IFR) must maintain a predetermined speed from the altitude where the transition from Mach number to Indicated Air Speed (IAS - in knots) occurs down to the next altitude where speed restrictions are in place. The gains of a harmonised descent speed are twofold. The uniform behaviour of descending aircraft will make sequencing the aircrafts easier, thus limiting the ATCO tactical intervention, while the pilots will be aware ahead of the descent phase of the preferred airspace descent speed. It would allow the Flight Crew to factor it into their descent planning, and accomplish the descent without the use of drag or level flight. These gains are balanced against reduced freedom for the operators and a slight time cost increase.

6.7.2 Case Study

This study presents results and analysis performed for the SWEA (Sweden Airspace Project) project that is ongoing in Sweden, aiming to redesign the Swedish airspace for today and tomorrow's traffic. Harmonised descent speed was singled out as one of the potential solutions to increase the level of predictability for ATC, generate optimum fuel savings for the airlines, while reducing noise and emissions for the community below. The objective of the case study is to find the variation/ranges in descent speed in the Swedish airspace and to understand the impact a harmonised descent speed would have on the fleet in Sweden. The fuel savings linked to the harmonised speed and the extra time spent in the airspace need to be carefully weighed against, as well as a good understanding on how many aircraft would be impacted by such a decision.

Descents are normally performed in three phases on a constant IAS / Mach descent speed schedule:

- Constant Mach number is maintained until the crossover altitude
- Constant IAS speed is maintained until approaching 10,000ft (FL100)
- 250 kts IAS or less is maintained below FL100, until the aircraft decelerates for landing.

An example of a single-aisle jet aircraft is shown in Figure 17. In this example, the aircraft maintains an IAS speed of 260 knot between the cross-over altitude to FL100.

The following results were computed on a traffic period of three years, computing all jet traffic that flew in Swedish airspace between 2020 and 2023. About 300,000 flights were analysed during the study, for the descending phase, from cross-over altitude to FL100.

