Transportation Research Part D 58 (2018) 1–13

Contents lists available at ScienceDirect

Transportation Research Part D

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

Life cycle assessment of air transportation and the Swiss commercial air transport fleet

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A R T I C L E I N F O

Keywords:
Life cycle assessment
Aircraft
Aviation
Fleet

A B S T R A C T

In this work we present a life cycle assessment of air transportation, the Swiss commercial aircraft fleet, and its potential development from 1990 to 2050. We first perform a life cycle assessment of air transport with 72 common aircraft types for different flight distances. These results are globally valid. Based on these results, a parameterized model of 5 aircraft size categories is developed that includes variation in aircraft production year, flight distance and maximum seating capacity. Future aircraft improvement is modelled with two scenarios that consider conservative and optimistic assumptions regarding future improvements to aircraft weight, fuel efficiency, aerodynamics, and exhaust emissions. In a third step, this model is calibrated to Swiss and European conditions and used to calculate the environmental burdens from Swiss passenger and freight civilian air transport. The model is found to accurately predict national aircraft fuel consumption to within 7% accuracy over a 25 year period, with the exception of the aftermath of the terrorist attacks of 2001. Results show that, despite significant improvements in per passenger kilometer emissions, overall environmental burdens due to air transportation are likely to continue increasing in the future due to rapidly increasing demand. Results further show that as exhaust emissions from aircraft are further reduced, the main cause of many environmental impacts caused by air transport will be due to upstream impacts of kerosene production, and not the direct operating of aircraft.

1. Introduction

Aviation is responsible for approximately 12% of global transport related CO_2 emissions, emitting approximately 500 Mt per year (ICAO, 2013). Global passenger and freight air transportation is expected to grow annually at 3–5% per year over the next decades (ICAO, 2013). In Switzerland, air transport accounts for approximately 10% of national transport related CO_2 emissions, and air transport demand is expected to grow slightly slower, at a rate of roughly 3.5–4% per year (Federal Office of Civil Aviation, 2012). At the same time, aircraft have been becoming more efficient, improving fuel efficiency by 1% per year on average over the past few decades (Graham et al., 2014). Additionally, airlines have also increased their efficiency, for example improving load factors and air traffic management.

Several studies have examined the performance improvement of aircraft fuel consumption or operating emissions in the past and future (Dray et al., 2012; Graham et al., 2014; IATA, 2011; Lee et al., 2001; Schäfer et al., 2016). The European Commission has also published goals for the performance of future aircraft (European Commission, 2011). Further studies have built on these performance improvements. They consider how technology improvements may penetrate into the aircraft fleet and calculate fuel consumption and

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https://doi.org/10.1016/j.trd.2017.10.017

Available online 09 November 2017

operation emissions of the fleet as a whole (Cansino and Román, 2017; Dray, 2013, 2014; EASA et al., 2016; Huang et al., 2016; ICAO, 2013; Macintosh and Wallace, 2009; Owen et al., 2010; Timmis et al., 2015).

There have also been several life cycle assessments (LCA) of aircraft performed in the past (Chester, 2008; Facanha and Horvath, 2007; Howe et al., 2013; Lewis, 2013; Lopes, 2010; Timmis et al., 2015). However, in our opinion, there are two main gaps in the literature regarding LCA of air transport.

The first gap is that most LCA studies consider only a single or very few aircraft and flight distances. This makes it difficult for readers to determine average impacts, or the impacts of certain flight distances. In order to fill this gap we supply life cycle inventories and impact assessment results for 72 of the aircraft included in the EMEP/EEA dataset (European Environment Agency, 2013). These results are globally valid. We further quantify fleet average environmental impacts for Switzerland which can be considered to be valid for Western Europe.

The second main gap is that most studies focus on global warming potential and do not present results for other environmental impact categories. Furthermore, no LCA study of air transport known to the authors considers the fact that aircraft exhaust emissions during the cruise phase do not have the same environmental impacts as emissions that occur at ground level. We include the complete set of ReCiPe midpoint impact categories and make a first attempt to adjust characterisation factors for cruise phase emissions.

We further examine how the environmental impacts of air transportation have changed over time and how they may develop in the future. Business As Usual (BAU) and Optimistic (OPT) future technology development scenarios are created to model the performance of individual aircraft from 1970 to 2050. We also examine the penetration of these future aircraft into the Swiss fleet and examine the sector average and total impacts from 1990 to 2050 for two future demand scenarios.

2. Life cycle assessment methodology

In this section, we describe methodology used to calculate the life cycle environmental impacts of air transportation by individual aircraft as well as the Swiss air transport fleet. In Section 2.1 we shortly explain the methodology of LCA and discuss the special considerations needed to more accurately quantify the impacts of emissions from the aircraft's cruise phase.

2.1. LCA methods

LCA involves compiling all environmentally relevant flows related to a process or product. These include emissions, natural resources, materials, energy, and waste. All flows related to all stages of a product's life cycle including production, use and end-of-life are included. The life cycle environmental impacts of a product are defined as the cumulative burden of all these environmental flows (Guinée, 2002). This LCA follows the methodology defined in the International Organisation for Standardisation ISO 14040 and ISO 14044 series (ISO, 2006a, 2006b). The scope of this assessment is considered to be "cradle-to-grave" and includes all environmental flows associated with the life cycles of the airport and the aircraft as well as the operation emissions of the aircraft and the production of the aircraft's fuel. See Table 1.

We use the ecoinvent database (v3.2) for background life cycle inventories (Wernet et al., 2016). For Life Cycle Impact Assessment (LCIA) we use the IPCC 2013 method with 100 year time horizon for global warming potential (Stocker et al., 2013), and the ReCiPe 2008 midpoint method with the hierarchist perspective for all other impact categories (Goedkoop et al., 2009). Although all ReCiPe midpoint categories are calculated and included in the excel sheets in the supporting information, due to space constraints we present only four impact categories in the main paper. These four impact categories are considered to reflect the major environmental concerns most relevant to air transportation and transportation in general (ICAO, 2013).

Table 1
Summary of life cycle inventory for air transportation.

Flow	Description
Airport construction, operation, maintenance, and end-of-life	We use the ecoinvent dataset *airport construction*, which considers the entire life cycle of Zurich airport including construction, operation and end-of-life. We allocate the impacts of the airport equally to each passenger that leaves the airport, regardless of flight distance. The ecoinvent dataset has been updated according to annual passenger data for Zurich airport from 2012 and is assumed to remain constant over time
Aircraft construction, maintenance, and end-of-life	For the LCA of existing aircraft, we use the ecoinvent dataset *aircraft production, medium haul* to model aircraft production. We scale the dataset using aircraft operating empty weight. For the representative aircraft we use the emissions and energy consumption from this dataset, but use different material inputs for each construction year as shown in Fig. 2
Fuel production, refining, and delivery	We model aircraft fuel production using the ecoinvent dataset *market for kerosene*. We do not include future changes to fuel production and also exclude biofuels as out of scope
Aircraft emissions during operation	We model exhaust emissions to air separately for LTO and Cruise phases based on data from the EEA/EMEP inventory guidebook and our own calculations. We include global warming potential impacts resulting from aircraft contrails and induced cloud formation in the upper troposphere and lower stratosphere. We use characterisation factors from Fuglestvedt et al. (2010) to include these impacts in our results. Additionally, particulate matter from tire and brake wear from landing and take-off are included according to Infras (2012) and scaled according to aircraft weight. These emissions are modelled using ecoinvent datasets for wear particles from freight truck tires and brakes