Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

Bachelor Thesis

Department of Automotive and Aeronautical Engineering

Background to the 3-Liter-Aircraft – How Clean is Aviation?

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Abstract

According to **IATA 2011**, air passengers will increase from 2.5 billion in 2009 to 3.3 billion by 2014. This indicates an increase of 32 % in air passengers by 2014, compared to the value of 2009. Despites of the increase number of air passengers, emissions of air transport are expected to be reduced in the future. This thesis contains a literature research about the fuel consumption and emissions of different type of aircraft. First of all, the visions of air transport in year 2020 and year 2050 are described in this thesis. The goals and aims set by Advisory Council of Aeronautics Research in Europe (ACARE), International Air Transport Association (IATA), Air Transport Association of America (ATA) and International Civil Aviation Organization (ICAO) and their ways to achieving the aims and goals will be further discussed. The completed European programme, 6th Framework Programme and the on-going European programme, 7th Framework Programme by the European Commission, as well as the Clear Sky JTI will be investigated in this thesis. These programmes are aiming to achieve the goals of ACARE by year 2020. Furthermore, a further investigation on IATA's four pillars strategy will be made. To cope up with the increased awareness towards the environment, aircraft manufacturers (Airbus and Boeing) have also applied some of the latest technologies in their new generation aircraft or more specifically Airbus A380 and Boeing 787. Air transport contributes to 2 % of the total emissions in the world (**ITR 2010**). The global and local impacts of these 2 % of emissions on the environment will be discussed, giving a clear view of how the aircraft emissions being harmful to human health, construction, agriculture and the Earth. Besides that, the energy consumption and the gaseous emissions per passenger kilometres (pkm) of air transport during operation will also be compared with road and rail transport. The emissions are broken down to identify and analyze the emissions of air, road and rail transport individually. During operation, air transport releases more greenhouse gases (GHG) than rail transport but lesser than road transport as shown in chapter 3. Nitrous Oxide is the highest criteria air pollutant (CAP) gas released by air transport. Other CAP gases indicate a relatively low value compared to road and rail transport. Additionally, a life cycle assessment of air, road and rail transport has been made to give an overview of the energy consumption and emissions in the entire life cycle, from manufacture to disposal or recycle. Emissions during operation of aircraft contribute to the biggest portion, about 80 % of GHG emissions. The other components of life cycle inventory such as maintenance of aircraft and infrastructure, contribute to only about 20 % of the GHG emissions (**Chester 2008**). Besides that, calculations based on Breguet range equation have been done to estimate the fuel consumption per pkm for turbofan aircraft and propeller aircraft during cruise. The first part of the calculations is based on maximum lift-to-drag ratio. The second part is based on the estimation of lift to drag ratio through the values obtained from **Jane's 2001**. Moreover, this thesis also includes the effects of different load factors on the fuel consumption per pkm for short, medium and long haul flights. If the landing take-off (LTO) cycle is eliminated, short haul flights indicate the lowest fuel consumption per passenger kilometre (pkm) whereas long haul flights indicate the highest fuel consumption per pkm.

Hintergründe zum 3-Liter-Flugzeug - Wie sauber ist der Luftverkehr?

Aufgabenstellung zur *Bachelorarbeit* gemäß Prüfungsordnung

Hintergrund

Flugzeughersteller und Luftverkehrsgesellschaften werben mit dem "3-Liter-Flugzeug" und suggerieren damit einen geringen Kraftstoffverbrauch des Flugzeugs im Vergleich mit dem PKW.

Aufgabe

Es soll der Auftritt der Flugzeughersteller und Luftverkehrsgesellschaften zum Thema "Umweltfreundliches Fliegen" recherchiert werden. Wie wird der Verbrauch des "3-Liter-Flugzeugs" definiert. In welchen anderen Lebensbereichen wird noch mit der magischen Grenze der "3 Liter" geworben? Welche Flugzeuge erreichen welche Verbräuche ausgedrückt in l/100 km? Wie viel verbrauchen andere Verkehrssysteme im Vergleich dazu? Wie sähe ein Vergleich der Verkehrssysteme aus, wenn alle Umweltfaktoren berücksichtigt würden (Stichwort Ökobilanz)? Welche Besonderheiten/Charakteristika ergeben sich für den Luftverkehr hinsichtlich der hohen Fluggeschwindigkeiten und großen Flugstrecken? Welche absoluten Kraftstoffmengen werden pro Kopf und Jahr verbraucht mit den unterschiedlichen Verkehrsträgern unter Berücksichtigung der Lebensgewohnheiten (Naherholung, Fernurlaubsreise, Geschäftsreisen: Inland/Ausland)?

- Recherchieren Sie zu den oben gestellten Fragen und stellen Sie die Ergebnisse übersichtlich zusammen!
- Stellen Sie die recherchierten Daten zu eigenen Statistiken zusammen!
- Berechnen Sie die absoluten Kraftstoffmengen pro Jahr überschlägig mit plausiblen Annahmen.

Die Ergebnisse sollen in einem Bericht dokumentiert werden. Es sind die DIN-Normen zur Erstellung technisch-wissenschaftlicher Berichte zu beachten.

Declaration

This Bachelor thesis is entirely my own work. Where use has been made of the work of others, it has been totally acknowledged and referenced

2011-07-30
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Date Signature

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List of Symbols

R	range
E	lift to drag ratio
V	aircraft speed
B	Breguet factor
c	specific fuel consumption
g	gravity
k	factor
S	area
AR	wing aspect ratio

Greek Symbols

ρ	density
η	efficiency

Subscripts

$(\ )_{wet}$	wing wetted
$(\ )_{w}$	wing
$(\ )_{F}$	fuel
$(\ )_{p}$	propeller
$(\ )_{e}$	factor
$(\ )_{initial}$	initial
$(\ )_{end}$	end
$(\ )_{max}$	maximum
$(\ )_{OEW}$	OEW
$(\ )_{PL}$	payload

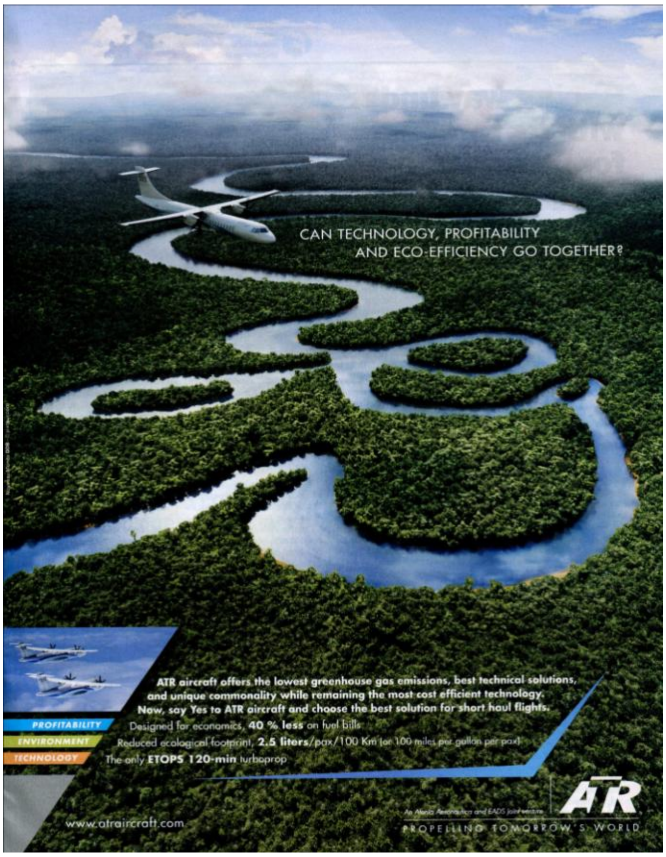
List of Abbreviations

AAS	Integrated Airport Apron Safety Fleet Management
ACARE	Advisory Council of Aeronautics Research in Europe
ACFA 2020	Active Control of Flexible 2020 Aircraft
APU	Auxiliary Power Unit
ATA	Air Transport Association of America
ATAAC	Advanced Turbulence Simulation for Aerodynamic Application Challenge
ATM	Air Traffic Management
BPR	Bypass ratio
BWB	Blended Wing Body
CAAFI	Commercial Aviation Alternative Fuels Initiative
CAEP	ICAO's Committee on Aviation Environmental Protection
CAP	Criteria Air Pollutant
CDA	Continuous Descent Approaches
Celina	Fuel Cell Application in a New Configured Aircraft
CFRP	Carbon Fibre Reinforced Polymer
CH_4	Methane
CNG	Carbon Neutral Growth
CO	Carbon Monoxide
CO2	Carbon Dioxide
COSMA	Community Oriented Solutions to Minimise Aircraft Noise Annoyance
CROR	Counter Rotating Open Rotor
CSN	China Southern Airlines
CWB	Carry-through Wing Box
DESIREH	Design, Simulation and Flight Reynolds-Number Testing for Advanced High-Lift Solutions
DREAM	Validation of Radical Engine Architecture Systems
EC	European Commission
ECATS	Environmentally Compatible Air Transport
EDA	Eco-Design for Airframe
EDS	Eco-Design for Systems
Elect-AE	European Low Emission Combustion Technology in Aero Engines
ELUBSYS	Engine Lubrication System Technologies
EPNL	Effective Perceived Noise Levels
ERICKA	Engine Representative Internal Cooling Knowledge and Applications
ETS	Emissions Trading Scheme
EU	European Union
EUROLIFT II	European High Lift Programme II
FBW	Fly-By-Wire
FEGA	Fuel Efficiency Gap Report
FLOCON	Adaptive and Passive Flow Control for Fan Broadband Noise
FT	Fischer-Tropsch
FUTURE	Flutter-Free Turbomachinery Blades
GHG	Greenhouse Gases
GLARE	Glass Laminate Aluminium Reinforced Epoxy
GPS	Global Positioning System
GRA	Green Regional Aircraft

GSE	Ground support equipment
HFC	Hydrofluorocarbon
HVAC	Ventilation and Air-conditioning
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
KIAI	Knowledge for Ignition, Acoustics and Instabilities
LAQ	Local Air Quality
LCA	Life Cycle Assessment
LRT	Light Rail Transit
LTO	Landing Take-off
MOET	More Open Electrical Technologies
MTOW	Maximum Take-off Weight
NACRE	New Aircraft Concept Research
NEWAC	New Aero Engine Concepts
NOx	Nitrous Oxide
OEW	Operating Weight Empty
OPENAIR	Optimisation for Low Environmental Noise Impact Aircraft
PAX	Number of Passengers
pkm	Passenger Kilometres
PM	Particulate Matters
R&D	Research and Development
REACT4C	Reducing Emissions from AVIATION by Changing Trajectories for the Benefits of Climate
RF	Radiative Forcing
RNP	Required Navigation Performance
RNP	Required Navigation Performance
SADE	Smart High Lift Devices for Next Generation Wings
SAGE	Sustainable and Green Engines
SESAR	Single European Sky ATM Research
SFC	Specific Fuel Consumption
SFWA	SMART Fixed Wing
SOx	Sulphur Oxide
SRA	Strategic Research Agenda
SUV	Sport Utility Vehicle
TECC-AE	Testing for Laminar Flow on New Aircraft
TET	Turbine Entry Temperature
TLC	Towards Lean Combustion
VALIANT	Validation and Improvement of Airframe Noise Prediction Tools
VITAL	Environmentally Friendly Aero Engine
VKT	Vehicle Kilometres Travelled
VOC	Volatile Organic Compound

1 Introduction

1.1 Motivation



ATR aircraft offers the lowest greenhouse gas emissions, best technical solutions, and unique commonality while remaining the most cost efficient technology. Now, say Yes to ATR aircraft and choose the best solution for short haul flights.

PROFITABILITY Designed for economics, **40 % less** on fuel bills
ENVIRONMENT Reduced ecological footprint, **2.5 liters**/pax/100 Km (or 100 miles per gallon per pax)
TECHNOLOGY The only **ETOPS 120-min** turboprop

www.atraircraft.com

An Alenia Aeronautica and EADS joint venture

Fig 1.1 ATR's brochure (**ATR 2011**)

Air transport emissions are claimed to be higher than other modes of transportation. Along with the increased awareness towards the environment, air industry is trying to cut down its fuel consumption. Some new generation aircraft are believed to consume less fuel and generate less emission than a normal passenger car, if expressed in unit of passenger per kilometre (pkm). ATR advertises its aircraft, which consumes only 2.5 litres/PAX/100km, as shown in Fig 1.1. This paper aims to find out the fuel consumption and the gaseous emissions of aircraft during operation and in the entire life cycle. The results will be compared with road and rail transport.

1.2 Definitions

3 Litre Aircraft

3 litre aircraft are described as aircraft which consume 3 litres of fuel per 100 passenger kilometres.

Global Warming

Global warming is a warming effect of the earth caused by excessive greenhouse gases (GHG) in the atmosphere. Excessive GHG trap heat within the atmosphere by absorbing the energy received from the Sun. The major GHG are water vapour, carbon dioxide (CO2), methane (CH4) and Ozone. These are all products of combustion.

Local Air Pollution

Local air pollution is caused by criteria air pollutant (CAP) gases. CAP gases affect the local air quality (LAQ). These gases are harmful to human health and cause many diseases especially respiratory diseases. Besides health issues, CAP gases are also harmful to agricultural products and human-made constructions. CAP gases damage the yield of agricultural products and also speed up corrosion of buildings and monuments.

1.3 Objectives

The objective of this thesis is to find out the fuel consumption of aircraft and the impact of its emissions to the environment. Besides that, this thesis also compares the gaseous emissions of different modes of transportation with air transportation. A brief overview of the emissions in the entire life cycle of the vehicles will also be provided in this paper, comparing the total emissions of the vehicles in whole life cycles from manufacture to disposal or recycle.

1.4 Literature

Books

The aircraft information including the maximum take-off weight (MTOW), operating empty weight, wing aspect ratio, seats capacity and power plants can be obtained in **Jane's 2001**. From this book, we can have a brief overview on the aircraft, mainly the configurations of the aircraft. Design ranges with maximum passengers are also available in this book. With the design range and other parameters in the book, we can estimate the lift to drag ratio as well as the fuel consumption of certain aircraft.

As mentioned above, the models of aircraft engines can be found in **Jane's 2001**. For turbofan and turbojet aircraft, we will look into **Engine Book** for its SFC during cruise. Besides SFC value, other values that we can obtain from this book are the cruise altitude and cruise Mach number. With the availability of cruise altitude and cruise Mach number, we can then calculate the aircraft speed during cruise.

Calculations of the fuel consumption of aircraft are assisted by **Filiponne 2008**. This book explains how the Breguet range equation is derived. This book also tells me about the differences about the calculations of fuel consumption of turbofan aircraft and propeller aircraft. Besides that, this book has been totally helpful in better understanding of the fuel consumption of aircraft.

Reports

Reports from organizations and associations provide information about their efforts on reducing the environmental impacts of aircraft. The reports that I use in the thesis are **ACARE 2011**, **IATA 2010** and **EC 2010** etc. In these reports, we get to know the goals and aims of the organizations in achieving a greener air transport. For example, **ACARE 2011** tells us about the on-going projects and completed projects. It also gives brief descriptions about the projects. Another example from is the report from **IATA 2010**. The report illustrates IATA's four pillar strategy in reducing the aircraft emissions.

Besides that, reports from Airlines are also helpful in this thesis. For example, the fuel consumption of Lufthansa's fleet is published in Balance. In Balance, we can get the actual fuel consumption of major aircraft, not only from theory. Furthermore, it also shows that for a same type of aircraft, the fuel consumption fluctuates with the way of operations of different airlines. Other information that we can get from the airlines' reports are the strategy of airlines in reducing fuel consumption. Reduction in fuel consumption in one way reduces the Direct Operating Cost (DOC); and in another way saves the environment.

Internet

Internet is one of the main databases to get the information for this thesis. Website like **Wikipedia 2011** helps me to understand a new glossary. **Jet 2008** is a website I access to obtain the information of SFC for propeller aircraft. Other important websites are airline webpages, aircraft manufacturer webpages and organization webpages. In aircraft manufacturers' webpage like Boeing and Airbus, we can further understand the aircraft through the descriptions posted on the websites.

1.5 Structure of the thesis

The structure of this thesis is as follow:

Chapter 2	describes the aims and goals of air transport related organizations in the future, particularly in year 2020 and year 2050.
Chapter 3	describes the emissions of air, road and rail and the impacts of these emissions on the environment. The impacts are divided into two categories, which are global impact and local impact.
Chapter 4	describes the environmental efforts of major airlines in the world from different world regions (Europe, North America and Asia)
Chapter 5	estimates the aircraft fuel consumption by converting Breguet range equation
Chapter 6	describes the total emissions of air, road and rail in the entire life cycle, from manufacture to disposal or recycle.
Chapter 7	concludes the results of the above chapters and lists out the uncertainties

2 Visions of air transport in the future

2.1 Advisory Council for Aeronautics Research in Europe (ACARE)

To achieve the environmental goals of air transport in 2020, the Advisory Council of Aeronautics Research in Europe (ACARE) has been formed. ACARE is responsible in defining the content of the Strategic Research Agenda (SRA).The main goals of ACARE towards 2020 are to reduce CO2 emissions by 50 % per pkm, reduce the noise level by 50 %, reduce NOx emissions by 80 %, and to reduce the impact of the total life cycle of aircraft towards the environment, as shown in Table 2.1 (**Knoerzer**). Of the stated 50 % CO2 reduction, 15-20 % should be achieved by aircraft engines, 20-25 % by aircraft cabins and 5-10 % by the operation of the airlines. Besides that alternative fuels will also contribute a small percentage in CO2 reduction. Quieter, greener engines are needed to reduce the noise produced by aircraft and at the same time reduce the NOx emissions. More environmental friendly manufacturing, maintenance and disposal process contributes to reducing the environmental impact of aircraft.

Furthermore, ACARE has set its visions towards 2050. According to ACARE, the technologies and procedures available in 2050 will allow 75 % reduction in CO2 emissions, 90 % NOx emissions and 65 % noise reduction. Other goals of ACARE towards 2050 are emission-free taxiing of aircraft and more sustainable aircraft. Alternative fuels will also be used widely in aviation with Europe as the centre of excellence in this field. In addition, ACARE intends to put Europe in front of other world regions in terms of atmospheric research. Another goal of ACARE is to turn Europe into the leader in formulating environmental action plans and establishing global environmental standards (**EC 2011**).

Table 2.1 Goals of ACARE in year 2020 and year 2050 (**Knoerzer 2011**)

	Year 2020	**Year 2050**
CO2	-50 %	-75 %
NOx	-80 %	-90 %
Noise	-50 %	-65 %

As we can see in Fig 2.1 and Fig 2.2, although there is a declining trend in aircraft fuel consumption and noise level over the past years, it is not sufficient to achieve ACARE 2020 targets. Breakthrough technologies are required in order to meet the targets by 2020. Turbofans were first introduced in the 1970s to replace turbojets. The introduction of turbofans significantly reduced the fuel consumption as well as noise. The first generation of turbofan introduced in early 1970s, had successfully reduced the specific fuel consumption by 18 %. Later on, turbofans with higher BPR were introduced and again decreased the specific fuel consumption. However, the improvement in BPR will no longer significantly reduce the specific fuel consumption. A breakthrough in technologies as well as improvements in other aspects is crucial to bring the reduction of specific fuel consumption a step ahead (**ACARE 2002)**.

