

Fuel and Energy Benchmark Analysis of Continuous Descent Operations

Why CDO flight efficiency potential has not yet been utilized

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Abstract — In this paper the existing CDO procedures at three relevant German airports are analyzed with respect to both the achievable (maximum specific range) and the effectively achieved fuel savings in comparison to conventionally flown arrivals. To do so, we applied our highly precise flight performance model EJPM [1] to several thousand flown trajectories before and after CDO implementation, the data of which was provided to us as radar track data. A technique was developed to estimate the individual aircraft gross mass for calculating the optimum rate of descent starting from the computed flight-specific Top of Descent (ToD). Furthermore, we considered 3D weather and wind data to determine the CDO trajectory. When locating the trajectories within typical ICAO CDO procedure corridors, we found that the current, generic design criteria does not allow the fuel saving potential of CDO to be utilized. Often because of poor CDO execution from the ground and flight deck, only selected aircraft types managed to maintain the defined boundaries. To gain insight on how much detailed procedure guidance is required, a comprehensive weather and aircraft mass sensitivity analysis is also presented. We found analytic models to improve CDO procedures based on local traffic and meteorological conditions, which should supplement current guidance material.

Keywords: *Continuous Descent Operation; Fuel efficiency; Aircraft performance*

I. INTRODUCTION AND STATE OF THE ART

Along with the extensive and continuously growing economic pressure put on the ATM Systems and its users, flight efficiency optimization strategies are being excessively pursued. One such pillar with a significant operational maturity and impact factor is Continuous Descent Operations (CDO), which aims at generating flight descent trajectories into airports with no intermediate horizontal segment and inducing the best conversion of potential to kinetic energy (“minimum drag, low power”) from Top of Descent (ToD) to a limitation, ideally to the final approach fix (FAF) according to Eurocontrol [9].

We observed a rapid deployment of CDO throughout Europe reaching actually published procedures for 89 airports up until the end 2014 in Europe [10]. The procedure consists of Distance To Go (DTG) clearances based on CDO-RNAV transitions and can include sequencing concepts such as Point Merge Systems, (e.g. Hannover [19]). Based on current ICAO CDO guidance

material (see Chapter III), the expected savings in fuel (and noise) can typically be well achieved during ideal conditions (calm atmosphere and selected aircraft types) as various research demonstrates: Wubben and Busink (2000) [12] investigated the environmental benefits of CDOs compared with conventional approach procedures at Schiphol Airport. The results showed a fuel consumption of 25-40 % less during the last 45km of the flight for each aircraft, which correspond to fuel savings of 400 kg for a B747 and 55 kg for a B737. Clarke et al. (2004) [11] reported that 180-225 kg of fuel savings could be obtained by switching to CDO. Wilson and Hafner (2005) [13] conducted three scenario simulations for arrivals into Atlanta and measured the impacts of these scenarios on time, fuel consumption and distance. Sprong et al. (2008) [14] found significant reductions in fuel consumption, time flown and time in level flight for traffic based at the airports of Atlanta and Miami.

The studies listed show, despite some promising findings on fuel consumption, little insight on how valid its gradient is when switching from the conventional approach to CDO during realistic weather conditions and with varying aircraft types. Therefore, in the present study, we use the highly precise Enhanced Jet Performance Model algorithm (EJPM) [1] and keep a known fuel consumption prediction to determine this gradient based on a large set of real flown approaches into three German airports which were all subject to procedure switches in 2013/2014. In the data analysis, we maintain the hypothesis that the existing procedure guidelines are too vague to grant reliable average fuel savings for realistic fleet mixes and operational and climatic scenarios. The study also aims to conclude more about relevant design constraints to achieve these savings.

II. ANALYSIS OF ICAO’S CDO PROCEDURE DESIGN

According to ICAO’s CDO Doc 9931 [15], the CDO design procedure should start with the layout of the optimum lateral flight path. The design will follow either an Open or Closed Path Procedure. Closed Path Procedures rely on a fixed route down to the FAF and may contain altitude and/or speed constraints, both variables being very crucial for achieving

CDO behavior. Open Path Procedures, however, end right ahead of the FAF. Two options are typical:

- A *Vectored CDO* procedure, where the aircraft is laterally guided for the whole arrival and approach segment by ATC. The vertical profile then ideally follows a managed FMS descent or is flown in selected mode or manually by the pilot;
- An *Open CDO* procedure to downwind, where the pre-planned route ends in a vectoring segment, which then also directs the aircraft to the extended runway centreline by ATC instructions.

Both described methods are similar in that ATC provides the pilot with information regarding remaining Distance to Go (DTG) by ATC to approach best the CDO profile.

To ensure the usability of these CDO procedures also during times of high traffic density, sequencing through speed control, vectoring as well as path stretching methods (e.g. Point Merge Systems) are typically implemented and executed. This results in speed, altitude and heading restrictions which directly affect the adherence level to the targeted vertical CDO profile according to [1].

Subsequently, while designing a vertical profile with a high CDO adherence level for the majority of the predicted arrivals, several factors should be considered:

- Local restrictions due to given airspace and terrain structures (e. g. arrival/approach requirements as described in [16]) and local political and legal aspects;
- The current traffic mix, gross mass distribution, and traffic density at the given airport;
- Meteorological factors such as wind, temperature, and pressure/density distributions both laterally and vertically as they affect the important energy share factor (ESF) of kinetic versus potential energy.

For a typical configuration, the vertical CDO procedure corridor is depicted in Fig. 1.

- The upper boundary, which corresponds to a rate of descent of 350 ft/NM and — deemed “sufficient for most aircraft”[15]) — terminates with a Top limit of FL 340;
- The lower boundary with a sink rate 220 ft/NM, which considers two deceleration segments, one horizontal segment in FL 100 and one segment with a reduced sink rate of 160 ft/NM.

Although the values pictured above are exemplarily for a 2,500 ft FAF-Altitude procedure, it may be considered representative for the majority of operational circumstances according to ICAO. Also, according to [15], the listed sink rates can be flown by all modern aircraft at ISA conditions, but it remains unclear as to whether this is true under average, realistic circumstances up into adverse e.g. high wind speed conditions.

So in Chapter IV we will show that sink rates (or the Rate of Descent, ROD in the aircraft fixed coordinate system) above the upper as well as below the lower boundary can be observed under real meteorological conditions: A maximum specific range (CDO) flight profile, assuming constant speed and no thrust set, requires the aircraft to fly at the lowest descent angle γ to reach a maximum lift to drag ratio according to equation 1 [1].

$$\begin{aligned} \sin(\gamma_{min}) &= \frac{Thrust - Drag}{Weight} - \left(\frac{Drag}{Lift} \right)_{min} \\ &= \frac{Thrust - Drag}{Weight} - \left(\frac{Lift}{Drag} \right)_{max} \\ &= \frac{ROD_{min}}{TAS} \end{aligned} \quad (1)$$

By inserting typical approach speeds at low altitudes (e. g. $TAS = 250 kt$) and descent angles (e.g. $\gamma_{min} = 3^\circ$), we obtain results ($Sink\ rate = 1,300\ ft/min \approx 415\ ft/NM$) strongly differing from ICAO. As the unit of the geodetic sink rate reads in [ft/NM] [15], wind is obviously not considered.

