Eleventh USA/Europe Air Traffic Management Research and Development Seminar ATM2015

Fuel and Energy Benchmark Analysis of Continuous Descent Operations

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June 2015
Agenda

1. CDO design guidelines
2. How To – CDO Validation
3. Use Case – Flight Track Analysis
4. Parameter Sensitivity Analysis (PSA)
5. Conclusions
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CDO design Guidelines – ICAO Concept

“Concept Simplicity vs. complexity in reality”

CDO - various definitions:
• differing length, altitude and number of level-off-segments operationally existing at +80 airports in Europe
• General Aerodynamics target function:
  Lift to Drag ratio != max

ICAO design guidelines
• lateral: Closed Path/Open Path Descent
• vertical: ICAO CDO corridor
  Top-Limit (350ft/NM)
  Bottom-Limit (220ft/NM)
  one deceleration segment @10,000ft for max. 5NM

→ Corridor has to be adjusted to local constraints → not a generalizable design solution
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CDO - theoretical aspects

**Target:** Minimizing D/L ratio
- minimum descent angle leads to $\text{ROD}_{\text{MIN}}$
- $\text{ROD}_{\text{MIN}}$ leads to $v_{\text{MIN DRAG}}$

$$\sin \gamma = \frac{F_D - F_T}{F_W} \quad \text{with} \quad F_W \approx F_L$$

Real (non-optimal) flight trajectory:
- Increased airspeed leads to raising ROD
**General**

For correct comparability, all analyses refer to a distance covering the remaining **200 NAM to FAF** (and not between FAF and the individual ToD)

**Input Data**
- **Flight track data:** 4D radar-track-based trajectory data (total ca. 9,000 flights, FANOMOS) two time frames – before and after CDO implementation
- **Weather Data:** Wind speed and direction, temperature, QNH at various altitudes (GRiB2)
- **Aircraft Performance Data:**
  - A320-Family: Parameters determined out of real flight data
  - non-calibrated aircraft types: BADA 3.11 and 4.0 implemented
EJPM – General Concept for CDO analysis (2)

Processing
Development a JAVA Tool for rapid calculation (possible real time processing)

Mass Estimation
Problem: The significant parameter gross mass is not known out of radar tracks

Solution: Estimation of gross mass out of known approach speed, weather conditions and aircraft type (operator specific selection of engine type) → development of a mass estimation algorithm
EJPM – Aircraft Mass Estimation Algorithm

- Radar track data
- Aircraft model (engine type etc.)
- Operator specific fleet mix
- Aircraft type and operator

Mass estimation algorithm

- Distance to go [NAM]
- Altitude [ft]

- FAF
- THR
- Rwy

- Average $v_{REF}$ at THR-Position
- Quick Reference Handbook based $v_{REF}$ - gross mass correlations

- Analysis of last 10 data sets in front of THR

- Estimated gross mass at FAF-Position
EJPM - Validation

- Validation of EJPM was performed with flight Operational data (FODA)
- FDR Data (supported by Lufthansa Cargo) and corresponding Radar-Data as reference
- Excellent Fit

Real FODA vs. EJPM estimated fuel burn
(data source: FANOMOS Data of selected descent)
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Use-Case – Energy Dissipation Assessment

- Consideration of a specific traffic mix
- Verification of the relation between initial altitude and TAS
- Analysis considering ICAO Wake Turbulence Category → less than 2% of variation could be observed
- Comparable results only observable for a relatable traffic mix

Energy dissipation:

\[
dE_{pot} - dE_{kin} = (m_{FAF} \cdot g \cdot h_{FAF} - m_{cruise} \cdot g \cdot h_{cruise}) - \left( \frac{m_{FAF}}{2} \cdot V_{FAF}^2 - \frac{m_{cruise}}{2} \cdot V_{cruise}^2 \right)
\]

Total energy comparison before/after CDO implementation, reference airport
Use-Case – Energy Dissipation and Fuel Burn

- type-specific detailed analysis
- comparison of energy dissipation and fuel burn for period before and after CDO implementation
- No specific trend observable
  - e.g. A332 (black box):
    - lower energy dissipation, higher fuel burn in average after implementation of CDO
  - and A319 (red box):
    - constant energy dissipation, but lower fuel burn after implementation of CDO

