Study on Continuous Descent Operation for Efficient Air Transport System

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The effects of aircraft noise, fuel use and related pollutant atmospheric emissions can impact the quality of life in populated areas near to airports and represent environmental issues resulting in restrictions for air traffic procedures, aircraft manufacturing and airport facilities design. In order to mitigate the above-indicated environmental issues, specifically designed Curved and Continuous Descent Approach trajectories can be adopted for the implementation during approach and landing phases. This paper provides a study about Curved and Continuous Descent Approach concept for the future efficient flight operations in TMA. It aims providing the main concepts and mathematical models needed to implement a system able to generate descent profiles that are suitably optimized in terms of fuel consumption. These concepts and models are the basis for the development of dedicated tools and algorithms able to real-time generate optimal descent profiles, in the framework of a more efficient Air Transport System management with reduced environmental impact. In particular, this study investigates the differences between conventional descent and proposed curved and continuous descent techniques, starting from the analysis of procedures for a generic descent trajectory. Furthermore, detailed mathematical modelling of fuel consumption with reference to the descent phase is reported in the paper and, finally, high-level requirements and performance assessment indicators for Continuous Descent and Curved Approach profiles are discussed. The overall study here proposed, therefore, aims providing the basis for the development of automatic Continuous Descent and Curved Approach profiles real-time generation tools, able to take into account route structures and system operations, in compliance with the current rules of the air and integrating future ATM concepts and technologies.

Nomenclature

AGL = Above Ground Level
ANSP = Air Navigation Service Provider
ATC = Air Traffic Control
ATM = Air Traffic Management
CDA = Continuous Descent Approach
D = Aerodynamic drag [N]
d/dt = time derivative [s⁻¹]
FAF = Final Approach Fix
g = gravitational acceleration [9.81 m/s²]
h = altitude [m]
IAF = Initial Approach Fix
ISA = International Standard Atmosphere
m = aircraft mass [kg]

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THE effects of aircraft noise, fuel use and related pollutant atmospheric emissions can impact on quality of life of highly populated areas near to airports, leading to restrictions applied to aircraft operations in these areas in order to mitigate these effects. Furthermore, uncertainty factors due to wind gradient, deviation from International Standard Atmosphere ISA and other causes, can affect aircraft operations in term of unpredictability and possible loss of separation. In order to manage the above-mentioned restrictions as well as uncertainties during the flight, Air Traffic Controllers can apply tactical corrections by means of standard procedures such as radar vectoring, speed change, altitude change. These practices in Terminal Maneuvering Area TMA result in conventional descent step-down techniques, such as throttle-up settings, with level flight segments in vertical profile to ensure the required safety, causing increase in fuel burn, gas emissions and noise. These environmental issues can lead to restrictions on traffic flow and inefficient maneuvers to perform a ground track path allowing to reduce the noise footprint on ground.

I. Introduction

International organizations provide recommendations and guidance on efficiency and environmental measurements in order to overcome these difficulties, contributing to a sustainable balancing between the growing demand in the aviation sector and negative consequences of human activities. One of the innovative concepts introduced in the last years in order to reduce noise and pollutant emissions is a direct descent at idle or near-idle thrust, beginning at entry to the terminal control area (Top Of Descent point, TOD) from cruise until touchdown. This technique is generally referred to as the Continuous Descent Operation CDO. ICAO defines CDO “an aircraft operating technique aided by appropriate airspace and procedure design and appropriate ATC clearances enabling the execution of a flight profile optimized 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).”

Doc 9931 also gives the following definition: “The Generic term “Continuous Descent Operations”, has been adopted to embrace the different techniques being applied to maximize operational efficiency while still addressing local airspace requirements and constraints. These operations have been variously known as, Continuous Descent Arrivals, Optimized Profile Descents, Tailored Arrivals, 3D Path Arrival Management and Continuous Descent Approaches CDA”. Therefore, the terms CDO and CDA are interchangeable and should be read and understood in the same context.

This paper provides a study on CDO/CDA techniques that is part of the EATS – Efficient Air Transport System Project, an Italian funded project of CIRA – Italian Aerospace Research Center, started in September 2015, developed within activities of the Air Transport Sustainability Department. In addition to the improved capability of traffic awareness and collision avoidance systems currently available in CIRA, the EATS project plans to define and validate a system enabling to compute curved and continuous trajectories along more optimized approach and arrival profiles in terms of aircraft fuel consumption, emissions, and noise in TMA environment. This paper reports the first phase of the project based on the study of CDA concept, with the aim of providing the main inputs for the design and implementation of an automatic system integrating suitable algorithms able to generate optimized descent profiles for the reduction of the TMA operations environmental impact. First, the CDA concept is provided here in terms of aircraft, with low engine thrust settings and, where possible, a low drag configuration, thereby reducing fuel burn.

