Predictability, Variability and Operational Feasibility Aspect of CDA

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Abstract— **The current research focuses on predictability, variability and operational feasibility aspect of Continuous Descent Arrival/Approach (CDA), which is among the key concepts of the Next Generation Air Transportation System (NextGen). The idle-thrust CDA is a fuel economical, noise and emission abatement procedure, but requires increased separation to accommodate for variability and uncertainties in vertical and speed profiles of arriving aircraft. Although a considerable amount of researches have been devoted to the estimation of potential benefits of the CDA, only few have attempted to explain the predictability, variability and operational feasibility aspect of CDA.**

The analytical equations derived using flight dynamics and Base of Aircraft Data (BADA) Total Energy Model (TEM) in this research gives insight into dependency of vertical profile of CDA on various factors like wind speed and gradient, weight, aircraft type and configuration, thrust settings, atmospheric factors (deviation from ISA (DISA), pressure and density of air) and descent speed profile. Application of the derived equations to idle-thrust CDA gives an insight into sensitivity of its vertical profile to multiple factors. This suggests fixed geometric flight path angle (FPA) CDA has a higher degree of predictability and lesser variability at the cost of non-idle and low thrust engine settings. However, with optimized design this impact can be overall minimized.

The CDA simulations were performed using Future ATM Concept Evaluation Tool (FACET) based on radar-track and aircraft type data of the real air-traffic to some of the busiest airports in the USA (ATL, SFO and New York Metroplex (JFK and EWR)). The statistical analysis of the vertical profiles of CDA shows 1) mean geometric FPAs derived from various simulated vertical profiles are consistently shallower than 3° glideslope angle and 2) high level of variability in vertical profiles of idle-thrust CDA even in absence of uncertainties in external factors.

The present investigation also suggests that prediction and guidance of fixed FPA descent trajectory by the performance based Flight Management System (FMS) would help in reduction of unpredictability and variability associated with vertical profile of aircraft guided by the FMS coupled with auto-pilot (AP) and auto-throttle (AT). The statistical analysis of the vertical profiles of CDA also suggests that for procedure design; 'AT or above', 'AT or below' and 'Window' type altitude constraints and FPA constraints are more realistic and useful compared to obsolete 'AT' type altitude constraint because of variability in vertical profiles.

Keywords — Continuous Descent Arrival/Approach (CDA), Flight Management Systems (FMS), Air Traffic Management (ATM).

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1. Introduction

In March, 2016, the U.S. Department of Transportation's Bureau of Transportation Statistics (BTS) reported that U.S. airlines and foreign airlines serving the United States carried an all-time high of 895.5 million system-wide (domestic and international) scheduled service passengers in 2015, 5.0 percent more than the previous record high of 853.1 million reached in 2014. The system-wide increase was the result of a 5.0 percent rise from 2014 in the number of passengers on domestic flights (696.2 million in 2015) and 4.7 percent growth from 2014 in passengers on U.S. and foreign airlines' flights to and from the U.S. (199.4 million in 2015)[1].The consequence of the continued growth in air traffic is especially cause of concern for residents living in areas surrounding airports because of aircraft noise and local air pollution [2,3]. International aviation has been cited as a contributor that accounts for roughly 2% of manmade greenhouse gas emissions [4]. Apart from growing environmental sensitivity, recent volatility in jet fuel prices has also contributed towards investigation into methods for reducing air transportation fuel consumption [5-8].

2. BACKGROUND

All aircraft operations are subjected to unpredictability due to uncertainties in atmospheric factors such as wind, wind gradient, deviation from International Standard Atmosphere (DISA) and others. However, large number of conventional flights can still operate predictably and safely confined to small airspace near vicinity of an airport since the ATC can correct potential loss of separation between the aircraft by tactical practices such as radar vectoring, speed and/or altitude change. As a result conventional (step-down) descent usually has multiple intermediate level segments in its vertical profile to ensure the required safety under uncertainties [9]. These tactical corrections, however, results in throttle-up settings at low altitudes in descent flight phase causing increase in fuel burn, gas emissions and noise.

A concept of Continuous Descent Arrival/Approach (CDA) has been lately a promising Arrival and Approach procedure to overcome aforementioned problems [5-11].

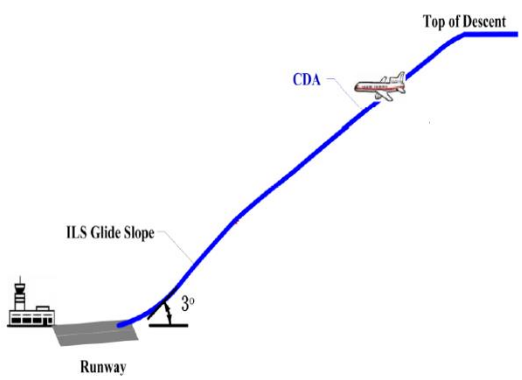

Fig.1: Illustration of vertical profile of CDA

An ideal CDA is a continuous descent from top of descent (TOD) i.e. from the cruise altitude to the runway threshold at idle or minimum thrust without being interrupted by level segments (unlike traditional Step-Down Arrival or Approach). However, so far there has been no precise definition of CDA. In the current study, CDA corresponds to smooth descent from the TOD till intercepting glide slope angle of 3 degree (practical ILS standards).

A. Motivation for Current Study

While flying CDA profile the 2002 field test at Louisville International Airport (SDF) [6] reported approximately 200 kg of fuel savings for B767, whereas the 2007 field test at Atlanta International Airport [7] suggested 462 kg of fuel savings for B757 and 602 kg for B767. Robinson et al. [8] examined more than 480,000 flights to find out that CDA saves no more than 100 kg of fuel for over 87% of all the flights. In addition, Robinson et al. noted that the main reason why CDA saves fuel is that CDA shifts the level segments in the terminal area to the cruise altitude. Therefore, the Continuous Descent Arrival/Approach (CDA), which has demonstrated significant noise abatement, gas emission reduction, and fuel savings, is seen by many researchers as a promising method to alleviate the environmental impacts of the aviation industry.

Regardless of various promising features, CDA has not been standardized as regular arrival or approach procedure in high air traffic density airports during busy hours because of safety and workload concerns. For an example, in the Louisville airport trial [6], the designed procedures were only assigned to UPS aircraft and conducted during nighttime hours. In 2009, a trial at Atlanta airport [7], only considered flights from Delta Air Lines and AirTran Airways. Similarly, trials at the London Metroplex (Luton, Stansted, Gatwick, and Heathrow) only reported benefits based on statistics from nighttime operations [10]. The 4-dimensional (4D) trajectory of CDA is sensitive to multiple factors. This creates problem for ATC as variations and uncertainties in CDA cannot be subjected to tactical corrections to ensure safe aircraft separation like those used in conventional step-down approach. Hence ATC needs to block large chunks of airspace, which consequently increases the landing interval from nominal 1.8 min to 4 min [11,12,13]. To enable CDA operations on regular basis at an airport requires airspace design, procedure design and facilitation by ATC. As the standardization of procedures is important for flight safety and optimization of airport arrival rate (AAR) therefore it is important to understand the flight characteristics, limitations and capabilities of aircraft fleet that are expected to perform CDA. Feedback from flight simulations is one way to ensure that proposed design does not adversely affect aircraft and/or it can facilitate CDA to the majority of the expected aircraft fleet [14,15]. Evaluation of CDA trajectory with a range of variables such as aircraft weight, airspeed, rate of descent, geometric descent path angle, aerodynamic descent path angle, wind vector & gradient and atmospheric conditions for the aircraft fleet using Monte Carlo simulations provides meaningful insight to design CDA procedure at an airport [14].