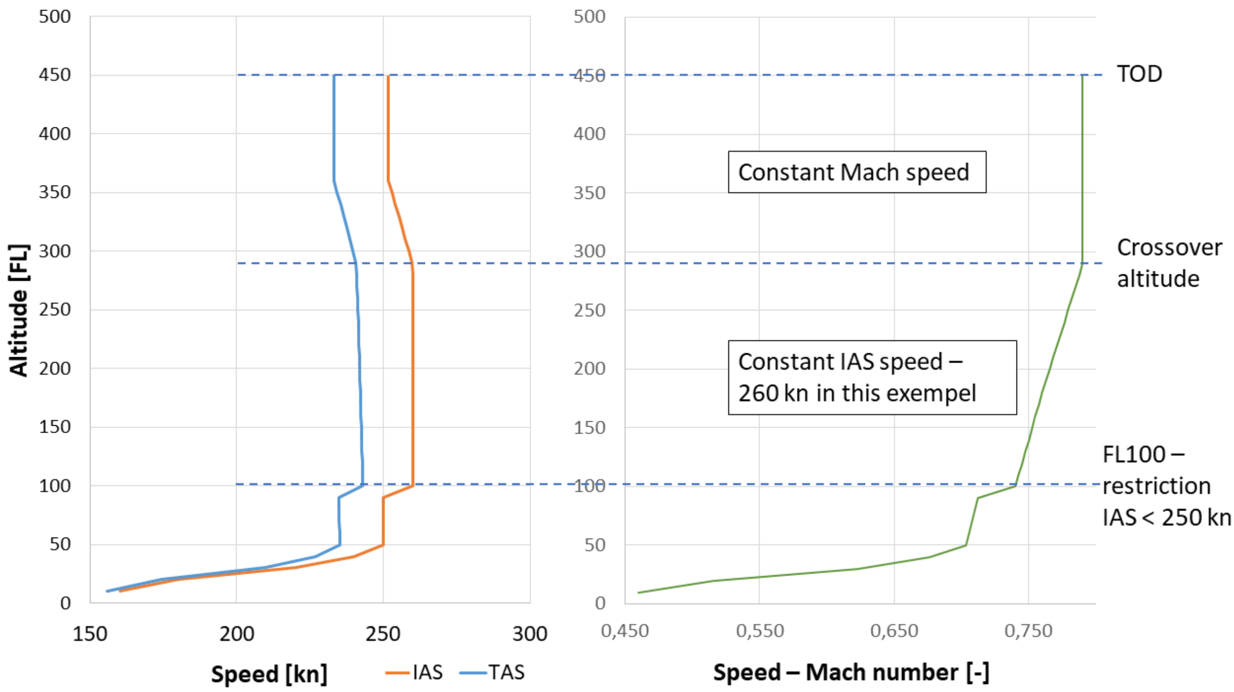

Figure 17: behaviour of a descending aircraft from ToD to ground. Between ToD and crossover altitude, the aircraft flies at constant Mach number. Due to increasing speed of sound for decreasing flight levels, the IAS speed increases when the aircraft descends. When the intended IAS is reached (IAS=260kn in this example), the cross-over altitude is reached, and the aircraft switched from constant Mach number to constant IAS speed until reaching altitudes where speed restrictions are enforced (FL100 here).

6.7.3 Results and analysis

The speed variation of the descending aircraft in Swedish airspace is very large, and presents a challenge for the ATCOs to efficiently sequence the traffic down to the ground. The analysis detailed in Figure 18 details the top 10 major airlines in Sweden anonymised and their respective average descent IAS speed between cross-over altitude and FL100. There is a large discrepancy for the different airlines descending speed. The difference in the descending speed is partially linked to the Cost Index (CI) that airlines set for each aircraft. A higher Cost Index leads to a higher descent speed and a steeper descent angle. The difference between low and high CI scenarios may result in speeds between around 250-340 kts.

Even within the same company, Figure 19 shows that the difference between different flights performed by the same aircraft can be major. This figure shows the envelope of constant IAS speed for 500 different landings performed by the same aircraft type. The speed varies from 260 to 310 kts.

Figure 20 shows the share of aircraft traffic across the variation in descent speeds. As can be seen in the figure, around 80% of the aircraft descend with an IAS descent speed equal or above 260 kts.

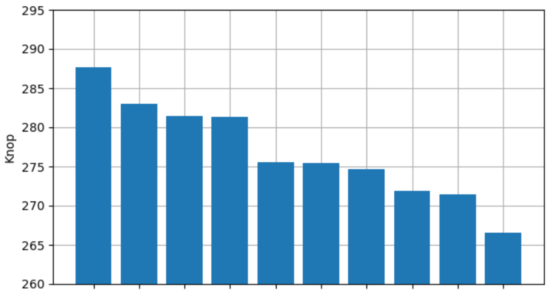

Figure 18: average descending IAS speed for the ten major airlines present in Swedish Airspace.

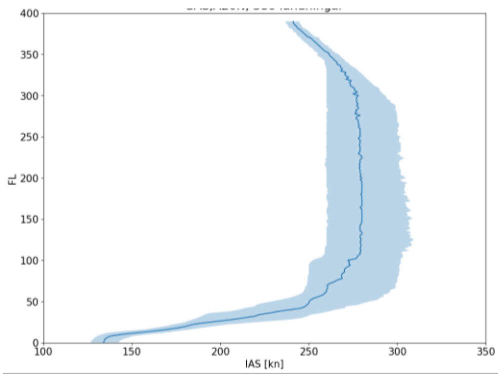

Figure 19: Average IAS descending speed envelope for 500 landings performed by the same aircraft at the same airline.

