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Investigation of Potential Fuel Savings Due to Continuous-Descent Approach

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The continuous-descent approach is among the key concepts of the Next Generation Air Transportation System. Although a considerable number of researchers have been devoted to the estimation of potential fuel savings of the continuous-descent approach, few have attempted to explain the fuel savings observed in field tests from an analytical point of view. This paper focuses on the evaluation of the continuous-descent approach as a fuel-reduction procedure. This research gives insights into the reasons why the continuous-descent approach saves fuel, and design guidelines for the continuous-descent-approach procedures are derived. The analytical relationship between speed, altitude, and fuel burn is derived based on the base of aircraft data total-energy model. A theoretical analysis implies that speed profile has an impact as substantial as, if not more than, vertical profile on the fuel consumption in the terminal area. In addition, the continuous-descent approach is not intrinsically a fuel-saving procedure: whether the continuous-descent approach saves fuel or not is contingent upon whether the speed schedule is properly designed or not. Based on this model, the potential fuel savings due to the continuous-descent approach at the San Francisco International Airport are estimated, and the accuracy of this estimation is analyzed.

I. Introduction

THE continuous-descent approach (CDA) is one of the key concepts of the Next Generation Air Transportation System [1]. A number of researchers reported that the CDA results in significant noise abatement as well as fuel savings [2]. The noise abatement results from increased altitude and idle thrust [2], and the fuel savings are to some extent due to the same factors. However, the specific amount of fuel savings is difficult to determine. The 2002 field test at the Louisville International Airport (SDF) [2] reported approximately 200 kg of fuel savings per flight for B767s, whereas the 2007 field test at the Atlanta International Airport [3] suggested 462 kg of fuel savings per flight for B757s, and 602 kg for B767s. Robinson and Kamgarpour [4] examined more than 480,000 flights and concluded that the CDA saves no more than 100 kg of fuel for over 87% of all the flights. In addition, they noted that the main reason why the CDA saves fuel is that the CDA shifts the level segments in the terminal area to the cruise altitude.

Nonetheless, little research has been dedicated to the theoretical justification of the CDA as a fuel-saving procedure. Although field tests are the most accurate and reliable method for the estimation of fuel consumption, they are expensive and time consuming, and involve huge amounts of labor. On the other hand, mathematical modeling provides an alternative methodology to analyze the macroscopic behavior of fuel consumption of a variety of aircraft types, and provides the basis for further development of practical CDA procedures. Therefore, this research is devoted to the theoretical analysis of the influence of approach procedure on fuel consumption. In this research, the condition for a fuel-saving CDA is derived, and multiple design guidelines are proposed.

This paper is organized as follows. Section II reviews some previous research. In Sec. III, an analytical link between flight operation parameters and fuel consumption is derived based on the base of aircraft database (BADA) total-energy model (TEM), resulting in some guidelines for the CDA design. Based on the results from Sec. III, Sec. IV presents a case study at the San Francisco International Airport (SFO), in which the macroscopic fuel savings are estimated. Remarks and comments are provided in Sec. V.

II. Background

Conventionally, an aircraft experiences some level-offs during its descent. The level-offs, as illustrated in Fig. 1, are assigned by the air-traffic controller (ATC) to provide the controller with the opportunity to command the aircraft to meet a variety of constraints [5]. Such level-offs tend to produce significant noise and fuel consumption [2]. On the other hand, the CDA is a continuous, idle-thrust descent without any level-offs. There has not been a precise definition of the CDA so far [5]. In this research, the CDA is defined as an approach procedure without level segments under a certain altitude, typically 12,000 ft, and level segments above that altitude are allowed. Such a definition is widely accepted [2,6–8]. So far, no definition of the CDA's speed profile has been proposed. The CDA typically avoids such level segments at low altitude, and thus reduces noise and fuel consumption. However, one more reason why the CDA reduces fuel consumption has not been revealed by previous research (i.e., that the CDA typically changes the speed profile). The trajectory of a descending aircraft is extremely difficult to predict, and the ATC typically does not interrupt a descent [5]. Such poor predictability of descent is the major obstacle that prevents the CDA from being employed in high-density operations [9–11].

A significant number of investigations have been dedicated to the estimation of the potential fuel savings of the CDA, a few of which will be reviewed here. Robinson and Kamgarpour [4] estimated the potential fuel savings for 25 major airports in the National Airspace System using the BADA model. A distance-constrained and a time-constrained CDA trajectory were designed for each flight using the nominal speed specified by the BADA. Dinges [8], on the contrary, assumed a CDA speed profile that is identical to the average speed profile derived from realistic conventional procedures. Shresta et al. [12] used a similar strategy to model the CDA procedure. Level segments at lower altitude were shifted to the cruise altitude, and the speed profile was assumed unchanged.

The BADA is employed in this research for fuel estimation. Because the BADA is a database derived from reference sources instead of field tests [13], error is inevitable when it is used to estimate fuel consumption. Robinson and Kamgarpour [4] reported that the BADA (revision 3.7) recommends excessively high speed in

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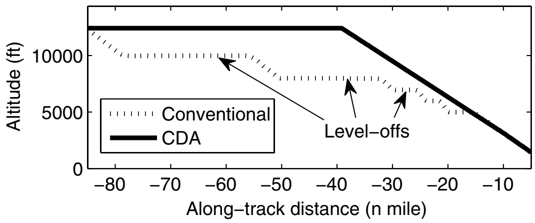


Fig. 1 Comparison between the vertical profiles of a conventional, step-down approach and the CDA.

final approach. Senzig et al. [14] found that the BADA (revision 3.6) gives inaccurate thrust specific fuel consumption (TSFC). Some of the inaccuracies are fixed in the latest revision 3.9, which is used in this research. Nevertheless, as will be discussed in Sec. IV, this revision still gives higher airspeeds in the terminal area than those retrieved from radar records. Therefore, the CDA operating speed is adjusted in this research. In addition, to further improve the accuracy, the TSFC model proposed by Senzig et al. [14] is used.

III. Theoretical Analysis of Fuel Consumption in the Terminal Area

In this section, the analytical relationship between procedure variables (vertical profile and speed profile) and fuel consumption is derived. The fuel consumption is expressed as a function of the vertical profile and the speed profile, which is fundamentally nonlinear. Such nonlinearity will produce some nonintuitive effects, for instance, elevation of flight level, increasing fuel consumption. The results from this derivation will be applied to two special cases to provide insights into fuel consumption in the terminal area, and to explain the reason why the CDA typically reduces fuel consumption.

A. BADA TEM

The quantitative analysis in this research is largely based on the fuel model of the BADA developed by EUROCONTROL [15]. The key idea of this fuel model is the TEM [13], which is analytically demonstrated by

$$(\mathrm{Thr}-D)V_{\mathrm{TAS}} = mg_0\dot{h} + mV_{\mathrm{TAS}}\dot{V}_{\mathrm{TAS}} \tag{1}$$

in which

Thr	=	thrust's projection along the velocity vector
D	=	aerodynamic drag
m	=	aircraft mass
h	=	geodetic altitude
g_0	=	gravitational acceleration
V_{TAS}	=	true airspeed

The dotted terms are derivatives with respect to time.