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2
considered. It is worth noticing here, nevertheless, that the fuel consumption can be related to the pollutant emission, so the reduction of the fuel consumption in the TMA is implicitly aimed to reduce the pollutants emissions and, therefore, to reduce the environmental impact of the approach and descent operations in the TMA.

II. Descent trajectories

A generic trajectory for a commercial aircraft can be divided into a set of flight segments as shown in the figure below.

![Figure 1. Main phases of flight.](image1)

Apart the phase of taxiing which refers to the movement on the ground, the take-off is the phase of flight in which an aircraft transits from the ground (according to taxiing instructions) to flying in the air, usually starting the initial climb on a runway. Following take-off, the aircraft has to climb to a certain altitude before it can flies along cruise phase at a predefined and safe altitude. During the cruise, the flight is most fuel efficient, unlike the descent phase in which the fuel consumption, aircraft noise and emission increase during the approach and landing. The last part of a flight is the landing, where the aircraft returns to the ground. Each segment includes different flight segments that are mathematically defined by flight parameters (i.e. Mach number, wind gradient, calibration speed and glide path angle). Furthermore, a trajectory can be identified through vertical and lateral profiles. The following figure shows examples of trajectories generated starting from predefined points of airways and aviation charts, for A320 flight respectively from Naples to Frankfort airport, and from Malpensa Milan to Naples airport.

![Figure 2. Examples of 3D trajectory for A320 flight for two different airports.](image2)

More in details, a descent path during air travel is considered as a portion along which an aircraft decreases altitude. During the approach and landing phases, the descent procedure plays a key rule. Other partial descents might be implemented in order to avoid traffic, bad weather conditions, turbulence, or to take into account the wind direction at different altitude. Usually, descent paths are achieved at a constant airspeed and constant angle of descent (3 degree final approach at most airports). The pilot controls the angle of descent by varying engine power and pitch angle to keep the airspeed constant.

The following sub-sections define the profiles for conventional descent approach and continuous descent approach, including the concept of curved path for CDA procedures.

A. Lateral profile

The lateral profile is intended as the aircraft path on a certain flight level turning at constant bank angle and using pre-defined waypoints, such as aRea NAVigation (RNAV). The RNAV concept defines an expected trajectory within a coverage volume (VHF Omnidirectional Range - VOR e Distance Measuring Equipment - DME).
The reported waypoints are necessary points to the navigation. They can be waypoints identified and described on the aviation chart, generally designed on airways. Other waypoints are intended as geographic points, which report the temporary position of aircraft (typically declared by pilot with a whole number of degrees, and used on oceanic areas).

B. Vertical profile

The vertical profile is defined by a set of slope and level flight segments. From a current ATM procedure point of view an aircraft follows a standard arrival procedure, namely Standard Terminal Arrival Routes STARS. The STAR allows the aircraft to leave the en-route phase in a controlled way and to follow a path by predefined waypoint. A STAR covers the phase from the Top Of Descent TOD until the runway. The initial point is defined as Initial Approach Fix IAF and the transitions are addressed to description of routes by the waypoints. Then, the aircraft can intercept the Instrument Approach Point IAP or can be vectored by Air Traffic Controllers ATCo.

C. Conventional descent profile

From TOD a conventional initial approach segment is divided up to five segments: arrival; initial; intermediate; final; and missed approach.

The arrival segment starts from the last segment of the cruise, maintaining constant Mach and constant altitude of cruise, achieving a deceleration before the descent. Then, between initial and intermediate segments, a constant Mach segment and then a constant calibrated speed segment are achieved. Here a new condition of deceleration is meet in a
level flight segment, and after a slope segment at a constant speed, a last level flight segment. Some of these conditions are meet in practices taking into account the Rules of the Air\textsuperscript{2}. In approach procedure, for instance, the final vector has to enable the aircraft to intercept the ILS localizer course at an angle not greater than 30 degrees and to provide at least 1 NM straight and level flight prior to ILS intercept. This vector shall allow the aircraft to be established on ILS localizer course in level flight for at least 2 NM before reaching the ILS Final Approach Fix FAF or Glide Path intercept point.