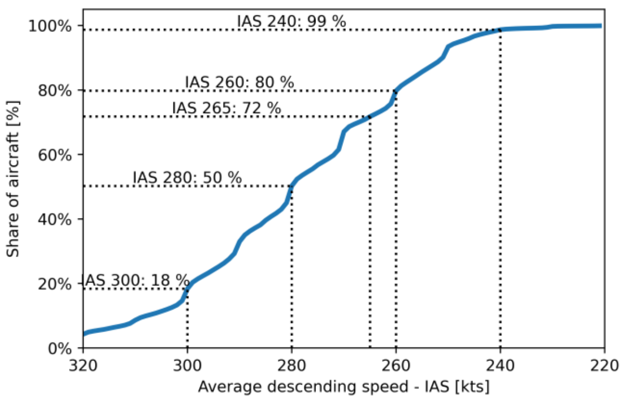

Figure 20: average descending speed against the share of landing aircraft.

Together with the major airlines in Sweden, a decision was made to use 260 kts IAS as the proposed harmonised descent speed which would affect 80 % of all landing jet aircraft as can be seen in Figure 20. Using this speed, the operational and environmental consequences were analysed. The analysis of such a decision shows potential fuel savings of around 19 kg per landing for flights that would be impacted by the slower descent speed from the speed alone at the cost of a delay of around 64 seconds per flight. The fuel saving comes solely from a reduction in speed. It does not include any potential extra saving that might come from a more optimum descent profile. All flights that already fly their descent phase at a 260 KIAS average speed or lower are not impacted in this analysis. Regarding operational consequences, there are largely only positive effects of a harmonised descent speed, both from the perspective of the pilot and air traffic control. Such a harmonised descent speed could improve predictability for ATC. Other performance parameters, such as the height of Top of Descent (ToD) or descent rate (feet/minute), are also affected but not to such an extent that it has a significant operational impact.

6.7.4 Conclusion

The analysis performed in Sweden showed that implementing a 260kts harmonised IAS speed could, on average, save up to 19kg fuel per landing, resulting in a potential fuel saving of 2500 tons of fuel per year. The fuel saving was computed solely through a harmonised speed. It is important to note that such a harmonization comes with a slighter lower degree of freedom for the airlines, and a slighter longer flight time for most of the aircraft.

The harmonised descent speed should however not be more than a guideline. It should be well understood that if a higher IAS descent speed is required by the pilots it should be not be denied. Likewise, when choosing an appropriate harmonised descent speed, it should be calculated to fit the preferred descent speed of the traffic mix without forcing a fraction of the flights to fly below a Cost Index of CI 0, typically around IAS 250kts.

6.8 OS 8: Noise analysis in the arrival phase

6.8.1 Background

Arrival procedures vary greatly from one airport to another as STARs are tailored to each airport`s layout, surrounding terrain, and predominant traffic patterns. Thus, determining one broadly applicable case for assessing the environmental interdependencies for noise impacts is nearly impossible. Interdependencies may be encountered when designing a flight path for the sake of noise mitigation:

- In certain cases, flight path planning can decrease the noise impact of flights on communities, e.g., by routing traffic over water or uninhabited land;
- In some cases, extra track miles may be incurred for noise mitigation, thus increasing fuel burn;
- In other cases, the applied track changes to mitigate noise may actually decrease track miles and associated fuel burn.

In the latter case the scenario is a win-win for both fuel burn and noise. If the track miles are extended in favour of noise mitigation, the interdependencies between fuel burn scenarios can be approximated by OS2 (i.e., track extension to enable CCO/CDO) in section 6.2. Note that OS2 does not consider any noise parameters.

Due to the individuality of lateral noise mitigation, a more generic case for the noise and fuel burn impacts of flying a Continuous Descent Operation (CDO), as described in ICAO Document 9931, was considered for this operating scenario. How a CDO is performed can also vary greatly from one airport to the next, impacting the associated noise and fuel burn impacts. More in-depth studies were not available due to the time constraints of the task and available resources.

