Environmental Pollution 236 (2018) 226–235

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Empirical analysis of the effect of descent flight path angle on primary gaseous emissions of commercial aircraft☆

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ARTICLE INFO

Article history:
Received 4 August 2017
Received in revised form
11 January 2018
Accepted 24 January 2018

Keywords:
Continuous descent approach
Flight path angle
Aircraft emissions
Aircraft mass

ABSTRACT

In this study, the effects of descent flight path angle (between 1.25° and 4.25°) on aircraft gaseous emissions (carbon monoxide, total hydrocarbons and nitrogen oxides) are explored using actual flight data from aircraft flight data recording system and emissions indices from the International Civil Aviation Organization. All emissions parameters are corrected to flight conditions using Boeing Fuel Flow Method2, where the ambient air pressure, temperature and humidity data are obtained from long-term radiosonde data measured close to the arrival airport. The main findings highlight that the higher the flight path angle, the higher the emission indices of CO and HC, whereas the lower the emissions index of NO_x and fuel consumption. Furthermore, during a descent, a heavier aircraft tends to emit less CO and HC, and more NO_x. For a five-tonne aircraft mass increase, the average change in emissions indices are found to be −4.1% and −5.7% (CO), −5.4% and −8.2% (HC), and +1.1% and +1.6% (NO_x) for high and low flight path angle groups, respectively. The average emissions indices for CO, HC and NO_x during descent are calculated to be 24.5, 1.7 and 5.6 g/kg of fuel, whereas the average emissions for descending from 32,000 ft (9.7 km) and 24,000 ft (7.3 km) are calculated to be 7–8 kg (CO), ~0.5 kg (HC) and ~3 kg (NO_x).

1. Introduction

As a highly competitive and mainly non-sustainable industry, improved fuel efficiency in aviation is a key element for economically and environmentally advantageous air transportation. Hence, significant efforts have been spent on reducing fuel consumption by manufacturers, air navigation service providers and airlines. Among these efforts, better air traffic management and aircraft technology as well as the introduction of alternative fuels are recognized to be important research and development drivers despite the complexity they involve. Projections on the increase in aircraft (3.5% per year) and passenger (4.7% per year) over the next 20 years (Boeing, 2017) underpin how necessary is improved air traffic management.

Each flight phase has inherent fuel savings options, even though most of these introduce compromises with other important flight factors, such as capacity, aircraft conflict avoidance, delay, and aircraft weight, or they may impact with the efficiency of previous or subsequent flight phases. Therefore much research has focused on trajectory optimization of an entire flight to minimize the vertical and horizontal inefficiencies (Dalmau and Prats, 2015, 2014; Matsuno et al., 2015; Park and Clarke, 2015; Soler et al., 2015). In addition, numerous studies have been reported on individual flight phases. For instance, the single-engine taxi concept can provide considerable fuel savings and emissions reductions for some species, depending on airport traffic (Herndon et al., 2009; Stettler et al., 2011; Whitefield et al., 2008; Yim et al., 2013). Reduced thrust takeoffs also can decrease fuel use and emissions, as well as reducing engine wear (Koudis et al., 2017). To reduce the additional fuel consumption due to holding time during arrival at an airport, the cruise speed can be optimized with a preference for a proper cost index (Delgado and Prats, 2009) or to reduce environmental impact by lowering cruise altitudes under certain circumstances (Koch et al., 2011). Continuous cruise climb also promises fuel and time savings, particularly for long-haul flights (Dalmau and Prats, 2015).

Similarly, during the descent phase, avoiding level offs at low level altitudes (i.e., having no step stair descents) can reduce fuel use, even though the implementation of such descent procedures is difficult to perform with the current air traffic system. It has been

☆ This paper has been recommended for acceptance by Charles Wong.
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https://doi.org/10.1016/j.envpol.2018.01.084
0269-7491/

reported that the night-time CDA procedure implemented in Amsterdam Schiphol Airport leads to increased landing interval of 1.8–4.0 min; it was implemented to guarantee sufficient spacing between aircraft due to the large dispersion in aircraft approach speed and conflicts between inbound aircraft (Nieuwenhuisen and Gelder, 2012; Wubben and Busink, 2000). The lower fuel consumption in CDA is in part attributable to lowering engine power and to increasing the propulsive efficiency due to reduced kinetic energy losses and the requirement for less cooling air. Many situation-specific studies have demonstrated significant fuel and/or time savings through continuous descent approach (CDA) procedures (Clarke et al., 2004; Errico and Di Vito, 2017; Filippone, 2007; Nikoleris et al., 2016; Park and Clarke, 2015; Sprong et al., 2008; Stibor and Nyberg, 2009; Tong et al., 2003; Wilson and Hafner, 2005). Nonetheless, uncertainties in wind prediction may challenge a default flight path angle (FPA) that is established to provide minimum descent fuel use (Jong et al., 2014; Wu et al., 2015). In addition to fuel savings, it is generally acknowledged that CDA procedures reduce noise (Park and Clarke, 2015) and CO_2 emissions (Clarke et al., 2013). Interestingly, however, one study found that there might be certain surface areas (albeit relatively smaller) below a flight path for which the noise annoyance caused by CDA procedures is greater than that from applying a regular approach (White et al., 2017).