This equation is derived from the work–energy theorem. The left-hand side of this equation is the power given by thrust and drag, and the right-hand side is the rate of change in mechanical energy, with the first term accounting for potential energy and the second term for kinetic energy. True airspeed is a scalar in this circumstance, and therefore $\dot{V}_{\mathrm{TAS}}$ is the rate of change in magnitude of true airspeed rather than the acceleration. In this research, in which the four-dimensional (4-D) trajectory is known, this equation is used for the determination of thrust, and thus the fuel flow rate. Drag is also an unknown quantity, but it can be calculated from the altitude, true airspeed, and air density using the BADA TEM.

Equation (1) is intuitive in that it yields the conclusions that a descending aircraft ($\dot{h} < 0$) requires less thrust than a cruising aircraft ($\dot{h} = 0$), and that a decelerating aircraft ($\dot{V}_{\mathrm{TAS}} < 0$) requires less thrust than an aircraft at a constant speed ($\dot{V}_{\mathrm{TAS}} = 0$). Such conclusions are also the fundamental reason why cruise and descent are distinguished in this TEM, inasmuch as, from an ATC's point of view, $\dot{h}$ and $\dot{V}_{\mathrm{TAS}}$ are among the major parameters characterizing the flight mode of an aircraft. It has to be clarified here that in this paper, the term "cruise" is used to refer to level flight with a clean flap configuration (i.e., the cruise mode in the BADA) rather than the en route phase between climb and descent.

B. Derivation of Fuel Consumption

Consider an aircraft flying over a linear track of a fixed length. For simplification, it is assumed in this derivation that geopotential pressure altitude H_p is equal to the geodetic altitude h, and that true airspeed V_{TAS} is equal to ground speed v, which implies the international standard atmosphere and no wind. Dividing by speed on both sides, Eq. (1) is reduced to

$$\mathrm{Thr} = mg\frac{\dot{h}}{v} + m\dot{v} + D \tag{2}$$

Because this derivation is intended for a given track of a given length without any time specifications, time derivatives inhibit such derivation. To eliminate the time derivatives in Eq. (2), $\dot{h}/v$ is substituted by the flight-path angle $\gamma = \sin^{-1}(\dot{h}/v)$, and $\dot{v}$ is substituted by

$$\frac{\mathrm{d}v}{\mathrm{d}s}\frac{\mathrm{d}s}{\mathrm{d}t} = \frac{\mathrm{d}v}{\mathrm{d}s}v$$

in which s is the along-track distance. Now, the thrust is given by

$$\mathrm{Thr} = mg\,\sin\gamma + m\frac{\mathrm{d}v}{\mathrm{d}s}v + D \tag{3}$$

Note that for descent, γ typically ranges from -2 through -4 deg. According to the aerodynamic model, the drag is given by

$$D = \frac{C_{D0}\rho S}{2}v^2 + \frac{2C_{D2}m^2g_0^2}{\rho S}\frac{1}{v^2} \tag{4}$$

in which C_{D0} and C_{D2} are BADA coefficients associated with the drag coefficient that are dependent of the flap setting, ρ is air density, and S is the wing reference area. The thrust can thus be derived using Eqs. (2) and (4). For jet aircraft, the TSFC η modeled by the BADA is given by

$$\eta = C_{f1}\left(1 + \frac{v}{C_{f2}}\right) \tag{5}$$

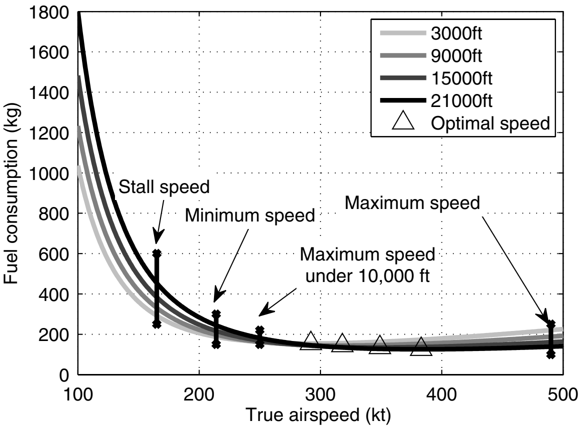
It is worth noting that this linear formula proposed by the BADA is used for derivation in this section because of its simplicity and adequate accuracy. However, this formula is replaced by the more accurate formula proposed by Senzig et al. [14] in Sec. IV. The reason why a more accurate formula is not used here is that that formula contains an exponential term, which would make the time integral [Eq. (8)] extremely difficult. Such simplification is reasonable, inasmuch as the numerical difference is insignificant and the general characteristics of the entire model are not impeded (see Fig. 2b). The TSFC model for turboprop engines is similar, whereas for piston engines the TSFC is assumed to be constant for all altitudes and all speeds. The fuel flow rate is given by

$$\mathrm{fr} = C_f\mathrm{Thr}\cdot\eta \tag{6}$$

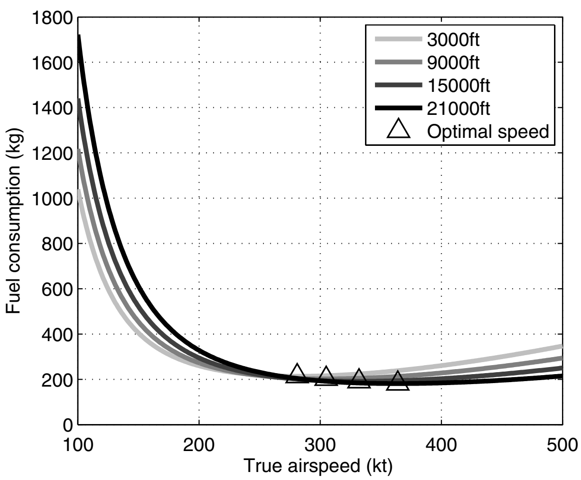
in which C_f is a coefficient defined differently for cruising and the other flight modes. Substituting Eqs. (3) through (5) into Eq. (6) gives the expression of fuel flow rate:

$$\mathrm{fr} = A_3v^3 + \left(A_{21}\frac{\mathrm{d}v}{\mathrm{d}s} + A_{22}\right)v^2 + \left(A_{11}\frac{\mathrm{d}v}{\mathrm{d}s} + A_{12}\right)v + A_0 + \frac{A_{-1}}{v} + \frac{A_{-2}}{v^2} \tag{7}$$

in which



a) Relationship between fuel consumption and speed



b) Fuel curves given by the Volpe model [14]

Fig. 2 Influence of speed on fuel consumption (constant-speed cruise) for the B747-400. a) Altitudes indicated in the inset, and b) only insignificant differences are observed.