Furthermore, both γ_{min} and the potential energy E_{pot} rely on the geodetic height and depend on given atmospheric conditions. QNH deviations will therefore lead to differing sink rates and DTG from the ToD.

The design shown is said to rely on simulation data of approach trajectories for certain aircraft types and for a “typical arrival route” [15]. It is further noted that a large set of parameters was altered, including random inputs (representing e.g. delayed pilot inputs) and deterministic inputs (e.g. aircraft type) in order to define the corridor shape. Monte Carlo simulations generated probability distributions for altitude and distance to FAF. These were used for that purpose. Fig. 2 depicts this concept as postulated by ICAO. According to it, a significant data volume is required to complete the task, which seems to be undervalued in today’s CDO applications. At Louisville International Airport (KSDF), the design referred to data sets of cargo aircraft operating at night only [11]. In such cases, later widening of the corridor to grant access to the procedure for other aircraft types or operations may induce excessive CDO shape envelopes. A generalized design would consequently either be too vague (very large corridor width) or out of the ESF requirements of individual aircraft.

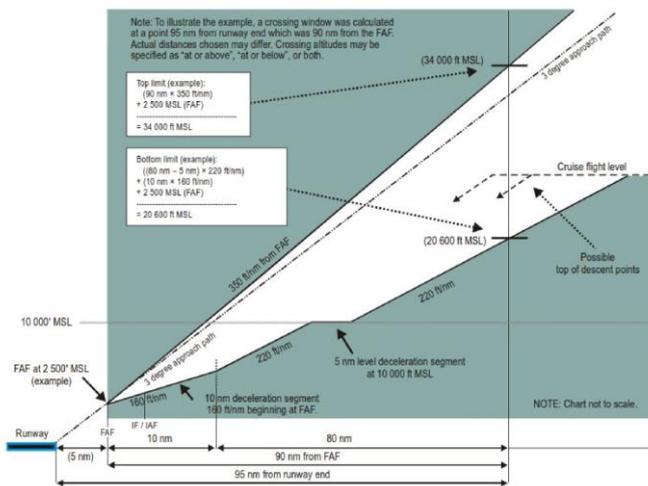


Fig. 1 Typical closed CDO procedure approach corridor [15]

From a reverse flight progress perspective, the corridor boundaries are both ascending from the FAF altitude and position, where:

- Monte Carlo: Iteratively simulate the effects of random factors by covering all possible values of input parameters and their combinations

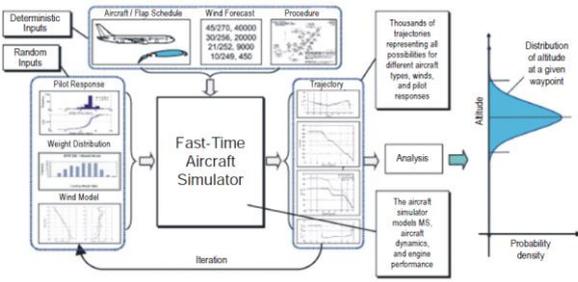


Fig. 2 Design parameter generation for the CDO corridor [15]

The EJPM [1], which is briefly referenced in Chapter III, is a tool candidate for the “Fast Time Aircraft Simulator” (Fig. 2) used to solve this problem and grant suitability of the resulting CDO procedure design of dedicated operational modes and fleet mixes. Besides the ability to handle a high data volume, the required quality set out by ICAO can be achieved by considering all of the already mentioned environmental parameters. The model can be utilized for both pre-processing CDO trajectories during the design phase and ex-post validation of real trajectory data after procedure implementation.

The ANSP DFS (Deutsche Flugsicherung) published charts depicting the usage of CDO procedures at different airports in Germany [17] which rely on ICAO guidance material. We will later show (see Chapter IV) that current CDO implementations do not always allow the execution of precise CDOs for several aircraft constellations. Two further candidate hypotheses can be drawn from here. Either:

- Current ICAO guidance material is based on a too limited set of flight performance data all operating conditions which cannot be achieved;
- Or the procedure implementation of the CDO execution was deficient.

These fields of interest are analyzed in the following Chapter III, which also describes the methodology developed for a CDO design and trajectory validation process based on the above ICAO guidelines. The main objective is to figure out, respectively, whether how far the implementation of a given CDO procedure in an operational environment really permits decreasing fuel burn of a single flight operation up to the traffic flow perspective.

III. HOW TO VALUE CDO

A. Key Parameters

The EJPM [1] allows for a highly precise prediction of 4D trajectories of jet aircraft, representing the majority of flights into large airports which are relevant to CDO applications. It may so be used for both economic and ecologic procedure and trajectory benchmarking. The EJPM relies on a six degree-of-freedom aircraft model with smart simplifications to improve speed and stability of computation. It is specifically capable of providing trajectory data for cruise [2] and (CDO)-descent [3] with a position / fuel consumption error around 1% for deriving

flight intent or target information on where the aircraft should fly to achieve its target function (e. g. minimum fuel).

In this study we applied the EJPM to determine the fuel used per approach [1] of about 9,000 arrivals containing various aircraft types. The data was kindly provided by DFS as recorded flight tracks. Furthermore, detailed 3D weather data records where provided by the German Weather Service (DWD) to allow consideration of the meteorological environment in which the arrivals took place (see Chapter IV for more details). Out of these 9,000 arrivals, roughly half of them were performed as conventional approaches, the other half as CDO procedures, each for the same set of airports. This procedure upgrade entered into service in 2014 [17].

B. Gross Mass Estimation

As mentioned, the determination of the individual aircraft mass per approach is paramount for allowing the generation of correct CDO profiles. However, this parameter is not known to ATC, and consequently, not included in flight track data. Aircraft mass prediction has already been the subject of research for many years: [6] estimated the aircraft mass based on its past trajectory, introduced current wind and mass as uncertain parameters and executed a probabilistic Monte Carlo process. The most often (less uncertain) trajectory generated was judged to be the most realistic and chosen for deriving the aircraft mass. [8] introduced an adaptive mechanism for dynamically optimizing the modeled thrust. However, both results showed very limited quality. [7] introduced an algorithm estimating the aircraft mass based on an adaptive mechanism which improved robustness compared to [8]. [5] proposed three strategies: The first “naïve” relied on approximating the physical mass in order to best align the calculated and observed altitude (assuming the correct flight intent. E. g. Cost Index = 0 is known); the second, called “adaptive”, dynamically adjusted the mass so that the excessive energy calculated is close to the recorded speed and altitude change (kinetic / potential energy equivalents); the third refers to the second while generating a set of masses for a set of waypoints per trajectory. By applying a linear regression on the individual power functions onto this data set, it yields the equation holding the minimum square root error to the average.