For measuring the noise impact, several methods and indicators can be used, including analytically generating a noise footprint, or real-world noise monitoring. The reduction of the number of people exposed to a specific level of noise is highly dependent on each local environment and population density. Beyond the population distributions surrounding each airport, the threshold of significant level of noise varies from state to state, and sometimes even city to city. While the specific benefit will still vary for each real-world implementation, a more generic case was studied for this report.

6.8.2 Case study

To assess the qualitative differences of a CDO versus an approach with level segment, an analytical model was used to simulate the noise and fuel burn of the two different arrival types. The presented study compares a typical single-aisle aircraft arriving at an airport performing two different arrivals: an optimal CDO approach versus an approach including a 5 NM level segment at 3,000 ft. In both cases the profile starts at FL 60 with the initial landing weight kept constant. The fuel burn for the approach, as well as different noise footprint contours were generated to assess the benefits of performing a CDO. The schematic of both approach scenario is represented in Figure 21.

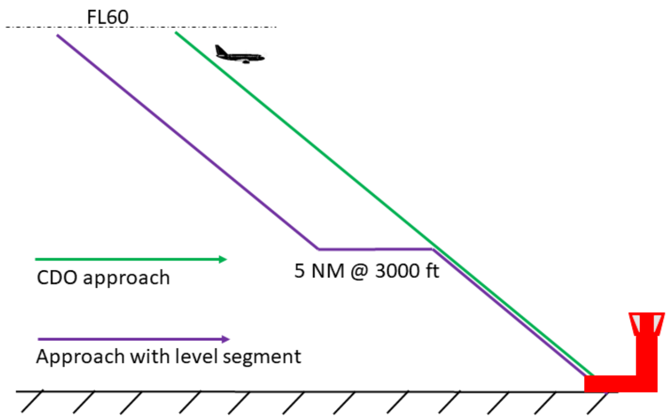

Figure 21: CDO vs level-segment approach scenarios.

The results from the study case are specific to the airport, aircraft, descent profile, and represent a sample case of what can be expected from a CDO.

6.8.3 Results and analysis

The CDO approach generates a noise footprint that is approximately 30% smaller than that of the level segment arrival at the 60 dBA level. Additionally, the 65 dBA and 70 dBA footprints areas are reduced by 25% and 15%, respectively, for the CDO approach. The CDO approach also consumed approximately 60 kg less fuel compared to the level segment arrival. Figure 22 shows the summary of the arrival noise and fuel burn analysis.

The reduction in the noise footprint and fuel burn can be explained by two changes to aircraft performance in a CDO. On the one hand, a level segment requires additional thrust to maintain altitude and airspeed compared to a CDO. The higher thrust increases the noise generated by the aircraft and increases the fuel flow of the aircraft. On the other hand, at points before the completion of the last level segment, the aircraft on the CDO flight profile will be higher in the sky compared to the level case. Increased atmospheric absorption from the increased distance between the aircraft and the ground, further contributes to a lower noise footprint.

Note that as both arrivals pass the final approach fix (FAF), and maintain the final 3-degree glideslope towards touchdown, the difference to the noise footprint or fuel burn between the two procedures is reduced to zero. The primary benefit of the CDO is achieved by eliminating the level segment, and is not seen in the direct vicinity of the airport. In the example shown the level segment is low and occurs over heavily populated areas. Level segments will normally be assigned for traffic management and energy management purposes. One way to mitigate the noise impact when a CDO cannot be flown would be to adjust the location of the level segment, e.g., over unpopulated areas or by raising the altitude so the resulting noise increase is smaller.

Because of the benefit to both noise and fuel burn of a CDO, no specific trade-off is seen in this scenario. However, a win-win interdependency is seen from the procedure itself, demonstrating the benefits of the operational decision to enable CDO.