$$A_3 = \frac{C_f C_{f1} C_{D0} S\rho}{2C_{f2}}$$

$$A_{21} = \frac{C_f C_{f1}}{C_{f2}} m$$

$$A_{22} = \frac{C_f C_{f1} C_{D0} S\rho}{2}$$

$$A_{11} = \frac{C_f C_{f1}}{C_{f2}} m g_0 \sin\gamma$$

$$A_{12} = C_f C_{f1} m$$

$$A_0 = C_f C_{f1} m g_0 \sin\gamma$$

$$A_{-1} = \frac{2C_f C_{f1} C_{D2} m^2 g_0^2}{C_{f2} S\rho}$$

$$A_{-2} = \frac{2C_f C_{f1} C_{D0} m^2 g_0^2}{S\rho}$$

Note that those coefficients that contain air density are typically varying when the altitude is changing. Then, the fuel consumption is the integral of fuel rate with respect to time.

$$\mathrm{FC} = \int_0^T \left[A_3 v^3 + \left(A_{21} \frac{\mathrm{d}v}{\mathrm{d}s} + A_{22} \right) v^2 + \left(A_{11} \frac{\mathrm{d}v}{\mathrm{d}s} + A_{12} \right) v + A_0 + \frac{A_{-1}}{v} + \frac{A_{-2}}{v^2} \right] \mathrm{d}t \tag{8}$$

in which T is the final time. Because $\mathrm{d}t = \mathrm{d}s/v$, replacing the integral variable t by s yields

$$\begin{aligned} \mathrm{FC} &= \int_0^S \left[A_3 v^2 + \left(A_{21} \frac{dv}{ds} + A_{22} \right) v + \left(A_{11} \frac{dv}{ds} + A_{12} \right) + A_0 \frac{1}{v} + \frac{A_{-1}}{v^2} + \frac{A_{-2}}{v^3} \right] \mathrm{d}s \\ &= \int_0^S \left(A_3 v^2 + A_{22} v + A_{12} + A_0 \frac{1}{v} + \frac{A_{-1}}{v^2} + \frac{A_{-2}}{v^3} \right) \mathrm{d}s + \int_{V(0)}^{V(S)} (A_{21} v + A_{11}) \mathrm{d}v \end{aligned} \tag{9}$$

in which S is the length of the entire track. Usually, the speed profile v is specified by the ATC as a function of along-track distance $v(s)$ (i.e., speed constraints). Therefore, the first integral in Eq. (9) could be difficult if $v(s)$ were difficult. However, the second integral in this equation is only determined by $v(0)$ and $v(S)$ (i.e., the initial and final speeds). An analytical interpretation of Eq. (9) is available in the next section.

C. Impact of Speed and Altitude on Fuel Consumption

Generally speaking, for a given type of aircraft and a given weather condition, flight speed and altitude play the most significant roles in the determination of fuel consumption. The generic analysis in this section will be further substantiated by the case studies for specific aircraft types demonstrated in Sec. III.D.3.

1. Impact of Speed

An inspection of Eq. (9) yields the conclusion that the influence of speed v on fuel consumption FC is nonlinear and not monotonic. Such conclusion largely results from the nonlinear nature of aerodynamic drag [see Eq. (4)]. As speed increases, the drag decreases at a low speed range, but increases at a high speed range. Such nonlinearity results in a nonlinear power curve, which typically consists of a front side and a back side [16].

Even if an aircraft is operating on the front side (i.e., where the power required increases as airspeed increases), the fuel burn is still not necessarily monotonically increased with speed, because a higher speed, although increasing power, reduces the flight time. Therefore, the behavior of fuel burn, which is associated with the product of power and time, is nonmonotonic. Because the speed term appears in the denominators in Eq. (8), the fuel consumption increases hyperbolically as speed becomes really low, as illustrated in Fig. 2a. The physical meaning of such a drastic increase is that low speed leads to a large lift coefficient and higher drag, as well as an increased operating time.

It is noteworthy that the feasible speed range is defined by the flight envelope, which is indicated in Fig. 2a. In the case of the B747-400, the cruise stall speed is 165 kt and the minimum operating speed is 214 kt, whereas the maximum speed is 490 kt. In addition, the Federal Aviation Administration (FAA) imposes a 250 kt speed limit for flight below 10,000 ft. Therefore, some of the data points in Fig. 2a are only mathematically meaningful, but not technically feasible.

2. Impact of Altitude

Flight altitude influences fuel burn by changing air density, on which aerodynamic drag is strongly dependent. According to Eq. (4), such influence is also nonlinear. Generally speaking, air density declines as altitude increases, and thus the drag is reduced. However, if the airspeed were really low, then the second term in Eq. (4), which is associated with lift coefficient, would tend to dominate, and the drag would increase rapidly with altitude. As illustrated in Fig. 3, whether fuel consumption increases or decreases with altitude depends on the speed range.

D. Two Typical Cases

Equation (9) can be reduced in some special cases. In this section, two typical flight modes will be analyzed, namely, constant-speed cruise and constant-speed descent. Constant mass is assumed for both cases.

1. Constant-Speed Cruise

Constant-speed cruise (or level flight) is one of the typical flight modes in the terminal area, and a significant portion of the potential fuel savings due to the CDA comes from this flight phase. For constant-speed cruise, $v(s) = V$ over the entire track. Also note that the flight-path angle vanishes for cruise. Now, Eq. (9) reduces to

$$\mathrm{FC} = \left(A_3 V^2 + A_{22} V + A_{12} + A_0 \frac{1}{V} + \frac{A_{-1}}{V^2} + \frac{A_{-2}}{V^3}\right) S \tag{10}$$

At a given altitude, all coefficients in this equation are constant. Boeing 747-400, which exhibits a significant potential for fuel savings in this research, is selected as the example type in this section. Consider a cleanly configured B747-400 cruising over a linear track of 10,000 m. As illustrated in Fig. 2a, in which curves of different colors represent different altitudes, a lower speed drastically increases fuel consumption, whereas a higher speed gradually increases fuel consumption. As a benchmark, a similar set of curves is generated using the TSFC model proposed by Senzig et al. [14] (Fig. 2b). For each altitude, a fuel-optimal speed that consumes the minimal fuel can be determined (see Fig. 4). Figure 2a implies that, for the sake of minimal fuel consumption, an aircraft has to fly at a speed as close to the fuel-optimal speed as possible. These fuel-optimal speeds appear to be feasible in that they are not far away from the practiced airspeed. Another implication is that a high-speed level flight at a high altitude is generally preferred to a low-speed level flight at a low altitude. In addition, it is observed that, in the low speed range, speed has more considerable impact on fuel consumption than altitude does. Moreover, at low speeds, fuel consumption increases with altitude, the implication being that a CDA procedure operated at a low-speed level probably increases fuel consumption, which is opposite to the intention of the CDA. Hence, level flight at a low speed should be reduced as much as possible. Similar fuel patterns are observed for other aircraft types (see Fig. 5).