3. FACTORS AFFECTING VERTICAL PROFILE OF CDA

This section theoretically demonstrates various factors that influence vertical profile of CDA. The insight into the derived equations would aid in design of airspace and procedure at an airport.

A. Definition of CDA

There are many types of definitions of CDA [16]. Typically, CDA is defined as an arrival/approach procedure with a very long idle descent, usually from at least 10,000 ft above ground level (AGL) or Top of Descent (TOD) till intercepting glide slope angle of 3 degree [10-11]. However, depending upon the goal, any of the following CDA procedures such as reduced noise (CDA-RN), reduced time (CDA-RT), reduced fuel consumption (CDA-RF) and maximum predictability (CDA-MP) can be designed and flown [9]. However, recently fixed and variable Flight Path Angle (FPA) descent without level segment between TOD and glide-slope intercept and at low thrust/power settings has also become part of CDA research [11, 17, 18].

Typically, CDA consists of a series of flight segments that are consistent with piloting procedures. Continuous descent consists of constant Mach segments till crossover altitude followed by various constant and decelerating CAS segments. However, incase cruise altitude is lower than the crossover altitude then descent phase of flight consists only of various constant and decelerating CAS segments.

B. Equations of Longitudinal Motion for Continuous Descent

The prediction of aircraft trajectory is modeled using point mass concept with three degrees of freedom. The equations then describe the motion of aircraft's center of mass, considered as a mass-varying body. The scalar equations of motion in aerodynamic frame of reference are formulated based on the general assumptions (Fig.2.):

a. Spherical, non-rotating Earth;

b. Rigid and symmetric aircraft;

c. Thrust vector parallel to the aerodynamic velocity of the aircraft;

d. Symmetric flight;

e. Negative FPA for descent phase of flight.

These assumptions are appropriate for subsonic, transport aircraft. Hence the scalar equations of longitudinal motion are [11, 19 – 24]:

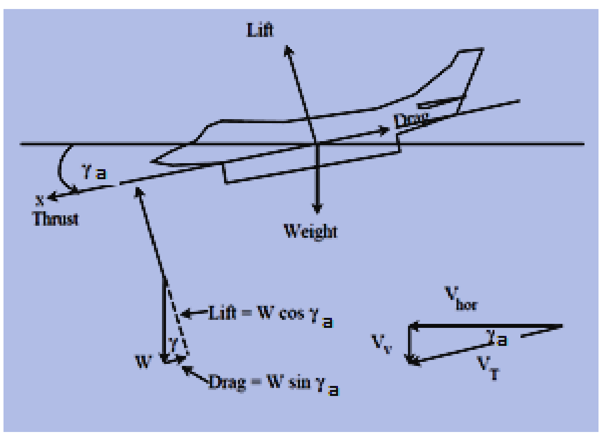

Fig.2: Forces acting on aircraft in descent (Aerodynamic Frame of Reference)

Equation of motion parallel to the flight path:

$$m\frac{dV_T}{dt} = T - D - mg\sin\gamma_a - mV_T\frac{dV_{wind}}{dh}\sin\gamma_a\cos\gamma_a \quad (1)$$

Equation of motion perpendicular to the flight path:

$$mV_T\frac{d\gamma_a}{dt} = L - mg\cos\gamma_a + mV_T\frac{dV_{wind}}{dh}\sin^2\gamma_a \quad (2)$$

Equation for geometric FPA (Inertial Frame of Reference):

$$\gamma = \sin^{-1}\left(\frac{\frac{dh}{dt}}{V_{gs}}\right) \quad (3a)$$

Since in most cases absolute value of geometric FPA (γ) is less than 4 deg., the above equation can be approximated as:

$$\gamma = \frac{\frac{dh}{dt}}{V_{gs}} \quad (3b)$$

Equation for aerodynamic FPA (assuming no wind in vertical direction [24]):

$$\gamma_a = \frac{V_v}{V_T} = \frac{\frac{dh}{dt}}{V_T} \quad (4)$$

Vector relationship (considering direction as well as magnitude) between ground speed, true airspeed and wind is given by:

$$\vec{V}_T = \vec{V}_{gs} - \vec{V}_{wind} \quad (5a)$$

Scalar form of equation (5a) is given by:

$$V_{gs} = V_T \pm V_{wind} \quad (5b)$$

Where + / – sign is used for tailwind / headwind respectively.

The rate of descent is assumed to be equal to true vertical speed, because for geodetic altitude less than 35,000 ft and away from the vicinity of ground, the component of wind velocity in vertical direction is almost zero [19,24].

Relationship between aerodynamic and geometric FPA (assuming negligible wind component in vertical direction) [24,25]:

$$V_T\sin\gamma_a = V_{gs}\sin\gamma \quad (6)$$

From equations (3a), (3b), (5a), (5b), and (6) with small angle approximations:

$$\gamma_a = \gamma\left(1 \pm \frac{V_{wind}}{V_T}\right) \quad (7)$$

The + / – sign signifies tailwind / headwind respectively. Where,

T = thrust's projection along the velocity vector,

D = aerodynamic drag,

m = aircraft mass,

h = geodetic altitude,

g = gravitational acceleration,

γ = geometric FPA,

γ_a = aerodynamic FPA,

V_T = true airspeed,

V_gs = ground speed,

V_wind = wind speed,

dh/dt = rate of descent,

V_v = vertical speed,

d/dt = derivative w.r.t time.

C. Energy Equation for Continuous Descent

The energy equation for continuous descent is derived from work-energy theorem by considering the aircraft (point mass) plus Earth as the system. The Total-Energy Model [TEM] used in BADA equates the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy [25]:

$$(\mathrm{T}-\mathrm{D})\mathrm{V_T} = \mathrm{mg}\frac{\mathrm{dh}}{\mathrm{dt}} + \mathrm{mV_T}\frac{\mathrm{dV_T}}{\mathrm{dt}} \tag{8}$$

D. Derivation of FPA using TEM

The time derivative of true airspeed (magnitude) can be written as:

$$\frac{\mathrm{dV_T}}{\mathrm{dt}} = \frac{\mathrm{dh}}{\mathrm{dt}}\frac{\mathrm{dV_T}}{\mathrm{dh}} \tag{9}$$

Hence, equation (8) is given by:

$$(\mathrm{T}-\mathrm{D})\mathrm{V_T} = \mathrm{mg}\frac{\mathrm{dh}}{\mathrm{dt}} + \mathrm{mV_T}\frac{\mathrm{dh}}{\mathrm{dt}}\frac{\mathrm{dV_T}}{\mathrm{dh}} \tag{10}$$

Re-arranging the above equation and substituting for aerodynamic FPA (γ_a) from equation (4) yields:

$$\gamma_a = \frac{\mathrm{T}-\mathrm{D}}{\mathrm{mg} + \mathrm{mV_T}\frac{\mathrm{dV_T}}{\mathrm{dh}}} \tag{11}$$

$$\gamma = \frac{\mathrm{T}-\mathrm{D}}{\left(1 \pm \frac{\mathrm{V_{wind}}}{\mathrm{V_T}}\right)\left(\mathrm{mg} + \mathrm{mV_T}\frac{\mathrm{dV_T}}{\mathrm{dh}}\right)} \tag{12}$$

Where + / – sign signifies tailwind / headwind respectively.