In the final approach, the alignment and descent for landing are made. The conventional technique for vertical path control is a step-down descent that shall start at not below the minimum step-down fix altitude. For example, the controller provides clearance to pitot to descent from bottom of holding stack at 6000-7000 feet altitude. Therefore, aircraft flies to intermediate altitudes about 5000-3000 feet AGL, before transitioning onto the final approach path and final descent to the runway. Then, the aircraft follows a certain nautical miles on level flight segment before to intercept the glide slope. During this level flight segment, the pilot need to apply additional engine power to maintain the constant speed. This lead to an increasing of noise and emission near to aerodrome.

D. Curved and Continuous Descent profile

A curved and continuous descent is a technique that simplifies the non-precision final approach with precision curved approach and vertical guidance procedures, resulting in a continuous vertical path calculated by on-board equipment or manually based on a required rate of descent without level flight segments, as shown in the figure below.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Continuous_Descent_Appearance}
\caption{Continuous Descent Approach.}
\end{figure}

Curved approaches with vertical guidance are part of the performance based navigation (PBN) concept\textsuperscript{3} defined by ICAO. The Required Navigation Performance RNP concept defines an implementation of the PBN concept. In general, RNP defines a volume containing the trajectory, the final approach with the shortest possible length (straight), missed approach procedure, and the compliance with Radius-To-Fix RF leg, that defines a circle of specified radius enabling an aircraft to fly a precise curved flight path relative to the surface of the earth. This procedure allows a curved path, resulting in a predictable and repeatable ground track during a turning. Its implementation preserve the dispersion of tacks.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{RF_leg}
\caption{RF leg\textsuperscript{3}.}
\end{figure}
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The following figures show the differences between current ground navaids or RNAV and RNP concept, highlighting the limited design flexibility in the first case. From a mathematical point of view, cubic spline interpolation is usually adopted for trajectory generation in TMA in order to insure a continuous trajectory curvature.

Figure 8. Comparison between conventional and curved lateral profile.

CDA procedures consider two different lateral paths: closed path procedures and open path procedures. The first technique is a pre-defined lateral flight track including the Final Approach Fix FAF and thus the distance to runway is precisely known. The second ones is intended as an operation based on a combination of a fixed route delivering aircraft to a vectoring segment, normally as an extension of the downwind leg to the FAF. This is based on the Distance To Go DTG strategy through a 2D path that will be defined by successive vectoring towards the last level constrained point of the STAR initially allocated to the flight.

The CDA allows the aircraft to fly higher for a long time with respect to the conventional approach, descending continuously from the lower level of holding and avoiding any level flight segment before to intercept the glide path (typically defined to 3.5 degrees for the ILS). The vertical profile of a CDA may comprise the STARs. To perform it in such case, different modes are considered. First, a slope angle is pre-defined rather than the nominal idle rate of descent, so that the CDA waypoints are reached and the TOD is calculated according to the fixed angle. Second, the descent starts immediately with a computed rate of descent to reach the CDA target level. Another mode can consider an idle rate of descent to reach the CDA target level with a planned TOD.

Even if this technique is preferred to the conventional descent because it requires less engine thrust and consequently less emissions and acoustic impacts, the CDA procedure is influenced by the capacity of air traffic controllers and air traffic control systems, common speed constraints, altitude and separation, especially for high traffic areas.

III. The Mathematical analysis of fuel consumption in Terminal Area

The following section outlines equations derived by using flight dynamics and Base of Aircraft and Data (BADA) Total Energy Model (TEM)

A. Total Energy Equation

The Total-Energy Model equates the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy, that is:

\[(T - D)V_{TAS} = mg \frac{dn}{dt} + mV_{TAS} \frac{dv_{TAS}}{dt}\]  \hspace{1cm} (1)

Below the tropopause, the air density, \(\rho\), in kg/m³ is calculated as function of temperature as follows:

\[\rho = \rho_0 \left(\frac{T}{T_0}\right)^{\frac{g}{K_T R}}\] \hspace{1cm} (2)

where:

\[- \frac{g}{K_T R} - 1 \approx 4.25864\]

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with:
\[ R = 287.04 \text{ m}^2/\text{Ks}^2 \]
\[ g = 9.81 \text{ m/s}^2 \]
\[ k_T = -0.0065 \text{ °K/m} \]
\[ \rho_0 = \left( \frac{\rho_0}{\text{ISA}} \right) \text{ISA} / T_0 \]
\( \rho_0 \)ISA is the standard atmosphere air density at sea level. \( \rho_0 \)ISA = 1.225 kg/m³

**B. Fuel consumption**

The parameters (variables and constants) contributing to the fuel consumption formulation \( f \) are reported below. More details about the aircraft performance modelling are founded into BADA Manual⁴.