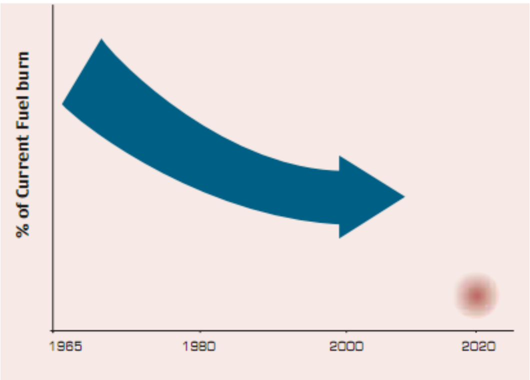


Fig 2.1 Fuel consumption improvement of aircraft engines over the years (**ACARE 2002**)

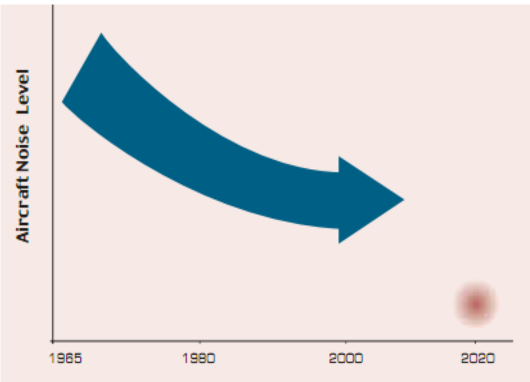


Fig 2.2 Noise level improvement of aircraft engines over the years (**ACARE 2002**)

Many researches and initiatives have been taken to enable the aviation industry achieving the goals set in 2020. EU collaborative research in Aeronautics and Air Transport (EC's Framework Programme), the Clean Sky JTI and Single European Sky ATM Research (SESAR) Joint Undertaking have taken some important initiatives.

The European Framework research programmes are responsible to achieve the environmental goals set by ACARE. The previous 6th Framework Programme and the current 7th Framework Programme by the EC contribute to developing a greener air transport system by doing exploiting current existing technologies and improving them through analytical and experimental means, as shown in Fig 2.3 (**Science 2005**). The Clean Sky JTI on the other hand focuses on developing breakthrough technologies which will significantly reduce the impact of air transport on the environment. SESAR aims to improve the efficiencies of the ATM system and reduce 10-12 % of the environmental impact (**SESAR 2011**). More direct flight paths will be created by SESAR to replace the current flight paths, which take a longer router than necessary. Besides that, a smoother descent and landing system will enable aircraft to avoid unnecessary fuel waste during holding while waiting for a landing slot.

Through the corporation between public and private including research companies, aircraft and aircraft components manufacturers, universities, it is hoped to speed up the technology breakthrough process. Table 2.2 shows the list of some of the projects by the EC.

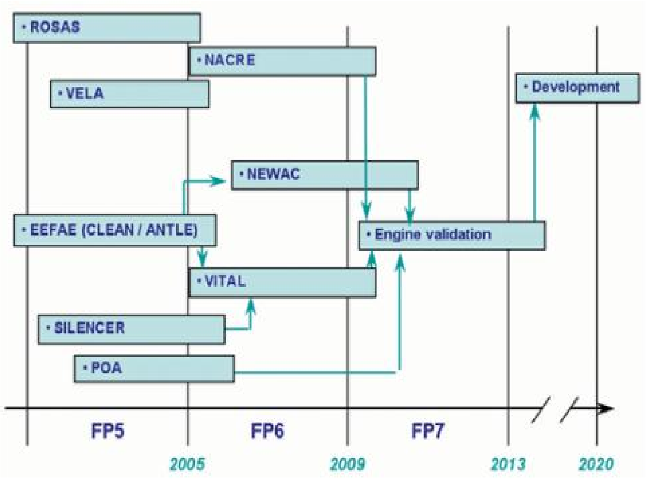


Fig 2.3 Major European programmes FP6 and FP7 (**Science 2005**)

Table 2.2 List of European projects

6th Framework Programmes	Environmentally friendly aero engine (VITAL), New Aero Engine Concepts (NEWAC), Fuel Cell Application in a new configured Aircraft (CELINA), European Low Emission Combustion Technology in Aero Engines (ELECT-AE), Environmentally Compatible Air Transport System (ECATS), Towards Lean Combustion (LTC), More open Electrical Technologies (MOET), European High Lift Programme II (EUROLIFT II), New Aircraft Concept Research (NACRE), Testing for Laminar Flow on New Aircraft (TELFONA) (**Cordis 2011**)
7th Framework Programmes	Integrated Airport Apron Safety Fleet Management (AAS); Active Control of Flexible 2020 Aircraft (ACFA 2020); Advanced Turbulence Simulation for Aerodynamic Application Challenge (ATAAC); Community Oriented Solutions to Minimise Aircraft Noise Annoyance (COSMA); Design, Simulation and Flight Reynolds-Number Testing for Advanced High-Lift Solutions (DESIREH); Validation of Radical Engine Architecture Systems (DREAM); Engine Lubrication System Technologies (ELUBSYS); Engine Representative Internal Cooling Knowledge and Applications (ERICKA); Adaptive and Passive Flow Control for Fan Broadband Noise Reduction (FLOCON); Flutter-Free Turbomachinery Blades (FUTURE); Generation of Hydrogen by Kerosene Reforming via Efficient and Low-Emission New, Alternative, Innovative, Refined Technologies for Aircraft Application (GreenAir); Knowledge for Ignition, Acoustics and Instabilities (KIAI); Optimisation for Low Environmental Noise Impact Aircraft (OPENAIR); Reducing Emissions from AVIATION by Changing Trajectories for the Benefits of Climate (REACT4C); Smart High Lift Devices for Next Generation Wings (SADE); Technology Enhancements for Clean Combustion (TECC-AE); Turboshaft Engine Exhaust Noise Identification (TEENI); Validation and Improvement of Airframe Noise Prediction Tools (VALIANT) (**EC 2010**)
Clean Sky JTI	SMART Fixed Wing (SFWA); Green Rotorcraft (GRC); Green Regional Aircraft (GRA); Sustainable and Green Engines (SAGE); Systems for Green Operation (SGO); Eco design; Technology Evaluator (**Cleansky 2011**)

FP6 Projects

Environmentally Friendly Aero Engine - VITAL

VITAL investigates alternative concepts to the current direct drive turbofan, geared turbofan, contra-rotating turbofan and counter-rotating integrated shrouded propfans. VITAL focuses on optimization of the efficiency of fan systems as well as low-pressure compressor, turbine and shaft systems. VITAL aims to develop low weight structures for very high BPR engines, more efficient low pressure turbo machinery, and advanced low pressure torque shaft, and overall engine installation. With these technologies, VITAL enables a 7 % CO2 reduction and a 6dB noise reduction per certification point.

New Aero Engine Concepts – NEWAC

NEWAC develops the core-engine technologies, to increase engine efficiencies. Breakthrough technologies that have been developed by NEWAC are intercooler, cooling-air cooler, improved combustion and active systems. All these new components will be tested and validated by NEWAC. The NEWAC core configurations include an intercooled recuperative core shown in Fig 2.7, which operates at low overall pressure ratio with a Lean Premixed Pre-vaporized combustor; an intercooled core configuration shown in Fig 2.4, which operates at high overall pressure ratio with a Lean Direct Injection combustor; an active core shown in Fig 2.6, which is applicable to Geared Turbofan using a Partial Evaporation & Rapid Mixing combustor and a flow controlled core shown in Fig 2.5, which operates at medium overall pressure ratio with Partial Evaporation & Rapid Mixing combustor or Lean Direct Injection combustor. NEWAC aims to achieve a 6 % reduction in CO2 emissions and a 16 % reduction in NOx with these new technologies.

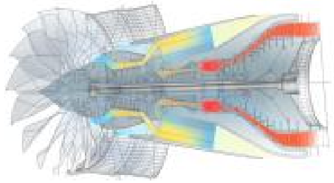


Fig 2.4 Intercooled core (**Servaty 2011**)

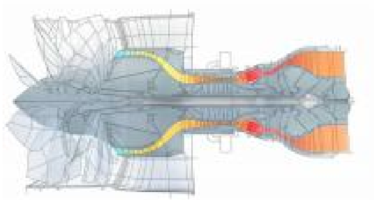


Fig 2.5 Flow controlled core (**Servaty 2011**)

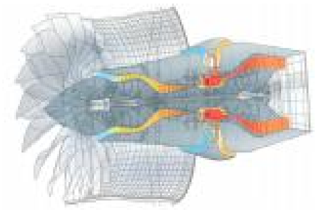


Fig 2.6 Active core (**Servaty 2011**)

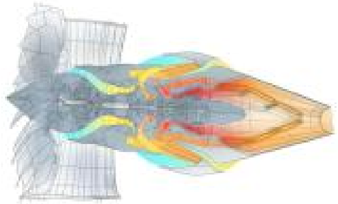


Fig 2.7 Intercooled recuperative core (**Servaty 2011**)

Fuel Cell Application in a new configured Aircraft - CELINA

CELINA aims to apply fuel cell systems to aircraft to reduce fuel consumption, noise and gas emissions, as well as improve the aircraft efficiency. More efficient fuel conversion compared to the current APU leads to the efficiency improvements stated above.

European Low Emission Combustion Technology in Aero Engines - ELECT-AE

ELECT-AE aims to bring together European companies particularly engine manufacturers to pool their resources and technologies to develop new low emissions combustion systems. Well focused and balanced research and development initiatives are needed to create a new generation of aero-engine combustors.

Environmentally Compatible Air Transport System - ECATS

The objectives ECATS are to bring together all expertises in the field of aeronautics and environment including leading Research Establishments and Universities, to create a European virtual institute for research of environmental compatible air transport. ECATS will take into account all the technologies available including engine technology, alternative fuels, and operation methods to create greener air transport.

Towards Lean Combustion - TLC

The emissions of aero-engines depend on the combustor technology. Breakthrough technologies in lean combustion will lead to reduction of NOx emissions as well as particulate matters during the LTO cycle and cruise phase. Besides that, TLC also analyses other gaseous emissions and soot performance characteristics.

More open Electrical Technologies - MOET

MOET aims to establish the new industrial standard for commercial aircraft electrical system design. With the new electrical system design, MOET aims to reduce aircraft emissions and at the same time improve the operational aircraft capacity. MOET will enhance the Power by Wire concept by developing new design principles, technologies and standards.

European High Lift Programme II - EUROLIFT II

EUROLIFT II aims to improve the aerodynamic efficiencies to keep and extend the competitiveness of the European aircraft manufacturers. EUROLIFT II aims to reduce significantly reduce the noise emissions during take-off and landing phase. To do so, EUROLIFT II needs to understand various vortex-dominated flow effects at the cut-outs of a high lift system and provides solutions to noise reduction.

New Aircraft Concept Research - NACRE

In order to meet the future air transport environmental requirements, new aircraft configurations have to be developed. NACRE investigates new concepts and technologies required for Novel Aircraft Concepts: the Pro-active Green Aircraft, the Payload-Driven Aircraft and the Simple Flying Bus, as shown in Fig 2.8. to FIG 2.10. NACRE intends to minimize the environmental impact and maximize the aircraft efficiency to cater the needs of future air traffic, which is forecasted to more than double in the future.

Fig 2.8 Pro Green Aircraft (**DLR 2011**)

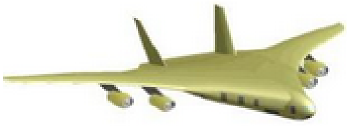


Fig 2.9 Payload Driven Aircraft (**DLR 2011**)

Fig 2.10 Simple Flying Bus (**DLR 2011**)

Testing for Laminar Flow on New Aircraft - TELFONA

TELFONA aims to develop the capability to predict the in-flight performance of a future laminar flow aircraft. Wind tunnel tests and computational fluid dynamic calculations will help TELFONA to more precisely predict the in-flight aerodynamic performance. TELFONA enables the configurations of a pro-green aircraft, which have higher aspect ratio wing and lower sweep compared to today's configurations or in other words lower drag and higher lift to drag ratio. With the new configurations, drag reduction could reach 20 % and leads to a large reduction in emissions.

FP7 Projects

Advanced Turbulence Simulation for Aerodynamic Application Challenge - ATAAC

The main objective of ATAAC is to improve the turbulence simulation approaches for aerodynamic flows. ATAAC will provide a more accurate Differential Reynolds Stress Models which current models fail to provide, for scenarios like stalled flows, high lift applications and swirling flows. Besides that, ATAAC is to provide guidelines in Computational Fluid Dynamic and contributes to reliable industrial Computational Fluid Dynamic tools.

Design, Simulation and Flight Reynolds-Number Testing for Advanced High-Lift Solutions - DESIREH

DESIREH aims to improve the aerodynamics in high lift system of aircraft by improving the high lift design efficiency by 15 % and by reducing the drag by 5 % through the introduction of a new compatible high lift system for laminar-flow wings. Furthermore, DESIREH also aims to speed up the aerodynamic design turnaround time by 4 % and increase the efficiency of the wind tunnel testing, which contributes to a reduction of 5 % in industrial aircraft development costs.

Reducing Emissions from Aviation by Changing Trajectories for the Benefits of Climate - REACT4C

REACT4C investigates alternative environmentally-friendly flying routes and flying altitudes to reduce the fuel consumption and emissions. It aims to improve aviation's environmental compatibility by pointing out the inefficiency in current aviation system.

Smart High Lift Devices for Next Generation Wings - SADE

SADE aims to reduce the emissions of CO2 and NOx by developing new intelligent low-weight structures. The devices under development are smart leading edge and smart single-slotted flap. SADE enhances the current airframe technologies and provides solution for realization of the aircraft. The reduction in weight of aircraft will lead to an increased lift over drag ratio thus enabling steeper climb and noise reduction. It also aims to develop a more-electric-aircraft to reduce the fuel consumption of the aircraft as well as the Direct Operating Cost. Fig 2.11 shows the design of SADE.

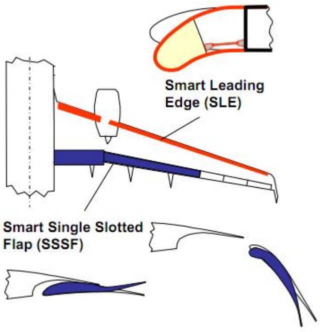


Fig 2.11 Smart High Lift Devices (**Monner 2011**)

Generation of Hydrogen by Kerosene Reforming via Efficient and Low-Emission New, Alternative, Innovative, Refined Technologies for Aircraft Application - GreenAir

GreenAir researches the possibilities and applicability of generating hydrogen from kerosene to operate the fuel cells on board. The fundamentals of two conventional methods, partial dehydrogenation and plasma-assisted reforming will be elaborated to develop the technology. The requirements for implementing this technology on board will be defined by GreenAir.

Integrated Airport Apron Safety Fleet Management - AAS

Due to the number of companies operating in aircraft apron, there are high levels of congestion in ramp areas which lead to vehicles misuses and accidents. The main objective of AAS is to reduce the congestion and to optimize the utilisation of ground support vehicles through more advanced fleet management concept, improved aircraft operations and enhanced luggage and passenger flow techniques. AAS will also introduce the implementation of GPS based location device in ground support activities.

Validation of Radical Engine Architecture Systems - DREAM

The DREAM project aims to reduce the CO2 emissions of aircraft engine by 27 % compared to aircraft engine manufactured in year 2000 to meet ACARE 2020 goal. A 3db noise reduction per operation point compared to year 2000 engine will also be reduced. The aim to reduce the engine fuel consumption also reduces NOx emissions. To achieve the aims as mentioned above, DREAM does researches and developments on open rotor technologies, novel concepts and alternative fuels. The open rotor technologies consist of blades, pitch change mechanisms, high speed turbine and contra rotating turbine. Open rotor significantly reduces the CO2 emissions but simultaneously produces more noise. More researches have to be done by DREAM to fully develop the potential of open rotor.

Engine Lubrication System Technologies - ELUBSYS

The importance of lubrication system in gas turbine engines is to lubricate the gearboxes and at the same down cools down the system. The current lubrication system technology has reached its limit and new technologies are required to fulfil the future engine requirements. Engines which have higher thermal efficiencies need an enhanced cooling system. ELUBSYS aims to reduce emissions and SFC by 60 % by introducing high performance seals and thermal management. By doing so, the bleed air that pressurizes the bearing chamber can be reduced. This leads to direct impact on the reduction of SFC. ELUBSYS also developing a new technology which integrates several lubrication functions into a single component and directly decreases the mass and complexity of current lubrication system. Another aim of this project is to validate methods on oil coking prediction and detection, as well as to develop solutions for oil coking. This enables oil with higher temperature to enter the engine turbine inlet hence increasing SFC.

Engine Representative Internal Cooling Knowledge and Applications - ERICKA

The SFC of an aircraft engine is highly dependent on its gas turbine. ERICKA aims to improve the cooling technology on turbine blade by reducing the cooling flow and increasing the turbine entry temperature (TET). However, the experimental data in the rotating turbine blades is hard to obtain and ERICKA is doing a research on this to further understand the internal cooling of turbine blades. New simulation software will be introduced by ERICKA to determine the best solutions for cooling problems in the turbine blades.

Flutter-Free Turbomachinery Blades - FUTURE

The flutter of turbomachinery blades can lead to failure of the engines. The main objectives of FUTURE are to study, understand and predict the flutter of the lightweight turbine and compressor blades. FUTURE needs to carry out experiments and establish a worldwide database based on their experimental results. This project will lead to decreased development cost in current engine programmes, reduced weight and fuel consumption, and increased efficiency in managing flutter problems.

Knowledge for Ignition, Acoustics and Instabilities - KIAI

Recent low NOx technologies are unstable and unpredictable. KIAI aims to provide reliable methodologies to predict the stability of industrial low NOx combustors. KIAI will speed up the process to achieve the 80 % NOx reduction set by ACARE before 2020.

Technology Enhancements for Clean Combustion - TECC-AE

TECC-AE is responsible to find the solution for limitations of lean combustion. Many limitations have been identified due to the limitation of NOx emissions. In addition TECC-AE aims to provide full combustor operability in terms of ignition, altitude relight and weak extinction performance. Another objective of TECC-AE is to develop a low NOx injection system and develop a more compact and lighter lean combustor.

Community Oriented Solutions to Minimise Aircraft Noise Annoyance - COSMA

COSMA helps to reduce the noise level by defining new criteria for aircraft design and operations. COSMA will do field studies and psychometric testing on the effects of aircraft noise in the airport community. With the results, techniques for realistic synthesis will be developed. On the other hand, COSMA will restrict the design and operations of aircraft to reduce the effects of aircraft's exterior noise.

Adaptive and Passive Flow Control for Fan Broadband Noise Reduction - FLOCON

Through the development of flow control technologies, FLOCON aims to reduce the broadband noise produced by the fan by 5dB. FLOCON carries out experiments on new noise reduction concepts and implement the concepts to reduce fan broadband noise from aero engines. FLOCON's noise reduction concepts will be used on all latest aero-engine designs.

Optimisation for Low Environmental Noise Impact Aircraft - OPENAIR

OPENAIR focuses on noise reduction from different aircraft components like engines, landing gears and wings. OPENAIR aims to deliver a 2.5dB noise reduction. Besides that, OPENAIR plays a significant role to enable future products to meet the ACARE noise reduction goals and to improve the current fleet noise levels through retrofitting.

Validation and Improvement of Airframe Noise Prediction Tools - VALIANT

VALIANT aims to reduce the airframe noise due to the interaction of the aircraft components like flaps, slats, landing gears etc. The so called most noise-dangerous areas are turbulent flow over a gap, flow past and airfoil with a flap, flow past and airfoil with a slat and flow past two struts. VALIANT will focus on these areas and generate solutions to reduce the noise produced in these areas. VALIANT will also determine the best AFN prediction tools for future aircraft designs. This project aims to reduce 3-5dB of AFN compared to year 2000.

Active Control of Flexible 2020 Aircraft - ACFA 2020

ACFA 2020 helps to develop a control system to supply the required handling qualities for blended wing body (BWB) aircraft, as shown in Fig 2.12. The advantages of BWB aircraft compared to the conventional ones are lighter weights and lesser wetted area, which results in lesser drag. Another concept which is considered by ACFA 2020 is the aircraft with carry-through wing box with a more slender cabin (CWB), as shown in Fig 2.13. Besides that ACFA 2020 aims to design an ultra-efficient flying wing aircraft, which believes to bring down the specific fuel consumption by 50 % compared to the conventional aircraft design.

