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A Preliminary Study on Relationship between Flight Path Angle and NO_x Emissions during Descent

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Interest in the continuous descent approach has recently increased due to opportunities it provides for fuel savings and emissions and noise control. However, the implementation of this procedure involves a number challenges not easily addressed with current technology. Generally, the continuous descent approach has been examined through the reduction in fuel consumption and descent time. However, in this study, the effect of continuous descent approach with various flight path angles, along with a number of flight performance parameters, on nitrogen oxides are investigated. Using actual flight data records of ten B737-800 commercial aircraft, it is shown that with flight path angles of 2.25 °-4.25 °, which are considered in the high flight path angle category, differ in terms of fuel flow, specific range and emission production patterns, compared to descents with flight path angles of 1.25 °-2.25 ° (low flight path angle category). In addition, the emission production pattern is quantified with respect to descent altitude, since the effect of flight path angle varies with altitude.

1. Introduction

In the operation of commercial aircraft, one of the largest direct operation costs is for fuel. As a consequence, significant efforts have been expended on reducing fuel consumption by airlines. Numerous operational measures for reducing fuel consumption at each flight phase have been demonstrated and are the subject of research, yet some of them have negative effects on flight time, flight range or the environment.

Of these strategies, in the descent phase, engine power is used at the lowest level compared to other flight phases when the aircraft at airborne. An economic descent can only be obtained with an appropriate balance between the potential and kinetic energies that the aircraft possess, within the constraints of the air traffic. Depending on the flight range, the importance of the descent phase can be significant. The distance and the time of a typical long range flight could be more than 100 NM (nautical miles; 185 km) and 20-30 min.

The importance of avoiding low level flight relates to the optimum cruise altitude. Neglecting other conditions such as weather and characteristics of the individual flight, aircraft are typically optimized to yield the best fuel economy at a certain altitude and speed. Hence, flights at lower levels than the optimum flight altitude incur an increase in fuel consumption, and as a consequence emissions as well as an increase in flight time due to the reduced flight speed at lower altitude.

The continuous descent approach (CDA) is a useful descent procedure since it allows descents that avoid low level flights, providing that a suitable air traffic system exists. Furthermore, descending at a constant flight path angle (FPA) results in utilizing lower engine power compared to a stair-step descent and, thereby, lower fuel consumption.

Most CDA studies have focused on determining an optimum FPA and comparing CDA and conventional descent procedures in terms of fuel economy. Of these, Weitz et al. (2005) investigated the integration of CDA and airborne merging and spacing for terminal arrivals, and found that a descent at a 3 ° FPA could yield better results than a 2 ° descent. In another study, Wilson and Hafner (2005) reported 45 h and

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16,700 km (9,000 nautical miles) savings per day for Hartsfield–Jackson Atlanta International Airport, when CDA procedures are implemented. For Stockholm Arlanda Airport, Stibor and Nyberg (2009) obtained 56–88 kg of fuel savings per approach during the actual implementation of the CDA with only B737 aircraft. Implementing CDA for night flights has been shown to lower fuel consumption by approximately 25-40 % during the last 45 km of the flight for specific types of aircraft, which corresponds to a fuel savings of 55 to 400 kg, depending on the aircraft type (Wubben and Busink, 2000).

In addition to the fuel consumption benefits, Clarke et al. (2004) demonstrated using statistical methods a reduction in aircraft noise between 3.9-6.5 dBA in Louisville International Airport, along with a fuel consumption reduction of 181-227 kg per flight, when CDA is implemented. An investigation of the noise effect at Stockholm Arlanda Airport showed that a significant noise reduction accompanies switching a conventional arrival of a B737-600 aircraft to a CDA arrival (Stibor and Nyberg, 2009).

Since CDA was first proposed as a noise abatement strategy, the emissions benefits of CDA have received little attention. The previous research suggests that CDA procedures have mainly been studied from a fuel economy perspective, with the effects of the CDA on emissions generally viewed as a by-product of the fuel savings (Shresta et al., 2009).