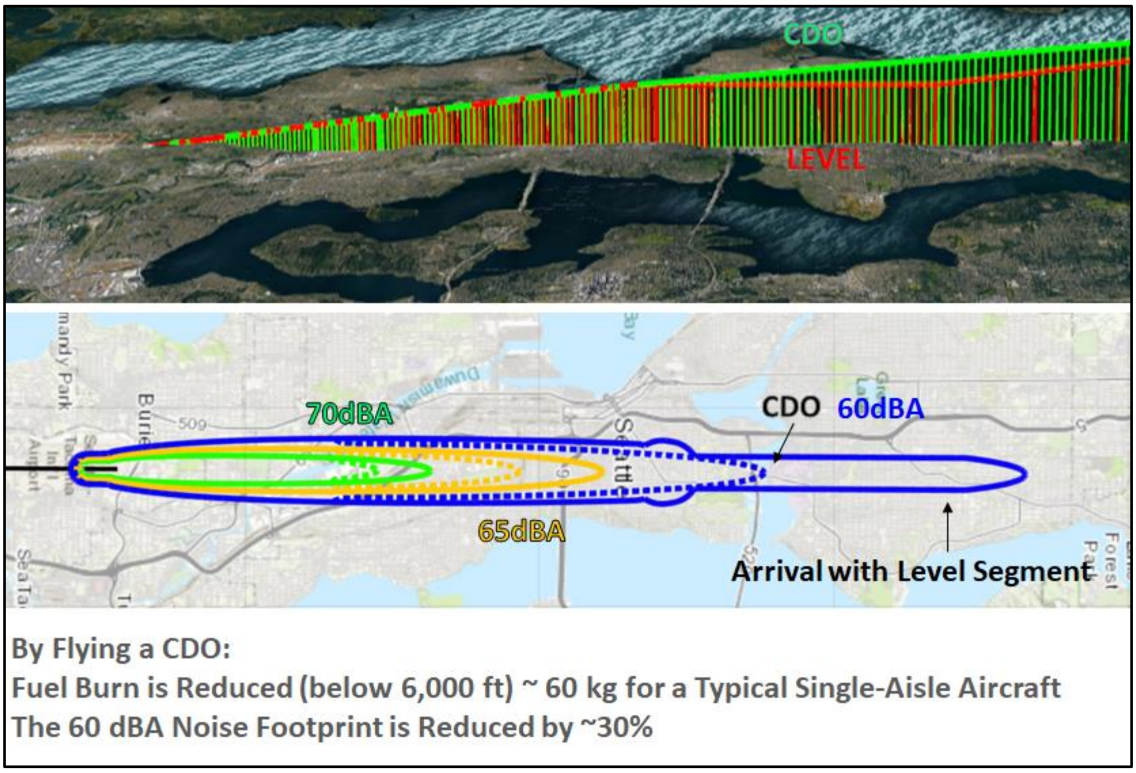

Figure 22: noise area impact of an arrival with a level segment (solid lines) and of a CDO arrival (dashed lines).

6.8.4 Conclusion

Operating a CDO in the arrival phase is not only beneficial to fuel burn, but also for noise. At points further away from the airport the elimination of a level segment minimises the noise footprint by the lowering thrust and increasing altitude. If level segments are needed for traffic sequencing, an effort should be made to avoid areas of population and at higher altitudes to minimize the impact to both fuel burn and noise.

7. OVERALL CONCLUSIONS

The report presents different operational scenarios of interest as identified through interviews and surveys with operational stakeholders. A primary area of interest was the interdependencies that might occur in the climb and descent phases.

In the climb phase, the focus was on the interdependencies between a level-off versus an off-track deviation when ATC needs to intervene on a climbing aircraft. The analysis concluded that all track-extensions add fuel burn at the cruising fuel burn rate and a large track extension should be avoided. However, the analysis shows that when the airspace allows it, a small angle deviation in the start phase extends the mission by a very small amount and may be better from an environmental perspective than a level-off. If furthermore the airspace and traffic allow it, a deviation can be combined with a shortcut, allowing for a reduction of the mission range and the en-route phase.