Fig 2.12 Blended Wing Body Aircraft (**Maeir 2011**)

Fig 2.13 CWB Aircraft (**Maeir 2011**)

CLEAN SKY JTI Projects

Green Regional Aircraft - GRA

The GRA structure consist of GRA1 (Low Weight Configuration), GRA2 (Low Noise Configuration), GRA3 (All Electric Aircraft), GRA4 (Mission and Trajectory Management) and GRA5 (New Configuration). The main goals of GRA are to reduce CO2, NOx and noise in order to achieve ACARE 2020 environmental goals. A lot of improvements in aerodynamics have to be made for drag and noise reduction. Aircraft weight is also another aspect that has to be reduced for regional aircraft in order to reduce the fuel consumption. GRA1 deals mostly with the aircraft structures whereas GRA2 deals mostly with aerodynamics and aero-acoustics aspects. The main technology that will be investigated in GRA2 to reduce the noise level of aircraft is the Natural Laminar Flow (NLF). The possibility to remove the extraction of pneumatic power from the engine will be investigated in GRA3. The main objective of GRA4 is to demonstrate optimized missions and trajectories tailored to the characteristics of regional aircraft. New high level technologies will be developed in GRA5.

Eco-Design

Eco-Design aims to reduce the impact of the whole life cycle of aircraft through greener design and production, withdrawal and recycle. Eco-Design also emphasizes on the optimisation of raw materials and energies used in the whole life cycle of aircraft. Eco-Design ITD consists of 2 major areas, which are EDA (Eco-Design for Airframe) and EDS (Eco-Design for Systems). EDA focuses on the integration of green materials in aircraft production and aircraft maintenance to minimize the overall environmental impacts. EDS on the other hand focuses on all-electric aircraft concept, which suggests the use of electricity as the only energy medium.

Sustainable and Green Engines - SAGE

The main objectives of SAGE are to develop new engine technologies to further reduce CO2, NOx and noise which contribute to the achievement of ACARE 2020 environmental goals. Besides that, SAGE aims to demonstrate open rotor engine, which significantly increases the SFC and at the same time find solutions for its high noise levels. Open rotor is currently still under development before its integration in aircraft. SAGE has to develop new technologies to reduce the weight of engine components like fans, compressors turbines etc and increase their efficiency. The 5 SAGE concepts are SAGE 1 (geared pusher counter-rotating open rotor) shown in Fig 2.15, SAGE 2 (direct drive pusher counter-rotating open rotor) shown in Fig 2.16, SAGE 3 (advanced large 3-shaft turbofan) shown in Fig 2.17, SAGE 4 (advanced geared turbofan) shown in Fig 2.18 and SAGE 5 (advanced turboshaft) shown in Fig 2.19. New developments and technologies are important to put Europe in front in aircraft industry and enhance their competitiveness in this industry globally.

Fig 2.14 SAGE 1 (**Taferner 2010**)

Fig 2.15 SAGE 2 (**Taferner 2010**)

Fig 2.16 SAGE 3 (**Taferner 2010**)

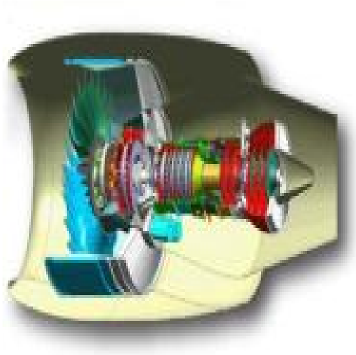


Fig 2.17 SAGE 4 (**Taferner 2010**)

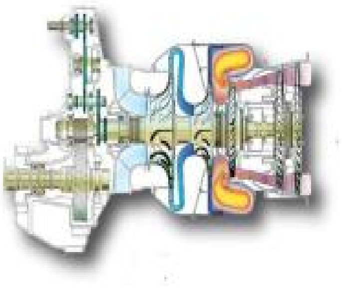


Fig 2.18 SAGE 5 (**Taferner 2010**)

SMART Fixed Wing - SFWA

SFWA aims to reduce the aircraft drag by 10 % through improved wing surface, weight reduction and improved control system. Besides that, with the integration of more advanced engines particularly the counter rotating open rotor (CROR), SFWA aims to reduce the fuel consumption by 20 %. With advanced configurations, 10dB of noise reduction will be achieved by SFWA.

2.2 International Air Transport Association (IATA)

IATA targets to achieve carbon neutral growth (CNG) by year 2020 and to halve the CO2 emissions in relative to 2005 emissions by 2050 (**IATA 2010**). Despite the growth of population in this industry, the carbon emissions of air transport will reach its peak in year 2020 and stop increasing after 2020. IATA's target can be achieved either by controlling the emissions of air transport or offsetting the emissions in other industries. IATA has introduced its four pillars strategy to achieve the goals in 2020 with commitments from airlines, aircraft manufacturers, fuel suppliers, airlines, airports and air navigation service providers. The four pillars strategy consists of Pillar 1 (Technology), Pillar 2 (Operations), Pillar 3 (Infrastructure) and Pillar 4 (Economic Measures).

Pillar 1 (Technology)

IATA aims to implement more available technologies on the current fleet either by replacing the old aircraft with newer ones or by modifying the old aircraft to improve the fuel efficiency as well as reduce the emissions. According to IATA, 27 % of current fleet will be replaced by newer aircraft by year 2020, hence resulting in a 21 % CO2 reduction.

Modifications on existing aircraft fleet are estimated to reduce the CO2 emissions by 7-13 %. Examples for retrofits that are done are winglets, more advanced engine components, lighter materials particularly composite materials and more energy efficient lighting and in-flight entertainment. Winglets for example, are mounted on the wingtips of aircraft to reduce the induced drag and hence increase the aerodynamic performance of the aircraft. More advanced and lighter engine components increase the thermal efficiencies and propulsive efficiencies of the aircraft engines as well as reduce the weight of aircraft engines. Lighter materials are used in the cabin to decrease the weight of aircraft. More energy saving lighting in cabin and less energy consuming in-flight entertainment also help to further reduce the fuel consumption of aircraft.

Furthermore, the replacement of newer, more fuel efficient aircraft contributes to a CO2 reduction of 7-18 %. The new aircraft have the following criteria: Lighter airframe structures made of lighter materials particularly composite materials like Glass Laminate Aluminium Reinforced Epoxy (GLARE) replacing aluminium and more powerful yet fuel efficient aircraft engines. A series of technologies are under development and are estimated to be done before 2020. These technologies are geared turbofan engine, open rotor engine, counter-rotating fan and advanced turbofan.

The use of alternative fuels particularly biofuels can reduce CO2 emissions by 80 %, on a full carbon life-cycle basis. The sources for biofuels are algae, jatropha and camelina. The advantage of using biofuels is that these fuels can be sustainably produced without causing great impacts on the environment. IATA's target is 10 % alternative fuel by 2017. IATA is responsible for providing information and knowledge about alternative fuels. Examples for industry initiatives in alternative fuels are Airbus Gas-to-Liquids Test 0208, Virgin/Boeing biofuels test 0208 and Air New Zealand biofuels test Q408 (**IATA 2010**).

Pillar 2 (Operations)

CO2 emissions can be reduced by more efficient aircraft operations. IATA has formed Green Teams (also known as Go-Teams) to tackle the operational inefficiencies within airlines. The Green Teams have been operational since October 2005. Green Teams identify and evaluate fuel efficiency and emissions reduction initiatives. Based on the data provided by the airlines, green teams generate Fuel Efficiency Gap Report (FEGA) that focuses on airline operations like flight planning, dispatch and operational control; flight operations; maintenance and engineering; and commercial. This report helps to advise airlines on fuel and emissions savings measures and best practice. IATA aims to reduce emissions by 3 % through improvement in airport operations by 2020 (**IATA 2010**).

Pillar 3 (Infrastructure)

There are opportunities to improve the air transport infrastructure to reduce CO2 emissions. The main target of this pillar is to improve air and ground traffic management. A 12 % inefficiency of air transport infrastructure was reported by the Intergovernmental Panel on Climate Change (IPCC). Until 2008, 4 % of the efficiencies had been fulfilled and there are around 8 % efficiencies improvements that can be done in the future. A more efficient Air ATM and airport infrastructure can lead to a 4 % decrease in CO2 emissions by 2020. In 2007, 395 routes had been shortened to decrease the fuel consumption as well as emissions. NextGen and SESAR are the projects that help to develop new technologies in air navigation to minimize the emissions. Improvements in airport operations such as improved arrival/departures and continuous descent approaches (CDA) have been suggested by IATA (**IATA 2010**).

Pillar 4 (Economic Measures)

The efforts from the first three pillars are to control and reduce the emissions of CO2 of air transport. Pillar 4 serves a slightly different purpose by offsetting the CO2 emissions in other industries to compensate the carbon growth of air transport. More than 26 airlines had participated in the carbon offset programmes in 2008 and this number will increase in the future. According to IATA, 90 million tonnes of CO2 have to be offset in 2025 to maintain emissions at 2020 levels. Besides that, IATA generates innovative solutions to accelerate clean technology development and fleet renewal. IATA suggests tax credits to encourage airlines to renew their fleets and to use alternative fuels. Furthermore, emissions trading scheme (ETS) introduced by the EU will encourage airlines to reduce their fuel consumptions due to the extra charges for extra emissions. ETS will come in to effect in 2012 for all airlines operating into or within the EU. IATA suggests that EU ETS will benefit the environment if used in a positive way and should be implemented globally, not only within EU. The charges from emissions trading will be used on carbon offsetting and Research and Development (R&D) funding (**IATA 2010**).

2.3 Air Transport Association of America (ATA)

ATA carriers have joined the world's other airlines to contribute to a 1.5 % decent in fuel consumption annually through 2020 (**ATA 2011**). To achieve this, commercial airlines continue to invest a lung sum of money in new technologies for engines, airframes, winglets and other features that contribute to improvement of fuel efficiencies. Optimisations in aircraft operations in the air and on the ground have also minimized emissions. New approaches that have been introduced include continuous descent approach (CDA), required navigation performance (RNP), single-engine taxiing and electric gate power. CDA allows a smooth, constant angle descent upon landing instead of the conventional way of stair-step fashion landing. Advantages of CDA are its low CO2 and noise emissions. RNP allows aircraft to fly a specific path between two 3-dimensionally defined points.

ATA also took part in alternative fuels developing. ATA is a co-founder and active supporter of the Commercial Aviation Alternative Fuels Initiative (CAAFI). CAAFI is doing researches on alternative fuels, including Fischer-Tropsch (FT) Fuels, Hydrotreated Renewable Jet (HRJ) fuels and Bio-derived fuels. CAAFI members such as Boeing, Rolls Royce, and Continental etc will take part in the flight tests for the new alternative fuels researched by CAAFI. ATA encourages all potential suppliers to work through CAAFI to ensure the alternative fuels to be more environmental friendly compared to traditional jet fuel, in a life cycle basis (**ATA 2011**).

2.4 International Civil Aviation Organization (ICAO)

ICAO has taken initiatives in improving the environmental performance of aviation through developing a range of standards, policies and guidance material regarding to aircraft noise and engine emissions. Besides that, ICAO is responsible for improving operating procedures, air traffic system, airports and land-use planning. All of the improvements and initiatives by ICAO have led to 70 % more efficient aircraft operations compared to 1970s (**ICAO 2011**). The three major environmental goals adopted by ICAO in 2004 are to reduce the number of people affected by aircraft noise; reduce the emissions impact on local air quality and reduce the greenhouse gases impact on the global climate. In short, ICAO's environmental activities are focused on aircraft noise and aircraft engine emissions. Council's Committee on Aviation Environmental Protection (CAEP) has been formed by ICAO to undertake most of the ICAO environmental activities. New policies and new standards on aircraft noise and aircraft engine emissions will be formulated with the assist of CAEP.

2.5 Aircraft manufacturers

Airbus A380 and Boeing 787 are the greenest aircraft produced claimed by Airbus (**Airbus 2011**) and Boeing (**Boeing 2011**) respectively. A380 and 787 both share some similar characteristics like lighter weights, better engines in terms of fuel efficiency and performance, better aerodynamic structures, higher seating capacity, better noise reduction technology and better control system.

2.5.1 Airbus

Fig 2.19 Airbus A380 (**Airbus 2011**)

According to Airbus, Airbus A380 (Fig 2.19) provides a seating capacity ranging from 400 to more than 800 with two passenger decks. The two-passenger-decks concept increases the efficiency of volumetric space use. The high seating capacity enables Airbus A380 to transport more passengers with lesser trips of flights and hence reduce the LTO cycle. Airbus claims that A380 consumes the lowest fuels in commercial aviation. Many intelligent innovations have been applied to A380 to increase its flight performance, operational effectiveness, fuel efficiency as well as to reduce the emissions. An Airbus A380 produces about 75g of CO2 per pkm, which is relatively low compared to other aircraft (**Airbus 2011**).

A380 benefits from significant weight savings through composites and other advanced materials. By using composites and other advanced materials, A380 saves up to 25 % of its overall weight (**Jupp 2011**). Fig 2.20 shows the use of CFRP in A380. Carbon-fibre-reinforced polymer (CFRP) takes up about 22 % of the overall structure weight of A380. CFRP is found in areas such as vertical tail plane, horizontal tail plane, outer flaps, centre wing box, J-nose, flap track panels and pressure bulk head. The application of CFRP has been tested successfully in Airbus A340 and therefore being applied in Airbus A380.

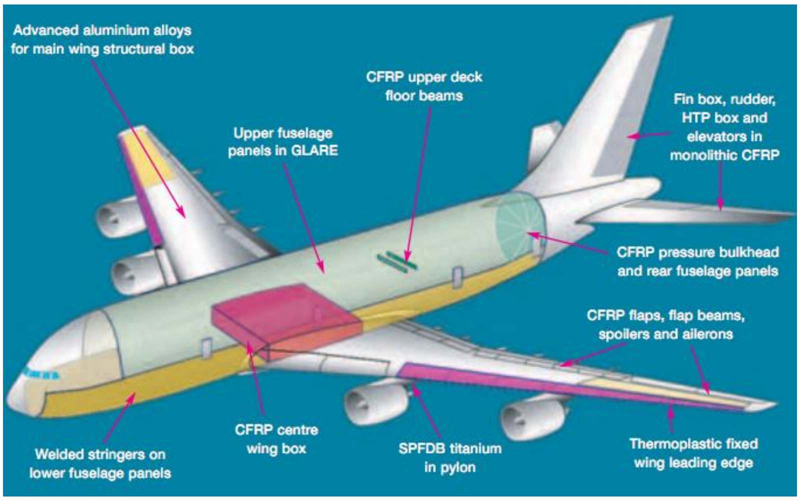


Fig 2.20 Use of CRFP in A380 (**Jupp 2011**)

A new material, Glass Laminate Aluminium Reinforced Epoxy (GLARE) is applied in the construction of Airbus A380. GLARE is used for the construction of the panels for the upper fuselage. GLARE is much lighter than the conventional materials and it reduces the A380 weight by about 500kg (**Jupp 2011**). Another advantage of GLARE is its high resistance against fatigue hence does not allow propagation of cracks.

Airbus A380 is powered by 2 types of engines, Rolls Royce Trent 900 and Engine Alliance GP7200. Trent 900 minimizes emissions, noise and fuel consumption by using a 116-inch swept fan, a low NOx combustor and a contra rotating high pressure system. Trent 900 reduces the fuel consumption by 5-10 % and NOx emissions by 20 %. Increased bypass ratio, swept low-speed fans, novel fan case and intake acoustic liners have enable Trent 900 to function quieter and achieve a noise reduction of 2-4 dB. The Engine Alliance GP7200 meets all ICAO gaseous and noise emissions requirements. Other factors that lead to lower noise emissions of A380 are optimisation of high lift systems and acoustic treatment nacelles. Airbus has patented its 0-splice inlet nacelle which reduces the noise generated by the engine fan as shown in Fig 2.21. The 0-splice inlet nacelle is used on Airbus A380. Compared to other aircraft, A380 has a better climb performance and lower approach speed as well as a better flight management system which enable A380 to emit lower noise.


3 Splices

2 Splices

0 Splice

Fig 2.21 Inlet nacelles of A320, A340-600 and A380 (**Jupp 2011**)

Airbus A380 is a fully fly-by-wire (FBW) aircraft. FBW technology was first introduced by Airbus in 1980s on the single-aisle family. FBW technology enables aircraft to fly and react more precisely towards different airflows and hence reduce the fuel consumption of aircraft. The weight reduction of FBW aircraft is through replacement of heavy mechanical control cables.

2.5.1 Boeing

Fig 2.22 Boeing 787 (**Boeing 2011**)

Boeing 787 (Fig 2.22) offers a seating capacity ranging from 210-290. Boeing claims that the 787 consumes 20 % less fuel than similar sized aircraft (**Boeing 2011**).

The weight reduction methods used by Boeing in the construction of 787 are the use of composite materials and the manufacture of one-piece fuselage section. Boeing has announced that as much as 50 % by weight of the primary structure, including the fuselage and wing of the 787 are made of composite materials. Fig 2.23 shows that, the composite materials used are mainly CRFP. Other composite materials that are used include graphite and toughened epoxy resin and titanium-graphite composite. Through the one-piece fuselage constructed mainly by composite materials instead of conventional way of combining aluminium sheets to form the fuselage, Boeing has saved up to 1500 aluminium sheets and 40000-50000 fasteners (**Hawk 2005**). The use of lighter material and the elimination of the fasteners to bring together aluminium sheets have significantly reduced the weight of the aircraft's fuselage.

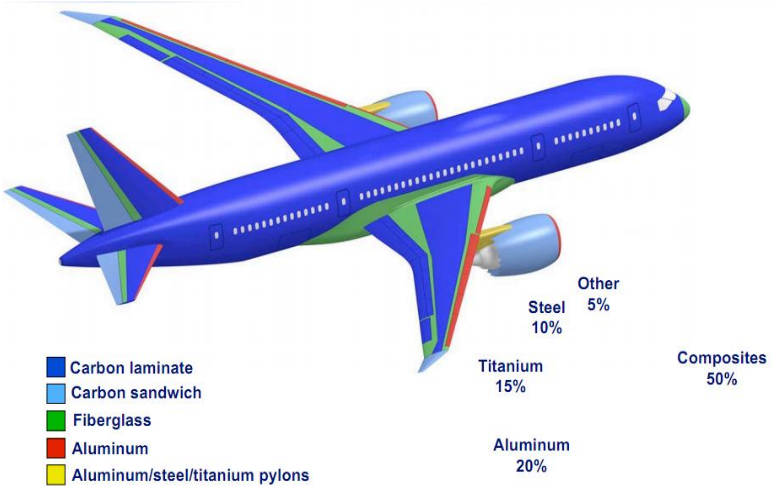


Fig 2.23 Use of composite materials in Boeing 787 (**Hawk 2005**)

Two engines that power the Boeing B787 are General Electric GEnx and Rolls Royce TRENT 1000. Rolls Royce Trent 1000 is the most fuel-efficient engine ever created by Rolls Royce and consumes up to 15 % less fuel than the older generation of turbofans. TRENT

1000 reduces noise by about 4dB compared to TRENT 800 which is mounted on Boeing B777. New combustion technologies have also enabled TRENT 1000 to produce lesser NOx. GEnx can be described as General Electric's most fuel-efficient engine. Many new innovations have been added in the construction of GEnx including a more advanced combustor, high-pressure 10-stage compressor, lightweight composite fan case and lightweight composite fan blades. With these new innovations, GEnx consumes up to 15 % less fuel than the previous engines. GEnx and TRENT 1000 have some common features such as high bypass ratio, no-engine-bleed systems, low noise nacelles with chevrons and laminar flow nacelles.