In this study, the effects on NO_x emissions are investigated in detail for specific FPA categories, in order to improve understanding of these emissions during descents and the benefits of CDA. First the actual fuel flow rate during descent is determined empirically based on selected flight parameters (i.e., altitude, speed, FPA and mass). Then, this value is used as a variable to define a NOx emission index, which is also determined empirically for the given engine type using the ICAO emission database. Therefore, the NOx emission index is defined as a function of sub-variables, such as altitude, flight speed and FPA.To prepare your paper use directly this template and simply replace this text by your text.

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2. Background

In this study, 10 randomly selected B738 commercial aircraft are considered, along with flights carried out in 2011. Five of the flights were for between the Antalya International (AYT) and the Sabiha Gokcen International (SAW) airports, and five were for flights between the Izmir Adnan Menderes International (ADB) and the SAW airports. Both airports are located in Turkey and the flights were performed by Pegasus Airlines, one of the largest scheduled airlines operated in Turkey. It is noted that different engines are used on those flights. Flights 2, 5, 9 and 10 use CFM56-7B26/3 engines, while the remaining flights use CFM56-7B26 engines. Details can be found elsewhere (Turgut and Usanmaz, 2013).

In a cruise flight, the fuel flow rate is mostly affected by such parameters as altitude, speed and mass of the aircraft. In addition, during descent or climb, the flight path angle (FPA) also affects the fuel flow rate since it affects the conversion from potential to kinetic energy during the flight. In the present study, all of the parameters need to be and are taken into consideration.

Since maintaining a constant FPA (with zero standard deviation) for each descent region is not realistic, mainly due to weather condition variations, aerodynamic forces and/or aircraft sudden attitude (not altitude) changes, FPA segments are determined within ±0.25 ° for each one and half of the integer value. For instance, a common 3 ° of FPA can be accounted by the FPAs from 2.75 to 3.25 °.

The sample data reveals that the FPAs are mostly distributed between 0.75° and 4.25 °. However, considering the observations flight by flight, it is seen for some flights that the number of data points in the FPA region between 0.75-1.25 ° is insufficient to perform appropriate statistical analyses. Therefore, this region is omitted and the analyses are performed for FPA regions between 1.25-4.25 °.

The altitude segments are organized in such a way so as to separate flights below approximately 3,000 ft (900 m) from the other parts of the descent. Below this altitude in SAW, during the precision approach with respect to the Instrument Landing System (ILS), the aircraft maintain a glide path angle until the decision altitude at a value of 3.5 °.

3. Analysis of Rate of Fuel Flow

Evaluating the fuel flow in addition to the FPA makes it evident that the altitude level where the corresponding FPAs are observed is important, since the fuel flow varies with altitude. According to the data it is seen that the fuel flow distinctly (steadily) increases with decreasing altitude for FPA segments between 2.25 ° and 4.25 °, according to the following relationship (Adj. $R^2 = 0.829$; $F = 33{,}040$; $p < 0.01$):

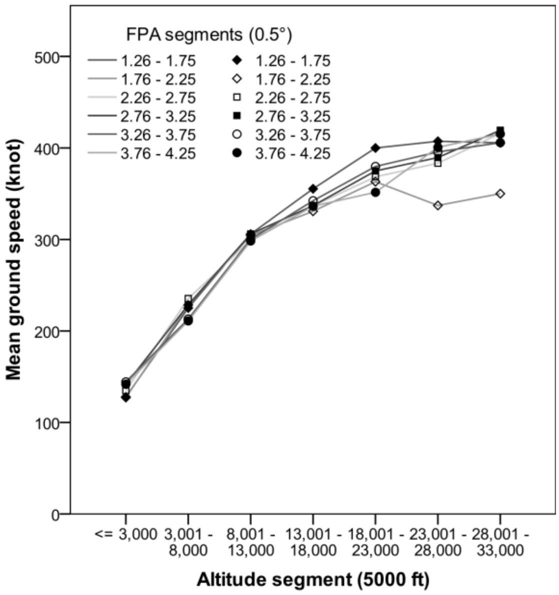

Figure 1: Mean ground speed variation during descent as a function of altitude and FPA segment