In this study, the benefits of CDA are investigated, in terms of FPA and its effects on engine primary gaseous emissions, namely carbon monoxide (CO), total hydrocarbons (HCs) and nitrogen oxides (NO_x). The variation in engine power, thereby fuel flow rate, does not straightforwardly effect all emissions at same extent or sense. Therefore, in the following sections, using actual flight data from ten flights, we quantified the relative variations of emissions indices and emissions with FPA. To correct the sea level emissions indices to altitude condition, long-term radiosonde data is also used with Boeing Fuel Flow Method2 (DuBois and Paynter, 2006). Finally, effect of aircraft mass is also discussed in three groups.

2. Material and method

A preliminary study regarding this topic was previously reported (Turgut et al., 2014). This paper differs considerably in extent from the previous study in several ways. In the previous paper, only NO_x emissions were considered and no altitude correction was made. In the present paper, all common gaseous emissions are considered with altitude correction. The correction method is selected to be the Boeing Fuel Flow Method2 and the ambient pressure, temperature and humidity data are obtained from long term radiosonde measurements (Turgut and Usanmaz, 2016). In addition, the discussion on mass effect is substantially enhanced with better visualization, and the total descent emissions are calculated for each flight.

2.1. Route and aircraft description

Flight data of ten aircraft, randomly selected from the most frequently used narrow-bodied commercial aircraft, are considered in the present study. Five of the flights (Flight01 to Flight05) occurred between the Antalya International (AYT) and Sabiha Gokcen International (SAW) airports, and five (Flight06 to Flight10) for flights between the Izmir Adnan Menderes International (ADB) and Sabiha Gokcen International airports. The flights were performed by Pegasus Airlines, one of the largest scheduled airlines operated in Turkey. The SAW airport is the arrival airport for each group. According to 2016 aircraft movement statistics, SAW, AYT and ADB are the 2nd, 3rd, 5th busiest airports in Turkey (DHMI, 2016). Note that these flights use different engines. Flights 02, 05, 09 and 10 utilize CFM56-7B26/3 engines, and the other flights CFM56-7B26 engines.

An independent *t*-test of the actual flight data records shows significant difference in the FPA ($t = -22$), the fuel flow rate ($t = 19$), the ground speed ($t = 19$) and the aircraft mass ($t = 31$) at ADB-SAW compared to the AYT-SAW route ($p < 0.05$), most likely due to air traffic regulation constraints. According to Table 1, the mean FPA for descents on the AYT-SAW route is higher than the ADB-SAW descents, while the mean aircraft mass and the mean flight speed are lower. This difference in parameters appears to explain substantially the difference in the mean fuel flow rate for the descents on the two routes. Since there are both a lighter aircraft and a steeper descent FPA at slower speeds, lower fuel flow rate (and relatively lower exhaust gas temperature) is observed during the descent for the AYT-SAW flights.

2.2. Analysis of flight parameters

At cruise, fuel flow rate is affected by numerous parameters, especially speed and mass of the aircraft, altitude and wind. Also, FPA affects fuel flow rate during descent or climb because it impacts the potential to kinetic energy conversion during flight. Here, consequently, all parameters need to be considered.

When examining the CDA at a specific FPA, the distribution of FPAs for all observations is shown in Fig. 1. Since maintaining a constant FPA for each descent region is not realistic, mainly due to weather condition variations, aerodynamic forces and/or controller instructions, the FPA data were binned into fifteen groups with an increment of 0.25°. It is seen from Fig. 1 that the FPAs are mostly distributed between 0.75° and 4.25°. Considering observations from flight to flight, however, shows that, for some flights, the number of data points is insufficient for the FPA region 0.75–1.25° for proper statistical analyses. This region is omitted as a consequence and analyses are performed for FPA regions between 1.25 and 4.25°.

The fuel flow rate and FPA demonstrate that the altitude at which the FPAs are observed is significant, since fuel flow rate is dependent on altitude. Therefore, the vertical descent distance is binned into altitude groups with 5000 ft intervals. These groups are organized such to distinguish flights below 3000 ft from other parts of the descent. Below 3000 ft at SAW, the aircraft holds to a glide path angle until the decision altitude of 3.5° during the precision approach relative to the Instrument Landing System (ILS). Fuel flow rate and exhaust gas temperature decrease significantly with increasing altitude for FPA groups between 2.25° and 4.25° (see Fig. 2). This is based on the following expression (Adj. $R^2 = 0.829$; $F = 33{,}040$; $p < 0.01$):

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

A direct relationship is not observed between FPA group and altitude, for the lower FPA group (<2.25°).

Table 1
Mean values of selected flight performance parameters during descents (above 3000 ft (~1 km)) with respect to routes (data for ten flights with total samples of N = 6401 for AYT-SAW; N = 6348 for ADB-SAW). Error values indicate 1σ.

Descent parameter	Route 1 AYT-SAW	Route 2 ADB-SAW
FPA (°)	2.58 ± 1.55	2.07 ± 0.99
Aircraft mass (tonne)	56.5 ± 3.0	57.9 ± 2.3
Fuel flow rate (kg/s)	0.127 ± 0.06	0.148 ± 0.07
Aircraft ground speed (knot)	306 ± 74	332 ± 81
Exhaust gas temperature (°C)	441 ± 40	447 ± 41