E. Derivation of FPA using Equations of Motion

Using small angle approximations, equation (1) can be written as:

$$\mathrm{m}\frac{\mathrm{dV_T}}{\mathrm{dt}} = \mathrm{T} - \mathrm{D} - \mathrm{mg}\gamma_a - \mathrm{mV_T}\frac{\mathrm{dV_{wind}}}{\mathrm{dh}}\gamma_a \tag{13}$$

By eliminating time derivative of true airspeed, the above equation can be written as:

$$\mathrm{m}\frac{\mathrm{dh}}{\mathrm{dt}}\frac{\mathrm{dV_T}}{\mathrm{dh}} = \mathrm{T} - \mathrm{D} - \mathrm{mg}\gamma_a - \mathrm{mV_T}\frac{\mathrm{dV_{wind}}}{\mathrm{dh}}\gamma_a$$

Re-arranging the above equation and substituting for aerodynamic FPA (γ_a) from equation (4) yields:

$$\gamma_a = \frac{\mathrm{T}-\mathrm{D}}{\left\{\mathrm{mg} + \mathrm{mV_T}\frac{\mathrm{dV_{wind}}}{\mathrm{dh}} + \mathrm{mV_T}\frac{\mathrm{dV_T}}{\mathrm{dh}}\right\}} \tag{14}$$

Hence, from equation (6) geometric FPA is given by:

$$\gamma = \frac{\mathrm{T}-\mathrm{D}}{\left(1 \pm \frac{V_{wind}}{V_T}\right)\left\{\mathrm{mg} + \mathrm{mV_T}\frac{\mathrm{dV_{wind}}}{\mathrm{dh}} + \mathrm{mV_T}\frac{\mathrm{dV_T}}{\mathrm{dh}}\right\}} \tag{15}$$

Where + / – sign signifies tailwind / headwind respectively.

By comparing equation (15) with equation (12), it can be seen that the equation for geometric FPA derived using flight dynamics captures effect of wind gradient on the FPA unlike the one derived using the TEM model.

F. Analysis Based on Continuous Descent Equations

The true airspeed (V_T) is a scalar quantity in above set of equations, and therefore $\frac{\mathrm{dV_T}}{\mathrm{dh}}$ is the rate of change in magnitude of true airspeed w.r.t altitude. From equation (15), thrust (T) required to fly continuous descent is given by:

$$\mathrm{T} = \mathrm{D} + \gamma * \left(1 \pm \frac{\mathrm{V_{wind}}}{\mathrm{V_T}}\right)\left\{\mathrm{mg} + \mathrm{mV_T}\frac{\mathrm{dV_{wind}}}{\mathrm{dh}} + \mathrm{mV_T}\frac{\mathrm{dV_T}}{\mathrm{dh}}\right\} \tag{16}$$

From the above equations, it can be seen that negative value of geometric FPA (γ) in descent phase of flight implies that for a given altitude and true airspeed, thrust required (T) in continuous descent is less than thrust required (T) during level segment (γ=0) at same conditions. Lower magnitude of thrust (T) required in continuous descent implies reduced fuel burn rate and hence reduction in over-all fuel consumption. This is the reason why aim of CDA is to eliminate intermediate level segments in descent phase of flight from fuel consumption's perspective.

4. STUDY OF OPERATIONAL FEASIBILITY

Each segment of the descent trajectory is defined by setting two control variables constant by the FMS. These variables are:

a) Thrust (T)

b) Airspeed (Mach(M) or calibrated-airspeed (CAS))

c) Altitude rate ($\frac{dh}{dt}$) or geometric FPA (γ).

In general, descent phase of flight is subdivided into the following sub-phases based on speed schedule(s), active procedure flown and distance from the runway by the FMS:

1. Arrival sub-phase of flight consists of integration of segments that have constant CAS/Mach airspeeds with aircraft in clean configuration.
2. Approach sub-phase of flight consists of integration of segments that have speed change points and configuration change points for deceleration of the aircraft to appropriate approach speed(s) (V_{App}). It is a transitional sub-phase between descent and landing sub-phase.
3. Landing sub-phase of flight consists of integration of segments that have landing speed(s) (V_{Land}) at landing configuration of the aircraft.

A.Idle Thrust CDA at Planned CAS/Mach

In idle-thrust descent, the throttle is set to idle and a constant Mach is maintained until desired CAS is captured (crossover altitude). Beyond this point (crossover altitude), descent is maintained at constant CAS till encountering the first speed change point related to transition altitude or speed constraint. Hence to maintain constant CAS/Mach in arrival sub-phase the following two variables are fixed (specified):

a. Thrust (Idle).

b. Airspeed (Scheduled CAS/Mach).

Hence, for each descent segment geometric FPA (γ) is a variable that is a function (equation 15) of the above mentioned constant/scheduled variables (CAS/Mach and Idle-thrust) and external variables (wind, wind gradient, density, pressure and DISA).

Preliminary analysis of the derived equations (12) and (15) give an insight that descent path of idle-thrust CDA becomes shallower with the following changes in the independent variables 1) increase in weight, 2) decrease in descent speed, 3) increase in magnitude of tailwind and 4) presence of positive wind gradient. On the other hand, extension of slats and/or flaps (i.e. increase in the drag (D)) would cause idle-thrust CDA at steeper FPA.

The dependency of the drag (D) on atmospheric parameters (DISA, density and pressure) together with uncertainties in wind gradient ($\frac{dV_{wind}}{dh}$) and wind speed (V_{wind}) plays a critical role in unpredictability of vertical profile of idle-thrust CDA (refer equation 12 and 15) by the Flight Management System (FMS) and Ground based ATC tool.

The sensitivity of vertical profile to external conditions causes actual vertical profile flown by aircraft in idle-thrust condition different from the FMS predicted vertical profile. The difference between actual and predicted trajectory may also be because of the following additional reasons: 1) Error/Mismatch in entry of wind and temperature forecast data into the FMS. 2) The FMS Aircraft Performance Model (APM) may not be accurate enough to predict actual response of aircraft in idle thrust condition to external variables (wind gradient, wind, DISA…etc.).

The second identifiable issue related with the idle-thrust CDA is discrepancies between ground based ATC tool and the FMS predictions. Laterally this profile is well defined by waypoints along the ground track. However, vertically the issue of predictability is complicated because of sensitivity of the vertical profile to external conditions. Ground based planning tools perform predictions based on available and assumed information such as aircraft type, nominal weight, operating conditions and ground based wind predictions. On the other hand, the airborne FMS computes, updates and executes the vertical profile based on aircraft specific operational procedures, actual weight, the FMS-specific vertical profile construction method, wind and temperature forecast data entered by the flight crew and sensed data (wind, temperature, current speed, current altitude…etc). With engine set to idle thrust, vertical profile of the CDA constructed by the ground based ATC planning tool and the FMS is sensitive to the above stated parameters. This can lead to huge discrepancies and cause of concern to Air Traffic Control (ATC) as accurate prediction of vertical profile is essential to ensure vertical separation between the aircraft at different altitudes [26, 27].

Idle-thrust descent at constant Mach or CAS is the most frequently employed airline procedure during arrival sub-phase of the step-down descent procedure. However, uncertainties in vertical profile is managed by imposing intermediate level segments in descent phase of flight (Figure 3). This helps ATC to merge aircraft and estimate the relative speeds of two aircraft given their CAS.