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

Top: energy buffet
Down: fuel burn
Left bar: before CDO implementation
Right bar: after CDO implementation
Use-Case – Real vs. Optimal Flight Trajectories

- detailed analysis of 5 flights before and after CDO implementation each
- calculation of fuel saving potential over last 200 NAM
- longer segments at lower altitude after Implementation → higher fuel saving potential observable

<table>
<thead>
<tr>
<th>Flight</th>
<th>Possible fuel savings before CDO implementation [%]</th>
<th>Flight</th>
<th>Possible fuel savings after CDO implementation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.8</td>
<td>6</td>
<td>12.4</td>
</tr>
<tr>
<td>2</td>
<td>11.6</td>
<td>7</td>
<td>13.6</td>
</tr>
<tr>
<td>3</td>
<td>14.5</td>
<td>8</td>
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<td>23.3</td>
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<tr>
<td>5</td>
<td>12.3</td>
<td>10</td>
<td>19.4</td>
</tr>
<tr>
<td>Avg.</td>
<td>12.9</td>
<td>Avg.</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Fuel saving potential in %
Use Case – Optimal CDO vs. ICAO Corridor

- ICAO CDO corridor features static conditions, dependence only at FAF height and a determinable entry-window
- Possibility of a/c operating out of the given limits under certain conditions, despite flying optimum CDO
- Reference [NAM]: Non-observation of violations possible

*CDO profiles relative to ICAO CDO corridor containment area*
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Parameter Sensitivity Analysis (PSA)

Analysis of parameter-induced impact on fuel burn and position of Top of Descent (ToD)

- Gross mass
- OAT
- QNH
- Wind Direction
- Wind Speed
- Level-Off-Segments (differing in length and altitude)

Execution of an Individual impact analysis as well as an Analysis of combined parameters

**Gross mass:**

- High effect on both fuel burn and ToD-distance
- Higher gross mass resulting in
  - Higher fuel burn and
  - longer CDO distance vice versa

![Graph showing correlation of fuel burn to CDO length and gross mass under ISA conditions](image-url)
**PSA – Parameter Variation Impact**

**Temperature and Pressure Impact:**
- Due to correlation of both parameters (ideal gas law) → comparable influence of both parameters observable
  (Hot temperatures (high pressures) → lower air density → decrease of overall aircraft performance)
- Linear positive correlation between temperature (pressure) and fuel burn
- Linear negative correlation between temperature (pressure) and CDO length, since the FAF pressure altitude increases

**Wind Direction and Speed Impact:**
- Wind direction and Speed has the already known effect on aircrafts, at an CDO they also influence the vertical trajectory according to geographic distances
- It could be shown, that under realistic wind conditions aircraft could be operated outside the ICAO limits (as shown in the use case before)
PSA - Effect of Level-off Segments

- created virtual level-off segments of varying size and/or altitude within the CDO
- segments at any altitude and length significantly increase fuel burn
- at lower altitudes a polynomial relation, leading to an excessive increase in fuel burn and ToD-distance

<table>
<thead>
<tr>
<th>Segment length [NM]</th>
<th>Segment Alt [ft]</th>
<th>TOD [NM]</th>
<th>Fuel Burn [kg/200 NM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>108,1</td>
<td>809,4</td>
</tr>
<tr>
<td>1</td>
<td>4,500</td>
<td>109,3</td>
<td>813,3</td>
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<td>20,000</td>
<td>108,8</td>
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<td>4,500</td>
<td>120,3</td>
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</tr>
<tr>
<td>10</td>
<td>20,000</td>
<td>117,9</td>
<td>825,4</td>
</tr>
</tbody>
</table>

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

- Environmental parameters **gross mass, temperature** and **QNH** impose a **significant impact onto the vertical CDO route**
- **Fixation of the ToD** during operation **leads to a non-optimal CDO trajectory**, which results 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;
- Optimum **CDO trajectories** can **partially be situated outside** of the **limits** given by the **ICAO CDO corridor**
- Neccessity of guidance material for planning and prediction of trajectories by the air traffic controller → e.g. charts etc.