3 Aircraft Emissions

In general, gas emissions of vehicles due to the combustion of fuel or kerosene consist of two types of gases, which are greenhouse gases (GHG), which cause greenhouse effect and criteria air pollutant (CAP) gases, which are harmful to human health as well as the environment. The main products of fuel or kerosene combustion are CO2 and water vapour. Other products of kerosene combustion are NOx, SOx, HFCs, and Methane etc. The combustion products have effects on local air quality (LAQ) and climate change. CAP gases and GHG are categorized in Table 3.1.

Table 3.1 CAP gases and greenhouse gases

Criteria Air Pollutant Gases (Local Air Quality)	Greenhouse Gases (Climate change)
Ozone (Ground level)	Carbon dioxide, CO_2
Carbon Monoxide, CO	Nitrogen Oxide, NOx
Nitrogen dioxide, N_2O	Methane, CH_4
Sulphur Dioxide, SO_2	Hydrofluorocarbons (HFCs)
Particulate Matter	Water vapour
Lead	

3.1 Criteria air pollutant (CAP) gases

CAP gases do not trap heat within the atmosphere and hence do not cause global warming. However, these gases are harmful to our health and have great negative impacts on our environment.

Ozone impairs lung function, makes asthma conditions worse, irritates respiratory tract, and causes cough, lung inflammation, throat irritation, chest pain and more susceptible to lung infection. It may also damage the yield of agricultural products. Carbon Monoxide affects cardiovascular, pulmonary and nervous systems which bring about symptoms like dizziness, fatigue, headaches, nausea, visual and memory impairment and decreased muscular control. Excessive amount of Nitrogen Dioxide in the atmosphere may also cause problems to our respiratory system. Nitrogen Dioxide irritates lungs, may cause damage to the lung and lower resistance to respiratory infections. It contributes to ozone and acid rain formation. The latter damages and increase the corrosive rate of human made buildings and constructions such as bridges and corrosions .Particulate matter causes irritation to eye, nose and throat, bronchitis, cancer and lung damage. It also weakens the defence system of our body. People who suffer from heart or lung disease are at higher risk. Additionally, particulate matter destroys man-made materials, and causes major reduced visibility, which will indirectly cause traffic jam and accidents. Sulphur Dioxide, same as most other CAP gases, may cause respiratory illness, breathing problems, alterations in the lung's defences, permanent damage to lungs and aggravation of existing cardiovascular disease. It also contributes to accelerated corrosion of buildings and monuments, acidification of lakes and streams. High levels of lead can cause damage to brain and nervous system and adversely affect kidney function, blood chemistry, and digestion. Due to cumulative effects, children are at special risk even at low doses. Lead can also harm wildlife through contaminated food sources (**EPA 2008**). Besides the effects stated above, there are still many side effects that haven't been discovered. Actions have to taken before the amount of CAP gases in the atmosphere reaches an uncontrollable state.

3.2 Greenhouse gases (GHG)

Greenhouse gases refer to the fundamental gases which cause greenhouse effect. Greenhouse effect occurs when the heat is trapped within the atmosphere and causes global warming. Carbon dioxide is the main greenhouse gases emitted from air transport. Carbon dioxide has a long term warming effect on the climate as it remains in the atmosphere for hundreds of years. Water vapour generated from the combustion of aviation fuel acts as a greenhouse gas. Water vapour, together with other particles forms contrails under certain atmospheric conditions. Contrails trap heat on the earth and lead to a warming effect. Compared to carbon dioxide, water vapour resides a shorter period in the atmosphere. Increased NOx in troposphere generates ozone, which has a warming effect on the climate (**EPA 2011**).

3.3 Local impact

Gaseous Emissions

The landing take-off (LTO) cycle includes all activities such as taxi-in, taxi-out, take-off, climb out, approach and landing below the altitude of 3000 feet or 915 m. All the emissions during LTO cycle affect the local air quality. International efforts have been taken to reduce the emissions during LTO cycle, particularly NOx. ICAO has undertaken some initiatives to improve the local air quality through its Airport Air Quality Guidance Manual, which is updated from time to time. This manual provides guidance to assist with the assessment of airport emissions sources, emission inventories and emissions allocation.

The emissions during LTO cycle are mainly from aircraft engines, APU, ground support equipment, motor vehicles, construction, generators, engine testing, de-icing, fuel storage facilities etc. The aircraft exhaust emissions are calculated by using the following operating modes as shown in table 3.2: taxi in and taxi out (7 % thrust, 26 min); approach (30 % thrust, 4 min); climb (85 % thrust, 2.2 min) and take-off (100 % thrust, 0.7 min) (**ICAO 2011**). The emissions vary depending on the facilities, vehicles and equipment in each airport.

Table 3.2 ICAO's LTO Cycle (**ICAO 2011**)

Operation	At thrust	Time
Taxi out	7 %	19 min
Take-off	!00 %	0.7 min
Climb	85 %	2.2 min
Approach	30 %	4.0 min
Taxi In	7 %	7 min

Aircraft Noise

High levels of noise are produced in the airport through take-offs and approaches of aircraft. All commercial aircraft must meet certification standards provided by ICAO in Annex 16. In addition, many restrictions have been made to secure the serenity of the community around airport areas. For example, at London Heathrow airport, all flights are restricted through Quota Count System. This system restricts the number of flights by accumulating points for each landing and take-off (**Antoine 2004**). The cumulative points are not to be exceeded. Besides that, Heathrow airport only allows the quietest aircraft to operate at night.

Noise emission measurements are made at three points during the take-off and landing process, which are shown in Fig 3.1. Effective Perceived Noise Levels (EPNL) measured from these three points must not exceed the noise certification limits. The limits are set based on the Maximum Take-off Weight (MTOW) and number of engines of the aircraft.

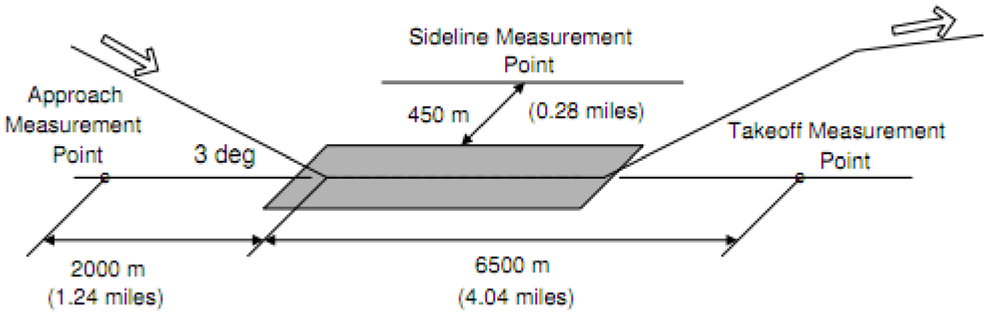


Fig 3.1 ICAO certification noise measurement points (**Antoine 2004**)

The main sources of airport noise are from aircraft during take-offs and landings as shown in Fig 3.2. Other sources that contribute to airport noise are ground support vehicles, APU, expansion and construction of airports etc. During take-offs, the main sources of the noise produced by aircraft are engine fan exhaust and engine jet exhaust whereas during approaches, engine fan inlet and air frame are the dominant noise sources.

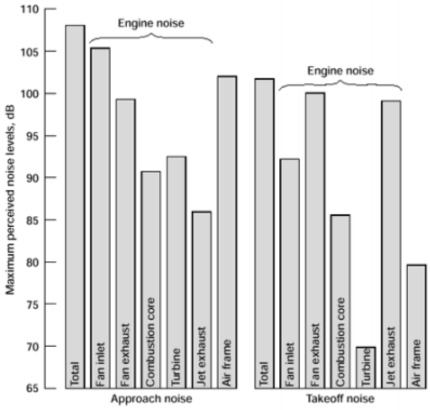


Fig 3.2 Breakdown of noise sources (**Antoine 2004**)

3.4 Global impact

Radiative forcing (RF) is to determine the net change of irradiance between different layers of the atmosphere. In other words, radiative forcing is a measure of how the energy balance of the atmosphere, expressed in units of 'Watts per square meter', is affected when factors that affect climate are altered. A positive radiative forcing can be interpreted as a warming effect in the atmosphere whereas a negative radiative forcing has a cooling effect (**IPCC 2007**).

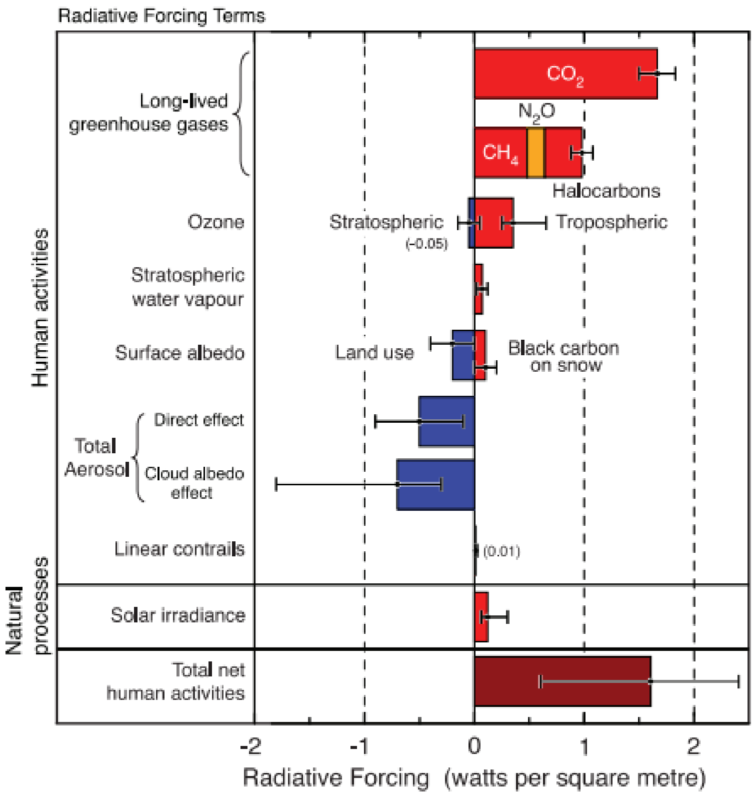


Fig 3.3 Summary of the principal components of the radiative forcing of climate change (**IPCC 2007**)

CO2 is the most abundant products from aviation fuel combustion, as shown in Fig 3.3. 3.16 kilograms CO2 are produced per kilogram of aviation fuel combustion. The accumulated CO2 spreads globally and causes a global warming effect. The CO2 produced by aircraft has the same effect as CO2 from other ground level sources (**Kollmuss 2009**).

Water vapour is the second most abundant products from aviation fuel combustion. Every kilogram of aviation fuel combustion produces 1.23 kilograms water vapour (**Kollmuss 2009**). Most water vapour emissions produced by subsonic aircraft are removed from the atmosphere through precipitation within one to weeks. The short-lived water vapour emissions in the atmosphere cause regional effects. These effects are directly proportionate to altitudes. The water vapour emitted in the upper stratosphere has greater climate impacts than the water vapour emitted in the lower stratosphere.

NOx alone does not heat up the atmosphere. NOx produced by aircraft catalyzes the production and destruction of ozone depending on the flight altitudes. In the troposphere, NOx contributes to the formation of ozone whereas in stratosphere NOx contributes to the destruction of ozone. The formation of ozone in troposphere leads to a global warming effect. On the other hand, NOx leads to the destruction of methane in the atmosphere. This results in a small cooling effect of the atmosphere. However, the cooling effect is relatively small compared to the warming effect.

Other aircraft emissions such as sulphates and soot particles also affect the climate. Sulphates have a cooling effect by reflecting sunlight. Soot particles absorb solar radiation and have a warming effect. The warming effect of soot particles reduces when the altitude increases. Besides that, the warming effect of soot particles varies depending on the location of emissions. Fig 3.4 shows that, soot particles have a stronger impact on the environment if emitted over white surfaces like snow and Arctic (**Quinn 2008**).

Contrails are formed through condensation of ambient water vapour into ice crystals in the atmosphere. Contrails have a warming effect which is similar to thin high clouds. Contrails trap infrared radiation and reflect solar radiation. The trap of infrared radiation in the atmosphere causes a warming effect whereas the reflection of solar radiation has a cooling effect. However, the warming effect is more significant than the cooling effect. Another concern of contrails is its effects on regional climate. Formation of contrails may lead to regional climate change.

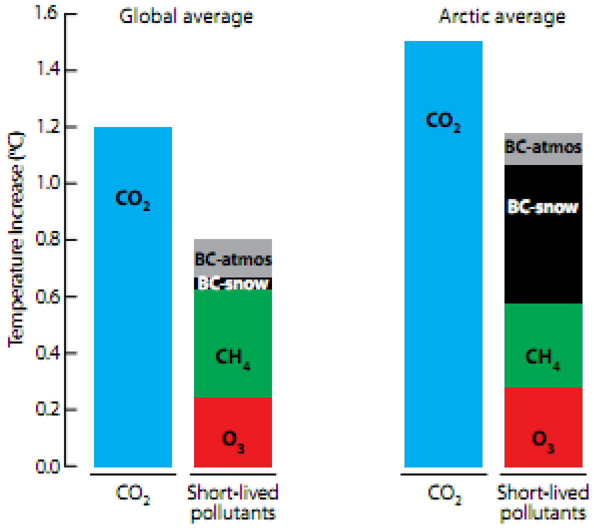


Fig 3.4 Regional and global difference of average temperature increase (**Quinn 2008**)

3.5 Emissions of different transport modes during operation

Air transport

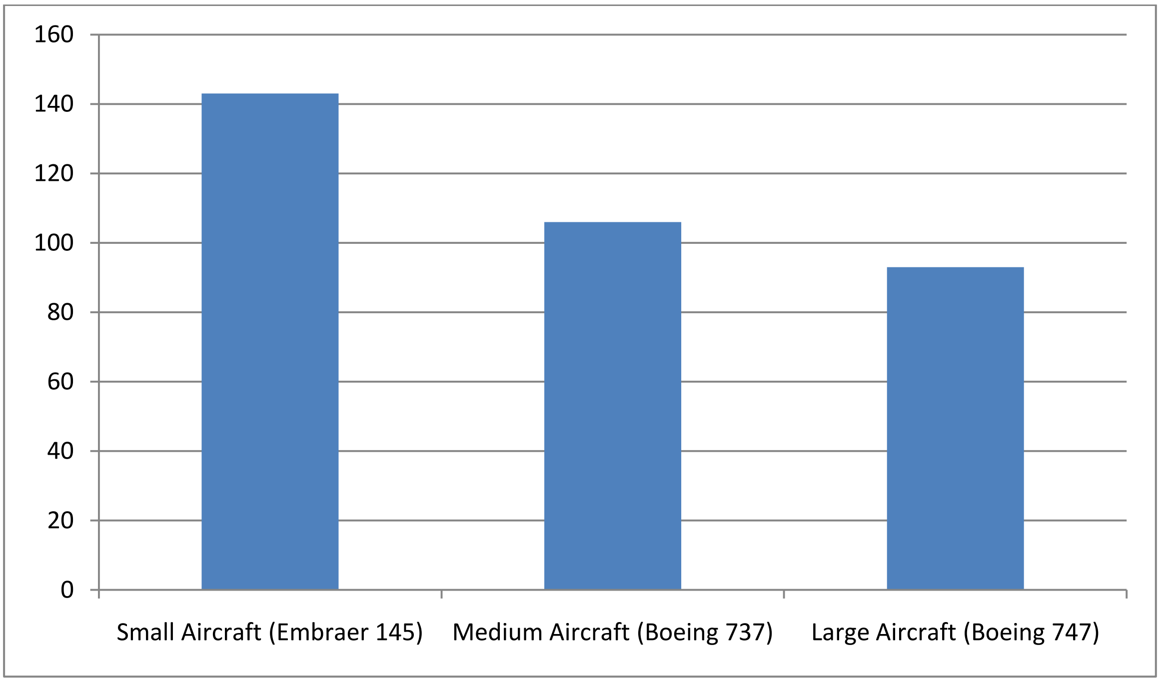


Fig 3.5 GHG emissions of air transport in g/pkm

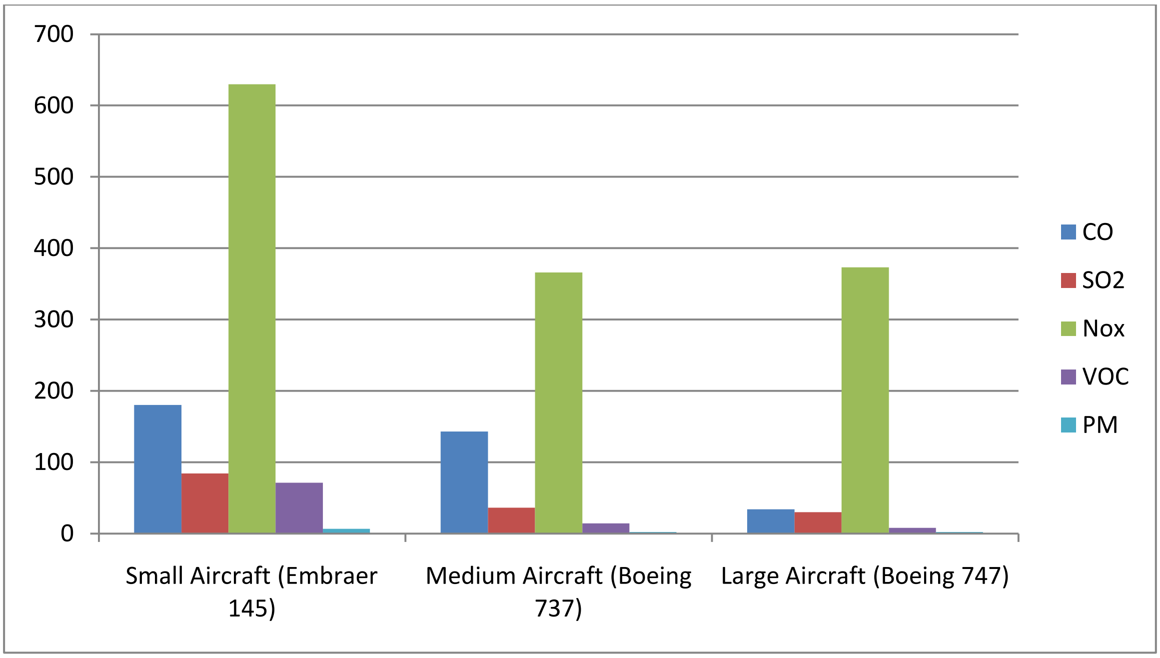


Fig 3.6 CAP emissions of air transport in mg/pkm

In general, larger aircraft which have more passengers and travel longer distance produce lesser GHG per pkm. For smaller aircraft which have less passengers and travel shorter distance, the cruise phase accounts for less percentage in the total GHG emissions per pkm whereas the LTO cycle accounts for more percentage. The GHG emissions per pkm during

LTO cycle of small, medium and large aircraft account for 32 %, 15 % and 4 % respectively of the total aircraft operational GHG emissions. NOx and CO are the most abundant CAP emissions produced by aircraft per pkm (**Chester 2008**).

