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Estimation of Commercial Aircraft Emissions According to Flight Phases

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ABSTRACT

The quantities of common emissions are investigated for a specific type of commercial aircraft. Actual flight data and ICAO emissions data are used. All flight phases are considered, including landing and takeoff phases. The investigation is carried out for the domestic flights only and considers relevant parameters, such as engine type, flight phase and ground or air operation of the flight. The findings suggest that the quantities of emissions of unburned hydrocarbon (HC) and carbon monoxide (CO) during the descent phase can exceed those for the taxi phases and the idle operation of the engines, depending on the approach procedure. The main source of NO_x is usually the climb phase. The effect of the duration of taxi phase on the production of HC and CO emissions is discussed.

Key words: Aircraft emission, environment, turbofan engine, flight data records

INTRODUCTION

The objective of this study is to improve understanding of common emissions (HC, CO and NO_x) resulting from aircraft, based on the ICAO databank (CAA, 2011). This databank includes exhaust emissions and fuel flow rates for currently used turbofan engines during landing and takeoff (LTO) phases. The investigation is carried out in such a way that the actual flight data are considered. In order to perform this task a novel method is developed, in which interpolation and extrapolation of the relationship between the fuel flow and the emission indices data of specific type of engine is provided. Data are obtained from flights of ten randomly selected B737-800 (hereafter B738) commercial aircraft. Two types of turbofan engines are used in these aircraft: CFM56-7B26 and CFM56-7B26/3.

METHODOLOGY

The most frequently used domestic routes, aircraft types and the engine types are considered for the data selection. For this purpose, ten randomly selected B738 commercial aircraft are used. Five of them are for flights between the Antalya International (AYT) and Sabiha Gokcen International (SAW) airports and five are for flights between the Izmir Adnan Menderes International (ADB) and the SAW airports in Turkey. The SAW airport is the arrival airport for each group.

The route selections relate to the frequency of flights to SAW. In 2009, for domestic flights, the two most frequent arrivals to SAW are from ADB and AYT with 2956 and 2684 total arrivals, respectively. For B738 aircraft only, the numbers of arrivals reduce to 1540 for AYT and 1134 for ADB. Of the total arrivals to SAW with B738 aircraft, therefore, flights from AYT and ADB account for 15 and 11%, respectively.

With respect to engines, six of the assessed flights were powered by CFM56-7B26 (hereafter 7B26) engines, while the remaining four were powered by CFM56-7B26/3 (hereafter 7B26/3) turbofan engines. Moreover, for the flights of each route, three 7B26 and two 7B26/3 engines are utilized.

In the ICAO emission databank there are 17 different models of the CFM56-7B series engine which can be defined according to by-pass ratio, overall pressure ratio and thrust parameters. The engine family can be classified into three groups: CFM56-7BX (single annular combustion), CFM56-7BX/2 (double annular combustion) and CFM56-7BX/3 (improved emissions single annular combustion), where X denotes model numbers such as 18, 20, 22, 24, 26 and 27 (U.S. Department of Transportation, 2008). The classification is mainly based on the combustion chamber design.

The ICAO emission database, has a disadvantage in that its emission 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 a precise identification of the emissions generated from commercial aircraft since the fuel flow rate is not constant. To address this problem here, the approach used in this study is developed based on linear and polynomial extrapolation and interpolation for three types of emissions: HC, CO and NO_x.

The variation of common emission indices with fuel flow rate indicates that linear relationships are present for certain fuel flow fragments, where fuel flow fragments are the fuel flow rate regions for a given flight phase for all of the engines. For instance, the given fuel flow rates for the climb phases of all the engine models constitute a fuel flow region while there are other specific fuel flow ranges for the other three flight phases: Takeoff, approach and landing. In other words, there is specific fuel flow region for each flight phase for the engines of each group. For these regions the relationship between the emission indices and the fuel flow rates can be straightforwardly identified. However, for fuel flow rates outside the specified regions, particularly between the two regions, the approach based on the aforementioned relationship can lead to incorrect results. Therefore one needs additional methods which can be obtained utilizing the sequential regions. For instance, if the overall fuel flow ranges are divided into three parts (highest, medium and lowest regions indicating the amount of fuel flow) then the region between highest and medium fuel flow rates and also between the medium and the lowest fuel flow rates can be described by additional relationships. The required model descriptions are presented in the next section.

RESULTS AND DISCUSSION

The relationships are developed for two sections, representing both engine series and given in Table 1 and 2. The fuel flow rate ff range is also given in Table 1 and 2. The coefficients of determination (R^2) for the regression models are given in the last columns of Table 1 and 2. All of the regression models exhibit high coefficients of determination, mostly over 0.960 (with the exceptions of 0.904 and 0.910 which relate to the fuel flow range of CO emissions). This means that these models explain more than 96.0% of the variation in emission index when compared to the total variation.