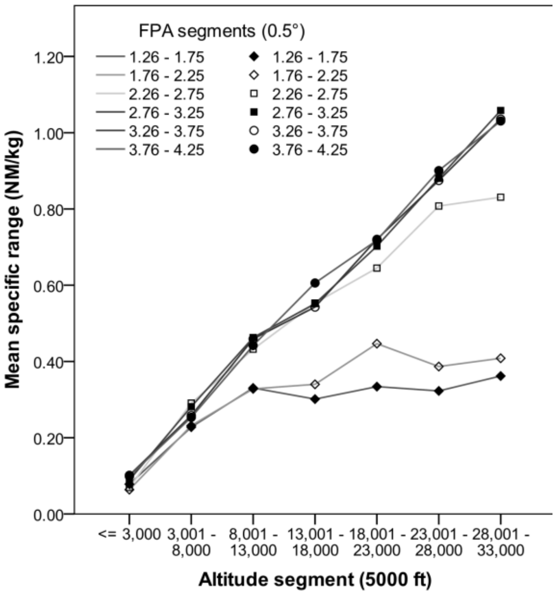

Figure 2: Mean SRG variation during descent as a function of altitude and FPA segment

$$\text{FF}=15{,}148.7\times(\text{Altitude})^{-0.408} \tag{1}$$

For lower FPA segments (< 2.25 °), no direct relationship is observed between the altitude and the FPA segments. As seen in Figure 1, ground speed is strongly dependent on altitude throughout the FPA segments, which implies that some of the fuel flow changes with altitude can be addressed by the changes in the ground speed. Therefore, investigating the FPA effect on only the fuel flow rate might lead inaccurate understanding, and the ground speed should also be considered.

In this context, we now consider another parameter, the specific range. This parameter can be used to improve understanding of the effect of speed on the fuel flow rate and to consolidate the two parameters into one. Specific range is defined as the ratio of the true air speed to the fuel flow (NAM/kg), which represents the amount of fuel per nautical air mile (NAM). Conventionally, this parameter does not include the wind effect. To determine the influence of wind, the ground speed (in knot) can be used. With ground speed, the specific range can be modified to a specific range at ground (SR_G). To observe also the wind effect, SR_G is used here. Furthermore, since we deal with descent flight only, so the SR_G parameter should id denoted by an additional index *D* for descent.

Note that the trend seen between fuel flow rate and altitude is also observed when comparing $SR_{G,D}$ and with altitude in Figure 2. Here, FPA segments above 2.25 ° exhibit a distinct linear variation with the altitude segments, while FPA segments below 2.25 ° exhibit a different relationship which as appears to be nonlinear. The average coefficients of variation at low and high FPA segments are calculated as 26 % and 44 %, respectively.

It is apparent from the data that the FPA can be partially related to the variation in the SR_G. Particularly, for certain FPA regions (such as up to 3-3.5 °) and aircraft masses, SR_G increases as the FPA increases. Yet, as expected, no direct relationship between SR_G and FPA is obtained throughout the continuous descent.

For high FPA segments (FPA ≥ 2.25 ° and FPA ≤ 4.25 °) the following relationship can be established between SR_G, and altitude and FPA (Adj. $R^2 = 0.962$; SEE = 0.101 NM/kg; F = 86,350; $p < 0.001$):

$$SR_{G,D}=3.202\times10^{-5}\times(\text{Altitude})+0.022\times(\text{FPA}) \tag{2}$$

In this FPA region, the effect of aircraft mass can be also observed as a predictor of Eq.(2). However, inserting the mass parameter has also a negative effect on the significance of the FPA variable. Without the mass, the t parameter for the FPA variable is 38.7, while it decreases to 3.3 when the mass parameter is included. Also no significant effect is observed on Adj. R2 or SEE, as the F parameter decreases to 57,929 when the mass variable is included. Therefore, this variable is not included, yet this does not mean that there is no effect of mass, but rather that the mass values of the sample are not sufficient to reveal a significant effect.

