Efficiency Analysis of Speed Managed Descent in the Presence of Wind Prediction Error∗

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Efficient flight operations are crucial for the sustainable development of aviation. Continuous descent is a potential solution in a terminal airspace. At present, descent is evaluated based on the length or duration of level flight segments only. Typically, modern flight management systems calculate optimal descent profiles with level segments added only for necessary deceleration. If no wind disturbance is present, the aircraft can follow the path calculated and achieve the optimal descent. In practice, however, differences between the predicted and actual wind require changes to the descent profile such as adding thrust, drag, or flying additional level segments. This research analyses different descent control strategies and investigates their effects on fuel burn, flight time and path deviation. Monte Carlo simulations are conducted to account for various wind conditions. Results show that even strategies with level segments increased by an average of 22% can result in lower fuel burn. Therefore, it is concluded that level segments by themselves are not a sufficient metric for descent efficiency and a strategy for lower fuel burn descents is proposed.

Key Words: Continuous Descent, Wind Prediction Error, Level Segments, Fuel Burn, Pilot Control Strategy

1. Introduction

Continuous descent operation (CDO) can lead to significant fuel savings and noise disturbance abatement in terminal airspace.1) CDO is an idle-thrust descent profile with minimum or almost no level segments. Several airports worldwide have already introduced CDO in their nominal operations (e.g., San Francisco International Airport2)). In Japan, CDO trials have been introduced at Kansai Airport during night operations with lower traffic density. According to the manual of the International Civil Aviation Organization (ICAO)3) and documents aiding the understanding of CDO procedures,4) CDO is characterized by “continuous descent,” “minimum thrust” and “minimum low drag configuration when possible.” In the above CDO definition, level segments are limited to the purpose of deceleration. Most researchers who analyze continuous descent operations in respect to fuel savings use the distance or time flown at level segments to evaluate inefficiencies.5,6) The authors followed the same approach and investigated the amount of level flight of descending aircraft into Haneda International Airport, Japan’s busiest airport. The analysis was based on CARATS Open Data7) for a sample day (May 9, 2012) for aircraft landing on runway 34L. The time spent flying level segments during the descent measured in percentage of the total descent time for each flight was determined and a histogram for the sample day traffic was plotted in Fig. 1. The average level flight time for this sample traffic of 395 flights was 3.9% of the entire descent time, a figure which suggested extremely efficient traffic flow. However, discussions with pilots and airline flight operation analysts suggested larger descent inefficiencies. This observation is supported by findings reported by other researchers. Bronsvoort and Huynh argued that level segments by themselves cannot provide a sufficient metric to measure operational efficiency in the terminal areas.8) Instead, they analyzed the speed profile flight history to evaluate the descent efficiency and applied the proposed metric to Australian continuous descent operations.

This research employs a different approach, focusing on the reasons for the variations from the optimal descent profile unique to each flight. In practice, an optimal descent profile, such as the CDO profile, is calculated by the flight management system (FMS), a system available onboard most modern aircraft that provides guidance to help reduce pilot workload and improve flight safety and efficiency. FMS calculates the flight profile and provides guidance commands based on the aircraft’s performance model, current state, specific operational constraints such as speed and airspace, and wind measurement and prediction data. One of the characteristics of the descent profile is the top of descent (ToD), which is the point at which the aircraft initiates its descent. Ideally, if there are no disturbances, the aircraft will be able to descend continuously from ToD at idle thrust all the way until performance or airspace constraint becomes active. In reality, however, variations in the predicted wind and/or aircraft weight lead to deviations from the calculated profile. Park and Clarke9) considered such weight variations and proposed a method to generate suboptimal descent profiles executable with current FMS, and very similar to the optimal trajectories theoretically derived. Vaddi et al. simulated arrival time uncertainties associated with NextGen FMS capabilities.10)
Here, we focus on wind prediction errors and the compensation necessary to adjust for deviation from the descent path performed by the pilot or the autopilot. This study models two different descent control strategies and evaluates the resulting level flight segments. We focus on nominal FMS capabilities available where a high-precision 4D functionality is not a prerequisite in order to assure the applicability of the analysis to current operations. For a detailed analysis of wind prediction requirements necessary for 4D operations, refer to Glina et al.\textsuperscript{11} The final goal of our research is to model and analyze all types of FMS modes and the resulting descent profiles in order to reveal the interdependency of fuel-efficient and level flight segments. This will lay the foundation for the development of a new descent metric that will adequately capture the characteristics of current operations and pilot (autopilot) control. Operations at Haneda International Airport are evaluated using this metric and potential improvements are proposed. In this paper, we consider vertical profiles only and focus on speed-managed descent, a type of FMS mode descent, and evaluate the CDO profiles in the presence of wind prediction error. Path-managed descent is a subject of future work. Additionally, air traffic control intervention is out of the scope of the research presented here.