The duration of the flight phases are depicted in Fig. 1. In the ICAO database, emission indices are given for only four flight phases. Utilizing the models developed in this study, one can obtain information related to other flight phases, such as cruise and taxi.

Table 1: Models emission indices for CFM56-7BX (flights 1, 3, 4, 6-8)

Emission index (EI) (g)	ff* range (kg s^{-1})	Model**	R^2
EI (HC)	$ff \geq 0.260$	$-92.07\times(ff) + 12.34$	0.978
	$0.260 > ff > 0.116$	$0.0029\times(ff)^{-2.988}$	0.979
	$ff \leq 0.116$	0.1	NA***
EI (CO)	$ff \geq 0.714$	$9.10\times(ff)^3 - 30.46\times(ff)^2 + 32.52\times(ff) - 10.61$	0.975
	$0.714 > ff > 0.349$	$0.42\times(ff)^{-1.446}$	0.904
	$0.349 \geq ff \geq 0.260$	$-24.64 \times (ff) + 9.95$	0.995
	$0.260 > ff > 0.116$	$0.17 \times (ff)^{-2.194}$	0.995
	$ff \leq 0.116$	$-536.95 \times (ff) + 79.89$	0.981
EI (NO_x)	$ff > 0$	$20.29 \times (ff) + 2.83$	0.989

*ff denotes fuel flow rate. **Coefficients in the models are rounded to two decimals in most cases, *** EI of HC for this range is given in ICAO database as a constant value of 0.1 gr HC kg^{-1} of fuel

Table 2: Models emission indices for CFM56-7BX/3 (flights 2, 5, 9, 10)

Emission index (EI) (g)	ff range (kg sec^{-1})	Model*	R^2
EI (HC)	$ff \geq 0.702$	$0.07\times(ff)^2-0.15\times(ff)+0.11$	0.972
	$0.702 > ff > 0.343$	$0.03\times(ff)^{-0.77}$	0.964
	$0.343 \geq ff \geq 0.256$	$-0.39\times(ff)+0.18$	0.973
	$0.256 > ff > 0.110$	$0.001\times(ff)^{-3.41}$	0.992
	$ff \leq 0.110$	$-161.40\times(ff)+19.09$	0.966
EI (CO)	$ff \geq 0.702$	$1.56\times(ff)^2- 3.03\times(ff)+1.63$	0.972
	$0.702 > ff > 0.343$	$0.18\times ff)^{-2.43}$	0.910
	$0.343 \geq ff \geq 0.256$	$- 31.11\times(ff)+13.37$	0.991
	$0.256 > ff > 0.110$	$0.32\times(ff)^{-2.07}$	0.999
	$ff \leq 0.110$	$- 944.89\times(ff)+132.56$	0.985
EI (NO_x)	$ff > 0$	$14.79 \times(ff)+3.04$	0.984

*Coefficients in the models are rounded to two decimals in most cases

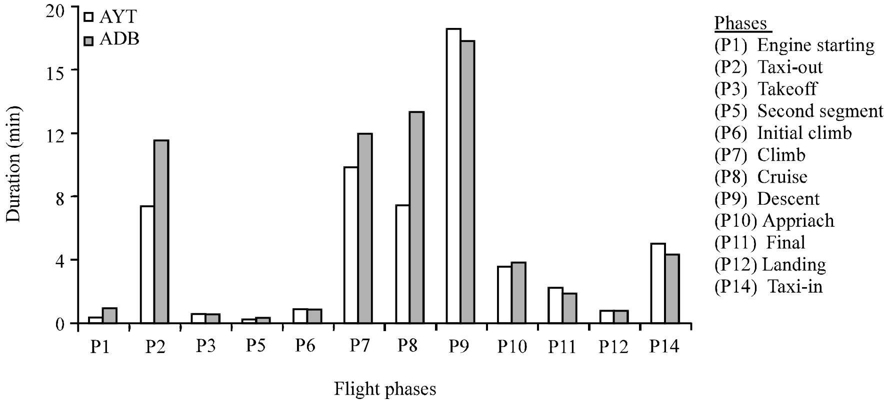

Fig. 1: Durations of flight phases. The average total flight times are 67.9 and 56.8 min for AYT and ADB, respectively