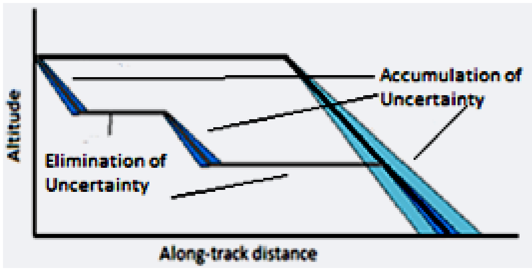

Fig.3: Idle thrust CDA (accumulation of uncertainty as function of along-track distance) [28,29]

B. Fixed FPA CDA at Planned CAS/Mach

In fixed geometric FPA (γ) CDA at planned CAS/Mach, thrust required (T) is a variable that is computed based on fixed geometric FPA (γ) and CAS/Mach for each descent segment. Typically, in arrival sub-phase, CAS/Mach is constant for each segment so the thrust required (T) is computed based on constant /scheduled CAS/Mach and fixed geometric FPA (γ) for each segment. However, in approach sub-phase of descent, CAS is not a constant hence the thrust required (T) is computed based on type of segment (i.e. deceleration, constant CAS or aircraft configuration change). From equations (15-16), it can be seen that non-idle thrust ($T \neq 0$) is required to maintain the fixed geometric FPA, and the benefits in noise, fuel burn, emissions and flight time is lower than the levels achievable with idle thrust descent. From equation (15), it can also be seen that for CDA segment with fixed geometric FPA (γ) and CAS/Mach, the thrust required (T) decreases with increase in absolute value of geometric FPA (γ) i.e. steepness of descent and it is maximum for level segment in descent phase of flight ($\gamma=0$). Even if a steep descent is achievable with the use of speed brakes, many pilots are reluctant, if not unwilling, to use them because of noise and ride discomfort. On the other hand, shallow descent angles burn more fuel, increasing cost and environmental impact. Hence to achieve reasonable reductions in loss of benefits with high-level of vertical profile predictability in support of high traffic operations proper design of geometric FPA (γ) arrival/approach procedures is required [26, 27]. However, multiple researchers [18, 21, 30 and 31] have shown that contrary to literature; with optimized geometric FPA (γ) it is possible to have better overall fuel efficiency than idle-thrust CDA for certain aircraft types. For an example, Izumi et al [31] compared fuel-optimal trajectory with idle-thrust trajectory for B747 and showed less fuel burn and a much-earlier top of descent (TOD) than the idle-thrust trajectory. In fuel-optimal trajectory, the fuel benefit gained due to shorter cruise segment i.e. earlier TOD, compared to the idle-thrust descent, exceeds the fuel penalty in the descent, resulting in an overall fuel burn advantage apart from highly predictable trajectory.

C. Idle Thrust CDA at Fixed FPA

Coppenbarger et al. [32] showed that idle thrust CDA at fixed geometric FPA (γ) has potential to reduce fuel consumption compared to the idle thrust CDA at constant CAS/Mach for certain aircraft types. They came to the conclusion based on simulation results using BADA version 3.9 for aircraft from Boeing family (B737, B747, B757 and B767). However, their results showed less fuel consumption from the idle thrust CDA at constant CAS/Mach for Airbus family (A310, A320 and A330).

The main drawback of this procedure is operational infeasibility for certain combination of aircraft type and configuration, wind, wind gradient and weight. Hence this procedure is rarely used by airlines.

D. Fixed FPA vs Idle-thrust CDA

Performance based Flight Management System (FMS) of business, regional and light jets performs descent path construction based on default geometric FPA (γ). The default FPA is used for descent path construction in backward direction starting from the End of Descent (EOD) i.e. Runway Threshold and terminated at the cruise altitude. During the backward construction of the descent path, default FPA is only altered if there is any violation of altitude constraint or at deceleration segment (shallower FPA is required for deceleration). Hence planned vertical profile of descent phase consists of integration of geometric segments that are constructed based on FPA, cruise altitude, speed schedule, constraints (speed/altitude constraints & airspace restrictions) and aircraft configuration change points (V_{App}) associated with the chosen aircraft type and arrival/approach procedure [32-34]. The performance based FMS of business, regional and light jets that is equipped with vertical navigation (VNAV), is capable of fixed-FPA descent in vertical path (VPATH) mode when the FMS is coupled with Flight Control System (FCS) i.e. Auto-pilot (AP) and Auto-Throttle (AT); this implies fixed FPA CDA at planned CAS/Mach is operationally feasible without any need for pilot intervention while in descent. However, the pilot still needs to extend flaps and gear upon sequencing configuration change points.

Contrary to the FMS of business, regional and light jets the large commercial jets are equipped with performance-based FMS capable of constructing and flying idle-thrust descents. Idle-thrust descents are intrinsically sensitive to the aircraft's performance parameters, the descent speed profile, and atmospheric conditions [32-34]. Hence, predictions of the idle-thrust descents have been proved to be especially challenging because of uncertainties in atmospheric conditions (wind, wind gradient, density, pressure and DISA). Nonetheless, potential procedures to execute fixed-FPA descents using performance-based FMS have been suggested for commercial aircraft [35].

From an operational point of view, the ability to decelerate during descent is an important parameter to be considered. For a descent with geometric FPA steeper than 2°, the trust required is only a small fraction of that required during level flight segment [31]. This leads to the potential of efficient operations with smaller fuel flow, emissions and fuel burn. When descending along fixed FPA, deceleration can also be achieved by engine thrust without changing the descent path. This is different from the case of idle-thrust descent where deceleration can be achieved by reducing the geometric FPA.

5. CASE STUDIES OF CDA VERTICAL PROFILES

The following statistical methods were used for the case studies in this research:

1. Frequency distribution was used to study distribution of the altitudes for the simulated CDA air traffic at equi-spaced along-track pseudo waypoints. This was performed for various arrival-runway combinations at KATL.
2. The mean and standard deviation of geometric FPA for the simulated CDA air traffic was computed and plotted using linear curve fit (altitude vs along-track distance from the runway) for various arrival-runway combinations.

To visualize variability aspect of idle-thrust CDA qualitatively, vertical profiles of the simulated CDA air-traffic were plotted as a function of along-track distance for few arrival-runway combinations.

A. Case Study 1: Hartsfield-Jackson Atlanta International Airport (ATL)

This section describes a case study at the Hartsfield-Jackson Atlanta International Airport (ATL), which is the busiest airport in the United States as well as in the world [30]. In general, the main purpose of the airspace and procedure design at an airport is to bring structured layout to vertical and lateral path for flight safety. However, for procedure design at an airport, it is important to understand the performance characteristics of various aircraft types that are expected to perform operations, as well as characteristics of the airspace and routes where they will be used. The scope of this research is limited to gain a holistic view of descent (arrival/approach) performance characteristics of various aircraft types that are expected to perform CDAs at ATL. Hence, in this case study, investigation on CDAs is performed in order to calculate mean altitude of air-traffic as a function of along-track distance from the runway for estimation of geometric FPA constraint to aid in CDA procedure design at ATL.

A.1. Data Source: The baseline of the study is the radar track trajectories that came from FAA Performance Data Analysis and Reporting System (PDARS). The data contains flight information, such as 4-D trajectories, flight plans, arrival fixes and ground speeds captured from 10/1/2005 to 10/14/2005 for 14 consecutive days [36]. ATL was chosen for this research primarily, because it is a hub airport that accommodates a large volume of traffic each day and large sample size improves level of statistical significance. Furthermore, the airspace in the vicinity of ATL is highly structured i.e. before flights entered the TRACON, they were distributed into their respective traffic flows based on their arrival gate and the available STARs[36]. The STAR information for this research was retrieved from the open source available to public. Trajectories observed from the PDARS data mostly used conventional step-down descent. However, to create CDA traffic, aircraft type specific information as well as ground tracks extracted from radar tracks was fed into FACET to synthesize CDA trajectories. FACET uses built-in aircraft performance data derived from BADA to construct the vertical profile for a given aircraft type. Hence, the ground tracks (lateral paths) from PDARS (step-down descent) and the corresponding CDA are exactly the same, with only different vertical profiles.