The remainder of this paper is organized as follows. Section 2 gives an overview of the descent path planning and flight modes available in current FMS, focusing on vertical guidance as the main subject of this research. The numerical simulation assumptions are discussed in Section 3. The effects of wind prediction error on descent profiles and level flight segment length are investigated in Section 4. In particular, we sample boundaries of wind error to understand how they affect the descent path. Several basic cases are presented in this section: the baseline (null wind error), increasing tailwind error, increasing head wind error and random wind error. Two pilot control strategies are modeled and implemented in descent simulations using sample wind prediction error in Section 5. These serve as the basis of the Monte Carlo simulations shown in Section 6, which are performed to evaluate the wind prediction error effect statistically and generalize the results obtain in Section 5. An analysis of the results obtained is presented in Section 7. Section 8 summarizes and concludes this paper.

2. Descent Path Planning and Flight Modes

2.1. Calculated descent path

A sample continuous descent profile is shown in Fig. 2. In order to minimize fuel burn, idle thrust is applied in descent plans. A descent profile can be divided into several segments. From a certain point, ToD, the aircraft descends at idle thrust, maintaining a constant Mach number. At a certain altitude, called “crossover altitude,” or “Mach transition altitude,” the target Mach number and the target calibrated airspeed (CAS) indicate the same true airspeed (TAS). Below the crossover altitude, the aircraft descends maintaining a constant CAS. At an altitude of around 10,000 ft, there are speed and/or airspace restrictions typical for most terminal areas. In order to comply with the speed restriction, the aircraft flies a level or close to level deceleration segment. The descent then continues and the pilot prepares the aircraft for landing. The landing configuration preparation is usually completed by the final approach fix.

The FMS takes into account the speed and waypoint constraints assigned in advance and calculates the optimal descent profile. Here, wind data is necessary. The FMS uses the wind data measured by onboard sensors, as well as wind prediction data, to calculate the descent path. If the wind prediction data is completely accurate, no adjustments to the vertical profile will be necessary along the descent. However, if there is a wind prediction error, adjustments using either potential or kinetic energy are necessary. FMS vertical navigation (VNAV) has two modes corresponding to these two energy adjustments: VNAV-SPEED and VNAV-PATH. In general, as long as the aircraft is flying its pre-calculated path, VNAV is in PATH mode, and once the aircraft deviates from the path, VNAV switches to SPEED mode. Depending on the aircraft type, constant flight path angle mode and 4D mode (including time constraint) is also available, but VNAV-SPEED and VNAV-PATH remain the basic FMS modes. Accordingly, the next subsection provides a brief overview of these two modes.

2.2. VNAV modes

A descent in a VNAV-PATH mode is referred to as a path-
managed descent. In this mode, the aircraft follows its predicted path by controlling its pitch angle. The thrust is generally set at idle, but extra thrust or extra drag (speed brakes) are applied when needed. Since the aircraft maintains its geometrical path, wind prediction error results in speed deviation.

On the other hand, when an aircraft descends using the VNAV-SPEED mode, pitch control is applied to maintain the target speed (Mach number or CAS) and wind prediction error results in path deviation. For the rest of this paper, we consider only VNAV-SPEED mode.

3. Simulation Assumptions

As discussed in Section 1, aircraft usually descend following the FMS-calculated path using one of the available modes (for example, VNAV-PATH or VNAV-SPEED). Therefore, the FMS-calculated path needs to be determined first, and this is done by adequately modeling the aircraft performance. This research applies the BADA ver. 3.11 aircraft performance model developed by Eurocontrol\(^\text{12}\) (Subsection 3.1). Numerous researchers have analyzed the BADA 3 model in terms of fuel burn estimation accuracy and agree there are inaccuracies, especially in the non-cruise flight phases\(^\text{13,14}\) that have been successfully addressed by the BADA 4 model.\(^\text{15}\) At present, access to BADA 4 is significantly more restricted than access to BADA 3, so most researchers still rely on BADA 3 for fuel burn modeling. Here, the influence of wind and fluctuating wind speed need to be investigated as well. Next, the pilot strategies corresponding to wind prediction error (or any other disturbances such as differences between planned trajectory and executed trajectory) need to be modeled (Subsection 3.2). This stage was developed together with a veteran airline pilot. Since it is revealed that not all pilot strategies can be sufficiently modeled using BADA ver. 3.11, the authors propose several model adjustments to reflect real operations (Subsection 3.3).

3.1. Basic aircraft performance (BADA model)

The numerical simulations presented in this paper are generally based on the BADA ver. 3.11 model. We consider the movement of a Boeing 767-300 aircraft. The aircraft movement is defined in body-centered coordinates \((x, y, h)\), true airspeed \(V_{\text{TAS}}\), flight path angle in respect to the air mass \(\gamma_{\text{TAS}}\), bank angle \(\phi_{\text{TAS}}\), thrust \(T\), drag \(D\), mass \(m\) and wind \(w_x, w_y, w_z\). In this paper, the nominal case considers null wind conditions, so the wind \(w_x, w_y, w_z\) actually represents wind prediction error. The simplified point-mass model considered in BADA is described by the following equations:

\[
\begin{align*}
\dot{x} &= V_{\text{TAS}} \cos \psi_{\text{TAS}} \cos \gamma_{\text{TAS}} + w_x, \\
\dot{y} &= V_{\text{TAS}} \sin \psi_{\text{TAS}} \cos \gamma_{\text{TAS}} + w_y, \\
\dot{h} &= V_{\text{TAS}} \sin \gamma_{\text{TAS}} + w_z, \\
\dot{V}_{\text{TAS}} &= \frac{T - D}{m} - g \sin \gamma_{\text{TAS}} - \dot{w}_x
\end{align*}
\]

\[\psi_{\text{TAS}} = \frac{L \sin \phi_{\text{TAS}}}{m V_{\text{TAS}}} - \dot{w}_y \]

\[\dot{\psi}_{\text{TAS}} = \frac{L \cos \phi_{\text{TAS}}}{m V_{\text{TAS}}} - g \cos \gamma_{\text{TAS}} - \dot{w}_z \]