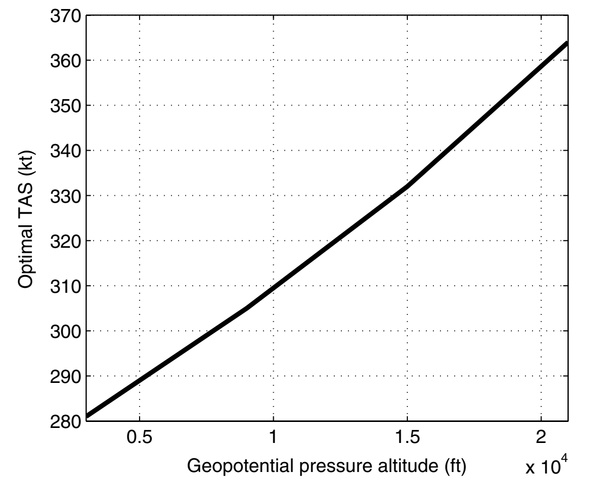


Fig. 4 Optimal speed for different altitudes for the B747-400. TAS denotes true airspeed.

2. Constant-Speed Descent

Constant-speed descent is fundamentally similar to constant-speed cruise except for two aspects. First, the flight-path angle does not vanish and will influence the fuel flow rate, which is the primary way that the TEM characterizes the differences between cruise and descent. In this section, the flight-path angle is set to be the nominal 3 deg. Second, the air density will be variable because the altitude is changing. Using the same methodology as indicated in the previous case, a similar set of curves for constant-speed descent is derived, as illustrated in Fig. 6b.

As implied by Fig. 6b, the fuel-optimal descent speed is typically lower than the fuel-optimal cruise speed. A descent procedure could follow this altitude–speed mapping to try to produce the minimal fuel. Although such procedure could suggest deceleration, which is not included in this constant-speed-descent model, it would give reference to the ATC for a speed profile with minimum fuel. Note that the altitudes indicated in the inset in Fig. 6a refer to the initial altitude.

3. How Does the CDA Save Fuel?

Most researchers have been reporting that the CDA reduces fuel consumption, but little analytical explanation has been developed to reveal the reason why the CDA saves fuel. To answer this question, the differences between the CDA and the conventional procedure have to be examined. Assuming the same ground track, the CDA and the conventional approach differ in three ways:

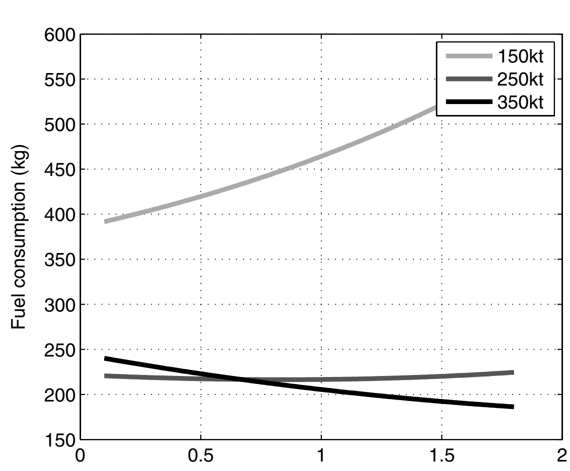


Fig. 3 Influence of altitude on fuel consumption for the B747-400 (constant-speed cruise).

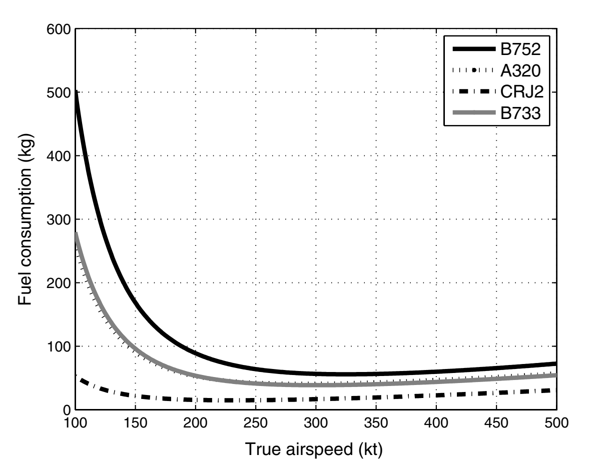
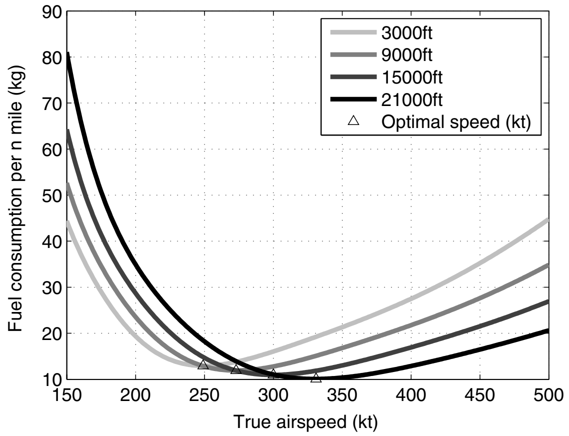
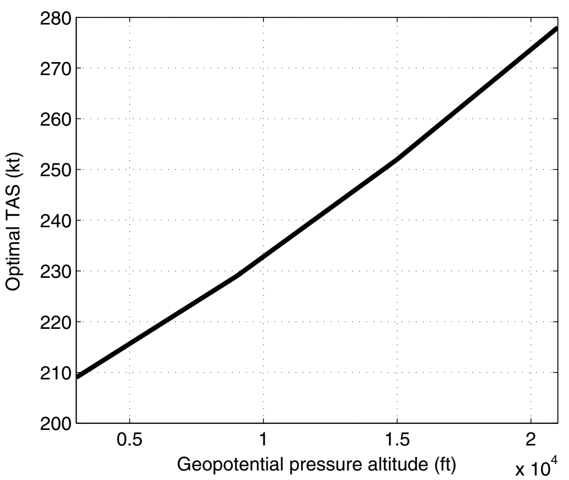


Fig. 5 Fuel–speed curves for some common aircraft types. The curves for the A320 and the B737-300 are very similar.



a) Relationship between fuel consumption and speed (altitudes indicated in the inset)



b) Fuel-optimal speed for different altitudes

Fig. 6 Influence of speed on fuel consumption (constant-speed descent). TAS denotes true airspeed.

1) The CDA eliminates level segments at low altitude by elevating them to a high altitude.

2) The CDA typically increases the average speed because in most cases, a higher indicated airspeed is assigned at a higher altitude. (As will be presented in Sec. IV, the fuel-optimal cruise speed is usually higher than the actual operating speed. Hence, the second reason can be further formulated as follows.)

3) The CDA moves the speed profile closer to the fuel-optimal speed profile.

Hence, the CDA saves fuel not only by elevating level-flight altitude, but, perhaps more importantly, by increasing speed, or more precisely, by shifting the speed profile closer to the fuel-optimal speed. The aforementioned arguments will be substantiated by the case study in Sec. IV.

Past research emphasized the elevated altitude of the CDA [4,6,8,12,17], but few researchers have mentioned the impact of speed. However, as implied by Fig. 3, speed influences fuel consumption as significantly as, if not more than, altitude. In other words, if a CDA procedure were designed without an appropriate speed profile, such CDA might consume even more fuel than the corresponding conventional procedure. This conclusion is further justified by the case study of a RJ-200 at the San Francisco International Airport, where the proposed CDA procedure consumes more fuel than the realistic step-down procedure (see Sec. IV.E.3).