A.2. Simulation of CDAs at ATL: As stated above, simulation was performed using FACET [36]. For each flight, flight plan was generated by comparing the waypoint sequence retrieved from the ASDI data with the standard approach procedures or STARs. CDAs were simulated based on the flown ground-tracks and STARs. However, the simulation was performed by ignoring all the altitude constraints associated with the STARs. The radar updated the aircraft position with an interval of around 1 minute. However, to obtain a finer resolution, the update interval was turned to 5 seconds in FACET SIMULATION mode. The speed profiles used in the simulation were from the BADA recommended model embedded in the FACET. This model assumes that the CAS/Mach speed schedules are unique to the aircraft type and phase of flight (take-off, climb, cruise, descent or approach). Hence, true airspeed (TAS) is dependent on aircraft type, phase of flight, altitude, wind and DISA. However, due to lack of wind data, it was assumed that the true airspeed (TAS) is equivalent to the ground speed (GS). This speed model has disadvantage of reflecting the nominal operational speed for an aircraft type. The speed profiles adhered to speed constraints associated with the airspace. For those aircraft types not explicitly included in the database embedded in the FACET, equivalent types with modification factors were used. The influence of lateral path (STAR) is significant. The traffic flow rate varied for different STARs; some routes were empty while some were busy. For the busy ones, more delay might be produced by CDA, which reduces fuel savings. For the empty ones, a CDA could probably be implemented without significant delay, and thus its environmental benefits were largely retained [36].

A.3. Simulation Results and Analysis: The CDAs that primarily consists in their flight plan either one of these STARs: ERLIN, CANUK and HONIE were investigated. As stated earlier, CDAs were simulated without any type of altitude constraints but with speed restrictions imposed on them. The vertical profiles of CDA were then evaluated at 20 equi-spaced pseudo waypoints, separated by along-track distance of 5 nm, starting from 5nm from the runway till 100 nm from it. The evaluation of vertical profiles of CDA was carried out using statistical analysis at each of these points. The variability was statistically measured using mean, standard deviation and frequency distribution plots of altitude at these pre-defined waypoints. This approach enabled to determine CDA profile characteristics of all simulated aircraft types and provide estimate of the required crossing altitude windows at various along-track waypoints based on realistic speed profiles.

A.3.1 STAR ERLIN: Runway 26L/26R ATL - The simulated CDA dataset that was analyzed contained 1187 samples of distinct flight arrivals to runway 26L/26R following STAR ERLIN without adhering to published altitude constraints of step-down approach.

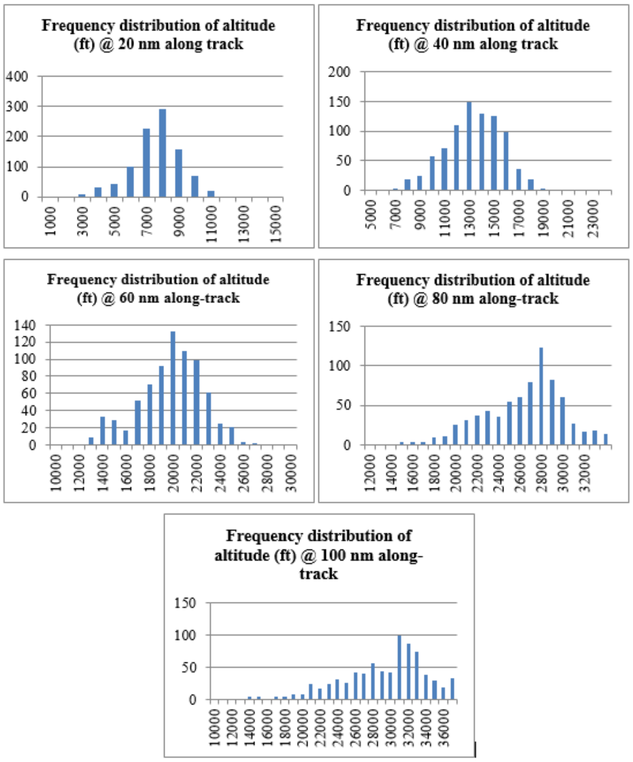

Fig.4: Illustrates frequency distribution of CDA altitude (ft) at various pseudo along-track waypoints (26L/R – ERLIN – ATL)

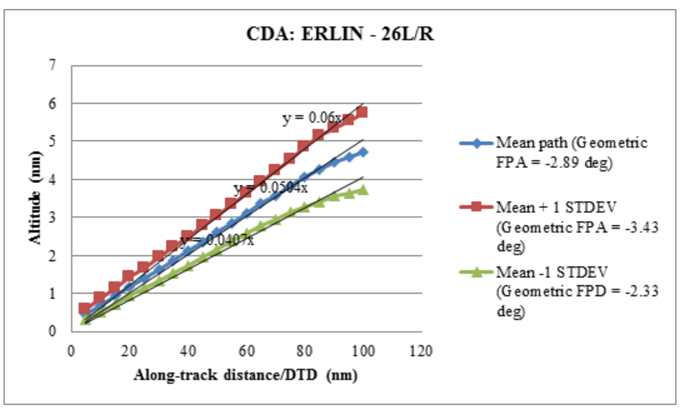

Fig.5: Captures variation in vertical profiles of CDA with Stdev (26L/R – ERLIN – ATL)

A.3.2 STAR ERLIN: Runway 27L/27R/28 ATL - The simulated CDA dataset that was analyzed contained 1158 samples of distinct flight arrivals to runway 27L/27R/28 following STAR – ERLIN without adhering to published altitude constraints of step-down approach.

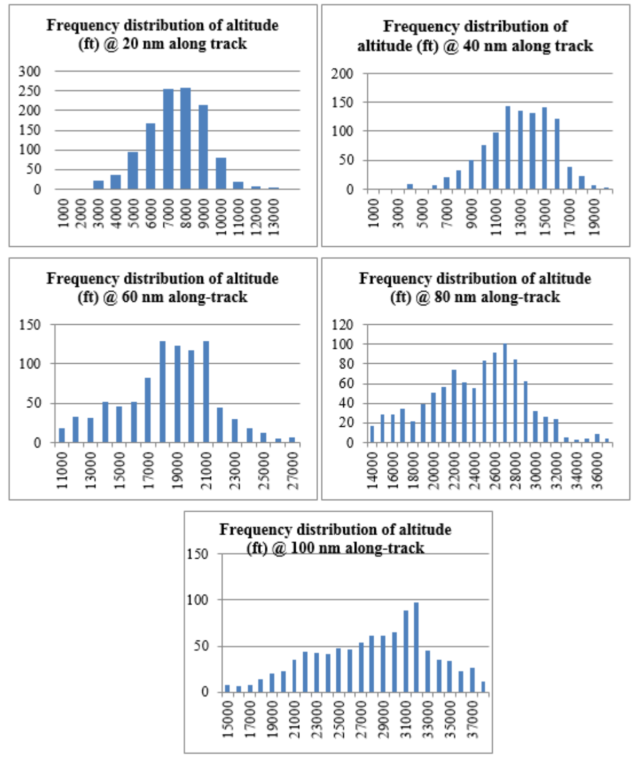

Fig.6: Illustrates frequency distribution of CDA altitude (ft) at various pseudo along-track waypoints (27L/R, 28 – ERLIN – ATL)

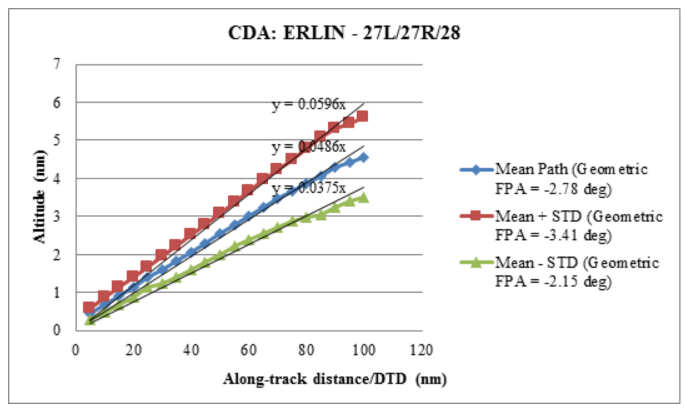

Fig.7: Captures variation in vertical profiles of CDA with Stdev (27L/R,28 – ERLIN – ATL)

A.3.3 STAR CANUK: Runway 9L/9R ATL - The simulated CDA dataset that was analyzed contained 95 samples of distinct flight arrivals to runway 9L/9R following STAR – CANUK without adhering to published altitude constraints of step-down approach.