This research considers only the vertical movement of the aircraft, so the above equations can be further simplified as follows:

\[
\begin{align*}
\dot{x} &= V_{\text{TAS}} \cos \gamma_{\text{TAS}} + w_x \\
\dot{h} &= V_{\text{TAS}} \sin \gamma_{\text{TAS}}, \\
\dot{V}_{\text{TAS}} &= \frac{T - D}{m} - g \sin \gamma_{\text{TAS}} - \dot{w}_x
\end{align*}
\]

The wind speed (magnitude and direction) changes with altitude. As the aircraft descends, \(\dot{w}_x\) denotes the time derivative of the wind speed in \(x\) direction \(dw_x/dt\).

The drag is defined by Eq. (10), where \(C_D\) is drag coefficient, \(\rho\) is air density and \(S_{\text{ref}}\) is reference wing area.

\[D = C_D \frac{1}{2} \rho V_{\text{TAS}}^2 S_{\text{ref}} \]

\(C_D\) is calculated as shown in Eq. (11). Here, \(C_{D0}\) and \(C_{D2}\) depend on the aircraft’s configuration. BADA distinguishes among clean, take-off and landing configuration, for example. Assuming trimmed flight conditions, the lift coefficient can be calculated as shown in Eq. (12).

\[C_L = \frac{2mg}{\rho V_{\text{TAS}}^2 S_{\text{ref}}} \]

This research computes the fuel burn during descent in order to evaluate the flight efficiency. Therefore, the thrust and fuel flow models need to be shown as well. In BADA ver. 3.11, the descent thrust (corresponding to idle thrust) is computed as shown in Eq. (13). \(C_{T_{\text{id}}, i}, C_{T_{\text{i}, i, i}}\) are aircraft-type dependent parameters.

\[T_{\text{idle}} = C_{T_{\text{id}}, i} C_{T_{i, i}} \left(1 - \frac{h}{C_{T_{i, 2}}} + C_{T_{i, 3}} h^2\right) \]

The fuel flow is determined as follows:

\[f_{\text{nom}} = C_{L, i} \left(1 + \frac{V_{\text{TAS}}}{C_{L, 2}}\right) T \]

\[f_{\text{min}} = C_{L, i} \left(1 - \frac{h}{C_{L, 4}}\right) \]

\[f = \max(f_{\text{min}}, f_{\text{nom}}) \]

\(C_{L, i, 1-4}\) depend on the aircraft type. Here \(f_{\text{min}}\) corresponds to idle descent fuel flow. It should be noted that \(f_{\text{min}}\) does not depend on the thrust, so we cannot calculate the fuel flow when some additional thrust is added during descent using these equations only.

3.2. Flight profile assumptions

This paper considers the descent from cruising altitude to
the end of the deceleration segment at 10,000 ft, referred to as “metering fix.” This flight profile segment is shown by the dotted section of the line in Fig. 2. The level segment is just long enough to allow for idle thrust deceleration from the descent speed to the required speed below 10,000 ft. Therefore, the FMS-computed trajectory consists of two main segments: an idle constant speed descent segment and an idle thrust level deceleration segment. Specific numerical constraints on the trajectory and aircraft performance will be shown in Section 5.

3.3. Pilot descent strategies model

From both VNAV modes discussed above, this paper considers VNAV-SPEED descent only. As mentioned in Section 2.2, in an idle thrust VNAV-SPEED descent, disturbances result in path deviation. If no thrust correction is applied, disturbances such as wind prediction error will result in either lengthening or shortening the level flight segment. Generally speaking, lengthening of the level flight segment means that the aircraft will have to add a steady level flight portion to its originally planned trajectory, and a shorter level segment will be equivalent to applying speed brakes, and thus increased drag in the level flight portion. In order to minimize or completely avoid such changes to the level flight segment, the pilot can opt for thrust adjustments like adding some partial power to keep the aircraft close enough to the original path and thus eliminate the need for a steady level flight segment. This research models the above descent strategies in respect to the additional thrust $\Delta T$ applied in the descent flight segment. Assuming,

$$T_{\text{descent}}(t) = T_{\text{idle}}(t) + \Delta T(t)$$  \hspace{1cm} (17)

we define two pilot strategies, as summarized in Table 1. $\Delta T$ is the extra thrust used in the descent, that is for idle descent $\Delta T = 0$ and for partial power descent $\Delta T > 0$. $s_{\text{lev, idle}}$ is the length of the level flight segment flown at idle thrust in order to decelerate from the descent speed to the speed required at the final metering fix. $s_{\text{lev, steady}}$ denotes the length of the steady level flight segment and $s_{\text{lev, brake}}$ is the length of a level segment at which time speed brakes are deployed.