The breakdowns of the HC, CO and NO_x emissions for the AYT-SAW route are shown in Fig. 2. It is seen that certain emission types produced at certain flight phases can vary greatly from those for the other phases. On the other hand, the same flight phase can exhibit a relatively lower amount of some kinds of emission types and a relatively higher amount of other

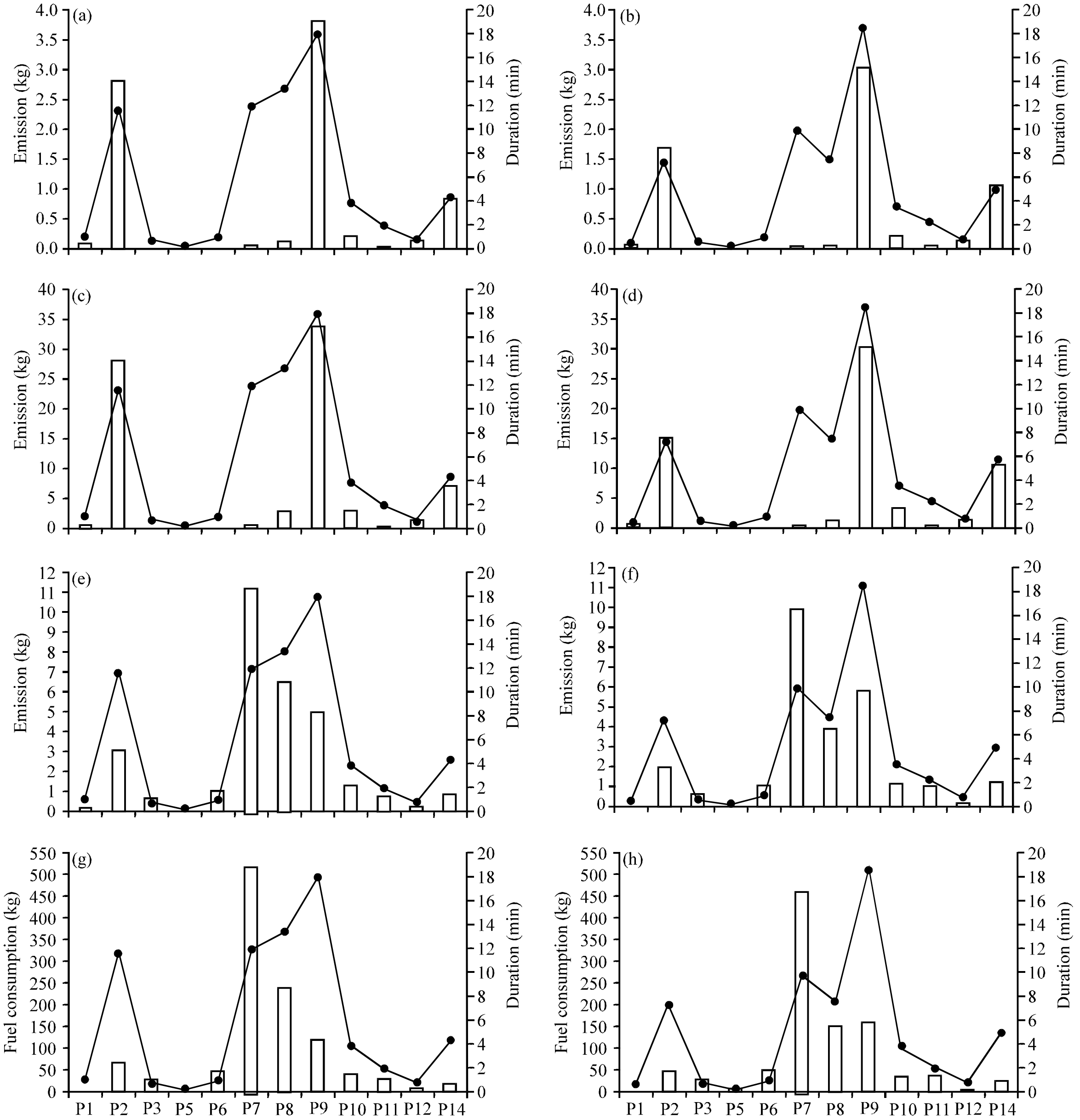

Fig. 2(a-h): Emission breakdown by flight phase for (a-b) HC, (c-d) CO AYT and (e-f) NO_X and (g-h) Fuel ADB departures. The black line in each graphic indicates the duration of the related phase. Phases P1 to P14 are described in the legend of Fig. 1

types of emissions. Here it is noted that the engine power setting and phase duration significantly affect emissions quantities.