Since we focus on rapid and robust mass estimation in this paper, we chose not to follow statistical modeling but instead introduce a new flight mechanical approach. Starting from FAF, we determined the measured approach ground (reference) speed v_{ref} based on radar data. v_{ref} is a formal speed required for aircraft certification and therefore correlates directly with the landing mass (holding an uncertainty of roughly 500 kg) as figured out in each aircraft flight manual (AFM). Following the analytic model as explained in above section A, the EJPM is then used to reversely model the end of CDO at FAF up until the ToD of the fuel burn along the real flown profile.

C. Minimum Fuel Determination

Additionally, we use the EJPM to determine the minimum-fuel-optimized vertical CDO-profile [3] as a potential offset to the observed trajectory. Conclusions are then drawn on the root causes of these offset figures, representing unintended extra

fuel burn. The CDO profile analysis [3] in fact begins shortly ahead of the ToD, forming a static “200 NM segment”, thereby including a limited cruise segment to allow fair comparison and correct statistical analysis of all observed flights, each of which possess an individual ToD location. As stated, the CDO finishes formally at FAF, the profile itself being described by radar track data. The aircraft tends to follow a continuous descent at maximum glide performance according to equation 1, thereby reaching maximum specific range ($R_{spec,max}$) at idle thrust. The aircraft consequently intends to fly at best lift to drag ratio $(L/D)_{max}$ speed which is equal to the minimum drag speed (v_{MD}) or the “green dot speed” following Airbus definitions. v_{MD} is calculated by the EJPM. It equals the minimum thrust required $F_{T,requ}$ speed curve. From the aerodynamic perspective, v_{MD} is an equivalent airspeed ($v_{EAS,MD}$) that requires conversion into a true airspeed ($v_{TAS,MD}$) and the consideration of air compressibility and density at a given altitude in order to allow specific range determinations. Fig.4 depicts the trend of $v_{TAS,MD}$ (green curve) versus the pressure altitude ending at the high speed buffet (red curve) and the low speed buffet boundary (blue curve). They coincide at the so-called coffin corner.

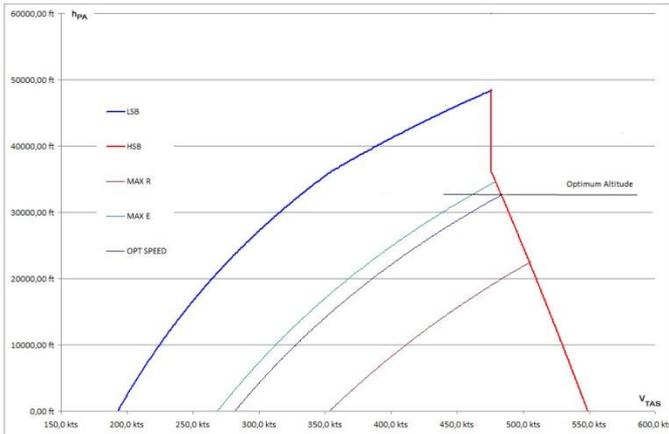


Fig. 3 True versus equivalent minimum drag airspeed with high and low speed buffet boundaries

EJPM CDO prediction starts at ToD and optimum altitude ($h_{Pa,opt}$) towards the FAF, whereas the mathematical iteration itself is done opposite to the flight progress as explained above. The ToD altitude is usually the dedicated flight level for maximum specific range ($R_{spec,max}$), which means maximum true airspeed ($v_{TAS,opt}$) at minimum fuel consumption (m_{fuel}).

The EJPM adds modeled aerodynamic and flight mechanical metrics to the radar track data. As such, e.g. real aircraft data (FODA) – always critical to assess – is no longer required. To grant correctness of the modeled data, we undertook various validations for selected trajectories which are presented in the next section.

D. Validation of EJPM modeled Fuel Consumption

For a selection of radar track data sets, which was identified so as to represent the most relevant aircraft types and load figures, we compare the resulting fuel burn from EJPM against

FODA. It should be noticed, that we however could not access all first principal data (beyond FODA) of the selected aircraft types. Consequently, we reverted to Eurocontrol BADA 4.0 data sets where required. Note further, that no explicit weather data was provided for the reference FODA data sets so we assumed ISA conditions. The result for one specific flight is shown in Fig. 4.

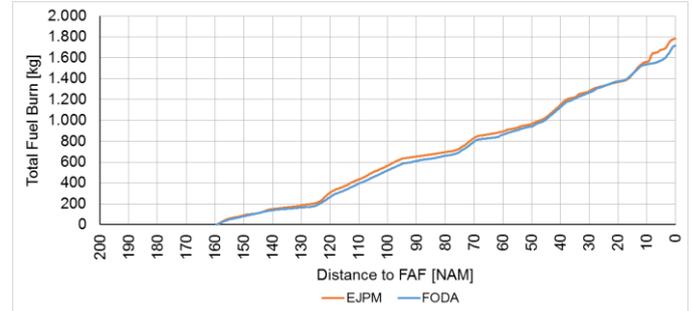


Fig. 4 Comparison of FODA vs. EJPM estimated fuel burn for a selected CDO descent

The overall validation is comprised of 12 single flight trajectories, for which FODA data was generously provided by different aircraft operators. The aircraft mass comparison was also done for these 12 flights. The results are presented in TABLE I.

TABLE I.
MEASURED TO MODELED MASS AND FUEL BURN DISCREPANCIES

| | Deviation modeled to recorded gross mass | Deviation modeled to recorded fuel burn |
|----------------|--|---|
| Average | +12.34% | +2.60% |
| Max | +25.21% | +12.02% |
| Min | +3.89% | -9.76% |

Obviously, mass, elementary aerodynamic first principal data, and particularly weather data estimates all hold errors: An average gross mass deviation of +12% equals a total error of up to 5 t aircraft mass. The fuel burn estimation, however, leads to an average deviation of only 2.6%. Taking into consideration the lack of real data (beyond FODA) listed, the EJPM fuel burn estimation based on radar track data is technically valid with an overall confidence of approx. 3%. With that level of accuracy, we performed a large investigation containing the mentioned approx. 9,000 arrivals into three major German airports.

IV. A USE CASE: EFFICIENCY ANALYSIS OF CDO APPLICATIONS AT GERMAN AIRPORTS

A. Underlying Traffic and Weather Data

For the real flight track analysis, we used the above two databases: European weather and Flight Track and Noise Monitoring System (FANOMOS) data. The weather data set consists of highly resolved details across Europe in GRIB2 format as follows:

- Grid resolution of 0.25° lateral/longitudinal
- 23 altitude and pressure levels

For each grid point, information about wind, temperature, density and local QNH are given with an hourly resolution. The overall data size reaches >20 GB, so significant preprocessing is needed for this data link.