Strategy 1 assumes no additional thrust regardless of the wind prediction error along the way. The aircraft descends maintaining the target descent speed $V_{\text{des}}$ (that is VNAV-SPEED mode) until it reaches an altitude of 10,000 ft. Due to the error in wind predictions, the point at which the aircraft reaches the target altitude 10,000 ft can be prior or further (overshoot) than the point originally calculated using FMS. Furthermore, wind prediction error for the wind speed and direction at 10,000 ft itself might lead to changes in the length of the idle thrust level deceleration segment. If the aircraft reaches 10,000 ft earlier than planned, it might need to fly an extra steady level segment to reach the metering fix. On the other hand, if the aircraft reaches 10,000 ft after the originally calculated point, the pilot will need to apply speed brakes to decelerate sufficiently before metering fix. There is a possibility that the remaining distance to metering fix is not enough for the aircraft to decelerate, and in this case we assume that Strategy 1 will fail. In reality, according to our interviews with veteran pilots, the pilot would notice the aircraft is too far away from the planned trajectory and would apply the speed brakes during the descent phase. Therefore, a failure in the descent strategy described above is unlikely. However, for the purpose of this research, we aim to investigate the application range of Strategy 1 considering a worst case scenario, so we opt for the “fail” definition as described above. Strategy 1 includes several inefficiencies, such as steady level flight segment or speed brakes, and is rarely applied in practice.

On the other hand, Strategy 2 is currently often practiced by airline pilots. In Strategy 2, the pilot aims to eliminate the steady level flight segment by adding some thrust (partial power) in the descent phase when the aircraft falls below the calculated path. In this research, we assume full knowledge of the wind along the trajectory (i.e., partial power added is just enough to eliminate the steady level flight segment). In reality, the pilot follows the progress of the aircraft in respect to the descent path calculated and adds thrust as necessary, so the assumptions for Strategy 2 would result in an overestimated efficiency.

3.4. Current research model adjustments

3.4.1. Adjustments reflecting pilot descent strategies

This research aims to accurately model the adjustments required for a flight profile that incorporates wind prediction error. The basic BADA ver. 3.11 model presented briefly in Subsection 3.1, however, does not explicitly model the speed brake drag effect in Strategy 1 and the partial power descent governing Strategy 2.

Regarding Strategy 1, the increase in drag resulting from applying the speed brakes is also not explicitly modeled in BADA ver. 3.11. This research models such pilot control by increasing the value of $C_{\text{D0}}$ in Eq. (11), so that the aircraft will achieve the required deceleration in the distance remaining until metering fix. Based on discussions with pilots, we assume that speed brakes can reduce the necessary distance for idle thrust level flight deceleration by 50%, and this constraint is reflected in the maximum increase of $C_{\text{D0}}$.

Furthermore, we model such a partial power descent as follows. First, we calculate the thrust necessary for steady level flight segment. For this segment, the thrust balances the drag.

$$T_{\text{steady,level}} = \frac{mg}{C_{L}/C_{d}}$$  \hspace{1cm} (18)

Then, we define the partial power thrust as shown in Eq. (19). Here, $p$ is a weight parameter with a value between 0 and 1. The additional partial power is determined so that it
is just enough to eliminate any steady level flight segments prior to metering fix.

\[ T_{\text{partial}} = T_{\text{idle}} + pT_{\text{steady,level}} \]  \hspace{1cm} (19)

We also assume that partial power thrust cannot exceed the thrust necessary for level flight \((T_{\text{partial}} < T_{\text{steady,level}})\). Similarly, the fuel flow for partial power descent is modeled as shown in Eqs. (20) and (21).

\[ f_{\text{partial}} = f_{\text{min}} + pf_{\text{nom}} \]  \hspace{1cm} (20)
\[ f = \max(f_{\text{partial}}, f_{\text{nom}}) \]  \hspace{1cm} (21)

The total fuel burn during the descent can then be calculated according to Eq. (22).

\[ m_{\text{fuel}} = \int_0^\tau f \, dt \]  \hspace{1cm} (22)

### 3.4.2. Wind effect modeling

In most air traffic management related research, the wind effect is modeled using only wind speed and direction, whereas the effect of wind change \(\dot{w}_x\) (wind shear forces) on the flight profile is often ignored.\(^{16,17}\) The main reason for such approximation is faster and more straightforward numerical simulations. Our discussions with pilots have implied, however, that the wind shear component \(\dot{w}_x\) might be important for the descent profile. Therefore, at this stage, we opt to keep the component in Eq. (9) and examine its influence in a series of simulations discussed in Section 4.

### 4. Wind Prediction Error Effects on the Descent Profile

In order to investigate how descent profiles change in the presence of wind prediction error, we run two series of numerical simulations. We compute a baseline assuming null wind conditions and then add wind \(w_x\) to see how the trajectory changes. This simulation setting is analogous to \(w_x\) wind error. The first simulation series considers steady wind only and the second series looks into variable wind (wind shear).

Here, we assume that a B767-300 aircraft descends from an altitude of 30,000 ft to 10,000 ft at a constant calibrated speed of 280 kt.