Road transport

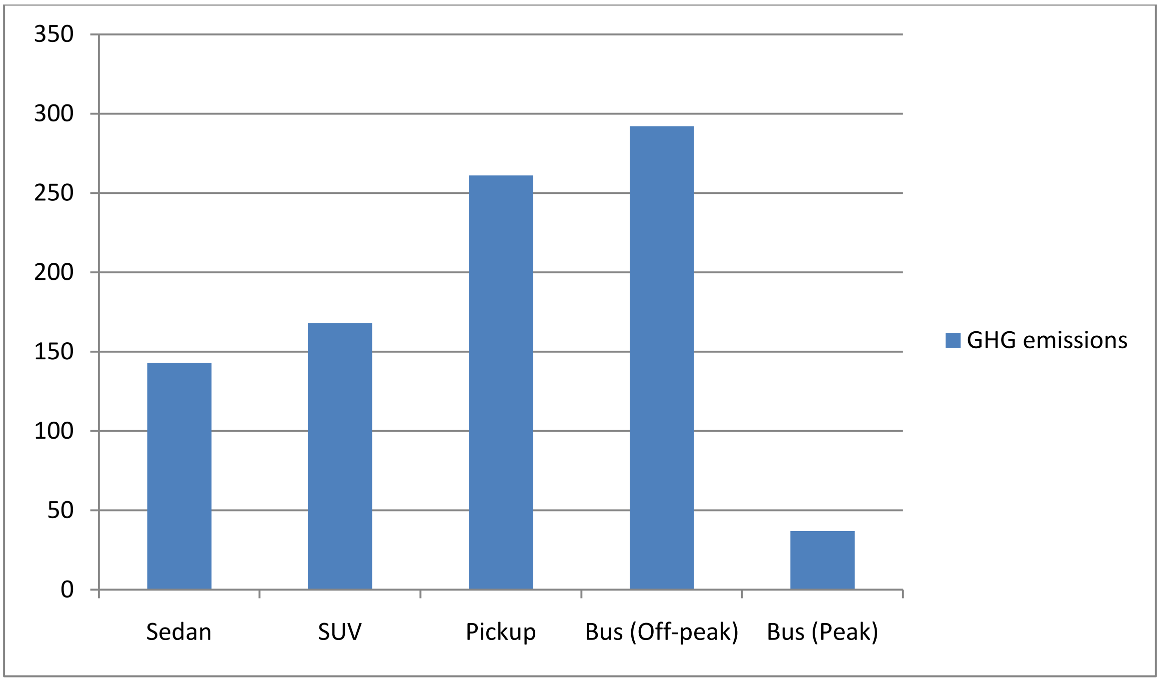


Fig 3.7 GHG emissions of road transport in g/pkm

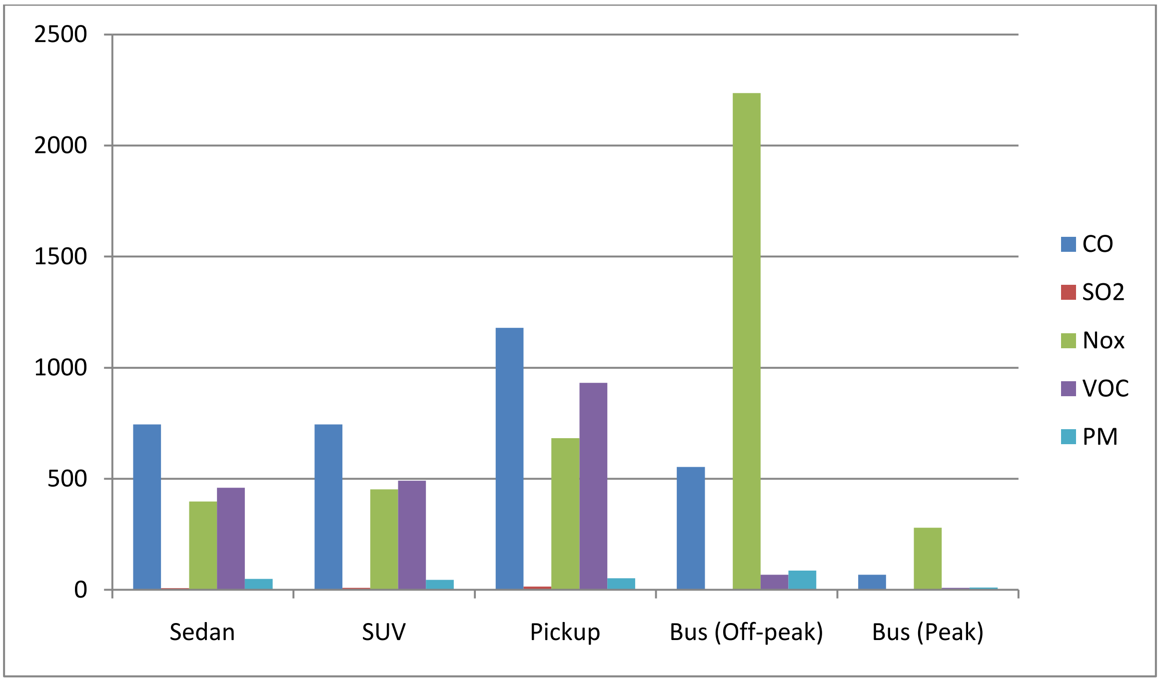


Fig 3.8 CAP emissions of road transport in mg/pkm

For passenger cars, sedan accounts for the least GHG emissions per pkm whereas pickup accounts for the most GHG emissions. It is to be noted that, there is a distinct difference between bus operated in peak and non-peak hours due to the load factor of the vehicle. During non-peak hours, bus emits more GHG per pkm than any other type of passenger cars. The most abundant CAP gases produced by personal cars per pkm are CO, VOC and NOx. The high amount of CO and VOC emissions are due to the cold starts of vehicles. During cold starts of vehicles, catalytic converter does not operate at its peak efficiency. Catalytic converter is to reduce NOx emissions by oxidizing hydrocarbons and carbon monoxide.
Therefore, NOx, VOC and CO emissions are higher when the converter is cold. Another factor that contributes to the high VOC emissions is the evaporative losses during operation of passenger cars, primarily from running, resting and hot soak (**Chester 2008**).

Rail transport

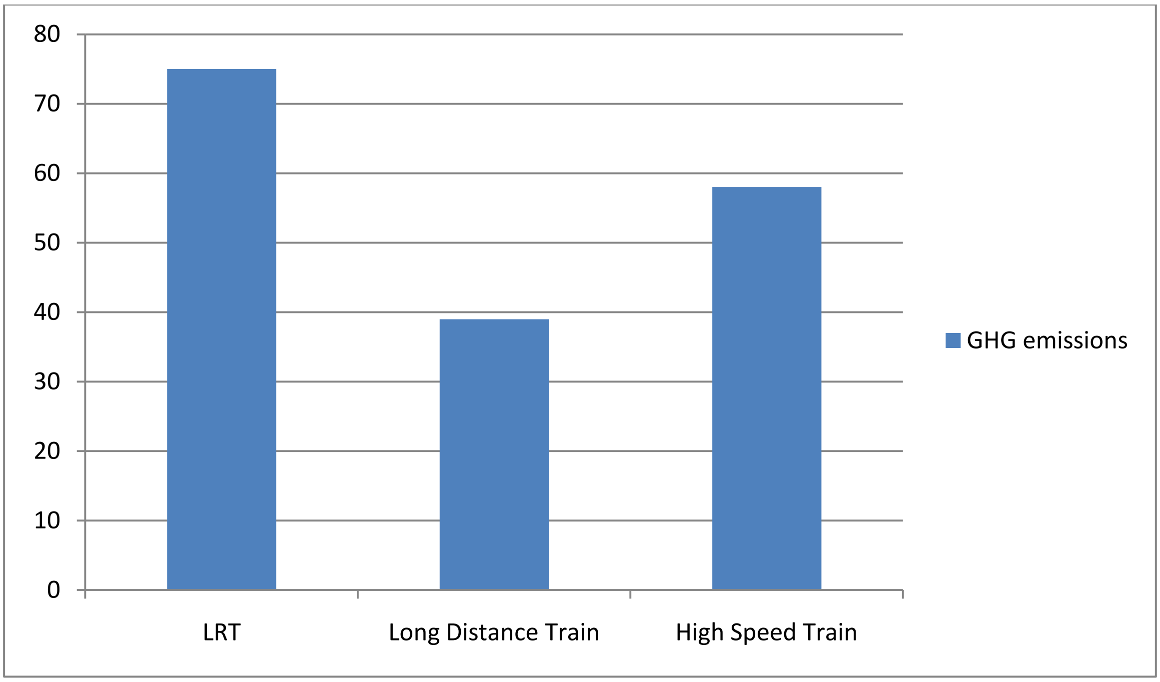


Fig 3.9 GHG emissions of rail transport in g/PKM

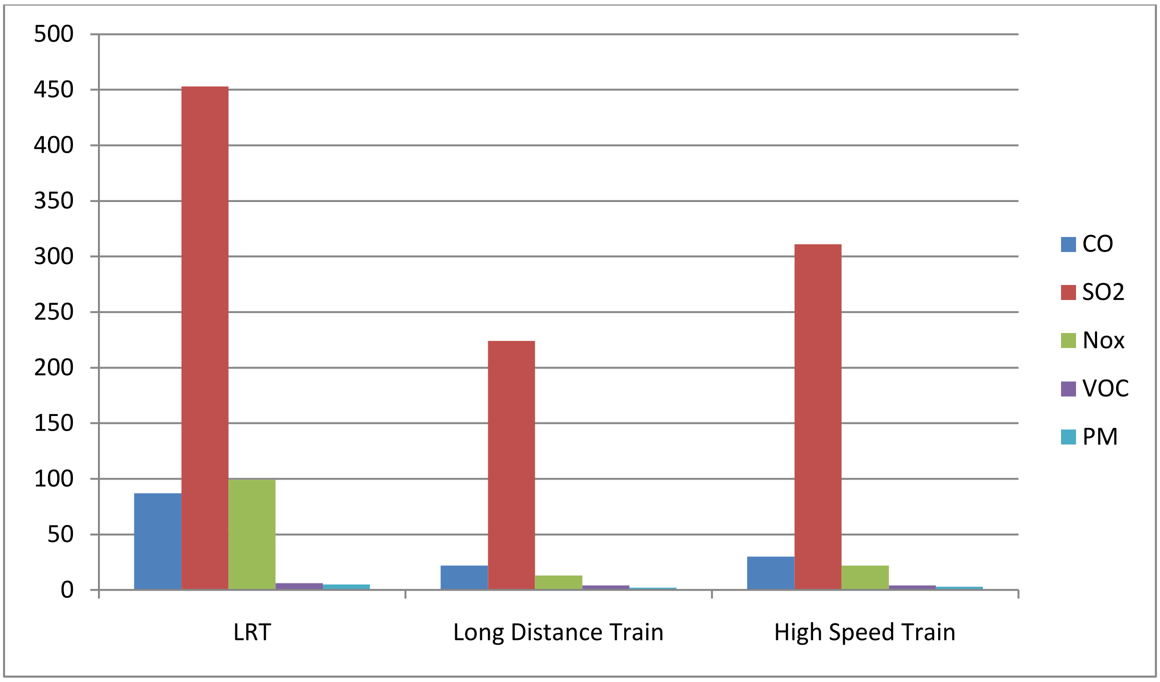


Fig 3.10 CAP emissions of rail transport in mg/PKM

Different from aircraft and on road vehicles, trains are mostly powered by electricity. The emissions of trains depend not only on the efficiency of the vehicles alone but also the efficiency of electricity generation in the power stations. The most abundant emissions of trains per pkm are SO2 due to electricity production in power stations. During electricity production, coal which contains sulphur produces SO2. Although the amount of sulphur in coal is not large, it leads to a significant amount when normalized per pkm (**Chester 2008**).