- **Problem**: **Uncertainty of wind at various altitudes** and restriction of level limits due to airspace structure
PSA - Outcome

Possible CDO Prediction Chart
(optimum length and resulting Fuel Burn, CI = 0, at optimum enroute flight altitude)

1. Choose Temperature and QNH at field elevation (e.g. -5°C; 1,023 hPa)

2. Find intersection with gross mass (e.g. 78 t)

3. Read out correlating fuel burn and CDO distance
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Conclusions

- Calculation of fuel burn out of Radar data is possible
- EJPM is performance-optimized and has therefore low demand of processing resources
- International clear Definition of CDO is non-existent → much room for interpretation
- ICAO Corridor is often not practicable → due to wind borders could be exceeded
- Due to level segments at lower altitudes, at the moment there is no significant fuel burn reduction after CDO implementation quantifiable
- ICAO Tailors Arrival concept is a good approach for optimum trajectory prediction and calculation in an high density airspace
Backup
CDO design guidelines - reality

Adjustment of corridor necessary:
- Complex airspace structure
- High traffic volumes
- Local terrain anomalies
- Aerodrome layout
- Location of residential areas in aerodrome vicinity

E.g. Frankfurt/Main (EDDF)
- DFS CDO “Tunnel” approach, 25L
- Displaced CDO corridor (complex airspace structure)

→ Long & low level segments
→ Leading to
  - Increased noise levels on ground
  - Increased fuel burn due to additional drag

compared to values of optimal trajectories possible

Implemented Corridor
ICAO Corridor at FAF
ICAO Corridor at Way-point
DFS Tunnel Approach EDDF, 25L vs. ICAO CDO Corridor

83 NM
6,000 ft
Fuel consumption / Energy conversion determination flight path

- Modular input/output concept → Flexible in use
- Validated through FODA → high accuracy
- Design based at finite element method (FEM) → integration at autonomous routines

$\delta = \delta_0 f(M_{\text{a}}) + k_f f(M_{\text{a}}) \cdot (c_f(p_{\text{e}}, V_{\text{TAS}}) - c_{\text{i,0}})^2$

Incremental calculation of the optimum trajectory based at known state parameter
EJPM Model – General Design

Speed Determination Module (SDM) Calculation of optimum speeds (consider compressibility effects)

Fuel Flow Calculation Module (SDM) Calculation of engine specific Fuel Flow

Thrust Wanted Module (SDM) Calculation of needed Thrust for a given flight path

INPUT DATA

I. PRE-PROCESSING

PRELIMINARY OUTPUT

II. PROCESSING

SOLUTION OUTPUT

State Parameter Class (SPC)

Environment Parameter Class (EPC)

Aircraft Parameter Class (APC)

Lift and Drag Module (LDM) aerodynamic calculations, aircraft specific polar

Fuel Flow Calculation Module (SDM) Calculation of engine specific Fuel Flow

Thrust Wanted Module (SDM) Calculation of needed Thrust for a given flight path

Dr. Hartmut Fricke

Fuel and Energy Benchmark Analysis of Continuous Descent Operations
Outlook - Approach for High Density Areas

- CDO corridor from Enroute up to Waypoint ADNIS at Frankfurt

**Pro:**
- Free vertical aircraft trajectory within the corridor (Blue line)
- Integration at existing air space structure

**Contra:**
- Also long Segment at low altitudes with no significant altitude change (82 Nm vs 6,000 ft)
CDO State of the Art – Various Definitions

**ICAO:** An operation, enabled by airspace design and ATC facilitation, in which an arriving aircraft descends continuously, to the greatest possible extent, by employing minimum engine thrust, ideally in a low drag configuration, prior to the final approach fix/final approach point.

**DFS:** Continuous Descent Operations (CDO) is an aircraft operating technique aided by appropriate airspace and procedure design and appropriate ATC clearances enabling the execution of a flight profile optimised to the operating capability of the aircraft, with low engine thrust settings and, where possible, a low drag configuration, thereby reducing fuel burn and emissions during descent. The optimum vertical profile takes the form of a continuously descending path, with a minimum of level flight segments only as needed to decelerate and configure the aircraft or to establish on a landing guidance system (e.g. ILS).

- Even Eurocontrol and other European ANSP have different definitions, e.g. the NATS, at LHR an CDO is below 6,000 ft and with an horizontal segment less than 2,5 NM (only relevant for Glide Path interception)

Source: Boeing Statistical Summary, July 2012