Due to incomplete combustion, the emissions of HC and CO for lower engine power settings are observed to be much greater than those for higher power settings (Sutkus *et al.*, 2001; Schurmann *et al.*, 2007; Mazaheri *et al.*, 2009; Anderson *et al.*, 2006). Therefore, such emissions obtained for flight phases such as taxi and descent are found to be higher than the phases such as takeoff and climb. This pattern is observed the graphs in Fig. 2. Accordingly, HC and CO emissions resulting from aircraft operation during taxi (P2 for taxi in and P14 for taxi out) and descent (P12), where the engine power setting is relatively low, are observed to be at higher levels. For instance, the HC emissions are calculated as 3.7 and 3.8 kg for the sum of P2 and P14 and P9, respectively. Since the phase duration can have a great effect on the emissions, the duration should be considered along with the amount of the emissions.

As can be seen from the graphs in Fig. 2, for relatively lower power settings as for the idle and taxi (P2 and P14) phases, higher quantities of HC and CO emissions are observed, depending on the phase duration. For instance, the highest levels of HC emissions are observed for the phases of descent, taxi-in and taxi-out, for which the corresponding durations are 18, 12 and 4 min.

The flight phases P3 (take off) and P12 (landing) are assumed to occur in the vicinity of the airport since the flight phases occur at a low height over the runway. For instance, the average heights for AYT-SAW routes are determined to be 19 m for P3 and 12 m for P12. As a result, the durations of the idle and taxi phases have significant effects on the quantities of HC emissions. For the above example, the longer ground operation duration (P1-P3) at departure airport AYT yields a higher HC emission (2.9 kg) while the shorter ground operation (P12-P14) in the arrival airport SAW yields a lower HC emission (0.8 kg). Thus for the high air traffic in busy airports, where aircraft often wait in taxi sequence or holding point for takeoff in long queues, or for airports with long taxi ways, there may be significant HC emissions in the vicinity of the airport.

The descent flight phase (P9) is the longest phase. In this phase, depending on the descent procedure, the power settings of the engine can be idle or at a value slightly higher than the idle. For instance, the N1 RPM of the engine for the 9th flight is calculated at around 30-35% of the actual RPM at full speed, after 89% of the descent time has elapsed. During the same phase, the EGT values are concentrated at 426-429°C. By comparison, the distributions of the N1 RPM and the EGT values for the taxi phase are concentrated at around 18-24% and 470-530°C, respectively. Although the lower power settings may lead to higher HC emissions, the net benefit can be positive due to reduced fuel consumption and amounts of other emissions, such as NO_x and CO_2.

The emissions breakdown of CO by flight phase is similar to those for HC emissions. However, the mass of CO emissions can be an order of magnitude higher than that of HC emissions. As seen in Fig. 2, the highest CO emissions are observed for the flight phases of descent (34.0 kg), taxi-in (25.3 kg) and taxi-out (7.4 kg) which is similar to the case for HC emissions. CO emissions are found to be quite low for the remaining flight phases, for which power settings are relatively high.

The highest levels of NO_x emissions are observed during the climb, cruise and descent phases. The average NO_x emissions for the five flights is 31.3 kg, of which 16.0% is produced in ground operations, 34.6% in climb, 20.6% in cruise and 15.9% is descent. Taxi-in exhibits higher NO_x emissions than taxi-out, due to the longer phase duration. Emissions and the fuel consumptions for the second route (ADB-SAW) are also shown in Fig. 2.

CONCLUSION

For short range domestic commercial flights, several key findings and conclusions can be drawn from the results of the present emissions study:

- For the common emission species, CO, HC and NO_x, linear and nonlinear models are developed for all of the flight phases, for two routes and two engine models. The models are based on the ICAO emission measurements. Actual flight data are obtained from flight data records. The models permit evaluation of emissions for all of flight phases for various fuel flow rates

- The models can be used for the other aircraft types using the same types of the engines. That is, for the same engine type and known fuel flow rates, emissions quantities can be calculated using the developed models
- A breakdown of emissions by flight phase is obtained and the findings agree well for flights on both routes. The highest CO and HC emissions are found in the descent phase, followed by the taxi phases (in and out). The highest NO_x emissions are found in the climb phase, followed by cruise and descent. There are less but not negligible NO_x emissions in the taxi phase due to the high taxi duration
- The mean total flight emissions are calculated as 8 kg of HC, 75 kg of HC and 31 kg of NO_x for the AYT route and 6 kg of CO, 60 kg of HC and 28 kg of NO_x for the ADB route
- The average ground time of the flights are calculated as 22-25% of the total flight time for both routes. Since the HC and CO emissions are mostly produced in the lower power settings of the engine, decreasing the taxiing time provides significant abatement of those two emissions

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