Chapter 11
Carbon Foot Print of a Passanger Aircraft Engine at Landing and Take-Off Cycle

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Introduction

In last decade, rapid civilization forces us to develop more eco-friendly systems with respect to the environmental issues. Mankind population growth on the earth and utilization of the sources callously leads to consider sustainable development. On the other hand, environmental impact reduction is as important as sustainability at the present time. Especially damage and impact of the energy industry on the environment become more of an issue for the future of the mankind. In this case, transportation industry, which is an ever-growing and consuming energy sources more and more, should be evaluated in terms of environmental issues (Winter 2014; Lee et al. 2009). Under consideration of the aviation transportation growth in Turkey, environmental impact of the aircrafts plays a key role for understanding slice of this industry within the contribution of Turkey to the global warming and climate change. As mentioned in a previous study (Ekici et al. 2013), number of aircrafts in aviation fleet enormously increases day by day.

Many researcher studied on exhaust emission related issues of the aviation with concern of environmental issues. Beck et al. (1992) presented the impact of the aircraft emissions on atmosphere's tropospheric layer by a two-dimensional model. Authors especially focused on ozone formation as a result of aircraft exhaust emissions in the paper. Role of the nitrogen oxides within the global warming was highlighted by authors. In another text, international airports in Korea was

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handled and dependence among the air pollution and the greenhouse gases emitted from commercial aircrafts was investigated. Fan et al. (2012) calculated fuel consumption and aircraft emissions from domestic flights for China in 2010. As a result of their study, an airline emitting excessive emissions is selected in China. Hu et al. (2009) evaluated air pollutants near an airport depending on real-time measurements. Aircraft engine exhaust emissions, exhaust gases emitted from other vehicles in the airport were discussed in the paper. Yilmaz and Ilbas (2012), presented the emission parameters of various aircraft engine in service. Consequently, the necessity of alternative fuel utilization in aircraft engines is emphasized by the authors. Aircraft engine emissions over the course of landing and take-off cycle are investigated by Ekici et al. (2013) for the busiest airports in Turkey. In another study, it is aimed to develop a model for nitrogen oxide emissions of a turbofan engine for determining environmental impact of aircraft engine emissions on the basis of the operational and meteorological conditions. In another text (Naugle and Fox 2014), contribution of the emitted gases from aircrafts to air pollution was discussed. Also, aircraft emissions caused health issues were highlighted by the authors. Exhaust emissions of an aircraft engine which is fed with both an alternative fuel and kerosene were evaluated by Santoni et al. (2011). Especially unburned hydrocarbon and nitrogen oxide emissions were given in details by authors. It is reported that, unburned hydrocarbon concentrations in engine exhaust were lower than ambient concentrations at higher thrust levels. Mazaheri et al. (2011) evaluated exhaust emissions of large aircrafts at an airport. Authors presented emission rates depending on aircrafts operating in the airport. Additionally, particulate matter emissions were discussed in details by researchers. Synylo and Duchêne (2014) modelled nitrogen oxide emissions of a turbofan engine to evaluate the impact of operational and meteorological conditions on nitrogen oxide formation. Additionally the environmental sustainability of the engine was discussed in the paper.

In the present paper, a turbofan engine of a commercial aircraft in service is investigated. Carbon footprint of the examined engine is intended to present with the aid of ICAO aircraft engine emissions inventory. The main goal and differences of the current paper from previous studies may be listed as follows:

- Introducing the correlation between emission index and carbon footprint.
- Revealing the carbon footprint of an aircraft engine for the first time.,
- Presenting a different perspective to understand environmental impact of the aviation.

Turbofan Engine and Evaluation Methodology

In this study, a mixed turbofan type aircraft engine is evaluated. The engine which is named as JT8D is operated on many aircraft such as Boeing 727 and 737 series, McDonnell Douglas DC-9 and MD-80. The JT8D serves the industry by providing

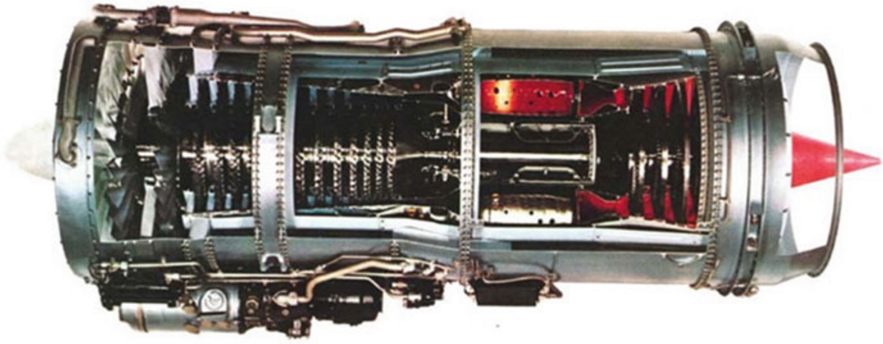

Fig. 11.1 The sectional view of the JT8D engine (Pratt & Whitney 2014)

power to more than 2400 aircraft. The sectional view of the engine is shown in Fig. 11.1 (Pratt & Whitney 2014). For evaluation of the engine, data is provided from the ICAO aircraft engine emissions inventory (EASA 2014).