During descent, it was concluded that altering the descent after the FMS has computed the optimum ToD can result in a fuel penalty. If the tactical intervention of the ATC leads to an extension of the planned descent, this can lead to a level-off that combined with a track extension, thus generating a fuel burn penalty. When an Open STAR procedure is used, communication between ATC and pilots is extremely important. Having distance to go information can enable the pilots to calculate the most efficient way to dissipate the aircraft energy in its descent phase. ATCO interventions through descent clearances can result in inefficient profiles and increased fuel burn.

Stakeholder outreach raised the question of which aircraft should be prioritized if a descending and climbing aircraft are in each other's vicinity. The analysis presented in this report indicates that intervening on the climbing aircraft may result in a smaller fuel penalty than intervening on the descending aircraft.

When analysing noise versus emissions in the take-off phase, it was concluding that although using speed constraints early in the flight are good a tool to reduce noise levels, but leading to a small fuel burn increase. In certain instances, noise regulations are set on an old fleet-mix and the speed constraint may no longer be needed to meet prescribed levels with newer technology aircraft. In those cases, alleviating the speed constraints could generate large fuel savings while not increasing the overall noise emissions.

Finally, in the descent analysis, the importance of performing a continuous descent operation was shown. Fuel and noise reductions are achievable in the decent phase if more continuous descents can be performed. A potential method to allow for a higher number of CDO in the descent phase is the use of harmonised descending speeds. Creating a more uniform descending speed for the fleet of aircraft can increase predictability for ATC, thus reducing the need for ATC intervention while also allowing the operator to set the right ToD to perform a CDO.

While the studies described in this report show high-level interdependencies of various operating scenarios, these studies are limited in scope. The scenarios presented in this report are intended to initiate further studies and discussion on way to increase the efficiency and reduce the environmental impact of the aviation sector.

APPENDIX A – POTENTIAL FUTURE SCENARIOS

The following scenarios were proposed for the report to CAEP13, but were not completed due to time and resource constraints. If additional work is proposed in the future, the following scenarios may prove of interest.

- OS9: Level (altitude) change vs off-track to ensure adequate separation between aircraft.

To prevent potential conflicts between two aircraft and ensure that the separation minima is respected, an ATCO has three main tools at hand for cruising level aircraft:

  - Vertical separation – if a potential conflict is predicted, the aircraft can be cleared to a higher or lower flight level, thus ensuring vertical separation.
  - Horizontal separation – to avoid potential conflicts, only very small adjustments are required and as little as a 5-degree change of direction can prevent a conflict.
  - Time-based separation, using speed control – this tool is used when potential conflicts can be detected further ahead.

This specific operational scenario looks at the environmental aspects of interdependencies between the additional fuel burn caused by the altitude change when ATCO uses the vertical separation tool at cruising altitudes versus the fuel cost of extending the trajectory through lateral separation.

- OS10: Speed change vs. off track to ensure adequate separation between aircraft.
  The third tool that an ATCO has at hand at cruising level is time-based separation using speed control. Speed control is a very efficient way of maintaining separation that already exists, for example for two aircraft following each other on the same route at the same level, while vertical and horizontal separations are more generally used to establish separation between intersecting aircraft.

OS10 looks at the environmental aspects of interdependencies between the additional fuel burn caused by an off-track instruction from ATCO to ensure continued separation between two aircraft on the same route versus the fuel cost coupled to a speed change of an aircraft.

- OS11: Early arrival outside airport opening hours vs. holding.
  This specific operational scenario was identified through the interviews with Oceanic ATCOs. It is a challenging scenario that looks at the interdependencies between benefits of the Jetstream at cruising altitude and thus saving fuel versus the consequence of arriving earlier than the slot time to the destination airport and therefore being forced into holding until a possible arrival time is available.

— END —