In addition, Fig. 2a suggests that skillful manipulation of the speed profile could potentially be a promising strategy to fuel reduction, especially when the altitude constraint is binding. As illustrated in Fig. 2a, as much as 60 kg of fuel would be saved during a 10,000 m level segment at 9000 ft simply by changing the speed from 200 to 250 kt. A similar result is observed in constant-speed descent.

Although the CDA is intended to reduce fuel consumption and to abate noise simultaneously, which is the case in the high speed range (e.g., over 300 kt at 15,000 ft for the B747-400), these two objectives tend to conflict with each other in the low speed range (e.g., under 250 kt at 9000 ft). As illustrated in Fig. 3, elevation of altitude in the low speed range increases fuel consumption, which is opposite to the intended fuel benefits of the CDA. Therefore, level flight at low speed is never recommended in terms of fuel consumption.

Finally, another possible reason why the CDA saves fuel is that repeated acceleration/deceleration is largely avoided. However, this issue involves rescheduling techniques, and is thus beyond the scope of this paper, which focuses on the trajectory itself.

IV. Case Study: Potential Fuel Savings at the San Francisco International Airport (SFO)

This section is dedicated to the estimation and analysis of potential fuel savings due to the CDA at the San Francisco International Airport (SFO). The motivation of this case study is to apply the analyses from the previous section to realistic tracks. The results in this section will further verify those analyses, and will provide hints on how to avoid the unwanted negative fuel savings or how to maximize the fuel reduction. The flight data were obtained from [18], and the weather data, including temperature and wind information, were retrieved from [19].

A. Scenario and Scope

The San Francisco International Airport is selected as the objective of this study. The SFO is the largest airport in northern California, where over 400 arrival operations were conducted every day in January and March 2006. The types of aircraft arriving at the SFO are also typical, with a mixture of both wide-body and narrow-body aircraft. Hence, estimation of potential fuel savings due to the CDA at the SFO will be a beneficial reference. The data set provided by [18] contains radar tracks of all flights over 50 days in 2006 in the Northern California terminal radar approach control (TRACON). The data set includes both arrivals and departures at all airports within the TRACON. However, this research is only concerned with the arrivals at the SFO. Piston aircraft are excluded from this research for two reasons. First, piston aircraft typically consume much less fuel than jet and turboprop aircraft, and their macroscopic influence is insignificant. Second, the BADA model for piston aircraft assumes constant fuel flow rate for all altitudes and for all speeds, and is thus extremely insensitive to procedure.

B. Design of the CDA Procedure

The following two assumptions are made for the CDA trajectory:

1) All ground tracks remain unchanged.

2) All CDA procedures share the same initial and final positions with their realistic counterparts (see Fig. 7).

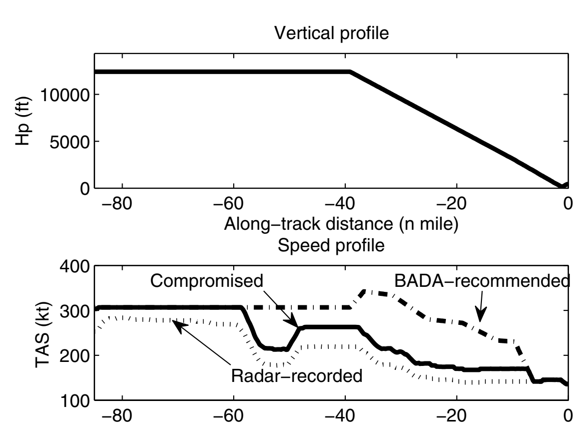


Fig. 7 Modeled CDA procedure and the realistic baseline procedure.

The first assumption is valid for distance-constrained procedures. The flown ground tracks were not altered because this research emphasizes the impact of vertical and speed profiles on fuel burn; path optimization, rescheduling, and runway balancing are beyond its scope. The results of this research can be seen as the upper bound of potential fuel savings [4]. The second assumption, which tends to result in a level segment at some 10,000 ft leading to underestimated fuel savings, was made due to lack of information of the flight track outside the terminal area. But this assumption is widely accepted and used [2,6,8,12,20]. In addition, such compromised CDA with a level segment at some 10,000 ft is even favored by the ATC because the level segment would considerably improve the predictability [2].

As illustrated in Fig. 7, the modeled CDA vertical profile typically consists of three phases, namely, cruise, a 3 deg descent, and a final approach/landing. This flight-path angle is accepted by most researchers and is a proper approximation for macroscopic estimation [21]. The last stage is set identical to the conventional baseline procedure because the CDA and the conventional approach do not differ in this stage [2,6,22]. Because fuel consumption strongly depends on speed profile, three CDA speed profiles are designed for each single flight (see Fig. 7). The first one assumes the same speed profile as recorded by radar for the original procedure. The second one uses the BADA-recommended speed profile. The third one is a compromise between the previous two models, which is defined as follows:

$$v(s) = \begin{cases} 0.8V_{\text{original}} & \text{when } V_{\text{BADA}} < 0.8V_{\text{original}} \\ 1.2V_{\text{original}} & \text{when } V_{\text{BADA}} > 1.2V_{\text{original}} \\ V_{\text{BADA}} & \text{otherwise} \end{cases}$$

The first strategy accounts for the local environmental and traffic condition as well as the realistic aircraft status, but it ignores the characteristics of the CDA. The second strategy designs the speed profile based on the vertical profile, but it does not account for the practical condition; frequently, even at the same altitude, the flown speed deviates considerably from the BADA-recommended value. The third one to some extent incorporates both factors. Therefore, the third strategy is assumed to be the most reliable one, but the other two strategies are also used for benchmarking.

However, the final approach speed (i.e., under 3000 ft) is always set equal to the radar-recorded speed profile because in this flight stage, the CDA and the conventional procedure are almost identical. In this research, true airspeed is approximated by the vector difference between ground speed and wind speed [23], as illustrated in the inset of Fig. 8. Figure 8 also shows that, as the heading angle changes, true airspeed becomes greater or less than ground speed. True airspeed is used for aerodynamic calculation, whereas ground speed is used for kinematic calculation.