The ICAO aircraft engine emissions inventory (EASA 2014) contains emission data for the ICAO landing and take-off flight envelope. A typical flight envelope is demonstrated in Fig. 11.2. ICAO landing and take-off flight cycle is the part of this envelope which is under the 3000 feet altitude. In the course of emission measurement, engine was operated under the relevant flight settings. That is to say, engine was operated at 100 %, 85 %, 30 % loads for 0.7, 2.2, 4.0 min at take-off, climb-out and approach flight phases respectively (ICAO 1993).

Carbon footprint is the total sets of greenhouse gas emissions caused by an organization, event, product or person and a useful parameter to understand contribution to the climate change. The calculation of the carbon footprint is performed by finding carbon dioxide equivalent for 100-year time horizon of the greenhouse gases emitted by an organization, event, product or person. In this framework, carbon footprint of the examined turbofan engine can be found as following (Schimel et al. 1996; Wright et al. 2011):

$$C = \sum (CO_2e)_i = \sum EI_i m_f GWP(100)_i \tag{11.1}$$

Here, C notates carbon footprint whereas CO_2e, EI, m_f, GWP(100) and i represents carbon dioxide equivalent, emission index, fuel mass flow rate, global warming potential for 100-year time horizon and ith greenhouse gas emitted from the engine. Carbon dioxide equivalent of any gas means global warming potential of the gas for 100-year time horizon. Emission index indicates emitted gas amount per consumed fuel amount within the combustion chamber. In Table 11.1, global warming potentials of emitted gases for 100-year time horizon are given.

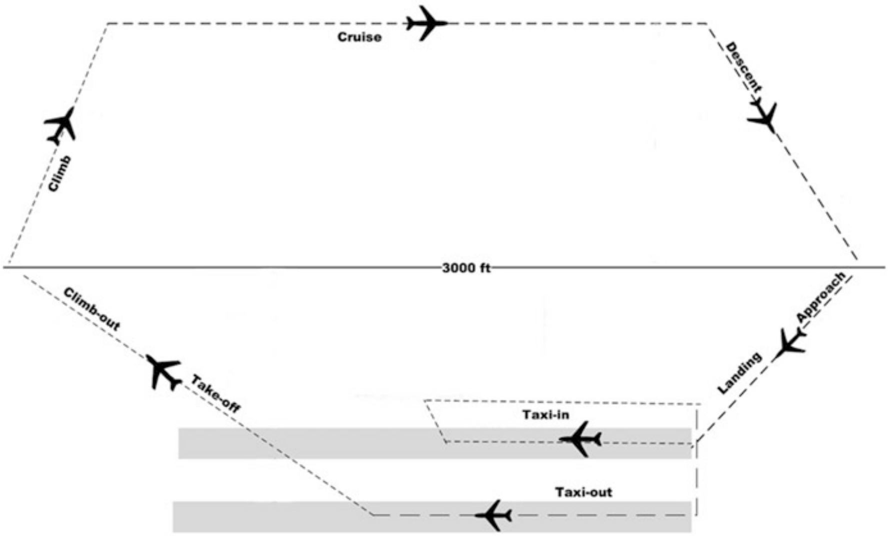

Fig. 11.2 A typical flight envelope for a commercial aircraft (adopted from ICAO 1993)

Table 11.1 Global warming potential values of greenhouse gases emitted from an aircraft engine for 100-year time horizon (Altuntas 2014; Schimel et al. 1996)

Greenhouse gas	GWP(100)
CO_2	1
CO	1
NO_x	310
CH_4	21

Table 11.2 Exhaust gas emissions of the JT8D engine at landing and take-off flight cycle (EASA 2014)

Flight phase	EI_{CO}	EI_{NOx}	EI_{UHC}
Take-off	0.74	19.20	0.69
Climb-out	1.00	15.23	0.79
Approach	8.54	6.10	1.96
Idle	31.00	3.30	0.00
Total	41.28	43.83	3.44

Results and Discussion

In this study, carbon footprint of emitted greenhouse gases from JT8D engine which is still operated on many commercial passenger aircraft. During a typical landing and take-off flight cycle, exhaust gas emissions of the engine are given in Table 11.2.