For the jet and turboprop engines, the Thrust Specific Fuel Consumption \( \eta \) [kg/(min·kN)], is specified as a function of the true airspeed, \( V_{TAS} \) [kt]:

\[
\eta = C_f1 \left( 1 + \frac{\nabla V_{TAS}}{C_f2} \right) \quad \text{jet} \]
\[
\eta = C_f1 \left( 1 - \frac{\nabla V_{TAS}}{C_f2} \right) \times \left( \frac{V_{TAS}}{1000} \right) \quad \text{turboprop} \quad (3)
\]

The nominal fuel flow, \( f_{nom} \) [kg/min] for both jet and turboprop, can then be calculated using the thrust, \( T \):

\[
f_{nom} = \eta \times T \quad (4)
\]

The minimum fuel flow \( f_{min} \) [kg/s], corresponding to idle thrust descent conditions for both jet and turboprop engines, is modelled as a function of the altitude \( h \) [ft]:

\[
f_{min} = k_3 C_f3 (1 - \frac{h}{C_f4}) \quad (5)
\]

where:
\[
k_3 = \frac{1}{60} \quad [\text{min/s}]
\]

\( C_0 \) is expressed in kg/(min·kN) for jet kg/(min·kN·knot) for turboprop, and kg/min for piston; it represents the first thrust specific fuel consumption coefficient.

\( C_0 \) is expressed in knots; it is the second thrust specific fuel consumption coefficient.

\( C_0 \) is expressed in kg/min; it is the first descent fuel flow coefficient.

\( C_0 \) is expressed in ft; it represents the second descent fuel flow.

All above coefficients are provided from BADA database⁴.

The cruise fuel flow, \( f_{cr} \) [kg/min], is calculated similar to nominal fuel flow using the thrust specific fuel consumption \( \eta \), the thrust \( T \), but also a cruise fuel flow factor, \( C_{fcr} \). For the moment the cruise fuel flow correction factor has been established for a number of aircraft types whenever the reference data for cruise fuel consumption is available. This factor has been set to 1 (one) for all the other aircraft models.

It is important to note that for both jet and turboprop engines, the idle thrust part of the descent stops when the aircraft switches to approach and landing configuration, at which point thrust is generally increased. Hence, the calculation of fuel flow during approach and landing phases shall be based on the nominal fuel flow.

In this section, a formula for fuel consumption is provided based on true speed and path angle parameters.

Assuming that the geopotential pressure altitude \( H_p \) is equal to geodetic altitude \( h \), and the true airspeed \( V_{TAS} \) is equal to ground speed \( v \) (that is ISA and no wind condition), it is possible divide the Eq. (1) by speed \( v \) on both side obtaining:

\[
\frac{(T-D)V_{TAS}}{v} = \frac{m_g dh}{v} + \frac{m V_{TAS}^2 dV_{TAS}}{v} \quad (6)
\]

with \( v = V_{TAS}, H_p = h \)
Eliminating the time derivatives in Eq. (6) and introducing the term of path angle $\gamma$, the thrust can be written as:

$$ T = mg \sin \gamma + m \frac{dv}{ds} v + D \quad (7) $$

The aerodynamic drag $D$ depends on the drag coefficient $C_D$ that is expressed as a function of $C_{D0}$ and the lift $C_L$ as reported below:

$$ C_D = C_{D0} + C_{D2} \cdot (C_L)^2 \quad (8) $$

$C_{D0}$ is parasitic drag coefficient, and $C_{D2}$ is the induced drag coefficient from BADA$^4$.

The lift coefficient, $C_L$, is determined assuming that the flight path angle is zero. However, a correction for a bank angle $\varphi$ is made. For each phases (approach, cruise and landing configuration) a different flap setting is used. The drag $D$ is defined as:

$$ D = \frac{C_{D0} \rho V_{TAS}^2 S}{2} \quad (9) $$

Replacing $C_L$, $C_{D0}$ and $C_{D2}$ into (9), and considering a small bank angle $\cos \varphi \approx 1$, the aerodynamic drag can be written as:

$$ D = \frac{C_{D0} \rho V_{TAS}^2 S}{2} + \frac{2 C_{D2} m g^2}{\rho V_{TAS}^2 S} \quad (10) $$

This formula demonstrates that the aerodynamic drag is nonlinear. At high values of speed, the drag decreases, and at low speed range it increases. Low speed leads to large lift $C_L$ and higher drag $D$, resulting into an increased operating time.