Radar track data holds information about time reference, aircraft type, airline, unified UTM position (latitude, longitude) and STD pressure altitude at a resolution of 0.25 Hz. Both airline and aircraft then need to be broken down to individual aircraft engine parameters. This can well be done by probabilistically allocating aircraft sub-types according to the specific, known fleet mix of each operator. The data covered approaches to the three airports for two successive time periods, each with a length of two months. One period holds data before formal implementation of a CDO at each of the airports [18], the second after its implementation.

B. Data Correlation and Analysis

After the above engine to aircraft allocation, we correlated time and position in 3D weather and radar track data, so as to precisely determine the environmental conditions for each flight. Then, we applied the mass at ToD estimation algorithm. As the radar track data itself does not end at the FAF, the algorithm can precisely determine the start conditions such as speed and descent rate of the aircraft shortly before passing the FAF as shown in the following Fig. 5.

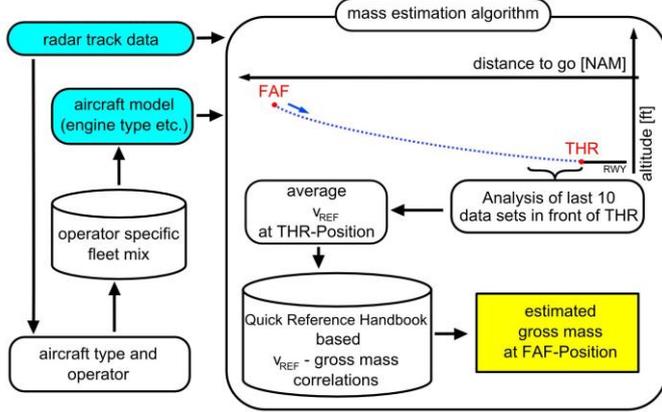


Fig. 5 Gross mass determination based on approach speed

We so determined fuel burn and total energy exchange per flight for the formalized 200 NAM.

The total energy exchange as second metric is used to verify the general equivalence of the two reference data sets per track, so as to systematically verify general equivalence of initial altitude and speed between conventional and CDO approaches. Fig. 6 shows the high compliance level for all approaches into one exemplary airport following eq. (2):

$$d_{E_{pot}} - d_{E_{kin}} = (m_{FAF} * g * h_{FAF} - m_{cruise} * g * h_{cruise}) - (\frac{m_{FAF}}{2} * v_{FAF}^2 - \frac{m_{cruise}}{2} * v_{cruise}^2) \quad (2)$$

Example: An Airbus A321 with a mass of 72,000 kg descending from 34,600 ft (ToD) at 450 kt TAS down to 3,100 ft (FAF), slowing down to 180 kt encounters an energy dissipation of -8.7 GJ.

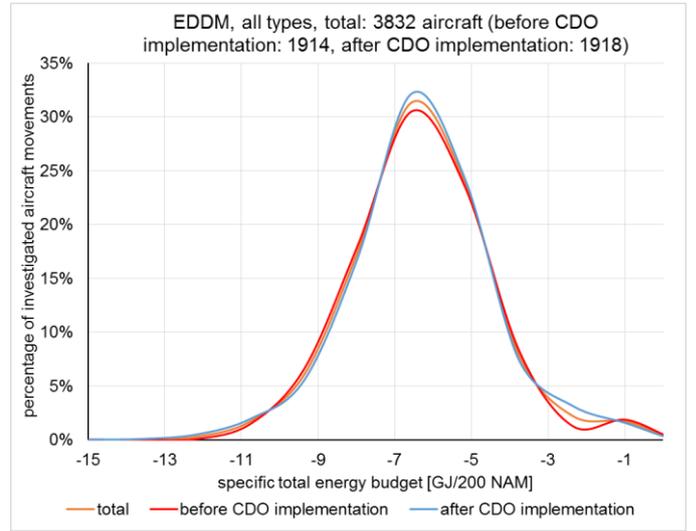


Fig. 6 Total energy comparison before/after CDO implementation, reference airport

Though nearly equal, a slightly higher energy dissipation of -9.3% results for the conventional descent:

TABLE II.

ENERGY DISSIPATION BEFORE/AFTER CDO IMPLEMENTATION

| | Before CDO Implementation | After CDO Implementation |
|----------------------|---------------------------|--------------------------|
| <i>Average</i> | -8.2E09 J | -7.5E09 J |
| <i>Dev.</i> | +6.6E09 J | +5.3E09 J |
| <i>Number of ACs</i> | 1,914 | 1,918 |

By analyzing the data per ICAO wake vortex category [20] we found a high category mix stability with less than 2% variation. As such, very similar average gross masses are given in both data sets. The energy reduction shown in TABLE II so impose that CDO aircraft started their descent in only slightly lower altitudes and/or speeds. We finally analyzed the energy exchange and fuel burn per specific aircraft type according to Fig. 7. We find the average energy dissipation per aircraft type shown at the top, the average fuel burn along the CDO segment (200 NAM length) at the bottom of Fig. 7. It clearly reveals the expected result of ascending energy budget for heavier aircraft. Beyond this, there is no observable uniform trend across the aircraft types. While the A319 (red framed) shows for both scenarios roughly the same energy dissipation (6.62 GJ) but a reduced average fuel burn of 6% with CDO, these trends are nearly inverted for e. g. the A332 (A330-200, black framed).

The same heterogeneous results were found for the other two airport-related flight data sets. Fig. 8 concludes these findings for all flights, at all three airports. For example, see E190 with its-1.2% lower average fuel burn (752.5 kg to 743.8 kg with CDO), and the B738 with again a contradictory higher fuel burn on average.

To conclude, the CDO approaches at all three airports only suit a few selected aircraft types.

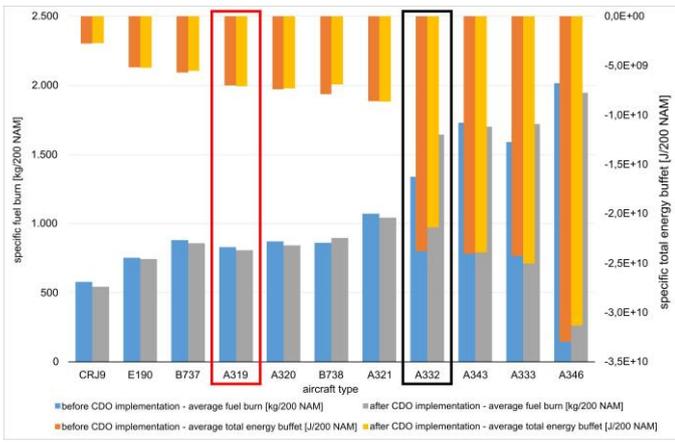


Fig. 7 Aircraft type specific energy dissipation and fuel burn before & after CDO implementation - reference airport

However, this conclusion may be biased on operational behaviors, such as pilots' non-timely CDO execution or adherence to ATC clearances. To figure out to what extent such poor CDO execution may hamper flight efficiency, we will perform a cause-effect analysis in the following section.