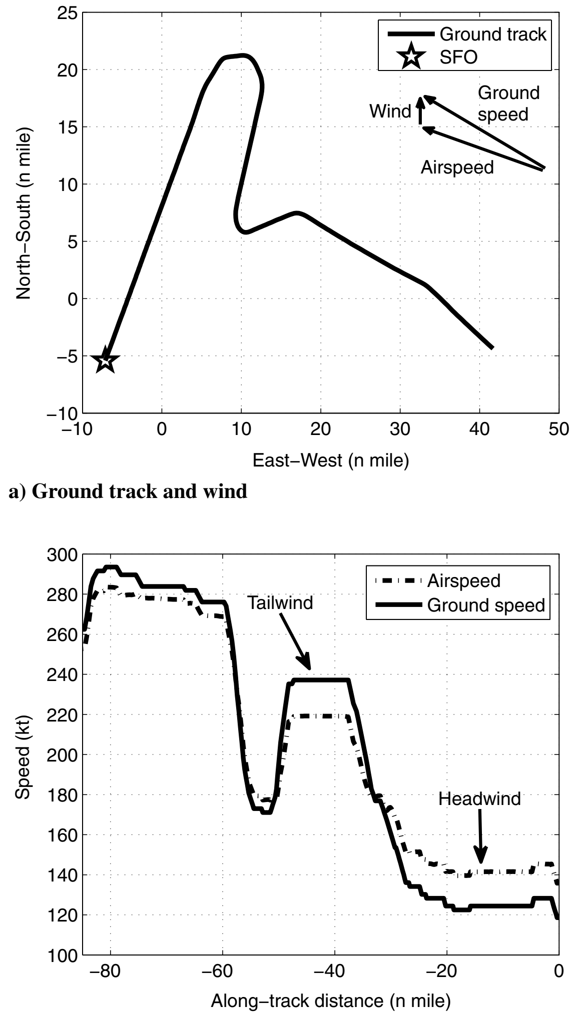
Another adjustment of the BADA model is the TSFC formula. Senzig et al. [14] proposed that Eq. (11) gives more accurate values:

$$\eta = \alpha + \beta_1 M + \beta_2 e^{-\beta_3 \frac{\text{Thr}}{F_0}} \tag{11}$$

in which M is the Mach number; F_0 is the static thrust; and α, β_1, β_2, and β_3 are empirical coefficients provided by the Aviation Environmental Design Tool (AEDT) database from the FAA. Because these coefficients are not developed for all aircraft types, for those aircraft types not included in the AEDT database, the BADA model [Eq. (5)] is used. In addition, a set of criteria in the BADA was employed to determine the flight phase or flap settings (cruise, approach, or landing) based on the 4-D trajectories, and different coefficients were used for different configurations.

C. Results

The estimation results are listed in Table 1. For both the radar-recorded speed profile and the compromised speed profile, the overall average fuel savings is negative, whereas the CDA procedure associated with the BADA-recommended speeds yielded positive fuel savings. The standard deviations are large, and therefore, a more specific investigation into this estimation has to be made.



a) Ground track and wind

b) True airspeed vs ground speed

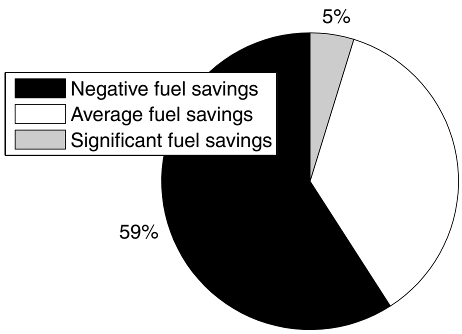
Fig. 8 Wind is incorporated in the kinematic and aerodynamic analyses. a) On the top right is the wind triangle [23].

As explained previously, the procedure associated with the compromised speed profile is the major objective of this research. For this speed-profile model, the distribution of the estimated fuel consumption is visualized in Fig. 9a. It is noted that the majority of the results (63%) exhibit negative fuel savings, more than one-third give average fuel savings (i.e., less than 100 kg), and the rest (5%) show significant fuel savings (>100 kg). Moreover, as illustrated in Fig. 9b (and indicated in Table 1), if the CDA were flown by all aircraft with the compromised speed schedule, the extra fuel consumed by the negative group would be even more than the fuel saved by the other two groups. Such a result does not necessarily imply that the CDA is an ineffective way to save fuel, but implies that the implementation of the CDA must be done with sufficient prudence and convincing justification: the CDA cannot be trusted as a fuel-saving procedure unless the procedure is properly designed for properly selected flights. Because nearly two-thirds of the fuel savings are associated with the significant group, which makes up only 5% of the total sample size, it is recommended that the

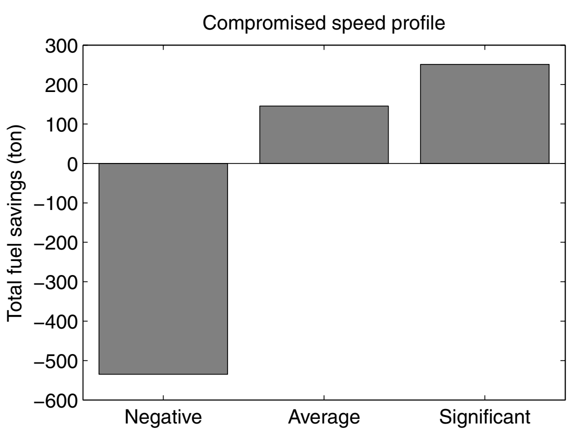
Table 1 Results for different speed profiles[a]

Speed profile	Radar recorded	BADA recommended	Compromised
Mean fuel savings, kg	−49.07	20.10	−6.19
Standard deviation, kg	65.02	113.34	78.04

[a]The sample size is 22,301.



a) Total distribution



b) Amount of saved fuel

Fig. 9 Distribution of fuel consumption associated with the compromised speed profile.

application of the CDA should be largely aimed at this group. The aircraft-type statistics of this group are to some extent revealed in Table 2. As illustrated in Fig. 10, heavier aircraft are generally associated with higher fluctuation in fuel consumption. This conclusion is intuitive because heavier aircraft generally have higher fuel flow rates; even a small percentage of change will result in a significant absolute value. The top five aircraft types associated with the most fuel savings are listed in Table 2. All types are of the wake-category heavy, except DC-9-40, which is of wake-category large. The top five aircraft types with the most extra fuel consumption are listed in Table 3, four of which are heavy and one of which is large. These two tables along with Fig. 10 suggest that fuel consumption of wide-body aircraft is more sensitive to procedure than narrow-body aircraft. Hence, the CDA design should be focused on wide-body aircraft because a well-designed procedure could result in significant fuel savings, whereas a poorly designed procedure could lead to a significant extra consumption.