For the lower FPA segments (FPA < 2.25) a predictive model is established as follows (Adj. R2 = 0.817; SEE = 0.150 NM/kg; F = 10,756; p < 0.001):

$$SR_{G,D}=5.897\times10^{-6}\times(\text{Altitude})+0.127\times(\text{FPA}) \tag{3}$$

Where the significance of this model is found to be lower compared to the previous one.

The emission indices are given as a function of rate of the fuel flow. Due to different descent speeds, $SR_{G,D}$ is used instead of rate of the fuel flow parameter, which then provides information regarding speed changes using $SR_{G,D}$ in EI equations as a function of rate of the fuel flow. The investigation also shows that there is a significant relationship between descent speed, altitude and aircraft mass. The empirical models of ground speed follow ($p < 0.01$). For high FPA category:

$$GS_D=0.020\ (\text{Altitude})-3.708\times10^{-7}\left(\text{Altitude}^2\right)+2.061\ (\text{Mass}) \tag{4}$$

For low FPA category:

$$GS_D=0.021\ (\text{Altitude})-3.916\times10^{-7}\left(\text{Altitude}^2\right)+2.269\ (\text{Mass}) \tag{5}$$

Here, the representative statistical parameters of Adj.R^2 = 0.991; SEE = 27; F = 252,134 for the high FPA and Adj. R^2 = 0.987; SEE = 38 knot; F = 126,817 for the low FPA categories. Note that the above equation can have higher significance if the flights are investigated individually. When no FPA categories are applied, better statistical parameters are obtained as follows:

$$GS_D=0.02\ (\text{Altitude})-3.724\times10^{-7}\left(\text{Altitude}^2\right)+2.131\ (\text{Mass}) \tag{6}$$

where the Adj. R^2, SEE and F are 0.989, 33 and 421, 765, respectively. Therefore, in the following analyses and diagrams, Eq(6) is used.

Up to this point, the descent flight at continuous FPA is investigated to establish models explaining the effects of altitude and FPA on SR_G. It is thus possible to calculate the overall descent NO_x emissions and to determine whether a lower FPA descent has any emissions benefits over the steeper descent, and, if so, at which altitude regions these benefits can be maximized.

4. Results and Discussion

Models for empirical emission indices (mass of pollutant per mass of fuel), EI, are briefly described in this section. Details of the analysis procedure used for determining empirical emission indices are provided elsewhere (Turgut et al., 2013).

As stated earlier, the emission indexes of NO_x are obtained from the ICAO emission database. A disadvantage of the ICAO emission database is that its emissions indices are obtained only for limited fuel flow rates. For instance, a single fuel flow rate is accepted for the entire flight phase. This prevents precise identification of the emissions generated from commercial aircraft since the fuel flow rate is in actuality not constant. To address this problem, the approach used in this study is developed based on linear extrapolation and interpolation for NO_x emission. Despite the approach taken here, it is noted that emission production mechanisms generally are not simple, and that ambient conditions as well as such engine power-dependent operating parameters as combustion temperature, equivalence ratio and compressor pressure ratio may significantly affect emissions. Note also that the ICAO emission database is mainly intended for certifying engines with respect to environmental regulations and not for investigating the environmental or climate impacts of aviation. Nonetheless the database can help estimates emissions conservatively because it provides has a comprehensive inventory of most emission test results as a function of various engine parameters. The empirical NO_x emission models for two types of engine are given in Table 1; details can be found in Ref. (Turgut et al., 2013a).

Table 1: Emission index model for NO_x (Turgut et al., 2013a)

Engine type	Range of fuel flow rate (kg s^{-1})	Model*	R²
CFM56-7BX (flights 1, 3, 4, 6-8)	ff > 0	20.29 × ff + 2.83	0.989
CFM56-7BX/3 (flights 2, 5, 9, 10)	ff > 0	14.79 × ff + 3.04	0.984

*Coefficients in the models are rounded to two decimals in most cases.
ff denotes rate of the fuel flow rate.