<u>Comparisons of air, road and rail transport during operation</u>

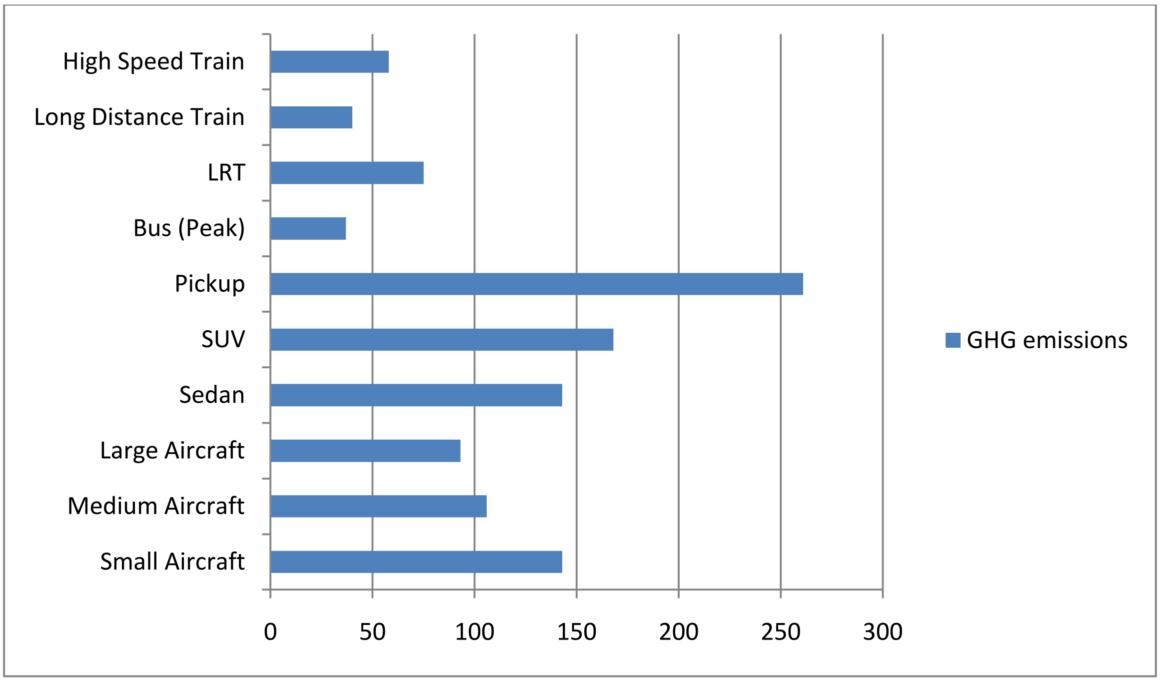


Fig 3.11 GHG emissions of rail, road and air transport in g/pkm

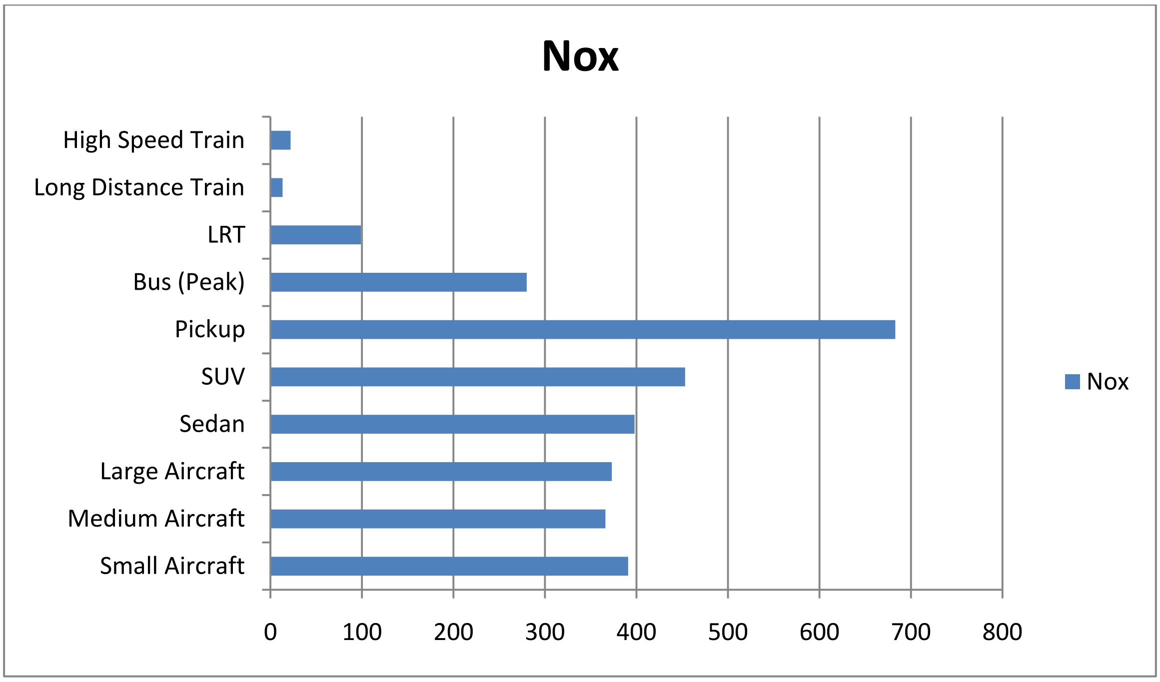


Fig 3.12 NOx emissions rail, road and air transport in mg/pkm

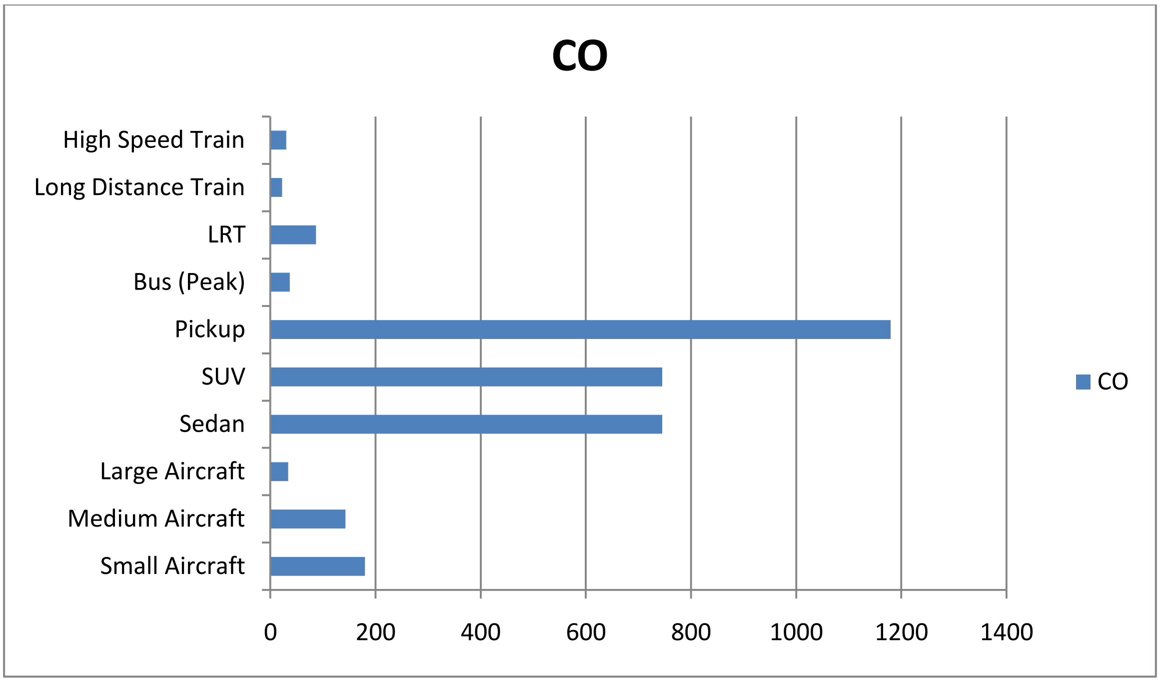


Fig 3.13 CO emissions of rail, road and air transport in mg/pkm

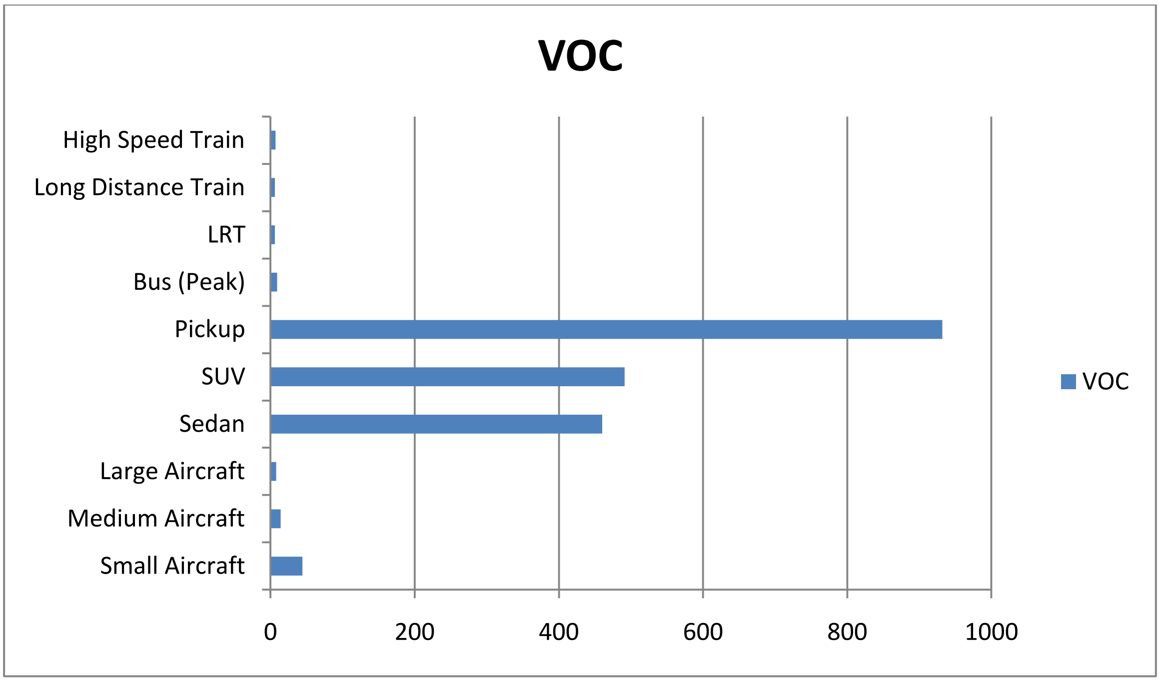


Fig 3.14 VOC emissions of rail, road and air transport in mg/pkm

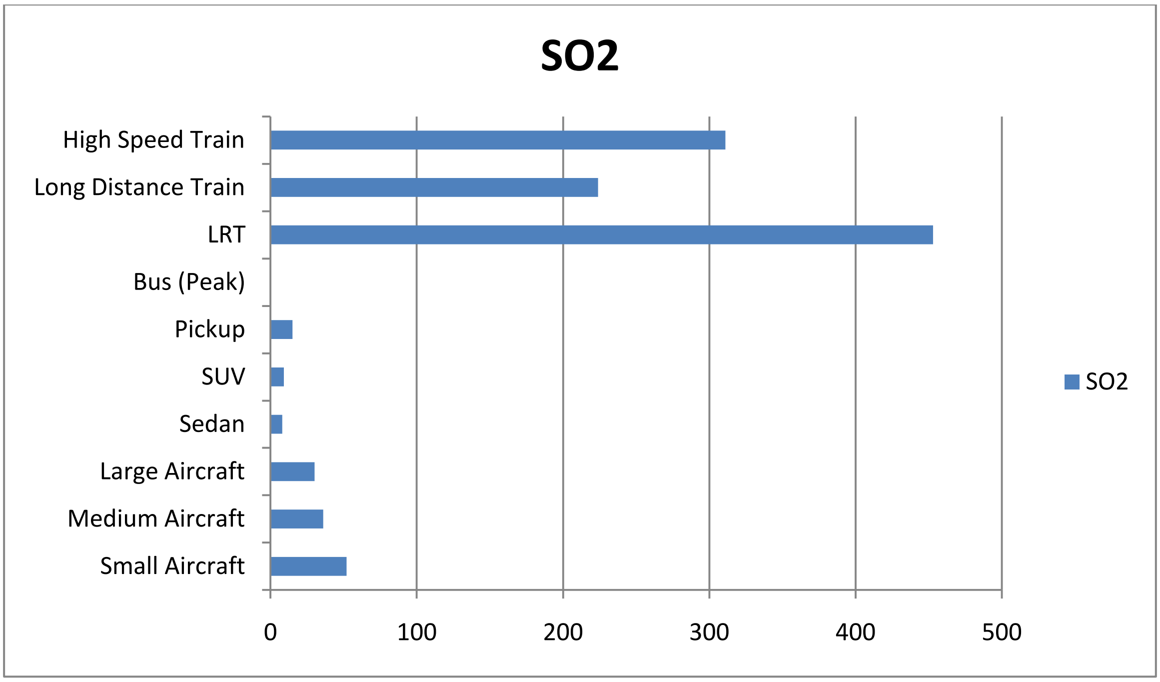


Fig 3.15 SO2 emissions of rail, road and air transport in mg/pkm

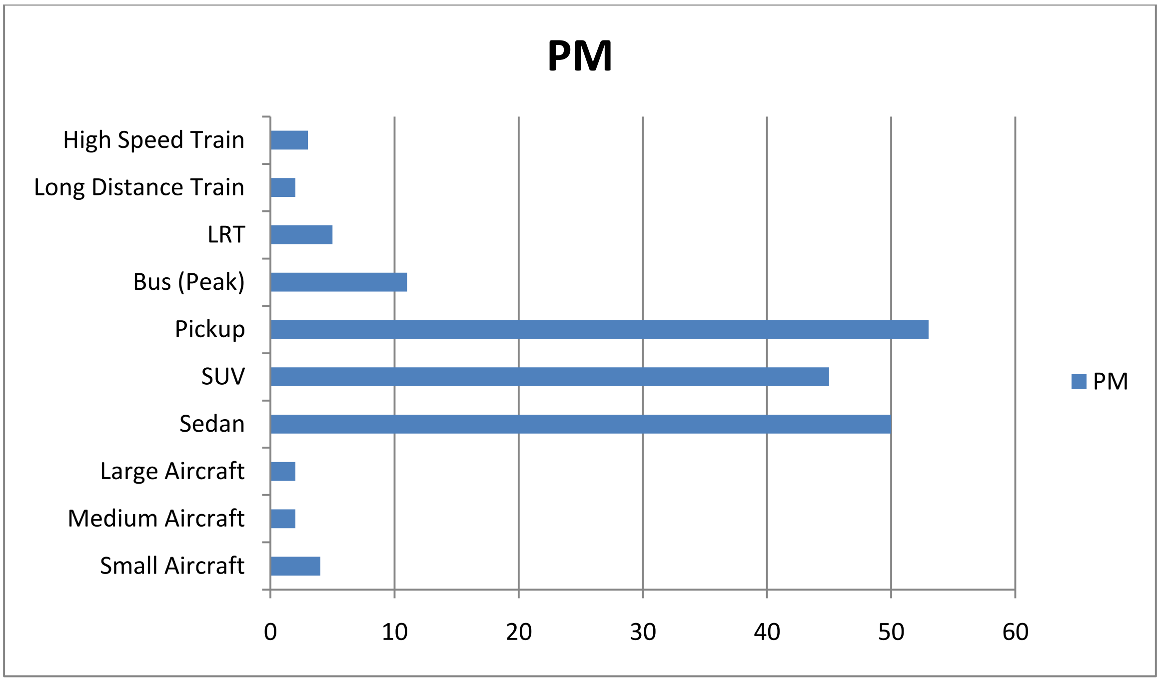


Fig 3.16 VOC emissions of rail, road and air transport in mg/pkm

3.6 Global aviation GHG emissions

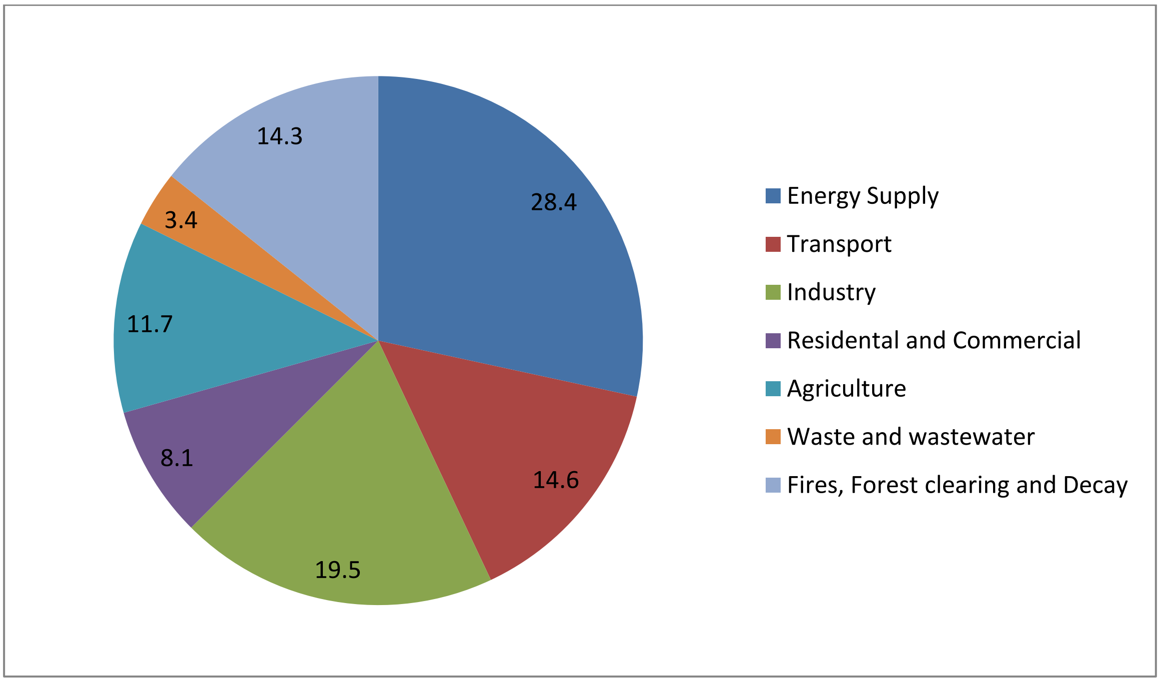


Fig 3.17 Breakdown of GHG sources in year 2005

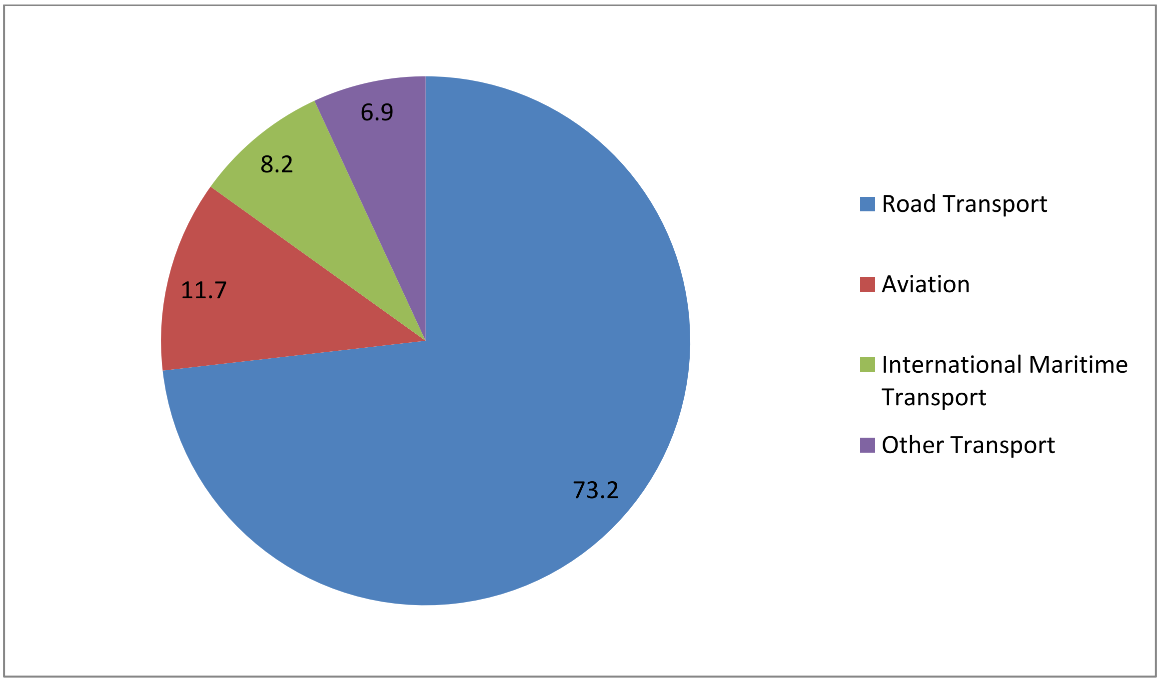


Fig 3.18 GHG emissions per transport sector

GHG emissions from all sorts of transportations account for 14.6 % of the total manmade GHG in 2005 as shown in Fig 3.17. Air transport GHG emissions contribute to 1.7 % of the total GHG emissions globally. Although air transport is only a minor contributor to global GHG emissions, the relative share is constantly growing if no action I taken. Fig 3.18 shows that, road transport is the largest contributor to the GHG emissions globally in the transport sector. It contributes about 73 % of the total emissions caused by transportation (**ITR 2010**).

4 Airlines' environmental efforts

4.1 Southwest Airlines

Southwest Airlines is one of the biggest American airlines and operates 548 Boeing 737 jets. Southwest's fleet has an average age of approximately 11.21 years (**Southwest 2011**).

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Southwest Airlines has taken initiatives to show their passion for the environment. The Green Team of Southwest Airlines is responsible for the environmental efforts. Southwest Airlines cooperates with vendors, academic researchers and industry organizations to improve the environmental performance of air transport. Southwest Airlines is a leading corporate which uses green power. Green power is electricity generated from renewable sources such as wind, solar, geothermal etc. Green power is used to provide electricity for its facilities in Dallas and Houston.

Southwest Airlines reduces its emissions by conserving jet fuel and cleaner GSE. Researches on cleaner burning technologies, including electric, biodiesel and repowering of older gasoline and diesel engines with cleaner-burning diesel engines are being conducted by Southwest Airlines.

Sustainable materials are used on board. For example, its coffee paper cups are made from post-consumer recycled materials. Southwest Airlines also promotes its recycling programs on board. In addition, Southwest Airlines encourages its employees to take part in Project Save (Serious about Volunteering for the Environment). This project aims to offset the emissions produced by Southwest Airlines and at the same time keep the environment clean. Its employees have shown their passions through trees and gardens planting; community parks, beaches and trails cleaning; trash collecting around airports; recycling programs; and green activities at schools across the country.

In 2009, 8.5 million gallons in fuel consumption have been saved. Fig 4.1 shows the percent breakdown of the total fuel savings. Improvements in flight efficiencies have the greatest impacts on fuel saving of Southwest Airlines, which contributes 57 % of the total fuel saved in 2009 (**Southwest 2011**).

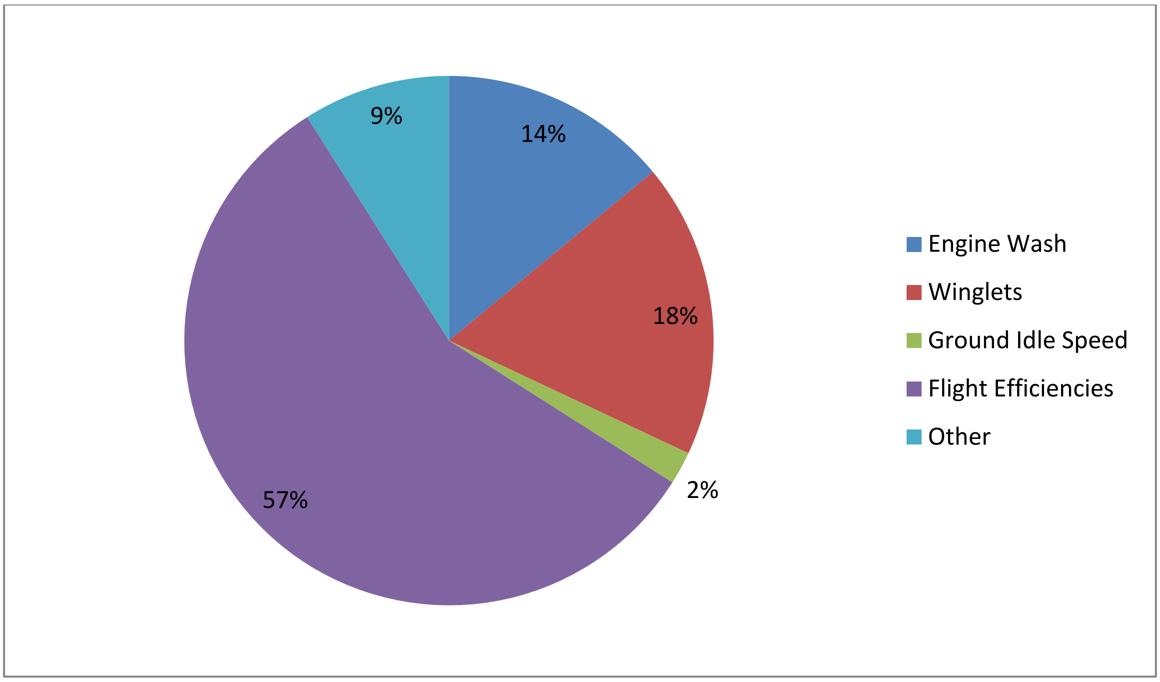

Fig 4.1 Jet fuel savings of Southwest Airlines in 2009

Table 4.1 Improvements done by Southwest Airlines to reduce fuel consumption

Efforts	Description
Winglets	- Winglets are added to 21 additional Boeing 737-300 aircraft - Winglets reduce aircraft fuel consumption by 2.5 %-3 %
Ground Idle Speed	- Control ground idle speed through adjustments of aircraft engines - It saves up to 3.1 gallons of fuel per hour of idle time
Flight Efficiencies	- Introduce of Required Navigation Performance (RNP) - Replace ground-based GPS system with space-based GPS - RNP results in fuel savings of approximately 4.8 million gallons in 2009
Engine Wash	- Refinement of engine wash program for 737-700 - It results in fuel savings of 1.2 million gallons in 2009
Gate Electrification	- Replace jet-fuel-powered gates with electric-powered gates - It results in fuel savings of more than 46000 gallons per day
GSE Conversion	- Convert diesel-powered GSE, particularly pushback tractors, to electric-powered GSE - Repower GSE with cleaner-burning engines - It results in fuel savings of approximately 46000 gallons in 2009

4.2 Lufthansa

Lufthansa aims to reduce its CO2 emissions by 25 % in 2020, relative to CO2 emissions in 2006. This is only one of the aspects of Lufthansa Strategic Environmental Programme introduced in 2008. 15 guiding principles have been established by Lufthansa to achieve crucial progress by 2020. The 15 guiding principles are: reduce carbon emissions, cut nitrous oxide emissions, modernise the fleet, promote alternative fuels, increase operational efficiency, improve infrastructure, implement emissions trading on a global scale, continue offsetting carbon emissions, develop further incentive systems, reduce aircraft noise, improve aircraft, optimise flight procedures, develop comprehensive traffic concepts, build green, and expand environment management (**Lufthansa 2011**).

In 2010, the specific fuel consumption of Lufthansa Group's fleet hit the lowest Fig in the company's history, which is 4.2 litres per 100pkm. The Lufthansa Group's fleet consists of Deutsche Lufthansa AG, SWISS Austrian Airline, British Midland, Germanwings, Lufthansa Cityline, Air Dolomiti, Eurowings and Lufthansa Cargo. The total number of aircraft operated by the group is 710. Fig 4.2 shows the fuel consumption over the past 10 years (**Balance 2010**).