Calculations based upon data given in Table 11.2, are performed with the aid of Eq. (11.1). Herein, unburned hydrocarbon (UHC) emission was assumed to be

Table 11.3 Carbon footprint equivalents of emitted greenhouse gases from JT8D engine at landing and take-off flight cycle

Flight phase	C(CO)	C(NO_x)	C(UHC)
Take-off	0.921	7410.240	18.040
Climb-out	0.997	4707.136	16.540
Approach	3.023	669.414	14.570
Idle	4.557	150.381	0
Total	9.498	12937.170	49.150

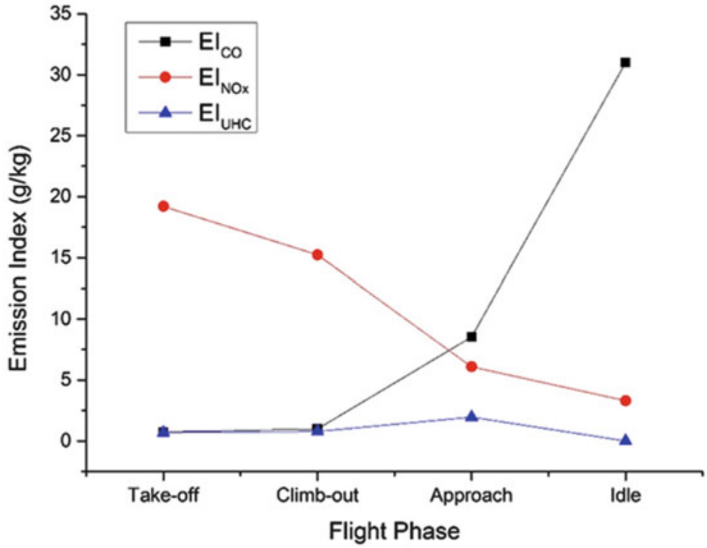

Fig. 11.3 Emission index variation of JT8D engine greenhouse gases with flight phases

methane (CH_4). As a result of the study, obtained carbon footprint equivalent of each emission gas was summarized in Table 11.3 on the basis of flight phases.

For better comprehension of the situation, Figs. 11.3 and 11.4 are plotted. As indicated in Fig. 11.3, unburned hydrocarbon emission index of the engine is approximately same at take-off and climb-out phases of flight. However, emitted unburned hydrocarbon per consumed fuel increases at approach phase and dramatically decreases at idle. Additionally, reverse proportion among carbon monoxide and nitrogen oxide emission index is clarified in the graph. So, it can be asserted that, while amount of emitted carbon monoxide per consumed fuel raises, nitrogen oxide emission descents over through the landing and take-off flight cycle.

Figure 11.4 reveals the carbon footprint of the engine during landing and take-off flight cycle in simple terms. Herein, carbon footprint values of carbon monoxide and unburned hydrocarbon are approximate to zero in comparison with nitrogen oxide emission. However, carbon footprint of emitted nitrogen oxide decreases from 7410.24 g to 150.381 g. So, impact of nitrogen oxides emitted from aircraft engines on global warming is clearly proven.

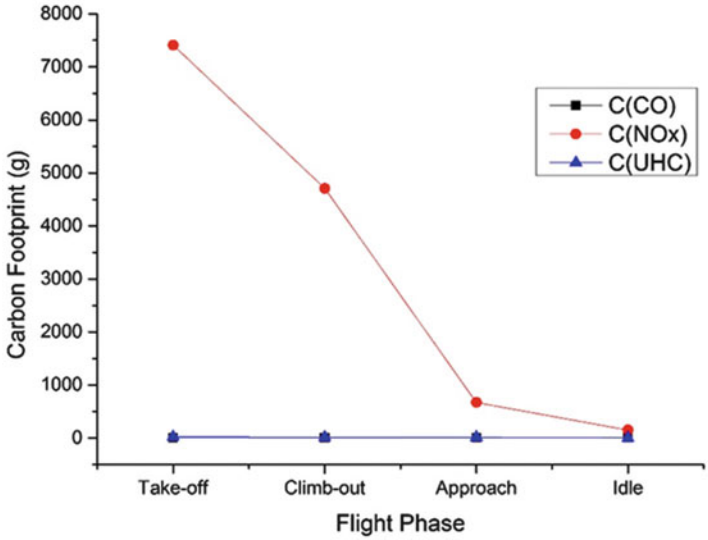

Fig. 11.4 Carbon footprint variation of JT8D engine greenhouse gases with flight phases

Conclusions

As a result of the study, following statements are concluded by authors:

- With regard to emission measurement, emitted greenhouse gases from the engine are concern. On the other, in terms of carbon footprint calculation carbon monoxide and unburned hydrocarbons can be disregarded in future studies. But it is not possible to assert for nitrogen oxide emission.
- Conducting similar study for various engine types can be beneficial as a comparison. So that, contribution of aircraft engine exhaust emissions to global warming and carbon cycle can be revealed in details.
- If the flights all around the world are considered, obtained results can be more meaningful. However, from this point of view, impact of aircraft transportation on the environment may be more comprehensible.

In a future study, it is planned to cover that issue from perspective of aviation fleet and comparison of different aircraft engine types.

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Nomenclature

C	Carbon footprint
CO_2e	Carbon dioxide equivalent
EI	Emission index (g kg^{-1})
GWP	Global warming potential
m	Mass flow rate (kg s^{-1})

Subscripts

f	Fuel
i	ith greenhouse gas emitted from the engine

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