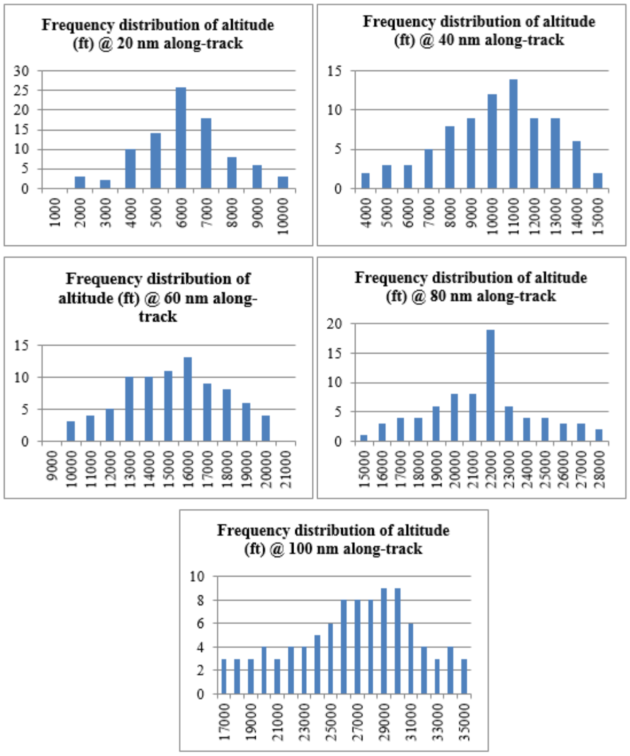

Fig.8: Illustrates frequency distribution of CDA altitude (ft) at various pseudo along-track waypoints (9L/R – CANUK – ATL)

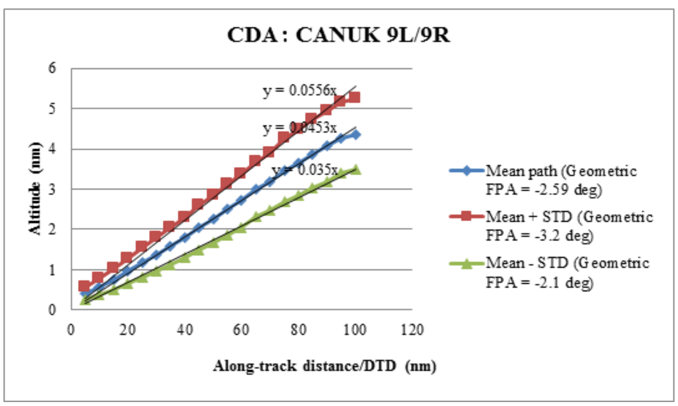

Fig.9: Captures variation in vertical profiles of CDA with Stdev (9L/R – CANUK – ATL)

A.3.4 STAR HONIE: Runway 27L/27R/28 ATL - The simulated CDA dataset that was analyzed contained 286 samples of distinct flight arrivals to runway 27L/27R/28 following STAR – HONIE without adhering to published altitude constraints of step-down approach.

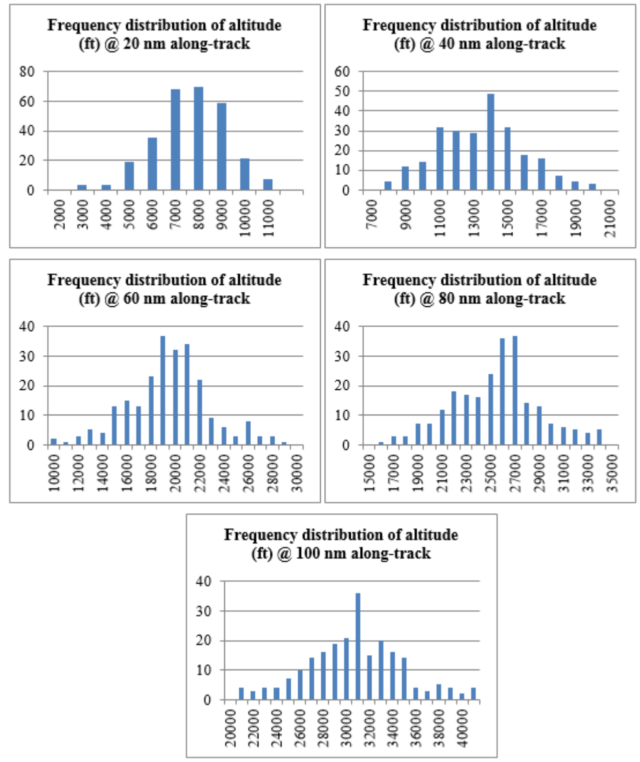

Fig.10: Illustrates frequency distribution of CDA altitude (ft) at various pseudo along-track waypoints (27L/R, 28 – HONIE – ATL)

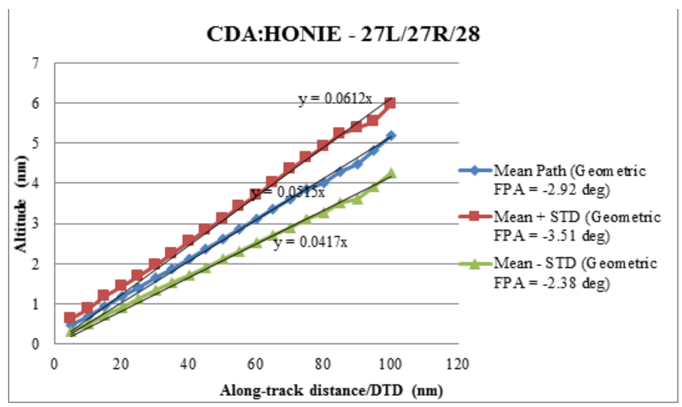

Fig.11: Captures variation in vertical profiles of CDA with Stdev (27L/R, 28 – HONIE – ATL)

B. Case Study 2: San Francisco International Airport

This section is dedicated to evaluation of vertical profiles of CDA at San Francisco International Airport (SFO). San Francisco International Airport is selected as the objective of this study because it is the largest airport in northern California, where average aircraft operations per day is 1179. The aircraft arriving at SFO are also typical mixture of all aircraft types with 7 jet aircraft operations per 10 aircraft on the field [37]. Hence evaluation of crossing altitudes at waypoints due to CDA will be a beneficial reference. The motivation of this case study is to apply the conclusions from the previous section to the real flown procedures. The results in this section will further verify those conclusions, and will provide hints on how to design altitude constraints at waypoints based on descent profile characteristics of various aircraft types.