The definition of nominal fuel flow (4) can be written substituting the Eq. (3) for jet, Eq. (7), and Eq. (10), and assuming that the geopotential pressure altitude $H_p$ is equal to geodetic altitude $h$, and the true airspeed $V_{TAS}$ is equal to ground speed $v$. It will represent the fuel flow rate $fr$:

$$ fr = C_f \left( 1 + \frac{v}{C_{f2}} \right) x \left( mg \sin \gamma + m \frac{dv}{ds} v + \frac{C_{D0} \rho S v^2}{2} + \frac{2 C_{D2} m g^2}{\rho v^2 S} \right) $$

Collecting in bracket the terms multiplied per the same $v$ value, the fuel flow rate is:

$$ fr = C_f \left( \frac{C_{f1} C_{D0} S}{C_{f2}} \right) v + \left( \frac{C_{f1} C_{D0} S}{C_{f2}} + \frac{C_{f1} m}{C_{f2}} \frac{dv}{ds} v \right) v^2 + \left( \frac{C_{f1} m}{C_{f2}} + \frac{C_{f1} m g \sin \gamma}{C_{f2}} \right) v + C_f m g \sin \gamma $$

$$ + \left( \frac{C_{f1} 2 C_{D2} m^2 g^2}{C_{f2} \rho S} \right) \frac{1}{v^2} $$

$$ fr = B1 v^3 + \left( B2 + B3 \frac{dv}{ds} \right) v^2 + \left( B4 \frac{dv}{ds} + B5 \right) v + B6 + B7 \frac{1}{v} + B8 \frac{1}{v^2} \quad (11) $$

With the bracket expressed as below:

$$ B1 = \left( \frac{C_{f1} C_{D0} S}{C_{f2}} \right); \quad B2 = \left( \frac{C_{f1} C_{D0} S}{C_{f2}} \right); \quad B3 = \left( \frac{C_{f1} m}{C_{f2}} \right); \quad B4 = \left( \frac{C_{f1} m}{C_{f2}} \right) m g \sin \gamma \quad ; \quad B5 = \left( \frac{C_{f1} m}{C_{f2}} \right) m g \sin \gamma \quad ; \quad B6 = C_f m g \sin \gamma; $$

$$ B7 = \left( \frac{C_{f1} 2 C_{D2} m^2 g^2}{\rho S} \right); \quad B8 = \left( \frac{C_{f1} 2 C_{D2} m^2 g^2}{\rho S} \right) $$

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The above coefficients depend on air density and vary with altitude. The fuel consumption is the integral of fuel rate with respect to time:

\[
FC = \int_0^{T_f} \left[ B_1 \nu^3 + \left( B_2 + B_3 \frac{d\nu}{ds} \right) \nu^2 + \left( B_4 \frac{d\nu}{ds} + B_5 \right) \nu + B_6 + B_7 \frac{1}{\nu} + B_8 \frac{1}{\nu^2} \right] dt
\]  

(12)

with \( T_f \) the final time.

Considering \( dt = \frac{ds}{\nu} \) the integral (12) can be written with respect to \( \nu \) and \( s \):

\[
FC = \int_0^S \left[ B_1 \nu^2 + \left( B_2 + B_3 \frac{d\nu}{ds} \right) \nu \right. \left. + \left( B_4 \frac{d\nu}{ds} + B_5 \right) + B_6 \frac{1}{\nu} + B_7 \frac{1}{\nu^2} + B_8 \frac{1}{\nu^3} \right] ds
\]  

(13)

with \( \nu_0 \) and \( \nu_f \) respectively the initial and the final speed.

C. Considerations on altitude and speed

The fuel consumption is influenced by different factors. Many research projects investigated on the impact of altitude and speed [References 5-7].

The impact of altitude on fuel consumption is associated to the changing of air density. This influence is nonlinear because the air density decreases as altitude increases, and aerodynamic drag decreases as air density declines, but if speed is low, the second term into (10) tends to denominate and the drag \( D \) increases with the altitude.

In the equation (13) the speed effects the fuel consumption in a nonlinear and not monotonic way. The nonlinearity in addressed to drag formulation. Therefore, a higher speed, even though increasing power, reduces the flight time. Consequently, the fuel burn increases with speed in a non-monotonically way. As demonstrated into (10), if speed is low the lift \( \lambda_L \) and drag \( D \) increase; thus the fuel consumption increases hyperbolically for low speed because into (12) the speed performs in the denominators.

D. Considerations on path angle

The path angle characterizes the fuel flow rate because the existing of its value is the main difference between the level-flight path and continuous-descent path. Increasing the path angle, the fuel consumption decreases. Usually the range of path angle is \([-2, -4]\) degrees. Some elaborations within TMA of an Italian airport (LIRN ICAO code) demonstrate the possibility of achieving CDAs with a constant path angle up to 4 degree and CDAs with an optimized descent profile at different altitude and constant path angle. In the first case the TOD is calculated according to predefined angle. In the second case the trajectory follows a path at a fixed altitude up to intercept the glide path for the descent at constant path angle. All CDAs report TODs higher than the conventional step-down descent.