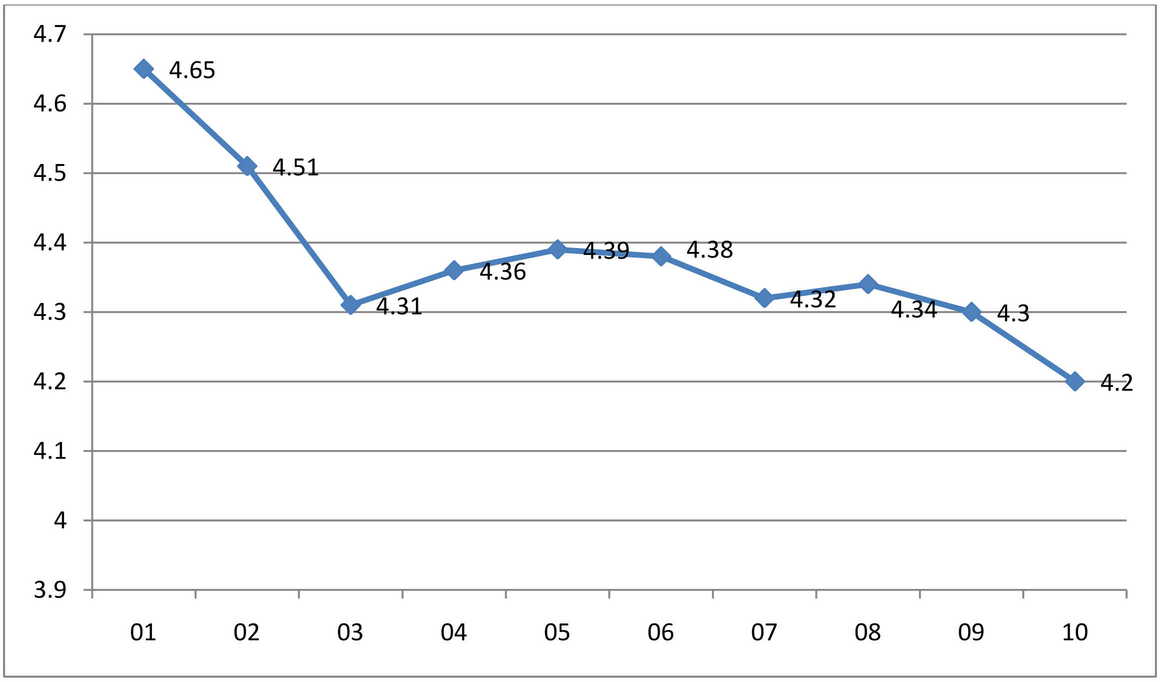

Fig 4.2 Fuel consumption in l/100pkm of Lufthansa's fleet from 2001 to 2010

To optimize operations-related measures on the ground and in the air, Lufthansa, along with other airlines, has developed the four pillar model for climate protection. The four pillar model is shown below in Table 4.2.

Table 4.2 Lufthansa's Four Pillar Model to reduce emissions (**Lufthansa 2011**)

Lufthansa's Four Pillar Model			
Technological Progress	Improved Infrastructure	Operational Measures	Economic Measures

Through technological progress, Lufthansa aims to bring in new technologies in aircraft and engine, and aircraft fuel. Lufthansa plans to modernize their fleet by replacing old aircraft with new aircraft or by doing modification on the existing fleet. One of the modifications that will be done is the optimization of the engines in the existing fleet. Besides that, Lufthansa has put a lot of efforts on researching alternative fuels in the framework of the project Aviation biofuel. Airport infrastructures will be built according to needs. Flight routings will be optimized to reduce fuel consumption of aircraft. The airspace will be more fully utilized. Besides that, Lufthansa is also part of SESAR project. On the other hand, Lufthansa aims to reduce its emissions by increase the operational efficiencies. This can be done by using more efficient aircraft sizes according to flight range and passengers, flying at optimal speeds and routes, and improve the ground handling processes. Lufthansa intends to increase its load factor and hence reduce the fuel consumption per pkm. The fourth pillar is to complement the first three pillars. The revenue from the global emissions trading will be complemented to the other three pillars. Lufthansa provides the opportunity for its customer to do voluntary compensation of CO2 emissions.

4.3 China Southern Airlines

CSN has shown its interest and cooperation in reducing its direct operating cost and at the same time provides more environmentally friendly services. In 2009, the fuel consumption is reduced to 4.47 litres /100pkm. The fuel consumption was reduced by 11.80 % compared to year 2005 (**China 2009**).

One of the initiatives taken by CSN is to reduce the fuel consumption through better flight procedures. According to IATA, every additional ton on the aircraft results in additional fuel consumption per hour of up to 40kg. For short and medium haul flights, water tanks are only partially filled to reduce aircraft weight. For example, from Guangzhou to Beijing, only about one third of the water tank is filled with water. This amount of water is sufficient to supply water on board from Guangzhou to Beijing according to statistics done by CSN. Through this method, an estimation of about 108kg of fuel is saved for every trip made from Guangzhou to Beijing.

Another emission reduction strategy by CSN is to modernize its fleet. 12 MD90’s, 9 MD82 and 2 A300’s have been replaced by more energy-efficient aircraft, A330. The average age of CSN’s fleet was 6.32 years, up to the end of 2009.

4.4 Air France

Air France has also put efforts on reducing the impact of aircraft operations on the environment. Between 2000 and 2006, a 12 % fuel consumption reduction per passenger has been achieved by Air France through fleet modernization. This is one of the many on-going efforts of Air France to achieve its target of 3.7 litres per 100 pkm in 2012. The new passenger aircraft, which Air France flies, are Boeing 777-300 and Airbus 318 (**Air 2008**).

Air France's hub organization at Paris Charles de Gaulle enables Air France to make more efficient flights. With a hub, Air France can carry the same number of passengers with fewer flights (**Air 2008**).

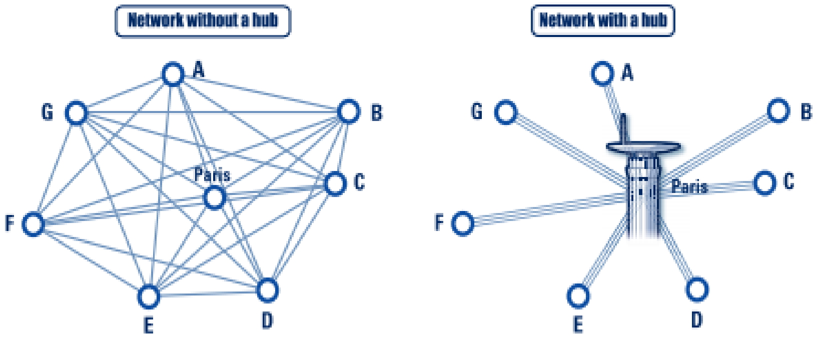

Fig 4.3 Flight network with and without a hub (**Air 2008**)

Other initiatives taken by Air France to reduce its emissions are reducing aircraft weight, flying with optimum fuel and adapting better flight procedures. In 2009, Air France phased in lighter seats on their short-haul aircraft. 8000 tons of CO2 are saved annually through the weight reduced. Through the help of statistics, Air France flies with optimum fuel carried on board (**Air 2008**).

5 Estimation of aircraft fuel consumption

5.1 Turbojet and turbofan

Breguet range equation is the main tool to estimate the cruise range of a generic aircraft (**Filippone 2006**). The Breguet range equation is only applicable during cruise conditions, when the weight of the aircraft equals the lift, and the drag equals the thrust. Besides that, the aircraft speed, specific fuel consumption, gravity and lift to drag ratio are assumed constant throughout the cruise. The range is then calculated by integrating the total weight of the aircraft, from the start of the cruise to the end of the cruise, to the changes of weight. The Breguet range equation for turbojet and turbofan can be expressed in equation below.

$$R = B \cdot ln \frac{M_{initial}}{M_{end}} \tag{5.1}$$

$$B = \frac{E \cdot v}{c \cdot g} \tag{5.2}$$

Fuel consumption of turbofan and turbojet aircraft with E_{max}

In order to calculate the fuel consumed during the flight, we have to first determine the flight range, the specific fuel consumption, the lift to drag ratio, the aircraft speed and the take-off weight. The values of the specific fuel consumption are obtained from **Roux 2010**. The maximum lift to drag ratio is calculated from the equation below.

$$E_{max} = k_e \cdot \sqrt{\frac{S_{wet}/S_w}{AR}} \tag{5.3}$$

The factor, k_e is estimated as 15.8 according to Raymer (**Scholz 2011**) and a value of 6.1 is taken as the relative wetted area, S_{wet}/S_w. E_{max} is then calculated and tabulated in Table 5.1. The values of wing aspect ratio of aircraft are taken from **Jane's 2001**. The value of wing aspect ratio of Airbus A380 is taken from **Hosder 2001**.

Table 5.1 The estimation of E_{max} of turbofan and turbojet aircraft

Aircraft type	Factor, k_e	Relative Wetted Area, S_{wet}/S_w	Wing Aspect Ratio, AR	Maximum lift to drag ratio, E_{max}
A340-200	15.8	6.1	10.1	20.33
A340-600	15.8	6.1	9.3	19.51
A380-800	15.8	6.1	7.5	17.52
A319-100	15.8	6.1	9.5	19.72
737-800	15.8	6.1	9.4	19.61
747-400	15.8	6.1	7.7	17.75
777-300	15.8	6.1	8.7	18.87

Table 5.2 Breguet Factor, B of turbofan and turbojet aircraft with E_{max}

Aircraft type	Engine Model	Specific fuel consumption, c ((kg/s)/N)	Lift to drag ratio (E)	Aircraft speed, v (m/s)	Breguet Factor, B (m)
A340-200	CFM56-5C2	1.54E-05	20.33	237	31893046
A340-600	Trent 556-61	1.65E-05	19.51	243	29238498
A380-800	Trent 900	1.59E-05	17.55	252	28371900
A319-100	V2522-A5	1.63E-05	19.72	237	28902605
737-800	CFM56-7B24	1.78E-05	19.61	237	26650358
747-400	RB211-524G	1.62E-05	17.75	252	28159077
777-300	Trent 892-17	1.58E-05	18.87	246	29967449

By converting the above equation, we can now calculate the weight of fuel consumed during the cruise flight. After that, by dividing the weight of fuel by the number of passengers, range travelled and the fuel density, the fuel consumption per pkm can now be determined. In this case, we take the values of design range with maximum PAX from **Jane's 2001**. We assume that there is no reserve fuel at the end of the flight. In the case of maximum payload, the initial weight is restricted by maximum take-off weight, M_{MTOW}, as shown in Fig 5.1. Therefore the initial weight is replaced by M_{MTOW} for the calculations.

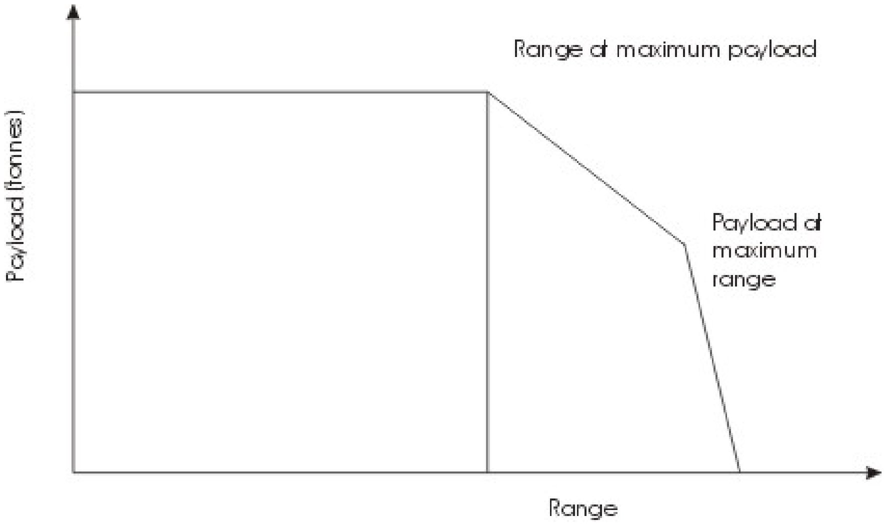

Fig 5.1 Range payload Diagram (**Wikipedia 2011**)

$$\frac{R}{B} = \ln\left(\frac{M_{initial}}{M_{initial} - M_{Fuel}}\right) \tag{5.4}$$

$$e^{\frac{R}{B_s}} = \frac{M_{initial}}{M_{initial} - M_{Fuel}} \tag{5.5}$$

$$K = e^{\frac{R}{B_s}} \tag{5.6}$$

$$K(M_{initial} - M_{Fuel}) = M_{initial} \tag{5.7}$$

$$M_{Fuel} = M_{initial} \cdot \frac{(K-1)}{K} \tag{5.8}$$

$$\frac{Fuel\ Consumption}{100PKM} = \frac{M_{Fuel}}{\rho_F \cdot n_{PAX} \cdot R} \cdot 100 \tag{5.9}$$

Table 5.3 Fuel consumption per 100 pkm of turbofan and turbojet aircraft with E_{max}

Aircraft Type	B(m)	$M_{initial} = M_{MTOW}$ (kg)	Design range, R (km)	PAX (max)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A340-200	31928875	275000	14816	239	102095	3.60
A340-600	29238498	365000	13890	380	138025	3.27
A380-800	28371900	548000	14445	555	218642	3.41
A319-100	28902605	64000	3357	124	7018	2.11
737-800	26650358	70535	3685	162	9109	1.91
747-400	28159077	362875	11260	416	119601	3.19
777-300	29967449	263080	7250	386	56533	2.53

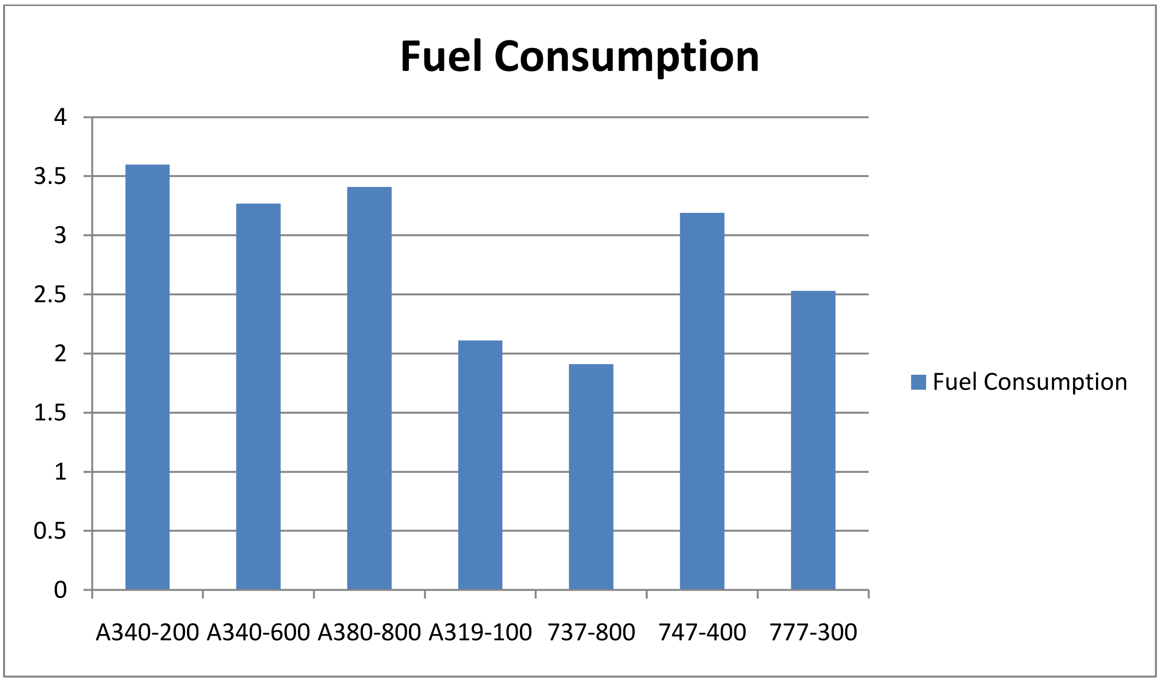

Fig 5.2 Fuel consumption of turbofan aircraft in l/100pkm

5.2 Propeller aircraft

The concept of Breguet range equation of propeller aircraft is similar to the Breguet range equation of turbofan and turbojet.

$$R = B_P \cdot \ln\left(\frac{M_{initial}}{M_{initial} - M_{Fuel}}\right) \tag{5.10}$$

$$B_P = \frac{E \cdot \eta_P}{c_P \cdot g} \tag{5.11}$$

Fuel consumption of propeller aircraft with E_{max}

The factor k_e is estimated as 11.07 according to Raymer (**Scholz 2011**). A value of 6.1 is taken for the relative wetted area, S_{wet}/S_w. E_{max} is then calculated and tabulated in Table 5.4. The values of wing aspect ratio of aircraft are taken from **Jane's 2001**.

Table 5.4 The estimation of E_{max} of propeller aircraft

Aircraft type	Factor, k_e	Relative Wetted Area, S_{wet}/S_w	Wing Aspect Ratio, AR	Maximum lift to drag ratio, E_{max}
ATR 72-500	11.07	6.1	12.0	15.53
ATR 42-500	11.07	6.1	11.1	14.93
DHC-8 Dash 8 Q-400	11.07	6.1	12.8	16.04
DHC-8 Dash 8 Q-300	11.07	6.1	13.4	16.41
DHC-8 Dash 8 Q-200	11.07	6.1	12.4	15.78
An-140	11.07	6.1	12.0*	15.53
XAC MA60	11.07	6.1	11.4	15.13
IL-114	11.07	6.1	11.0	14.87

(*) estimated value

To calculate the Breguet factor of propeller aircraft, we need the values of the propeller's specific fuel consumption, the lift to drag ratio and the propeller's efficiency. The propeller's efficiency is estimated as 0.85 for all the propeller aircraft. The propeller's specific fuel consumption is taken from **Jet 2005**.