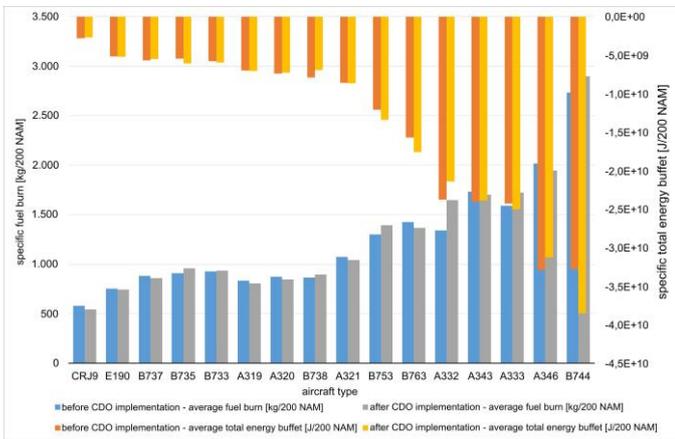


Fig. 8 Aircraft type specific average energy dissipation and fuel burn before & after CDO implementation – all airports

C. Poor CDO execution cause-effect analysis for selected flights

To reveal the effects on flight efficiency, in terms of reduced specific range due to the flight deck crew not precisely vertically guiding the aircraft or the aircraft becoming subject to offsetting radar vectors issued by ATC, selected flight tracks were verified. This was also done by taking into consideration the individual environmental conditions for each flight in comparison to an undisturbed optimal descent trajectory as calculated using the methodology described in Chapter III.

Fig. 9 plots both vertical profiles, highlighting detected level flight segments. The left picture shows that comparison before, the right after CDO implementation. It proves that with CDO introduction, less level flight segments but those in conjunction with low altitude did occur.

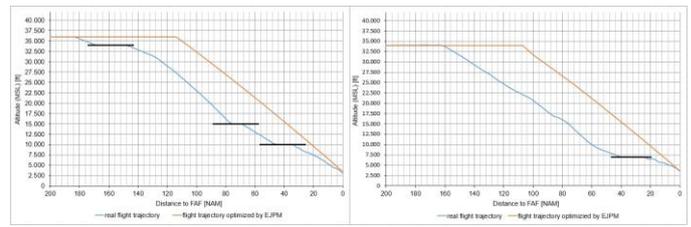


Fig. 9 Real to optimal CDO trajectory before (left) and after (right) CDO implementation

Those significant offsets confirm respectively loaded results, thereby showing that CDO is not unlocking its full economic potential. Quantitatively, we measured:

- A fuel burn of 852 kg for the conventional approach (Fig. 9, left) versus a minimum of 753 kg (CDO) equaling 11.6% fuel saving potential along the 200 NAM segment;
- A fuel burn of 982 kg for the CDO claimed (Fig. 9, right) versus a minimum of 848 kg (CDO) or 13.6%.

TABLE III compares these results for a total of ten flight tracks to grant representative findings.

TABLE III.
FUEL SAVING POTENTIAL BY AVOIDING POOR TRACK ADHERENCE BEFORE AND AFTER CDO IMPLEMENTATION, A320 AIRCRAFT AS REFERENCE

| Fuel Saving Potential [%] | | | |
|---------------------------|---------------------------|----------------|--------------------------|
| Flight | Before CDO implementation | Flight | After CDO implementation |
| 1 | 2.8 | 6 | 12.4 |
| 2 | 11.6 | 7 | 13.6 |
| 3 | 14.5 | 8 | 13.7 |
| 4 | 23.2 | 9 | 23.3 |
| 5 | 12.3 | 10 | 19.4 |
| Average | 12.9 | Average | 16.5 |

TABLE III shows on average a 3.6% improvement in fuel burn with CDO. However again, reverse effects can be noticed for single flights. According to Fig. 9, this potential equals relevant vertical deviations from the desired flight path. Specifically at low altitudes, deviations become very sensitive to fuel flow and have similar effects as horizontal segments in the standard step approach.

These findings confirm that current CDO implementations seem only to deliver potential to dedicated aircraft types. We so investigate this phenomena in the following section D.

D. Typical rates of descent

To localise the CDO profiles relative to ICAO guiding material, Fig. 10 depicts a recorded CDO, the corresponding E-JPM optimum flight profile and the ICAO CDO boundaries while both the lateral trajectory and environmental parameters were respected as prevailing during the recorded flight. Obviously, both profiles are contained only partly in the ICAO CDO design area. Fig. 10 shows a typical A321 trajectory as standard local procedure. The ICAO CDO corridor is clearly not working well with the operational CDO requirements.

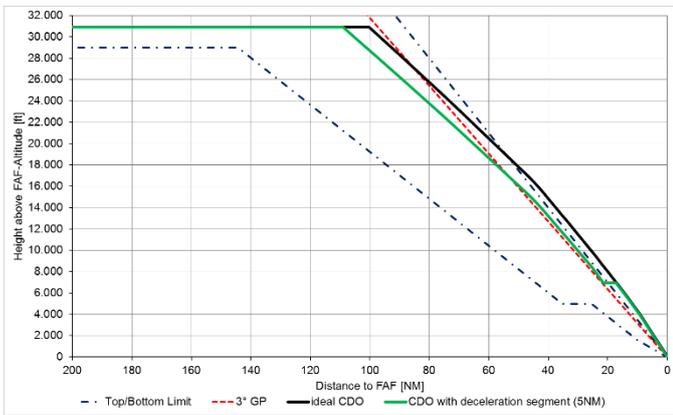


Fig. 10 CDO profiles relative to ICAO CDO containment area

To explore a potential weakness of existing guidance material, we will vary all relevant profile parameters based on the recorded flight tracks in a comprehensive sensitivity analysis in Chapter V and compare the resulting design area in order to best adjust to aerodynamic and operational requirements.

V. CDO PARAMETER SENSITIVITY ANALYSIS

A. Parameter Selection

The relevant parameters will become subject to the following sensitivity analysis, based on a thorough metric review collected from the state-of-the-art review in Chapter II. Starting with the aircraft type, the following parameters are dependent:

- Fuel flow relative to thrust setting;
- Glide coefficients relative to aircraft configuration;
- Aircraft overall flight dynamic performance;
- Optimum to maximum rate of descent.