![Figure 9](image)

Figure 9. Comparison between CDAs at different path angle (left) and between step-down trajectory and different CDAs techniques (right).

Many CDA procedures are implemented in practices in order to intercept the Glide Path of ILS systems (typically of 3.5 degrees). This component has generally a range of 10 MN for intercepting the path angle. This could limit the implementation of CDA with great path angle. A procedure based on increasing the slope of the final approach
procedure/segment and a level flight segment of at least 2 MN before FAF could be preferred to today’s procedures because its implementation reduces noise and emissions in the final approach phase maintaining the compliance with current limitations and rules of air.

Figure 10. Comparison between step-down trajectory and CDAs at different path angle.

### IV. High level requirements for CDA

As defined in Continuous Descend Approach – Implementation Guidance Information, CDA implementation is achieved through collaboration between operational stakeholders, in order to satisfy functional and non-functional requirements. This section summarizes the requirements identified from CDA guidance in the following table and provides the responsibilities of the Stakeholders to ensure CDA procedures.

<table>
<thead>
<tr>
<th>High level requirement description</th>
</tr>
</thead>
<tbody>
<tr>
<td>The CDA phraseology shall provide distance to touchdown information to the pilot and should complement ACT/pilot procedures related to level clearance, level restrictions and/or minimum flight altitudes. CDA may comprise any of following:</td>
</tr>
<tr>
<td>- Standard Arrival Routes (STARs),</td>
</tr>
<tr>
<td>- Provision of “distance to go – DTG information”,</td>
</tr>
<tr>
<td>- A combination of these: STARs and DTG.</td>
</tr>
<tr>
<td>Accurate and timely DTG information shall be provided to pilots in order to achieve CDA (i.e. where the radar-based CDA is implemented).</td>
</tr>
<tr>
<td>Appropriate speed requirements shall be provided to facilitate a continuous descent profile without the need for segments of level flight.</td>
</tr>
<tr>
<td>Unnecessarily early deployment of flap and undercarriage shall be avoided where this does not conflict with safety requirements and company operating procedures.</td>
</tr>
<tr>
<td>Low power/low drag techniques may be incorporated to extent possible.</td>
</tr>
<tr>
<td>The use of harmonised text and charts is recommended where the published CDA is implemented.</td>
</tr>
<tr>
<td>Unambiguous information pertaining to level clearances, level restrictions and/or minimum flight altitudes shall be integrated into pilot/controller CDA guidance.</td>
</tr>
<tr>
<td>The strategies for harmonised CDA implementation shall be developed with view to:</td>
</tr>
<tr>
<td>- Minimising impact on controller/pilot workload,</td>
</tr>
<tr>
<td>- Integrating into ATC guidance, general information pertaining to the environmental impact of aircraft, speed adjustments on aircraft CDA vertical profiles.</td>
</tr>
<tr>
<td>The planning shall be adequate, recognising:</td>
</tr>
<tr>
<td>- Variables that will affect the initial tactical plan,</td>
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<tr>
<td>- Complexity of integrating multiple traffic flow into a single stream,</td>
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<tr>
<td>- Controller workload may vary the point at a DTG update is given,</td>
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<tr>
<td>- Need for glide path intercept from beneath to avoid rushed or un-stabilised approach,</td>
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<tr>
<td>- Desire to have information available to airborne system prior to TOD,</td>
</tr>
<tr>
<td>- Flight crew procedures/airborne system ability to apply the appropriate profile for descent,</td>
</tr>
</tbody>
</table>
Publishing of DTG information as part of STAR and/or transition procedures will allow the descent trajectory to be optimized.

CDA application in STARs (including transitions) should be published in the following way:
- STARs are designed to specify standard routes from the en-route network to the initial approach fix and, with an appropriate transition, provide the necessary guidance to final approach fix.
- P-RNAV STARs and Instrument Approach Procedures (IAPs) should be designed with a vertical profile that allows for differing aircraft types/masses and atmospheric conditions.
- STAR and transition charts shall contain information on DTG at appropriate waypoints.
- STAR-based procedures may also include speeds at waypoints to enable a more predictable profile and enhance pilot monitoring of the descent.

The final approach path shall be intercepted at an appropriate height for the distance from touchdown.

Table 1. High-level requirements for CDA.