B.1. Data Source: The flight data were obtained from [37], and the weather data, including temperature and wind information, were retrieved from [37]. The dataset provided by [37] contains radar tracks of all flights over 50 days in 2006 in the Northern California TRACON. The dataset includes both arrivals and departures at all airports within the TRACON. However, this research is only concerned with the arrivals at SFO. Furthermore, the vertical profiles of CDA associated with the following STARs were studied in order to discern crossing altitudes at various critical waypoints.

B.2. Simulation of CDAs at SFO: The CDAs were simulated assuming ground tracks remained the same as their realistic counterparts. As illustrated in Figure 1, the modeled CDA vertical profile typically consist of smooth descent from TOD till intercepting glide slope angle of 3 degree (practical ILS standards) near the runway. Therefore, simulation was carried out without any altitude constraints. Once the CDA intercepts glide slope angle, the vertical path is set identical to the conventional baseline procedure, because CDA is not distinguished from conventional approach in this phase of flight. The CDA speed profile of each flight was assumed identical to speed profile of corresponding realistic counterpart (step-down) as recorded by radar. It is justifiable that the best way to do the comparison between CDA and realistic counterpart (step-down) is to develop speed profile for CDA that is consistent with the radar-recorded data. As this speed profile would account for the local environment, air traffic condition and realistic speed profile of various aircraft. In this research, true airspeed is approximated by the vector difference between ground speed and wind speed.

B.3. Simulation Results and Analysis: The CDAs that primarily consists in their flight plan destination as SFO were investigated. As stated earlier, CDAs were simulated without any type of altitude constraints but with speed restrictions imposed on them. The vertical profiles of CDA were then evaluated at 10 equi-spaced pseudo waypoints, separated by along-track distance of 10 nm, starting from 10 nm from the runway till 100 nm from it. The evaluation of vertical profiles of CDA was carried out using statistical analysis at each of these points. All the flights which involved cruise altitude less than 20,000 ft were filtered out in order to count only altitudes related to descent phase of flight for statistical analysis at pre-defined pseudo waypoints. The variability was statistically measured using mean, standard deviation and normal distribution plots of altitude at these pre-defined waypoints. This approach enabled to holistically determine CDA profile characteristics of all the simulated aircraft types and provide estimate of the required altitude and FPA constraints at various along-track waypoints based on realistic speed profiles.

B.3.1. STAR GOLDEN: SFO- The simulated CDA dataset that was analyzed contained 383 samples of distinct flight arrivals to SFO following STAR – GOLDEN without adhering to published altitude constraints of step-down approach.

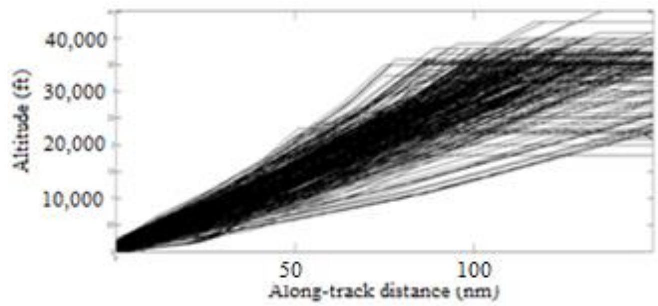

Fig.12: Illustrates various vertical profiles of idle thrust CDA at SFO along GOLDEN Arrival

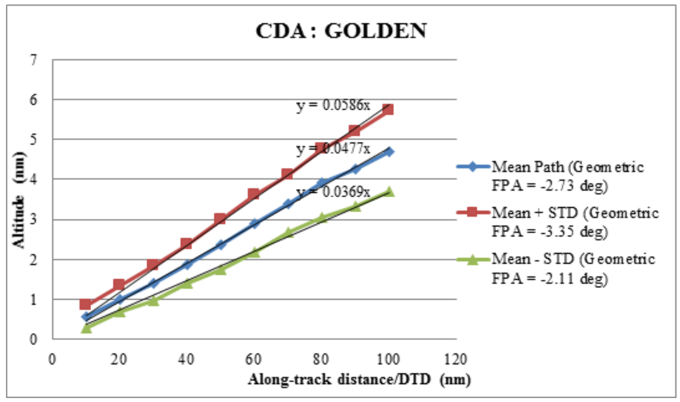

Fig.13: Captures variation in vertical profiles of CDA with Stdev (GOLDEN–SFO)

C. Case Study 3: New York Metroplex Area

The New York Metroplex Area, which consists of Newark Liberty International Airport (EWR), John F Kennedy International Airport (JFK), La Guardia Airport (LGA), and Teterboro Airport (TEB), is one of the busiest aerospace in the world. Table 1 shows the metrics of flight operation at New York Metroplex. EWR, JFK, and LGA are three major airports in this area, while TEB is a minor one. It is a typical example of a terminal aerospace with multiple major hub airports [38], and is thus an ideal sample to study the interactions among multiple airports within a small region. In this section, further investigation on vertical profiles of CDA will be carried out.

Table 1. Statistics for New York Metroplex on August 24, 2005

Airports	EWR	JFK	LGA	TEB	Total
Arrivals	717	597	682	268	2264

C.1. Data Source: The Aircraft Situation Display to Industry (ASDI) data, which was provided by the FAA, was used in this research. This dataset contains the detailed flight information of all flights arriving at or departing from any one of the four airports in the Metroplex on August 24, 2005[38]. The flight information includes latitude, longitude, altitude, ground speed, vertical speed, and heading, from initial climb through the runway threshold. The ASDI data also includes the flight plan, which was used to determine the standard approach procedure in this research.

C.2. Simulation of CDAs at New York Metroplex: The Aircraft Situation Display to Industry (ASDI) data, which was provided by the FAA, was used in this research. This dataset contains the detailed flight information of all flights arriving at or departing from any one of the four airports in the Metroplex. The flight information includes latitude, longitude, altitude, ground speed, vertical speed, and heading, from initial climb through the runway threshold. The ASDI data also includes the flight plan, which was used to determine the standard approach procedure in this research. Based on the inspection of the tracks, a waypoint-based model for the Metroplex was built. The CDAs were simulated using the same methodology as used for ATL[38].

C.3. Simulation Results and Analysis: The CDAs that primarily consists in their flight plan either one of these destinations: EWR and JFK were investigated. As stated earlier, CDAs were simulated without any type of altitude constraints but with speed restrictions imposed on them. The vertical profiles of CDA were then evaluated at 10 equi-spaced pseudo waypoints, separated by along-track distance of 10 nm, starting from 10 nm from the runway till 50/100 nm from it. The evaluation of vertical profiles of CDA was carried out using statistical analysis at each of these points. The variability was statistically measured using mean, standard deviation and normal distribution plots of altitude at these pre-defined waypoints. This approach enabled to holistically determine CDA profile characteristics of all the simulated aircraft types and provide estimate of the required altitude and FPA constraints at various along-track waypoints based on realistic speed profiles.

C.3.1. STAR DYLIN: EWR - The simulated CDA dataset that was analyzed contained 334 samples of distinct flight arrivals to EWR following STAR – DYLIN without adhering to published altitude constraints of step-down approach.