#### 4.1. Steady wind prediction error

The first series of numerical simulations considers the effect on steady wind \(w_x\) on the descent profile \((\dot{w}_x = 0)\). According to Eqs. (7)–(9), steady wind effect \(w_x\) can be expressed in coordinates change only, that is the true airspeed flight path angle \(\gamma_{\text{TAS}}\) does not change, but the ground flight path angle \(\gamma_{\text{ground}}\) changes by \(w_x\) only. Assuming a headwind, the path becomes deeper and the descent lateral distance becomes shorter. In the case of tailwind, the path becomes shallower than the calculated null-wind path and descent lateral distance is longer. These effects are verified in numerical simulations for 30 kt wind. The results for a 30 kt tailwind (Wind A, shown by solid line) and 30 kt head wind (Wind B, shown by dashed line) are shown in Fig. 3. The lateral distance necessary for the descent changes by 4.50 in both cases, but according to Eq. (8) the descent flight time remains unchanged.

#### 4.2. Varying wind prediction error effect

In reality, wind is not constant in respect to altitude and time. The following series of numerical simulations investigates the influence of wind shear \(\dot{w}_x\) on the descent profile. Assuming the wind magnitude and direction are constant at each altitude, \(w_x = \dot{w}_x / dt\) can be expressed in terms of \(\dot{w}_x / dh\). From Eq. (9)

\[ \sin \gamma_{\text{TAS}} = \frac{1}{g} \left( \frac{T - D}{m} - \dot{w}_x - \dot{V}_{\text{TAS}} \right) \]  \hspace{1cm} (23)

Substitution in Eq. (8) gives

\[ \dot{h} = \frac{V_{\text{TAS}}}{g} \left( \frac{T - D}{m} - \dot{w}_x - \dot{V}_{\text{TAS}} \right) \]  \hspace{1cm} (24)

In the case of an increasing tailwind, \(\dot{w}_x > 0\) and \(\dot{h}_{\text{nom}} < \dot{h}_{\text{baseline}}\). During descent, \(\dot{h} < 0\), so the increase in tailwind results in an increase in the descent rate. To verify this, we run simulations for increasing and decreasing tailwind conditions. Wind C is a linearly decreasing tailwind (30 kt at 30,000 ft and 0 kt at 10,000 ft) while Wind D increases linearly from 0 kt at 30,000 ft to 30 kt at 10,000 ft), as shown in Fig. 4. The bold blue line represents the null-wind baseline. When \(\dot{w}_x\) is not considered, the effects of both tailwinds C and D follow the explanations in Subsection 4.1; that is, the descent profiles shown in dotted lines are above the calculated baseline profile. On the other hand, increasing tailwind component \(\dot{w}_x\) (Wind D) acts towards increasing the descent rate and a steeper descent (bold purple line below the baseline). Similarly, decreasing tailwind results in a shallower descent (bold green line compared to the dotted green line, both of which are above the baseline).
As seen from the simulation results, the influence of \( \dot{w}_x \) on the descent rate cannot be neglected. Therefore, in the rest of this paper, all simulations include both \( w_x \) and \( \dot{w}_x \).

Analysis of the results show that the vertical deviation from the baseline varies with altitude in a non-uniform way. For example, in the case of Wind D, the vertical deviation from the baseline first increases and then decreases to reach an almost zero-value at 10,000 ft (see Fig. 4). Therefore, the relative location of the point at which the aircraft reaches 10,000 ft in respect to the baseline depends on both the initial altitude and wind prediction error (wind pattern). In other words, whether the aircraft will need to add an extra steady level flight segment to the final fix or use speed brakes depends on both initial altitude and wind prediction error. To avoid any misunderstanding, the sample descent simulations presented below are grouped based on the need for such a steady level flight segment, rather than only on the wind prediction error profile.

5. Descent Simulations

5.1. Descent simulation assumptions

This paper considers speed-managed descent modeling using VNAV-SPEED mode. In general, FMS calculates the optimal descent profile based on the target descent speed and available constraints. The idle-thrust descent starts at the cruise altitude of 30,000 ft and finishes at 10,000 ft, while maintaining a constant calibrated speed of 280 kt. At 10,000 ft, the aircraft decelerates at idle thrust until it reaches 230 kt, the required speed for metering fix. The ToD is calculated using FMS to comply with the above constraints.

We consider a B767-300 aircraft, the performance parameters of which can be found in BADA ver. 3.11.

5.2. Baseline simulation

This research investigates the effect of pilot control descent strategies in respect to wind prediction error. Accurate wind prediction is simulated as zero wind descent. Therefore, wind prediction errors are modeled using \( w_x \) and \( \dot{w}_x \) components, e.g. \( w_x = 10 \) kt means a wind prediction error of 10 kt.

The baseline null-wind simulation results are shown in Table 2. The aircraft starts its descent 59.8 nautical miles (nm) prior to the metering fix and, in total, burns 298.5 lb in 584 s.