For each flight, the following parameters will further be considered dynamic:

- Meteorological parameters, such as ambient temperature, air pressure, wind speed & direction;
- Altitude and location of the FAF;
- Aircraft gross mass and attitude
- Actual TAS;

Aircraft gross mass is being determined as explained in Chapter III, section B. TAS, altitude, and attitude (angle of attack, pitch, and roll) are calculated through the EJPM as highlighted in section C. The aircraft configuration is considered clean along the CDO. Meteorological alterations finally cover temperature and air pressure changes including varying STD to QNH-air-pressure transition levels down to the FAF Altitude.

B. Scenario Generation

The sensitivity analysis is comprised of the following steps:

- 1.) Configuration of a large set of scenarios (multiple parameters pre-set) wherein the reference scenario is labelled “Scenario 0”;
- 2.) Fuel burn determination along the CDO (fixed at 200 NAM length) and ToD location estimation using the EJPM per scenario;

- 3.) Offset determination between a given scenario and Scenario 0.

“Scenario 0” is configured as follows:

- Wind speed 0 kt
- Wind direction: any
- ISA temperature at field elevation: +15°C
- ISA air pressure at field elevation 1,013.25 hPa
- Gross mass at FAF-Position: 65,000 kg
- Cruise Altitude at ToD: 34,000 ft (STD)
- FAF-Altitude 5,000 ft (QNH)

To grant comparability along the scenario valuations (offset determination) in step 3, both a seemingly straight lateral flight path and a typical aircraft type (A321) were selected. To nonetheless also assure realistic behaviour under these constraints, a radar track of an A321-200 executing a southbound arrival into Frankfurt/Main Airport, runway 25R, was chosen as reference trajectory. This lateral flight path holds a fairly constant northward heading with only one left-hand turn at 10 NM before FAF.

We started with only varying a single parameter and concluded with fuel burn and CDO distance effects. We collected those flights having the most effect and let multiple parameters vary based in terms of scenarios. The energy dissipation rate is not computed in this step, since we already proved that the aircrafts hold comparable values, so altitude and speed changes within the approach are known.

The collection of parameters subject to variation is listed in TABLE IV with their alteration bandwidth:

TABLE IV.
INVESTIGATED PARAMETER VARIATIONS

| Parameter | Variation bandwidth (relative to Scenario 0) | Unit |
|----------------------------------|---|-------|
| Gross mass | $\pm 20, \pm 15, \pm 10, \pm 5$ | [%] |
| Temperature (field elevation) | $\pm 30, \pm 25, \pm 20, \pm 15, \pm 10, \pm 5$ | [K] |
| QNH | $\pm 40, \pm 20, \pm 15, \pm 10, \pm 5$ | [hPa] |
| Wind direction (field elevation) | N, NE, E, SE, S, SW, W, NW for all scenarios, wind speed set to 20 kt | [45°] |
| Wind speed (field elevation) | 5, 10, 15, 20, 25, 30, 35, 40 for all scenarios, wind direction set to 0°N | [kt] |

C. Results of the Sensitivity Analysis – isolated Parameters

Gross mass impact - Reference Scenario

Fig. 11 highlights a strong dependency and positive correlation of fuel burn and aircraft mass at start of CDO. The same is true for gross mass and CDO length, so heavier aircraft require longer descent distances, as expected. Inter-correlated, CDO length versus fuel burn can analytically be approximated with a 2nd degree polynomic curvature: E. g. a 20% additional gross mass leads to both a 20.5% increase in fuel burn and a 2 NMCDO length extension, whereas a 20% decrease in gross mass results in only a 16.2% decrease in fuel burn. The fitted analytic function is plotted in Fig. 12, which may be usable for enhanced procedure design:

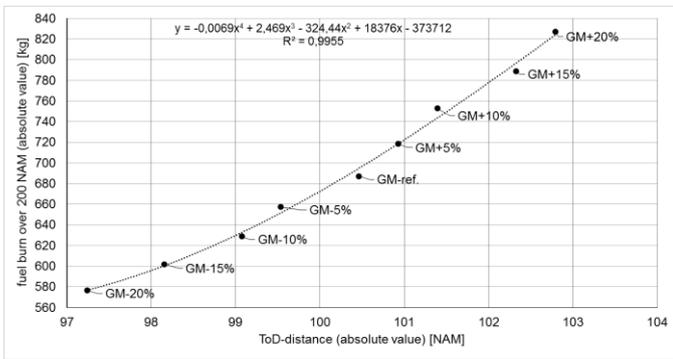


Fig. 11 Inter-correlation of fuel burn to CDO length and gross mass under ISA conditions

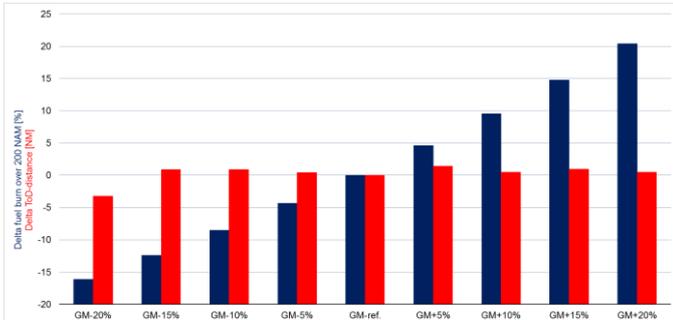


Fig. 12 Effect of Gross mass onto Fuel Burn and CDO length under ISA conditions

Temperature impact - Reference Scenario

Hot temperatures lead to lower air density and consequently to lower available air masses for the engines, thus negatively affecting the overall aircraft performance.

Detailed analysis shows a linear relation between temperature and fuel burn with a positive correlation, and CDO length with negative correlation, since the FAF pressure altitude increases with the temperature. The absolute values for fuel burn impact range from -3.89% (-15°C) to +5.5% (45°C) relative to Scenario 0. All findings are summarized in TABLE V.

Air pressure impact - Reference Scenario

Similar to temperature, the air pressure directly correlates with air density following the ideal gas law and subsequently, equally impacts engine performance and FAF altitude. Again, a linear correlation is found between air pressure, fuel burn (negative) and CDO length (positive).

Fuel burn changes relative to Scenario 0 range from -1.46% (ISA+40 hPa) to +2.54% (ISA+40 hPa) (see TABLE V).

Wind direction and speed impact - Reference Scenario

Wind directly impacts fuel burn and the still air to ground distance ratio along the CDO. However, wind fields are three dimensional, thus generally requiring an additional consideration of the lateral flight trajectory, which is not part of Scenario 0. Therefore, only general findings about the impact of wind are included in TABLE V. All results are valued

relative to Scenario 0, for which a fuel burn of 687.2 kg and a CDO length of 100.5 NM was determined.