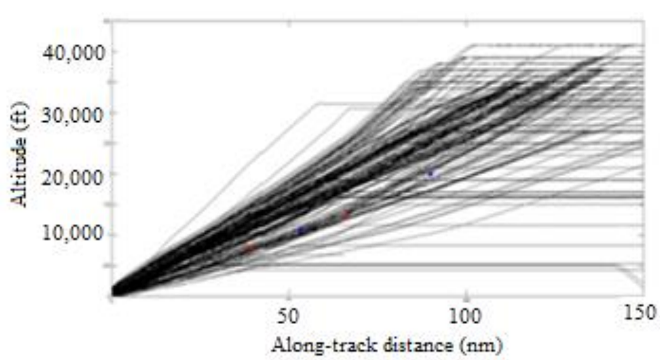

Fig. 14: Illustrates various vertical profiles of idle thrust CDA at EWR along DYLIN

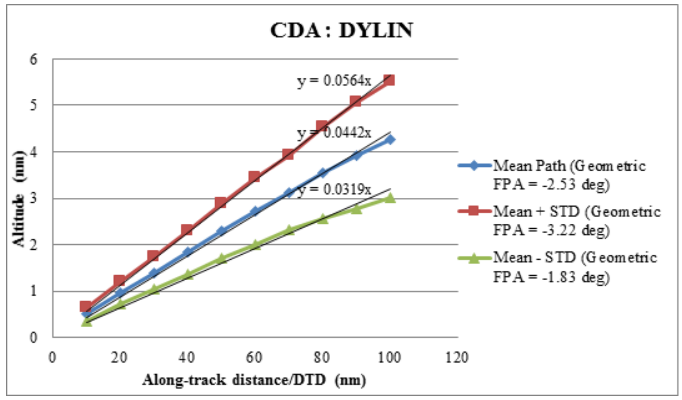

Fig. 15: Captures variation in vertical profiles of CDA with Stdev (DYLIN – EWR)

C.3.2. STAR CAMRN: JFK - The simulated CDA dataset that was analyzed contained 339 samples of distinct flight arrivals to JFK following STAR – CAMRN without adhering to published altitude constraints of step-down approach.

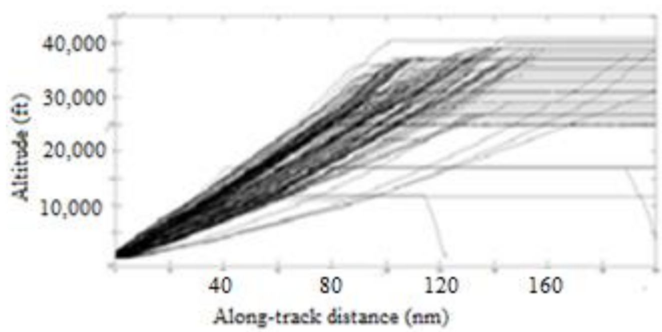

Fig. 16: Illustrates various vertical profiles of idle thrust CDA at JFK along CAMRN

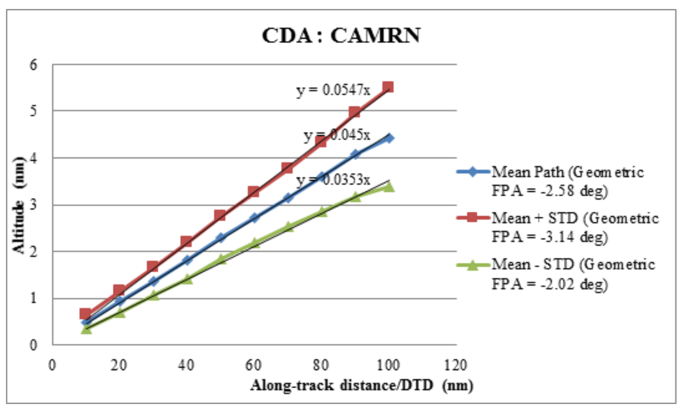

Fig. 17: Captures variation in vertical profiles of CDA with Stdev (CAMRN-JFK)

D. Error Analysis

The following might have introduced error in the statistical analysis of vertical profiles of CDA:

1) Laterally (ground-track) the synthesized CDA data was exactly matched with the corresponding conventional step-down descent. However, the BOD of the simulated descents in some occasions ended above the BOD altitude.

2) Wind is assumed to be insensitive to altitude in this research. However, both the magnitude and direction of wind vector could change with altitude (wind gradient).

3) Speed profile is another major potential source of uncertainty. As mentioned. although a compromised speed profile which to some extent accounts for both the CDA procedure and the realistic local condition is used in this research, any change from the modeled speed profile could result in significant error.

4) BADA model itself could also be a source of uncertainty. The speed profile recommended by BADA does not account for the local traffic and weather condition, and the accuracy of its aircraft performance data is challenged by some researchers [8].

5) Finally, nominal aircraft mass is used in this analysis, and is approximated as a constant. From the total energy model (TEM), for a decelerating aircraft in descent flight phase the fuel flow rate increases with decrease in mass of the aircraft. This implies that variation in geometric FPA with reduction in weight of the aircraft has been underestimated.

E. Consolidated Results

Table 2: Absolute value of Geometric FPA (Deg)

Case Study	**Mean Geometric FPA – 1*Stdev (Deg °)**	**Mean Geometric FPA (Deg °)**	**Mean Geometric FPA + 1*Stdev (Deg °)**
ERLIN – ATL (26L/26R)	2.33	2.89	3.43
ERLIN – ATL (27L/27R/28)	2.15	2.78	3.41
CANUK-ATL (9L/9R)	2.1	2.59	3.2
HONIE – ATL (27L/27R/28)	2.38	2.92	3.51
GOLDEN – SFO	2.11	2.73	3.35
DYLIN – EWR	1.83	2.53	3.22
CAMRN – JFK	2.02	2.58	3.14

Hence, from the above table it can be clearly seen that absolute value of mean FPA for CDA is less (shallower) than 3 degree glideslope angle.

6. CONCLUSIONS

The equations derived using flight dynamics and BADA TEM showed that vertical profile of idle-thrust CDA is highly sensitive to multiple factors like descent speed profile, wind speed and gradient, aircraft type and configuration, weight, and atmospheric conditions (DISA, density and pressure). Preliminary analysis of the derived equations gave an insight that descent path of idle-thrust CDA becomes shallower with the following changes in the input parameters 1) increase in weight, 2) decrease in descent speed, 3) increase in magnitude of tailwind, and 4) presence of positive tailwind gradient. On the other hand, extension of slats and/or flaps (i.e. increase in Drag) would cause idle-thrust CDA at steeper FPA. The predictability and variability of idle-thrust CDA is cause of concern to all the stakeholders responsible for CDA operations as regular arrival procedure. Given these uncertainties, ATC tend to reserve large airspace buffers (laterally and vertically) around each idle descent aircraft to ensure the required separation. From the derived equations it can also be seen that fixed geometry FPA CDA at planned CAS/Mach speed schedule has higher degree of vertical predictability and lesser variability compared to the idle-thrust CDA at planned CAS/Mach speed schedule, but this is achieved at the cost of non-idle thrust settings. However, with optimization of fixed FPA CDA overall impact of fuel burn per flight can be reduced.

Furthermore, from the operational perspective, for the FMS guided aircraft coupled with AP and AT, capability of the FMS to provide geometric descent path in prediction and guidance context is a must have feature in order to achieve high level of predictability in space (vertical and lateral).

The statistical analysis of the vertical profiles of CDA at ATL, SFO and New York Metroplex (JFK and EWR)) demonstrated that mean of fixed geometric FPAs derived from the statistical analysis of vertical profiles (CDA) of various aircraft at equidistant along-track pseudo waypoints are consistently shallower than 3° glideslope angle. The statistical analysis also suggested that for procedure design, window type, 'AT or above', 'AT or below' and 'Window' altitude and FPA constraints are more realistic and useful compared to obsolete 'AT' type altitude constraint because of variability in vertical profiles.

7. ACKNOWLEDGMENT

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9. BIOGRAPHY

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