V. Performance Indicators for CDA

Performance Indicators represent a good method to measure ATM system performance with respect to performance areas and to monitor its change in normal and abnormal conditions. Significant research projects highlighted the benefit of the analysis of systems through performance assessment. In particular, European projects like SESAR provided Performance Framework, in which performance metrics are reported. The following subsections report only an analysis of those KPIs that should be considered for CDA.

A. Safety

An implementation of CDA shall always be subject to a local safety assessment, in accordance with the Safety Management principles of EUROCONTROL Safety Regulatory Requirement ESARR4 – Risk Assessment &
Mitigation in ATM\textsuperscript{10}. A safe CDA is achieved considering the interaction between CDA and non-CDA traffic, the cockpit workload, the accurate DTG information to ensure a stabilised configuration on final approach, and the variability in descent and speed depending on aircraft weight, the type of FMS and pilot/ATC training.

B. List of Performance Indicators

Apart from safety-related aims, two of the main objectives of the Aviation communities focus on an increased efficiency for Airspace Users and a significant decrease of the aviation impact on the environment.

The performance indicators related to environmental impact are reported in the table below.

<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>Description</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (fuel)</td>
<td>Average Taxi/En-Route/TMA in fuel burn per flight</td>
<td>Amount of fuel burn in taxi/En-Route/TMA phase divided by number of movements: $KPI_{fuelburn} = \frac{1}{N} \sum_{i=1}^{M} f_i$ where $M$ is the number of movements of vehicles, $N$ is the number of flights. $f_i$ is the fuel burn in taxi/En-Route/TMA phase.</td>
</tr>
<tr>
<td>Environment</td>
<td>Emission</td>
<td>Amount of emissions of pollutant $e$ per flight for a given set of flights: $E_e = \frac{1}{N} \sum_{i=1}^{N} c_e \Delta F_{e,k}$ where $E_e$ is the amount of emissions of pollutant $e$ per flight for a given set of flights, $N$ is the total number of vehicles, $c_e$ is the emission factor for pollutant $e$ and $\Delta F_{e,k}$ is the amount of fuel consumed by aircraft $k$.</td>
</tr>
</tbody>
</table>

Table 2. Performance Indicators for the efficiency in terms of environmental impact.

The EATS Project aims to develop increased efficiency operations mainly on the arrival phase of flight in terms of significant fuel-savings and emissions-reduction, through improved ATM measures, and through enabling the aircraft to fly its optimised profile. As know, the word efficiency has meanings for different people. Therefore, also a common efficiency-target is difficult to define within ATM domain. For airline companies efficiency is not always about fuel only, because of different business needs. From the ground perspective, efficiency can depend on environment key performance area, on capacity key performance area, or on performance variations that exist between different aircraft. Again, from the airborne side it also includes the development of ground-procedures in terms of technical capabilities with respect to time of arrival. For this reason, this study provides another way to calculate the efficiency performance:

<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>Description</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (delay)</td>
<td>Delay</td>
<td>The time difference between the scheduled time at a certain point and the actual time over that point: $KPI_{delay} = \frac{1}{N} \sum_{k=1}^{N} \Delta t_{a,k} = t_{a,k}$ where $N$ is the total number of vehicles, $t_{s,k}$ is the scheduled time at a certain point for aircraft $k$ and $t_{a,k}$ is the actual time over that point for aircraft $k$.</td>
</tr>
</tbody>
</table>

Table 3. Performance Indicators for the efficiency in terms of delay.

CDAs implementation can improve also the capacity and the predictability of ATM systems because allows an improved management of space (air and on ground) and time of arrival.

The metrics related to capacity and predictability are reported in the following table:
### Table 4. Performance Indicators for the capacity and predictability.

<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>Description</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airspace Capacity</td>
<td>The percentage of additional airspace throughput</td>
<td>Total number of movements $M$ per volume of En-Route/TMA airspace per hour for specific traffic mix and density.</td>
</tr>
<tr>
<td>Airport Capacity</td>
<td>The percentage increase in peak additional runway throughput</td>
<td>Total number of movements $M$ per one runway per hour for specific traffic mix and density.</td>
</tr>
<tr>
<td>Predictability</td>
<td>The reduction in variability of block to block flight execution time compared to the Reference Business Trajectory</td>
<td>The variance across each flight phase, with a final aggregation to a standard deviation value</td>
</tr>
</tbody>
</table>