TABLE V.
SELECTED RESULTS FOR SINGLE PARAMETER VARIATION

| Parameter | Variation (compared to Scenario 0) | | | | [] |
|---|---------------------------------------|-----------|-----------|-----------|-------|
| | -20 | -10 | +10 | +20 | |
| Delta Gross mass | -20 | -10 | +10 | +20 | [%] |
| <i>Delta fuel burn</i> | -16.1 | -8.5 | +9.5 | +20.4 | [%] |
| <i>Delta CDO length</i> | -3.2 | -1.4 | +0.9 | +2.3 | |
| Delta Temperature at field elevation | -30 | -10 | +10 | +30 | [K] |
| <i>Delta fuel burn</i> | -3.9 | -1.1 | +2.1 | +5.6 | [%] |
| <i>Delta CDO length</i> | +9.2 | +3.3 | -3.2 | -10.0 | |
| Delta QNH | -20 | -10 | +10 | +20 | [hPa] |
| <i>Delta fuel burn</i> | +1.4 | +1.0 | -0.1 | -0.6 | [%] |
| <i>Delta CDO length</i> | -2.3 | -1.4 | +0.9 | +2.3 | |
| Wind direction at field elevation | <i>N</i> | <i>E</i> | <i>S</i> | <i>W</i> | [90°] |
| <i>Delta fuel burn</i> | -0.1 | -0.3 | -0.1 | -0.3 | [%] |
| <i>Delta CDO length</i> | -3.2 | -3.2 | +2.8 | +3.3 | |
| Wind speed at field elevation | <i>10</i> | <i>20</i> | <i>30</i> | <i>40</i> | [kt] |
| <i>Delta fuel burn</i> | 0.0 | -0.1 | -0.4 | -0.3 | [%] |
| <i>Delta CDO length</i> | -2.8 | -3.2 | -5.5 | -6.8 | |

D. Results of the Sensitivity Analysis – combined Parameters

As temperature and air pressure are positively correlating through the gas law, we extend the sensitivity analysis to combined parameter variations to explore any parameter dependency effects. We so varied temperature, air pressure (QNH) and gross mass at FAF.

In detail, we let the mass vary from -20% to +20% relative to Scenario 0, the temperature from -20 K to +20 K and the air pressure from -20 hPa to +20 hPa resulting in roughly 300 combinations. Fig. 13 shows representative dependencies, depicting a quite linear or flat polynomic correlation between gross mass, fuel burn and CDO length if only one parameter is varied. For simultaneous changes of temperature and pressure the correlations are analytically fitted with polynomic functions of higher degrees. In the above diagram, temperature / pressure combinations are color coded (see additional box). The most inefficient scenario is given for a high gross mass, hot temperature and low QNH resulting in high fuel burn and a short CDO length.

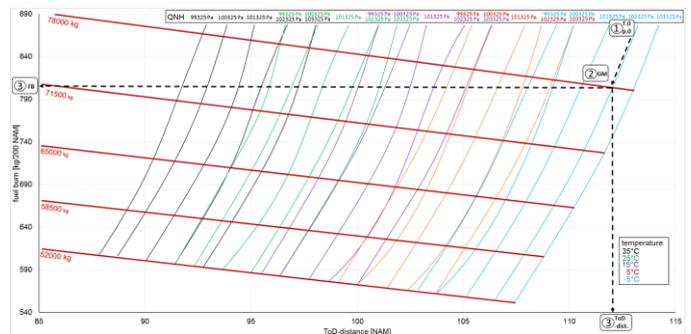


Fig. 13 Combined temperature and air pressure variation impact on fuel burn and CDO length

Consequently, the positive effects of low pressure and thereby low drag are overcompensated since jet engines efficiency correlate with a high compressor to ambient pressure ratio and a high turbine to ambient temperature ratio. The main findings are listed in TABLE VI:

TABLE VI.

SELECTED RESULTS FOR COMBINED PARAMETER VARIATION

| Delta Gross mass [%] | Delta T [K] | Delta QNH [hPa] | Delta fuel burn [%] | Delta CDO length [NM] |
|----------------------|-------------|-----------------|---------------------|-----------------------|
| -20 | -20 | -20 | -18.27 | +2.33 |
| | | +20 | -20.02 | +6.96 |
| | +20 | -20 | -12.03 | -12.67 |
| | | +20 | -14.00 | -8.19 |
| -10 | -20 | -20 | -10.51 | +3.72 |
| | | +20 | -12.22 | +8.34 |
| | +20 | -20 | -4.34 | -11.37 |
| | | +20 | -6.26 | -6.84 |
| 0 | -20 | -20 | -2.06 | +5.11 |
| | | +20 | -3.79 | +9.76 |
| | +20 | -20 | +4.39 | -9.99 |
| | | +20 | +2.30 | -5.48 |
| +10 | -20 | -20 | +7.35 | +6.49 |
| | | +20 | +5.50 | +11.18 |
| | +20 | -20 | +14.22 | -9.09 |
| | | +20 | +11.95 | -4.12 |
| +20 | -20 | -20 | +18.10 | +7.88 |
| | | +20 | +16.00 | +12.58 |
| | +20 | -20 | +25.60 | -7.74 |
| | | +20 | +23.10 | -2.76 |

Deriving data accuracy requirements

These findings may be further used to derive configuration accuracy requirements. E. g. we so can quantify the magnitude of bad gross mass estimates on fuel burn quantification errors. For combined parameter uncertainties, e. g. with a temperature and QNH with a 20% confidence interval around the estimate, CDO length would range from 2.3 NM to 7.9 NM depending on the gross mass given.

E. Level-Off-Segments within CDO to account for Human Errors

Another cause for not utilized CDO efficiency is assumed to lie in poor ATC advisories or limited flight deck compliance to ATC instructions. These behaviors operationally result in level-off-segments to buffer, e. g. late descents or an excessive ROD. To weigh in these penalizing effects, we have created virtual level-off segments of varying size and/or altitude within the CDO. We then determined the resulting ROD values and quantified their effects on fuel burn and CDO length.

To do this at high accuracy, a lateral trajectory of an A321 featuring corresponding weather data and a known gross mass at the FAF position at an initial cruising altitude of 34,000 ft and a cruising speed of Mach 0.7 was chosen as reference. Due to differing QNH in the weather date, the altitude of the FAF-Position also differs from Scenario 0 for this analysis part, now leading to:

- Gross mass at begin of CDO: 73,000 kg
- Final Cruise Altitude 34,000 ft (STD)
- FAF-Altitude 3,000 ft (STD)

30 of these combinations have been investigated, as shown in TABLE VII.

TABLE VII.

LEVEL-OFF SEGMENT ALTITUDE / LENGTH COMBINATIONS

| Segment Altitude [ft] | Segment Length [NM] |
|-----------------------|---------------------|
| 3,068.6 | 1 |
| 4,500 | 5 |
| 8,000 | 10 |
| 14,000 | 30 |
| 20,000 | 50 |
| 26,000 | |

The following Fig. 14 shows the effect on fuel burn as supplementary, relative changes for all combinations.