D. Error Analysis

There are some factors that could introduce errors into this research. Vertical profile is assumed as perfect in this research. However, one can hardly execute a perfect CDA vertical profile in high-density operations. Therefore, this research could potentially overestimate fuel savings by ignoring the interruption of a theoretical 3 deg descent. On the other hand, this research could underestimate the fuel savings by setting the starting point of descent at the initial point where an aircraft enters the TRACON instead of setting it at the

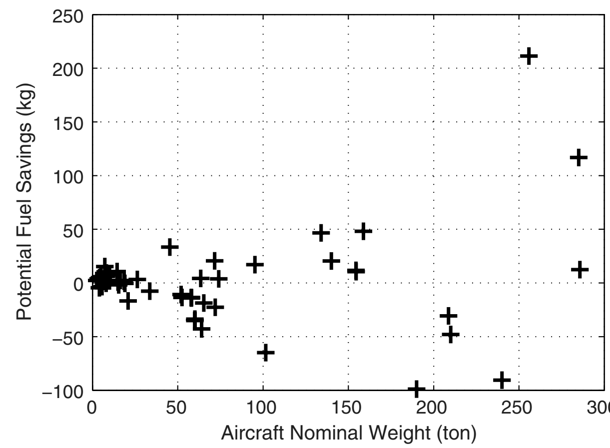


Fig. 10 Relationship between potential fuel savings and nominal weight.

initial cruise altitude. Speed profile is another major potential source of uncertainty. As mentioned in Sec. III, 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 a significant error. Ground track is assumed to be identical for the CDA and the conventional procedures. However, because the CDA typically increases the difficulty in separation, more vectorings are likely if the CDA is performed in high-density conditions. The BADA model itself could also be a source of uncertainty. The speed profile recommended by the BADA does not account for the local traffic and weather condition, and the accuracy of its aircraft-performance data is challenged by some researchers [4,14]. Wind is assumed to be insensitive to altitude in this research. However, both the magnitude and direction of the wind vector could change with altitude [2]. Finally, nominal aircraft mass is used in this analysis, and is approximated as a constant. By the TEM, for a descending, decelerating aircraft, the greater the mass, the smaller the thrust is, and thus the less the fuel flow rate. This implies that the fuel consumption has been underestimated. However, because the same mass was used for both the CDA and the conventional baseline, the net effect is still unknown.

E. Examination of Three Typical Individual Samples

This section is devoted to the detailed analysis of three individual samples. The B737-800 with average fuel savings stands for the case of most aircraft. The study on a B747-200 with significant fuel savings reveals the factors that could maximize the benefits of the CDA. The study on an RJ-200 with negative fuel savings suggests why the CDA may consume even more fuel if it is poorly designed.

1. Sample with Average Fuel Savings

Figure 11 shows the CDA procedure flown by a B737-800 on 25 March 2006. The compromised speed profile gives a fuel savings of 71 kg over a distance of approximately 80 n mile. The level segments of the conventional procedure were elevated to the initial altitude. As illustrated in the fuel flow plot, the CDA consumes more fuel at the initial cruise stage, but consumes less fuel thereafter. In other words, the fuel savings during descent outweigh the extra fuel consumption during the initial cruise. This is also the typical case of a CDA saving fuel. Note that the sudden jump at approximately 38 n

Table 2 Aircraft types with the highest fuel savings

Aircraft type	Fuel savings per aircraft, kg	Occurrence	Wake category
B747-200	211.31	157	Heavy
A340-600	116.88	6	Heavy
B767-400	48.12	178	Heavy
A300B2	46.66	49	Heavy
DC-9-40	33.42	12	Large

Table 3 Aircraft types with the highest extra fuel consumption

Aircraft type	Fuel savings per aircraft, kg	Occurrence	Wake category
A332	−98.82	50	Heavy
MD11	−90.59−90.59	74	Heavy
B753	−64.90	107	Heavy
A343	−48.01	98	Heavy
A320	−42.79	1969	Large

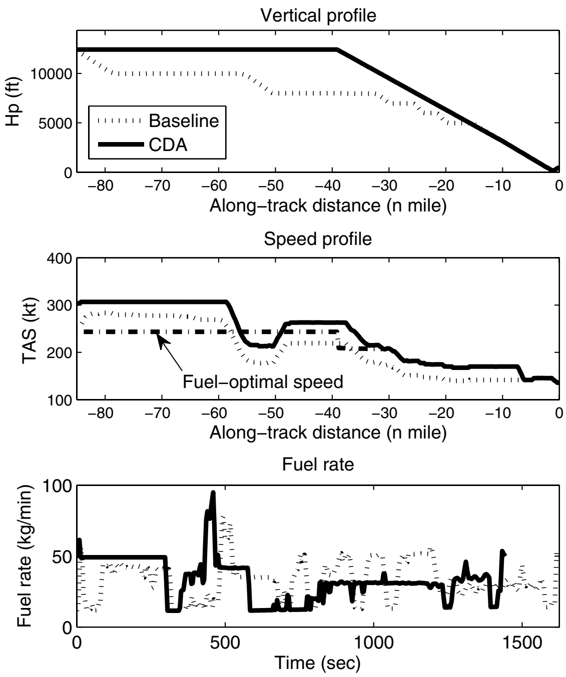


Fig. 11 CDA procedure that would produce average fuel savings.

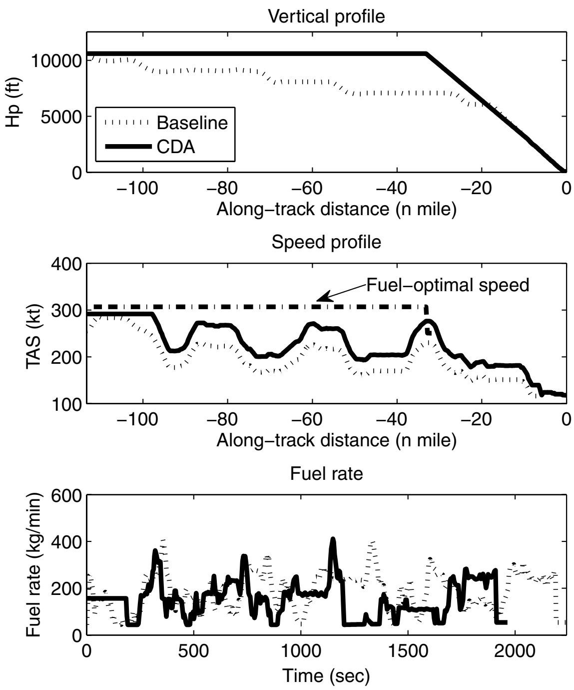


Fig. 12 CDA procedure that would produce remarkable fuel savings.

mile in the fuel-optimal speed profile results from the transition from cruise to descent.

2. Sample with Significant Fuel Savings

The simulation results show that 1853 kg fuel would have been saved if a B747-200 on 25 March 2006 had flown a CDA procedure. Such a huge amount of fuel savings results from three factors. First, the B747-200 has a large fuel flow rate, typically more than 200 kg/ min for cruise. Although the fuel savings appear to be large, its percentage with respect to the original fuel consumption is fair. Second, the ground track is long (more than 100 n mile within the TRACON), and the original vertical profile contains five level-offs (Fig. 12). Therefore, the CDA significantly improves the procedure. Finally, because the BADA recommends high speed, the compromised CDA speed profile, which is influenced by the BADA-recommended speed, is faster than the radar-recorded one. As illustrated in Fig. 12, although the fuel flow rates of both procedures do not exhibit remarkable difference, the CDA procedure reduces the flight time by 261 s (i.e., more than 4 min), which is another major reason why so much fuel could be saved.

3. Sample with Negative Fuel Savings

Some CDA procedures exhibit negative fuel savings, meaning that the CDA might consume even more fuel than the conventional approach. Figure 13 illustrates the procedure of an RJ-200, which suggests that the CDA consumes 90 kg more fuel than the conventional approach. This can also be satisfactorily explained by the results from Sec. III. As illustrated in the speed history, the modeled CDA speed profile is not as close to the fuel-optimal speed as the original speed is. As a result, the CDA does not exhibit any environmental benefits for this particular procedure.