The following results are yielded, considering the average mass of the aircraft (57.7 t). In addition, empirical emission expressions are developed using the ICAO emission database for emission measurements at sea level (i.e., altitudes below 3,000 ft). No further treatment is applied to calibrate the sea level values for higher altitudes. All of the results are shown in Figure 3.

In the high FPA category, the values of the EI of NO_x are found to be highest at lower altitudes, regardless of the FPA. Although for a given altitude level the difference is not large, it is observed that the higher is the FPA, the lower are the NO_x emissions. Noting that NO_x emissions are strongly dependent on engine power, this results is expected since a descent at both low altitude and low FPA is accompanied by a higher fuel flow rate and a higher engine power.

In terms of engine type, values of the EI for NO_x for 7BX engines are as expected found to be slightly higher than those for 7BX/3 engines. Considering the selected values of altitude and FPA, the highest EI for NO_x is to be 7.8 and 6.6 g/kg fuel at an altitude of 1,000 ft (300 m) and a FPA of 2.25 °, for 7BX and 7BX/3 engines, respectively. For a fixed FPA, the EI for NO_x at altitudes higher than 30,000 ft (9,000 m) is around 3.8 g/kg fuel for both types of engines. Increasing the FPA results in a slight decrease in values of EI for NO_x, due to the lower fuel flow rate. A comparison shows that for both engine types the greatest difference in the EI for NO_x is around 18 %, while the smallest difference is almost zero at the lowest values of EI for NO_x.

The emission indices in low FPA category exhibit different patterns, for both engine types. First, the highest and lowest fuel flow rates are observed to be 0.191 kg/s at 16,000 ft (4,800 m) with 1.25 ° and 0.07 kg/s at 1,000 ft with 2.25 °. Hence, the highest EI NO_x is observed to be 6.7 g/kg fuel for 7BX engines and 5.8 g/kg fuel for 7BX/3 engines at 16,000 ft and 1.25 ° of FPA, while the lowest EI NO_x is observed to be 4.2 g/kg fuel and 4.0 g/kg fuel at 1,000 ft (300 m) and 2.25 ° of FPA, for 7Bx and 7Bx/3 engines, respectively. It should be noted that since fuel flow rate is a strong function of flight speed, for a given flight and altitude level, various flight speed would typically lead to various fuel flow rates, and in turn various