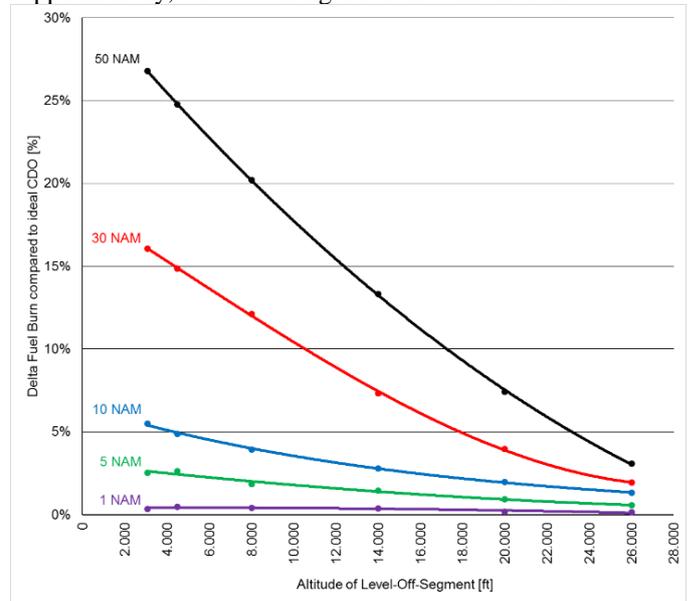


Fig. 14 Effect of level-off segments within a CDO on fuel burn

So horizontal segments at any altitude and length significantly induce extra fuel burn, increasing with segment length. More importantly, segments at lower altitudes produce a polynomial and excessive increase in fuel burn. A 50 NAM segment at 20,000 ft results in additional fuel burn of 7.43% compared to Scenario 0, at 4,500 ft of 24.76%!

It is worth to add that the resulting CDO length is not the sum of undisturbed CDO and segment length as Fig. 15 depicts. This effect is due to the decreasing speed (TAS) and so ROD with lower altitudes.

So level-off segments at low altitudes should be omitted. Ultimately, the following statements result from the investigation and have an impact on the design of a CDO trajectory:

- The environmental parameters gross mass, temperature and QNH impose a significant impact onto the vertical CDO design;
- Limited CDO length result in relatively high values of overall fuel burn and should be expected, especially at hot temperatures and low QNH value conditions, whereas increasing CDO length should be expected at reverse conditions, resulting in an overall more efficient fuel burn;
- low altitude level-off segments should be avoided by all means;

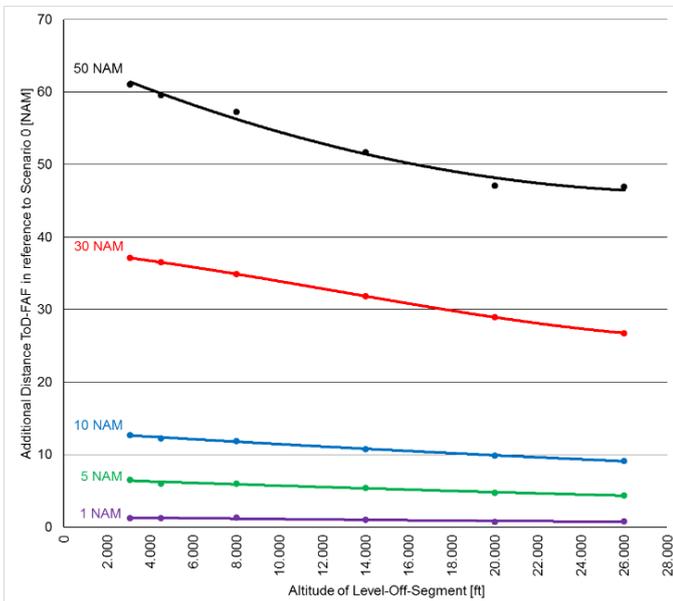


Fig. 15 Impact of segment lengths onto CDO length

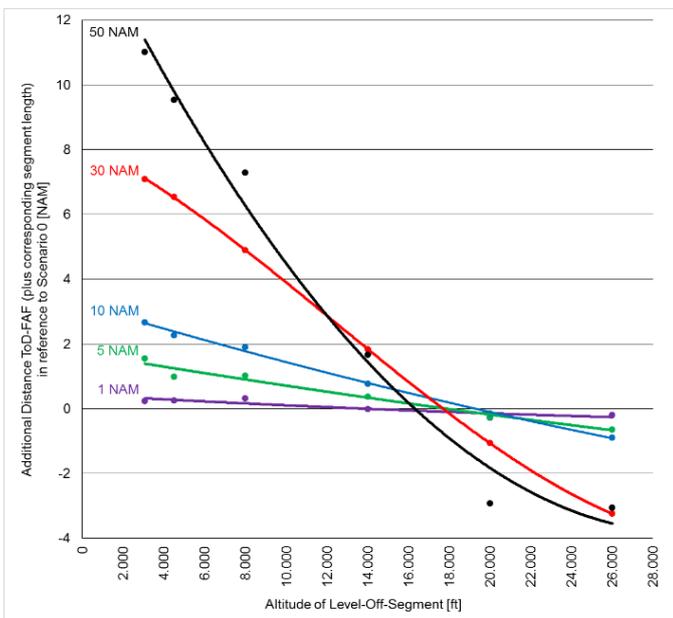


Fig. 16 Required extra CDO length due to level-off segments

VI. CONCLUSIONS

The present investigation validated CDO approaches into large airports based on approx. 9,000 trajectories for their fuel saving potential. This data consisted of partly conventionally, partly CDO guided operations, thereby providing good benchmark conditions. We could show that the expected CDO potential can be utilized only for dedicated flights, showing no relevant improvement for the whole flight ensemble.

During the subsequent cause-effect analysis, it was found that aircraft type, gross mass and meteorological parameters are crucial for defining the optimal CDO profile. However, these parameters are not explicitly considered in ICAO Doc. 9931/AN/476 for CDO corridor designs. It was therefore found

that several CDO trajectories lay outside the pre-set corridor. Beside weather and traffic aspects, poor adherence to the (ICAO) designed CDO path and speed led to significant offsets during real operations. We assume that pilots intend to avoid over- or undershooting of the FAF by applying differing descent rates, often leading to intermediate horizontal flight segments at the ending part of the CDO approach so that flight efficiency is hampered. The effect of QNH impacts on FAF approach altitude was further found important as a limited track adherence cause. These cause-effects should be considered during CDO procedure design, and we suggest adequate amendments to the ICAO guidance material. These considerations are also discussed in ICAOs Tailored Arrival Concept (TA) [15] and could be a starting point towards more precise guiding material.

ACKNOWLEDGEMENT

The authors would like to thank DFS, DWD, and Lufthansa Cargo for their helpful collaboration and provision of supplement data. We would further thank Michael Kaiser for continuously supporting the EJPM evolution.

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