5.3. Simulation of wind prediction error causing an additional steady level flight segment

If there are no wind prediction errors, the aircraft will be able to follow its planned descent path all the way to metering fix without any deviation. In reality, the wind often differs from the one used in the preliminary calculations of the descent path, which causes the aircraft to deviate from the planned path. Here, we assume that the wind prediction error increases as the aircraft descends. This is a reasonable assumption, because the aircraft can measure the wind at the cruising altitude, enabling the error at ToD to be neglected. In this example, we run simulations for Wind D, discussed earlier in Subsection 4.2. The maximum wind prediction error of \(-30\) kt is observed at 10,000 ft.

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Fig. 5. Descent trajectory and path deviation in the case of additional steady level flight.

Two simulations for Pilot Strategy 1 and Pilot Strategy 2 are conducted. The strategies are modeled as discussed in Subsection 3.3. Under Strategy 1, the pilot does not add any thrust regardless of the path deviation, whereas in Strategy 2, the pilot adds some thrust to eliminate the potential steady flight level segment at 10,000 ft, which might be necessary because of the flight path deviation from the original null wind calculated path.

The trajectory simulation results are shown in Fig. 5. The blue line shows the baseline trajectory (the line closest to the horizontal axis) and the rust and cyan lines show the trajectories following Strategies 1 and 2. Since wind prediction error leads to a path deviation of no more than 500 ft, the altitude profiles for all three cases (baseline, Strategy 1 and Strategy 2) look very similar and almost overlap, as seen in the upper graph of Fig. 5. For clarity, only the path deviation is shown in the lower graph. The figures shown in Subsections 5.4 and 5.5 follow a similar logic. Increasing wind shear along the descent leads to increasing path deviation at first, followed by decreasing deviation. The exact point where the profile intersects the baseline depends on conditions such as initial altitude and specific wind prediction error profile, and is not of any particular importance for our simulations.

The fuel burn and flight time for each strategy and phase are shown in Table 3. It is seen that, due to the wind prediction error, the aircraft needs to fly 0.5 nm of steady level flight and burn an extra 13.7 lb of fuel to reach metering fix when the pilot adds no thrust to the idle settings during the descent (i.e., Strategy 1). On the other hand, if the pilot chooses to eliminate this steady level flight portion (Strategy
2), he/she needs to add some partial power, and therefore, the fuel burn in the descent phase will increase to 299.7 lb compared to 285.8 lb in Strategy 1. Based on the partial thrust and fuel burn model presented earlier in Subsection 3.4.1, the partial power coefficient $p$ takes a value of 0.00665 (Eq. (19)), and the pilot adds some partial power throughout the entire descent. Considering the fact that for such optimal partial power setting, full knowledge of the wind error right after ToD is necessary, it can be concluded that, in this particular wind prediction error case, Strategy 1 is more beneficial.

5.4. Simulation of wind prediction error that requires speed brakes

Next, a wind prediction error sample case where speed brakes need to be used during level flight is shown. All initial conditions apart from the wind prediction error values are the same as those used in the simulation presented in Subsection 5.3. The trajectory and vertical deviation results are shown in Fig. 6. Because of the increasing tailwind component $\dot{w}_w$, and according to the simulation results discussed in Subsection 4.2, the aircraft deviates below the original calculated baseline. However, the presence of a 30 kt additional tailwind at 10,000 ft means that the aircraft will cover a longer distance during its deceleration at this altitude compared to the null-wind baseline. As a result, only Strategy 1 can be applied. At 10,000 ft, there is a 30 kt tailwind, and the aircraft needs 4.10 nm to decelerate from 280 kt to 230 kt. However, the remaining distance for level flight is only 3.70 nm, so the pilot has to deploy speed brakes, equivalent to an increase of 0.004 in the value of $C_D$. The level flight distance, flight time and fuel burn are shown in Table 4.

5.5. Simulation of wind prediction error leading to Strategy 1 failure

In the simulations presented in the previous two subsections, the wind prediction error increased linearly. In this subsection, we consider a varying wind prediction error profile such as the one shown in Fig. 7. As seen from the trajectory simulated, the aircraft reaches 10,000 ft only 0.3 nm prior to metering fix (Table 5). At 10,000 ft, there is a head wind error of 30 kt, which is the same condition as the one shown in Subsection 5.3, and idle thrust descent would require a lateral distance of 3.23 nm. According to the speed brake model assumptions discussed in Subsection 3.4.1, speed brakes can shorten the necessary distance by no more than 50%. Accordingly, in this case, descent Strategy 1 fails. Therefore, the pilot needs to use speed brakes during the descent phase in order to safely meet the speed requirements at metering fix. Strategy 2 (partial power adjustment) is also not applicable.
6. Monte Carlo Simulations

Section 5 presented three sample wind prediction error profiles and discussed the results from the trajectory simulations for Strategies 1 and 2. While the purpose of the previous section was to illustrate the possible outcomes of both strategies, a statistical approach to wind prediction error effect is presented here. The fuel burn and flight time benefits of both descent strategies are investigated using Monte Carlo numerical simulation.