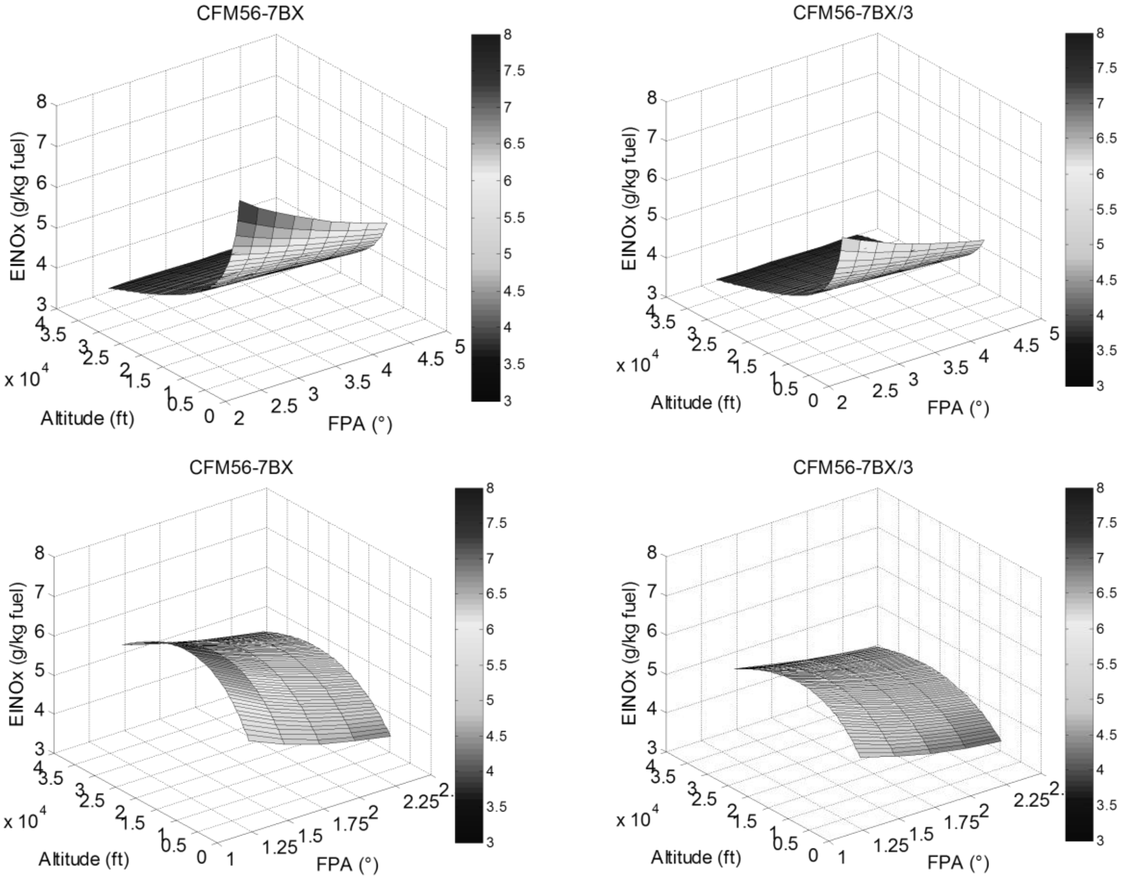

Figure 3: Effects of descent altitude and FPA on emissions, by engine category, for -7BX and -7BX/3 engines for the FPA categories 2.25 ° < FPA < 4.25 ° (upper) and 1.25 ° < FPA < 2.25 °

emission indices. Therefore, the altitude level where the highest EI NO_x is seen could be different flight by flight.

5. Conclusions

Although the engine power is relatively lower compared to all flight phases, the descent phase offers significant opportunities for fuel economy, considering its duration. Since emissions are high at low engine power, it may be possible to reduce emissions without modifying engine systems. However, increasing traffic volumes at airports appear to be driving airlines away from the benefits of the economic appropriate descent procedures, since they entail longer holding times and lower level flights. Therefore, most of the advantages provided by efforts to improve engine systems are diminished or lost.

To reduce the fuel consumption during descent, the continuous descent approach has recently received much interest, since it enables relatively lower engine power operation and, thereby, reduced fuel consumption, emissions and noise. This study has successfully quantified some of the results of the continuous descent approach at specific flight path angles in terms of NO_x emissions. Specifically, direct relationships are determined of specific range and fuel flow with altitude for various FPAs during descent, and these relationships are described for two FPA categories (i.e., high FPAs of 2.25 °-4.25 ° and low FPAs of 1.25 °-2.25 °).

Depending on the flight path angle, the highest descent NO_x production is calculated to be 6-8 g/kg fuel. Considering the actual descent profile of the flights, the highest NO_x emission for low FPA category is observed at an altitude of 16,000 ft (4,800 m), while for high FPA category, the highest NOx emission is observed at 1,000 ft (300 m) of altitude. In the ICAO emission databank, approach NOx emission index for below 3,000 ft (900 m) is given as 8.9 g/kg fuel and 10.8 g/kg fuel for CFM56-7B26/3 and CFM56-7B26 engines, respectively. However, even though the results of the current study include overall descent from top of descent altitude, it can be noted that various flight profiles lead to lower emission index. It can be also noted that the emission indices given in the ICAO emission databank can be significantly improved using interpolation of the data points of the same engine family.

Since in this study only NO_x emissions are investigated, there is much more to discover related to other emission species, such as carbon monoxide and hydrocarbons with the flight path angle and the other flight performance parameters. However, it should be noted that we do not report the descent at which FPA is better for the emissions since an accurate determination of this FPA requires in-depth analyses considering of a number of factors, e.g., added or reduced cruise distance and descent durations associated with changing the conventional descent procedure to an optimum FPA descent.

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