4. CDA Design Guidelines

Based on the observations in this case study, the following guidelines are proposed for CDA design.

1) The application of the CDA should be focused on heavy aircraft and some large aircraft. Although such aircraft account for only a small portion of the total arrival fleet, they are associated with the majority of potential fuel reduction.

2) Application of CDA on small aircraft is not recommended because the financial benefit for fuel savings would hardly outweigh the extra cost in ATC due to the introduction of the CDA.

3) In terms of fuel reduction, arrival procedures for small aircraft can be sacrificed to make fuel-optimal CDA procedures of larger aircraft possible. Because the fuel flow rate of narrow-body aircraft is significantly lower than that of wide-body aircraft, large and heavy aircraft should be given priority over small aircraft types. Even if such sacrifice increases the fuel consumption of narrow-body aircraft due to deconfliction, such increase will in most cases be outweighed by the fuel reduction of the associated wide-body aircraft. However, airline equity would have to be considered if such sacrifice were made.

4) The design of the speed profile should incorporate the fuel-optimal speed proposed in this research because improving the speed profile is also an efficient way of reducing fuel consumption.

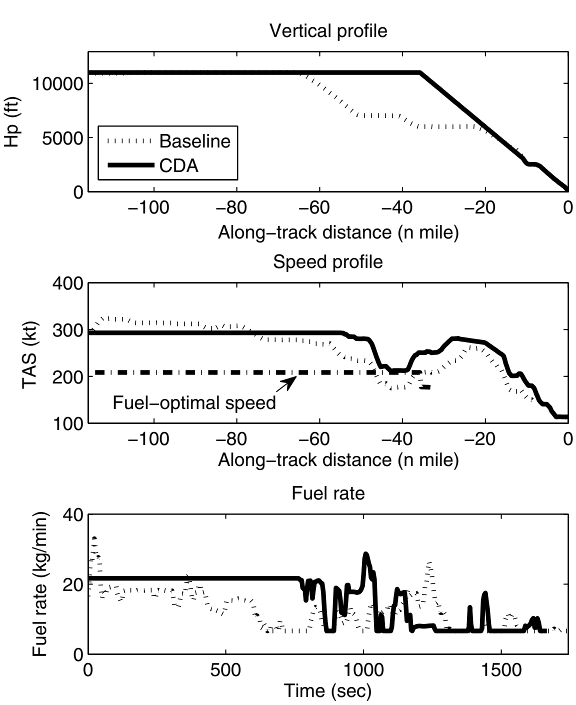


Fig. 13 CDA procedure that would consume more fuel.

F. Discussion

As expected, different speed profiles give significantly different results. The speed from radar data is usually lower than the fuel-optimal speed. As a result, a higher altitude increases fuel consumption, and thus the CDA consumes even more fuel (the radar-recorded column). The BADA-recommended column corresponds to the speed recommended by the BADA, which is typically high. Therefore, the BADA-recommended speed profile yields high fuel savings. Such difference suggests that, in the terminal area, a faster speed profile usually means less fuel consumption. As shown in Table 1, a large standard deviation of fuel saved is observed, meaning that the mean values are only macroscopically valid. For a particular flight, the potential fuel savings are extremely sensitive to a number of factors, including aircraft-performance parameters, procedure parameters, and weather. The data distribution suggests that the introduction of the CDA be focused on wide-body aircraft and be avoided for those flights with negative fuel savings.

The results from this research are fundamentally consistent with the results from a variety of estimation and field tests, but deviations due to various reasons are noticed. Some researchers [4,9] estimated fuel savings higher than this research because they assumed that both fuel flow rate and airspeed for a particular aircraft type are uniquely dependent of altitude. Shresta et al. [12] claimed greater potential fuel-saving benefit because they set the top of descent at altitudes considerably higher than the initial altitudes used in this research, and because they assumed idle thrust over the entire descent even if the vertical profile that they used would never be realized solely using idle thrust. The 2004 Louisville field tests [2] reported approximately 200 kg fuel savings for the B757/767, which is higher than the average results given by this research, but is similar to the samples associated with highest fuel savings. One likely explanation for this deviation is that for a given altitude, the BADA typically recommends a descent speed faster than the cruise speed, which leads to an unusual acceleration during the transition from cruise to descent, and thus increases the fuel consumption associated with the CDA.

V. Conclusions

This research derived the analytical relationship between approach procedure and fuel consumption, which provides insights into the continuous-descent approach (CDA) as a fuel-saving procedure. This relationship can be used as a tool for the design and evaluation of the CDA, and even for any other proposed approach procedures. Based on these results, optimized CDA procedures can be designed. The case study for the San Francisco International Airport (SFO) yields multiple design guidelines on the development of the CDA procedures, which not only involve the arrival procedure for individual flights, but also suggest the priority of some aircraft types over the others. The estimated fuel savings are a valuable reference for policy making, and can be consulted for estimation at other airports with comparable throughput and importance.

Fuel consumption in the terminal area strongly depends on the approach procedure, or, specifically, the vertical profile and speed profile. The relationship among fuel consumption, altitude, and speed is neither linear nor monotonic. At low speeds, fuel consumption increases with altitude, but decreases with speed. At high speeds, fuel consumption decreases with altitude, but increases with speed. For a given altitude, there is, in most cases, a fuel-optimal speed that minimizes fuel consumption. The CDA typically reduces fuel consumption by increasing cruise (or level flight) altitude as well as by increasing speed. If an excessively low speed profile were assigned to a CDA procedure, the CDA procedure would consume even more fuel than its conventional counterpart. To maximize the fuel savings due to the CDA, the speed profile has to be designed as appropriately as the vertical profile. As a result, the estimation of potential fuel savings due to the CDA strongly depends on the speed profile. Wide-body aircraft should be the target group of the CDA design because their fuel consumption would be considerably reduced through well-designed CDA procedures, and because unsatisfactory CDA procedures could result in a remarkable increase of fuel consumption. In terms of maximizing the CDA's environmental benefits, it seems that the approach procedures of narrow-body aircraft can be sacrificed for optimized CDA procedures of wide-body aircraft: deconfliction of the CDA for narrow-body aircraft is no easier than that for wide-body aircraft, but it gives few environmental benefits due to the low fuel flow rate of narrow-body aircraft. As a result, the CDA should be applied to wide-body aircraft, and the CDA of narrow-body aircraft is neither favorable nor necessary. However, in the real airline industry, more operational and economic factors, such as type of flight (passenger or freight), terminal and area runway operation, and airline equity, have to be considered, which are beyond the scope of this paper.

Several future works are suggested here. First, microscopic deconfliction can be incorporated in the evaluation of the CDA. Second, more laboratory simulations as well as field tests have to be conducted to verify the influence of speed on fuel consumption. Third, fairness among different aircraft operators should be incorporated in the optimization. Finally, detailed, feasible procedures should be developed based on the local geographical environment and traffic conditions, and simulation and evaluation should be performed for these procedures before put into practice.

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