6.1. Wind prediction error model

Most FMSs allow wind prediction data input for several altitudes from the ToD to the runway, and use this data together with the wind measurement data available onboard to determine the wind used in planning the descent trajectory. In this paper, we assume the wind prediction error at ToD is zero. We set three intermediate altitudes between ToD and 10,000 ft, where wind prediction error values are defined randomly, and model the wind prediction errors at all other altitudes based on linear functions (see Fig. 8). For each wind profile, normally distributed random values between −30 kt and 30 kt (mean 0) at altitudes 25,000 ft, 20,000 ft, 15,000 ft and 10,000 ft are generated. Furthermore, to reflect realistic wind shear conditions, all wind prediction error profiles comply with a 10 kt/1,000 ft wind shear constraint.

6.2. Monte Carlo simulation results

Wind prediction error profiles are generated as described in Subsection 6.1 and a 10,000-run Monte Carlo simulation is conducted. As shown in Section 5, depending on the wind prediction error, Strategy 1 might fail or Strategy 2 might not be applicable. The results are summarized in Table 6. Both strategies were applicable in 5,069 cases, i.e., 50.7% of all runs. In 4,931 runs the aircraft reached 10,000 ft closer to the metering fix so Strategy 2 cannot be applied, i.e., there is no need for partial power adjustment. In 4,368 out of the 4,931 runs, the necessary deceleration can be achieved using speed brakes (see sample wind prediction error simulation in Subsections 5.4). In 563 runs, increased drag caused by speed braking is not sufficient to achieve the required deceleration (see Subsection 5.5).

Comparisons of some key descent profile characteristics, in particular fuel burn, flight time from ToD to metering fix, and level segment flight time, are shown in histograms in Fig. 9–Fig. 11. In all cases, Strategy 1 descents burn less fuel than Strategy 2 (Fig. 9), but the flight time of Strategy 2 descent is shorter than that of Strategy 1 (Fig. 10).

Note that Strategy 2 minimizes the level flight segment, which is also verified in the Monte Carlo simulation results as well. As shown in Fig. 11, in all 5,069 runs, the level flight time in Strategy 1 is longer than that of Strategy 2. For reference, the average level segment flight time for Strategy 2 is 44 s.
7. Results Analysis

7.1. Strategy 1 level segment analysis

To investigate the relation between fuel burn and level segment, Monte Carlo results for Strategy 1 simulation are plotted in Fig. 12. The plot excludes the results for Strategy 1 failure, when the remaining distance to metering fix was not enough to achieve the deceleration required. The red (grey) dots represent cases when the pilot needs to deploy speed brakes in order to meet the speed requirement at metering fix. Therefore, generally speaking, these cases are associated with shorter level flight segments. The black points represent profiles including steady level flight portions necessary to reach metering fix. For reference, the baseline profile value is shown by the light blue star (level segment length 3.6 nm and fuel burn 298.5 lb). As seen from the figure, there is a correlation between level segment length and fuel burn. In other words, for Strategy 1, the length of the level segment is a reasonable metric of flight inefficiency. The dispersion observed is due to different wind profiles; in particular, to the wind prediction error at the level flight altitude of 10,000 ft. This is also the reason why the border line between the red and black points is not aligned with the vertical axis and deviates from the baseline value of 3.6 nm.

7.2. Strategy 1 failure

The results of Monte Carlo simulations show that Strategy 1 failed in 563 cases (i.e., 5.63% of 10,000 runs). In other words, the aircraft does not have enough available distance to decelerate to 230 kt after it reaches 10,000 ft, even when using its speed brakes. To investigate the conditions under which Strategy 1 fails, we analyze the wind profiles for these 563 cases. We define wind error parameter (WEP) as shown in Eq. (25), where $c_1$–$c_4$ are scalar parameters and $w(30,000\text{ ft})$ is the wind prediction error [m/s] at 30,000 ft.

\[
\text{WEP} = c_1 (w(30,000\text{ ft}) - w(25,000\text{ ft})) + c_2 (w(25,000\text{ ft}) - w(20,000\text{ ft})) + c_3 (w(20,000\text{ ft}) - w(15,000\text{ ft})) + c_4 (w(15,000\text{ ft}) - w(10,000\text{ ft}))
\] (25)

Since it is important to investigate in which wind prediction error cases the aircraft fails to achieve the required speed, the scalar parameters $c_1$–$c_4$ are chosen to successfully lead to the formation of a cluster of wind prediction error profiles for such Strategy 1 failure cases. Here, we set the following values based on trial and error. Further optimization of the values of $c_1$–$c_4$, as well as non-linear representation in WEP, are subject to future work.

\[
c_1 = -3.5 \\
c_2 = -1 \\
c_3 = 1 \\
c_4 = 3.5
\] (26)

Using the WEP defined as described above, the wind error profiles under which Strategy 1 failed can be segregated successfully, as shown in Fig. 13. The horizontal axis shows the wind error parameter and the vertical axis shows the ratio of the actual remaining distance for deceleration at 10,000 ft versus the required distance for idle deceleration at the same altitude. Here, we plot only results for the 4,931 runs in which speed brakes were necessary. A value of 1 suggests that the aircraft could decelerate without deploying any speed brakes, and a value of 0.5 means that the aircraft had only half of the required distance necessary for idle deceleration available. According to our assumptions, speed brakes can compensate for such short distances. Therefore, for values between 0.5 and 1, the aircraft could successfully meet the speed requirement at metering fix when applying Strategy 1. These cases are shown by the red dots. For the Strategy 1 failures, on the other hand, the ratio of the available versus required distance available for deceleration is below 0.5, and these cases are shown in black. As seen from the figure, Strategy 1 fails in all cases when WEP exceeds 79 and succeeds in all cases when WEP is below 62. For intermediate values between 62 and 79, no conclusion can be made. High values of the WEP correspond to wind prediction error profiles when large shear tailwind increases followed by a large increase in shear head wind increase. Therefore, it can be concluded that the typical pattern when Strategy 1 fails is the one similar to the wind prediction error discussed in Subsection 5.5.