#### C. Consideration about Efficiency (fuel) Performance Indicator

The efficiency in terms of fuel consumption can be analysed starting from the calculation of fuel burn saving for a single flight in TMA environment. Even if the capability of aircraft to perform CDAs is out of the scope, an example is provided here, adopting A300B4-622 parameters provided into BADA User Manual\(^4\). The generated trajectories at different path angle and different altitude are reported in the figure 15-16. The implementation of formula for fuel consumption demonstrates a reduction in percentage with respect to conventional trajectories. Furthermore, they report a better fuel burn saving for a greater path angle. Aircraft performance dataset is here used in order to provide an example of fuel consumption starting from TEM BADA equation. This methodology of implementing CDA and calculating fuel burn consumption is independent from used information. The efficiency in terms of saving of fuel burn in TMA is analysed comparing conventional trajectory with different CDAs. The fuel consumption formula is implemented considering the geopotential pressure altitude equal to geodetic altitude, and the true airspeed equal to ground speed (that is ISA and no wind condition) and constant. With respect to step-down approach, the theoretical CDAs with constant angle fixed to 3.5 degrees as for conventional trajectory, lead up to 47% of fuel saving. The optimized profile descent and increased glide path provide respectively a value of 0.5% and 33% w.r.t. CDA at 3.5 degrees. Among CDAs with different constant path angle the path with 4 degrees have a fuel saving up to 62%. An increased glide path starting from 3.5 degree up to 4 degrees led to a percentage of fuel saving of 38%. In this analysis the mass of aircraft is considered as a constant, the vertical path is assumed as a perfect vertical profile not considering the variability of speed and aircraft mass. Therefore, the fuel consumption is overestimated. Another consideration about the efficiency is that CDAs should evaluate their integration with not CDAs in low and high density of air traffic. This consideration results in errors in vertical and speed profile generation.

#### D. Future extension of CDA concepts

The CDA concept above described has been considered in this paper with specific reference to the fuel consumption reduction objective. Nevertheless, the potential application of CDA techniques is not limited in the scope to this objective. In particular, activities are ongoing in CIRA in order to consider additional objective constituted by noise impact reduction in TMA by means of proper Continuous Descent and Curved Approach profile design. The idea is the one of designing and implementing suitable tool that is able to automatically generate multiple descent profiles, which are all compliant with the vehicle performances and operational limitations in the considered TMA, that are evaluated real-time or near real-time in terms of related noise impact in the airport area. The evaluation is based on the use and extension of dedicated tools for noise impact calculation that have been developed by CIRA\(^11,12\). Based on the use of these tools, for each proposed descent profile the related noise impact will be evaluated, so allowing selecting the most convenient descent profile in terms of noise impact. Further improvement of the proposed methodology, then, will be constituted by integration of fuel consumption reduction and noise impact mitigation into a multi-objective descent optimization tool. Furthermore, in the future development of the Continuous Descent and Curved Approach tool, it is also needed the integration of suitable real-time Separation Assurance and Collision Avoidance systems developed by CIRA\(^13\), due to the need of managing in automatic way also possible loss of separation and collision conditions that may arise during approach and landing. Indeed, the most effective application of the proposed tool is foreseen in the future perspective where the whole TMA airspace is available for the descent.
so allowing to the Continuous Descent and Curved Approach tool to use all the TMA airspace when designing at strategic level the descent trajectory. This trajectory may need to be updated at tactical level during its execution, so benefitting of Separation Assurance system, or may be abandoned due to possible emergency conditions, so needing the integration of the proposed tool with suitable Collision Avoidance system.

VI. Conclusion

This paper provided a study of Curved and Continuous Descent Approach for Efficient Air Transport System, reported the defection of suitable mathematical model for fuel consumption evaluation during descent and indicated and discussed high-level requirements for the implementation of an automatic Continuous Descent Approach trajectory generation system. A list of performance indicators useful to assess benefits of CDAs has been also reported in the paper and possible future improvements and integrations of the proposed system have been provided. In particular, considerations on the efficiency of a generic flight in TMA have been emphasized and studied in terms of fuel burn, indicating that significant fuel savings can be achieved using CDA techniques with respect to conventional descent profile. Therefore, the Curved and Continuous Descent Approach profiles are preferable to the step-down trajectories currently in use, reducing the environmental impact in terms of fuel consumption. These trajectories with flight path angle at different altitude of TOD can provide support to the operational feasibility of CDA procedures for air traffic flow in TMA. The comparison of different flight profiles allows identifying the optimal profile with respect to fuel consumption.

Acknowledgments

This work is part of the EATS – Efficient Air Transport System Project, an Italian funded project of CIRA – Italian Aerospace Research Center, started in September 2015. In line with a common efficiency-target knowledge, CIRA has planned to develop a Continuous Descent and Curved Approach algorithms and systems for the future concept of efficient approach operations, taking into account the rules of the air and the coming Air Traffic Control (ATC) procedures.

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