The descent profiles for cases when Strategy 1 fails are shown in Fig. 14. In the later part of the descent, the aircraft increases its vertical deviation from the baseline. Thus, when applying Strategy 1, attention is needed when the aircraft flies above the baseline in the later part of the descent and
large shear head wind prediction error exists. Discussions with pilots suggest that, in such a case, the pilot would notice the irregularity and use speed brakes during the descent well before reaching 10,000 ft. The exact timing of speed brake deployment is a subject of future work.

Another potential solution to eliminate or at least drastically decrease Strategy 1 failures is to start the descent earlier than the point calculated by the FMS. Further discussion and simulation analysis on this solution can be found in another work by the authors.18)

7.3. Level flight segments and descent efficiency

This paper investigates pilot control strategies in order to evaluate the efficiency of various descent patterns. As mentioned in Section 1, the current descent efficiency metric is related to the time and distance of level flight segments after ToD. Indeed, an ideal continuous descent profile with zero wind prediction error has minimum level flight segments. In practice, however, wind prediction error requires adjustment, such as the one modeled by Strategies 1 and 2 here. One of the main benefits of continuous descent is reduced fuel burn, but the results of our simulations show that applying the same level segment metric is not adequate when considering non-zero wind prediction error. As seen from the histogram in Fig. 11, Strategy 2 has, on average, 9.8 s shorter level flight segments, which is equal to an improvement of 22% compared to the average 44 s level flight measured using the current metric. The fuel burn, however, is lower in Strategy 1, as seen in Fig. 9. Depending on the wind prediction error profile, the fuel burn difference between Strategies 1 and 2 is, on average, 3.7 lb (1.2% of the descent fuel burn) with a maximum of 18.9 lb (6.3%) in favor of Strategy 1. Therefore, it is concluded that the level flight segment by itself is not a sufficient measure for descent efficiency when considering real operations including wind prediction error. Using the wind error parameter defined in Subsection 7.2, we analyzed the dependency of fuel burn difference between Strategies 1 and 2 in the cases where both strategies were applicable in respect to the wind prediction error profile. The results are shown in Fig. 15. The importance of strategy choice increases as WEP decreases (i.e., large increase in shear head wind followed by large increase in shear tail wind).

7.4. Efficient descent strategies

In order to accurately set the additional partial power in Strategy 2, full knowledge of the wind prediction error right after ToD is necessary (i.e., numerical simulations presented in this paper offer the best case scenario). As a result, the fuel burn for Strategy 2 is expected to be higher in real operations. On the other hand, Strategy 1 requires no preliminary knowledge of the wind prediction error and is therefore more robust. It is also more fuel efficient, as discussed in Subsection 7.3. Therefore, it can be argued that, even though according to the current level flight segment duration metric Strategy 2 is superior, Strategy 1 is actually more efficient.

The interviews conducted by the authors have shown that, at present, most airline pilots favor Strategy 2, that is, trying to minimize the level flight segments by adding partial thrust when the aircraft is below the originally calculated flight path. The main reason for such a strategy choice is the aircraft inefficiency at low altitudes. In reality, pilots do not use partial power throughout the entire descent. Accordingly, there are certain differences due to the approximations made in the assumptions of our model. Even so, it can be argued that Strategy 1 deserves more thorough investigation in terms of efficient descent.

8. Concluding Remarks

This paper presented the initial results from an analysis of descent efficiency metrics focusing on speed-controlled descent and modeling real pilot control strategies used to adjust the path in respect to wind prediction error. It was clarified that neglecting the wind change component can lead to significant inaccuracies in the descent flight path calculated. Accordingly, when considering the effect of wind on descent, this component needs to remain. Two pilot control strategies were modeled and implemented in numerical simulations. Interviews with pilots revealed that most pilots opt for minimizing the level flight segment. However, our simulations showed that such an approach is not necessarily more efficient in terms of fuel burn, even though it shortens the flight time. It was also shown that shorter level flight segments do not automatically translate into more efficient descent, thereby proving the need for a new descent efficiency metric.

However, these results are dependent on partial power fuel
burn modeling, and further verification of this issue is ongoing, as mentioned below.

Future work in various areas is under consideration. First, verification of the proposed partial power fuel burn model is planned through experiments, including airline flight simulators and the use of high-fidelity models. Energy loss computations and analysis will also be performed as part of the validation. Next, path-managed descent patterns are going to be modeled and investigated to reveal the relationship between level flight segment length and fuel burn efficiency. Third, based on the above numerical simulation results, a new descent efficiency metric is going to be proposed.

References


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Associate Editor