Table 5.5 Breguet Factor, B Propeller Aircraft with E_{max}

Aircraft Type	Engine Model	Propeller Specific Fuel Consumption, c_p (kg/W/s)	Maximum lift to drag ratio, E_{max}	Propeller's Efficiency, η_P	Breguet Factor, B_P (m)
ATR 72-500	PW127F	7.80E-08	15.53	0.85*	17251496
ATR 42-500	PW127E	7.80E-08	14.93	0.85*	16584987
DHC-8 Dash 8 Q-400	PW150A	8.20E-08	16.04	0.85*	16948858
DHC-8 Dash 8 Q-300	PW123E	8.20E-08	16.41	0.85*	17339822
DHC-8 Dash 8 Q-200	PW123C	8.20E-08	15.78	0.85*	16674125
An-140	TV7-117VMA-SBM1	8.50E-08	15.53	0.85*	15830785
XAC MA60	PW127J	7.80E-08	15.13	0.85*	16807156
IL-114	TV7-117	8.40E-08	14.87	0.85*	15338454

(*) estimated values

Now we calculate the mass of fuel, M_{Fuel} with maximum payload by converting the equation below.

$$\frac{R}{B_P} = \ln\left(\frac{M_{initial}}{M_{initial} - M_{Fuel}}\right)$$

$$e^{\frac{R}{B_P}} = \frac{M_{initial}}{M_{initial} - M_{Fuel}} \qquad (5.12)$$

$$K_p = e^{\frac{R}{B_p}} \tag{5.13}$$

$$K_p\left(M_{initial} - M_{Fuel}\right) = M_{initial} \tag{5.14}$$

$$M_{initial}\left(K_p - 1\right) = K_p \cdot M_{Fuel} \tag{5.15}$$

$$M_{Fuel} = M_{initial}\frac{\left(K_p - 1\right)}{K_p} \tag{5.16}$$

$$\frac{Fuel\ Consumption}{100PKM} = \frac{M_{Fuel}}{\rho_F \cdot n_{PAX} \cdot R} \cdot 100 \tag{5.17}$$

(5.9)

Table 5.6 Fuel consumption per 100 pkm of propeller aircraft with E_{max}

Aircraft Type	Breguet Factor, B_P (m)	$M_{initial}$ = M_{MTOW} (kg)	Design Range (km)	PAX (max)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
ATR 72-500	17251496	22000	1322	68	1592	2.26
ATR 42-500	16584987	18600	1555	48	1643	2.79
DHC-8 Dash 8 Q-400	16948858	29256	2518	70	3727	2.69
DHC-8 Dash 8 Q-300	17339822	18642	1557	50	1546	3.17
DHC-8 Dash 8 Q-200	16674125	16465	1713	37	1587	3.17
An-140	15830785	19150	2100	52	2371	2.72
XAC MA60	16807156	21800	1600	56	1954	2.76
IL-114	15338454	23500	1000	64	1464	2.90

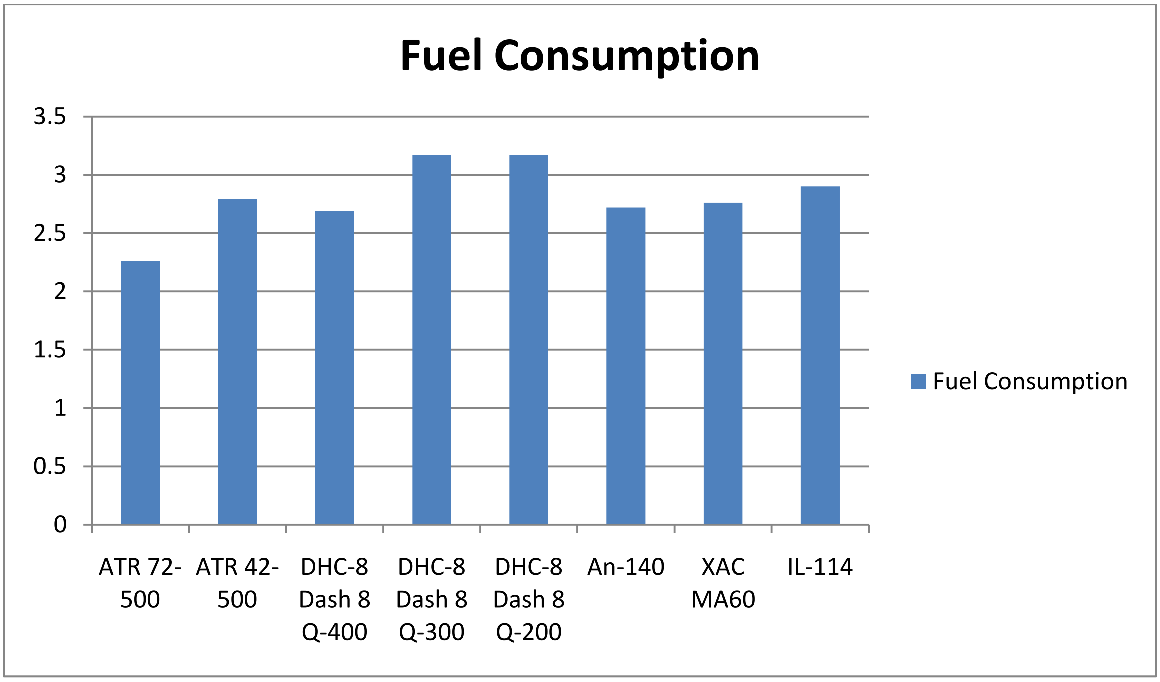

Fig 5.3 Fuel consumption of propeller aircraft in l/100pkm

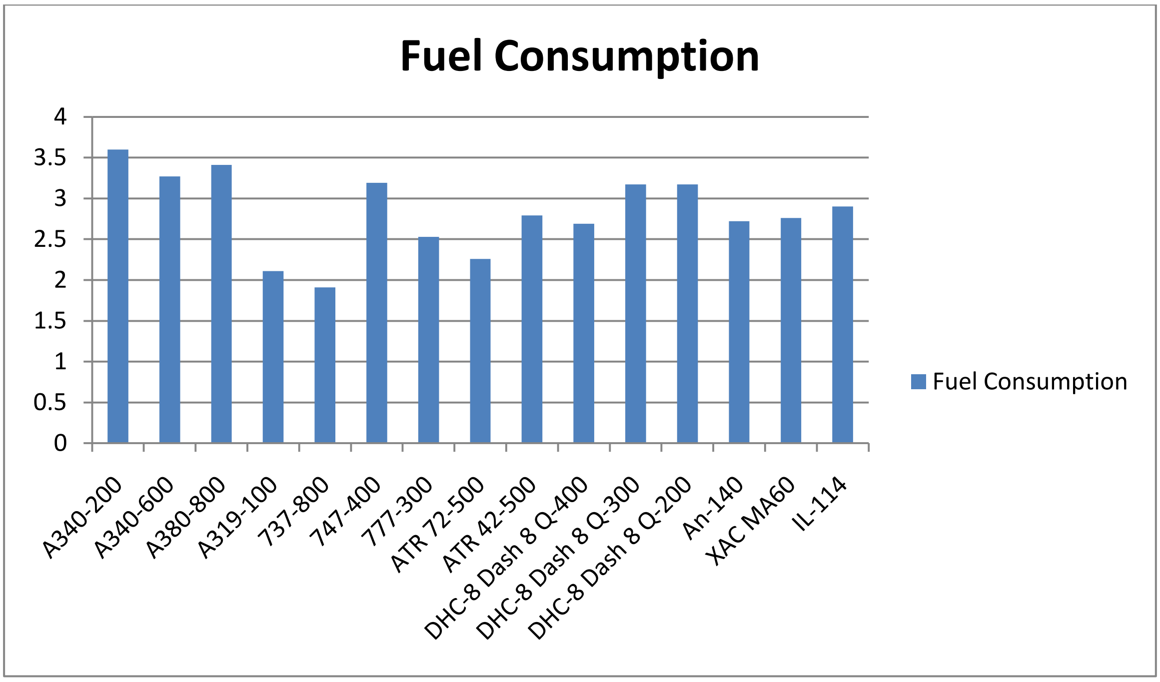

Fig 5.4 Fuel consumption of turbofan aircraft and propeller aircraft in l/100pkm

5.3 Fuel consumption with E_{max} and maximum payload for different ranges

Table 5.7 Short haul flight from Hamburg to Paris, ≈750km

Aircraft Type	B (m)	M_{MTOW} (kg)	R (km)	PAX (max)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A319-100	28902605	64000	750	124	1639	2.20
737-800	26650358	70535	750	162	1957	2.01
ATR 72-500	17251496	22000	750	68	936	2.29
ATR 42-500	16584987	18600	750	48	822	2.86
DHC-8 Dash 8 Q-400	16948858	29256	750	70	1266	3.02
DHC-8 Dash 8 Q-300	17339822	19504	750	50	826	2.75
DHC-8 Dash 8 Dash Q-200	16674125	16465	750	37	724	3.26
An-140	15830785	19150	750	52	886	2.84
XAC MA60	16807156	21800	750	56	951	2.83
IL-114	15338454	23500	750	64	1107	2.88

Table 5.8 Medium haul flight from Hamburg to Athens, ≈2027km

Aircraft Type	B (m)	M_{MTOW} (kg)	R (km)	PAX (max)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A319-100	28902605	64000	2027	124	4335	2.16
737-800	26650358	70535	2027	162	5166	1.97
777-300	29967449	263080	2027	386	17206	2.75
DHC-8 Dash 8 Q-400	16948858	29256	2027	70	3298	2.68
An-140	15887193	19150	2027	52	2294	2.72

Table 5.9 Long haul flight from Frankfurt to Kuala Lumpur, ≈10000km

Aircraft Type	B_s (m)	M_{MTOW} (kg)	R (km)	PAX (max)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A340-200	31928875	275000	10000	239	73946	3.87
A340-600	29238498	365000	10000	380	105727	3.48
A380-800	28371900	548000	10000	555	162780	3.67
747-400	28159077	362875	10000	416	108469	3.26

5.4 Fuel consumption with E_{max} and 70 % load factor for different ranges

In the case of 70 % load factor, the initial weight is not the maximum take-off weight. The take-off weight will be decreased since the number of passengers is decreased. A value of 97.5kg has been chosen for each passenger on board regardless of the length of the flight. This value is chosen to simplify the calculations.

$$M_{TO} = M_{MTOW} - PAX(70\ \%) \cdot 97.5kg \tag{5.18}$$

Table 5.10 Short haul flight from Hamburg to Paris, ≈750km with 70 % load factor

Aircraft Type	B_s (m)	M_{TO} (kg)	R (km)	PAX (70 %)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A319-100	28902605	55537	750	87	1423	2.73
737-800	26650358	59479	750	113	1651	2.43
ATR 72-500	17594089	17359	750	48	739	2.59
ATR 42-500	16812982	15324	750	34	678	3.36
DHC-8 Dash 8 Q-400	17173902	24479	750	49	1060	3.60
DHC-8 Dash 8 Q-300	17985260	16092	750	35	681	3.24
DHC-8 Dash 8 Dash Q-200	16903430	13940	750	26	613	3.95
An-140	15887193	15601	750	36	722	3.31
XAC MA60	17038670	17978	750	39	785	3.34
IL-114	15541571	19132	750	45	913	3.40

Table 5.11 Medium haul flight from Hamburg to Athens, ≈2027km with 70 % load factor

Aircraft Type	B_s (m)	M_{TO} (kg)	R (km)	PAX (70 %)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A319-100	28902605	55537	2027	87	3761	2.67
737-800	26650358	59479	2027	113	4356	2.37
777-300	29967449	236736	2027	270	15483	3.53
DHC-8 Dash 8 Q-400	17173902	24479	2027	49	2759	3.47
An-140	15887193	15601	2027	36	1869	3.17

Table 5.12 Long haul flight from Frankfurt to Kuala Lumpur, ≈10000km with 70 % load factor

Aircraft Type	B_s (m)	M_{TO} (kg)	R (km)	PAX (70 % load factor)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A340-200	31928875	258688	10000	167	69560	5.20
A340-600	29238498	339065	10000	266	98214	4.62
A380-800	28371900	510121	10000	389	151529	4.88
747-400	28159077	334483	10000	291	99982	4.29

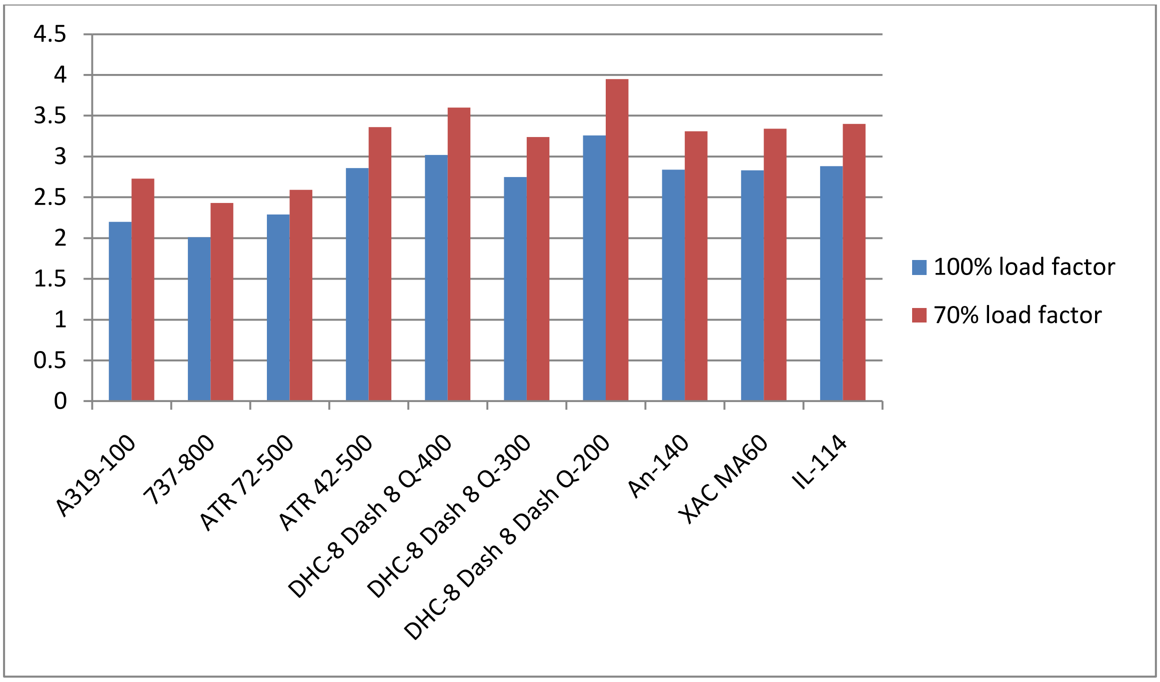

Fig 5.5 Fuel consumption of short haul flights with E_{max} in l/100pkm

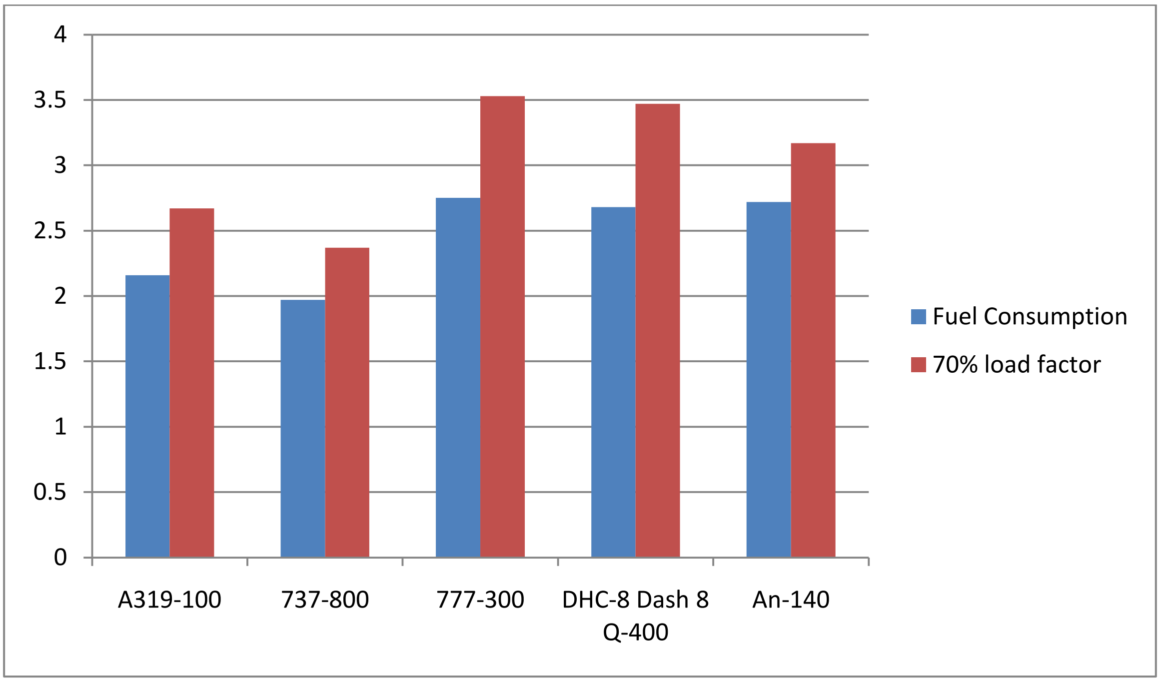

Fig 5.6 Fuel consumption of medium haul flights with E_{max} in l/100pkm

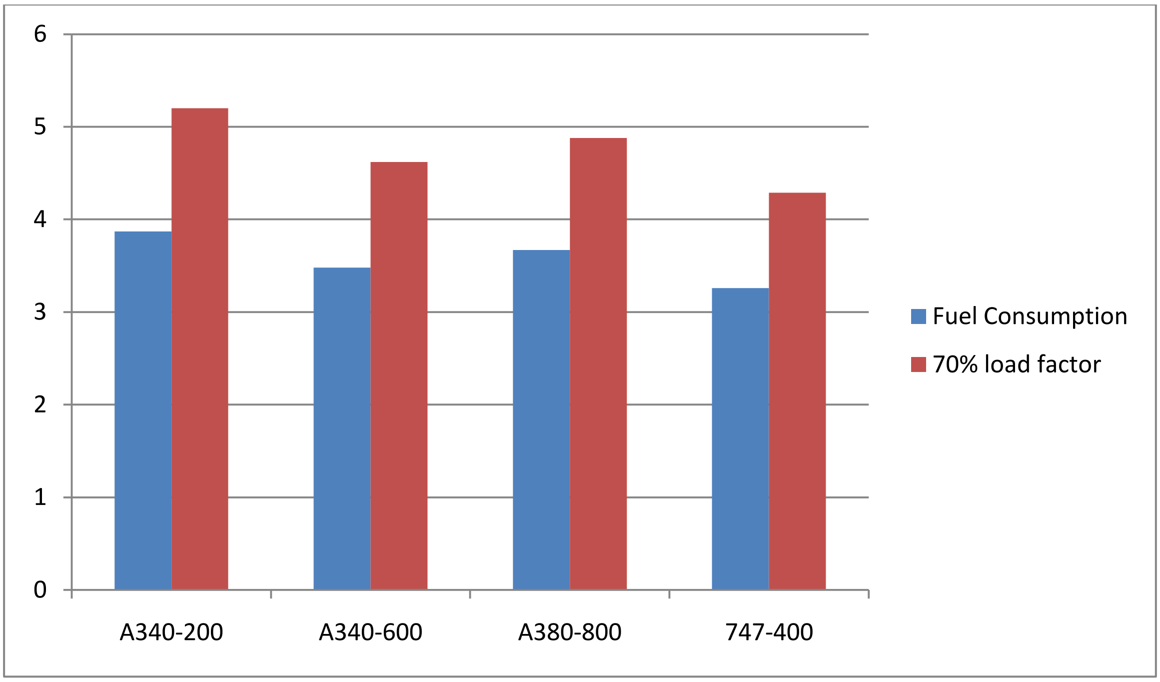

Fig 5.7 Fuel consumption of long haul flight with E_{max} in l/100pkm

5.5 Fuel consumption with estimated E

Turbofan and turbojet

Different from the calculations made above, we now estimate the lift to drag ratio by assuming that the aircraft fully consume the fuel carried on the aircraft for the design range with maximum payload. The minimum fuel weight is calculated by subtracting the maximum take-off weight with maximum payload weight and operating weight empty.

$$E = \frac{R \cdot c \cdot g}{v} \cdot \frac{1}{ln \frac{M_{initial}}{M_{end}}} \tag{5.19}$$

$$M_{Fuel} = M_{initial} - M_{end} = M_{initial} - M_{OEW} - M_{PL} \tag{5.20}$$

Table 5.13 Estimation of minimum fuel weight on turbofan and turbojet aircraft with maximum payload

	Maximum Take-off Weight (kg)	Operating Empty Weight (kg)	Maximum Payload Weight (kg)	Minimum Fuel Weight (kg)
A340-200	275000	129000	45530	100470
A340-600	365000	177000	55800	132200
A380-800	548000	275000	83000	190000
A319-100	64000	40160	16653	7187
737-800	70535	41145	20545	8845
747-400	362875	181390	61280	120205
777-300	263080	155675	68850	38555

Table 5.14 Lift to drag ratio and Breguet factor of turbofan and turbojet aircraft with maximum payload

Aircraft Type	Engine Model	Specific fuel consumption, c ((kg/s)/N)	Design range (km)	Aircraft speed, v (m/s)	M_{MTOW} (kg)	Minimum Fuel Weight (kg)	Lift to drag ratio, E	Breguet Factor (m)
A340-200	CFM56-5C2	1.54E-05	14816	237	275000	100470	20.77	32585952
A340-600	Trent 556-61	1.65E-05	13890	243	365000	132200	20.57	30886047
A380-800	Trent 900	1.59E-05	14445	252	548000	190000	21.00	33928975
A319-100	V2522-A5	1.63E-05	3357	237	64000	7187	19.01	28182160
737-800	CFM56-7B24	1.78E-05	3685	237	70535	8845	20.26	27502628
747-400	RB211-524G	1.62E-05	11260	252	362875	120205	17.65	27985172
777-300	Trent 892-17	1.58E-05	7250	246	263080	38555	28.83	45749664

Table 5.15 Estimation of fuel consumption of turbofan and turbojet aircraft with maximum payload

Aircraft Type	Range (km)	PAX (max)	Minimum Fuel Weight (kg)	Fuel Consumption (l/100PKM)
A340-200	14816	239	100470	3.55
A340-600	13890	380	132200	3.13
A380-800	14445	555	190000	2.96
A319-100	3357	124	7187	2.16
737-800	3685	162	8845	1.85
747-400	11260	416	120205	3.21
777-300	7250	386	38555	1.72

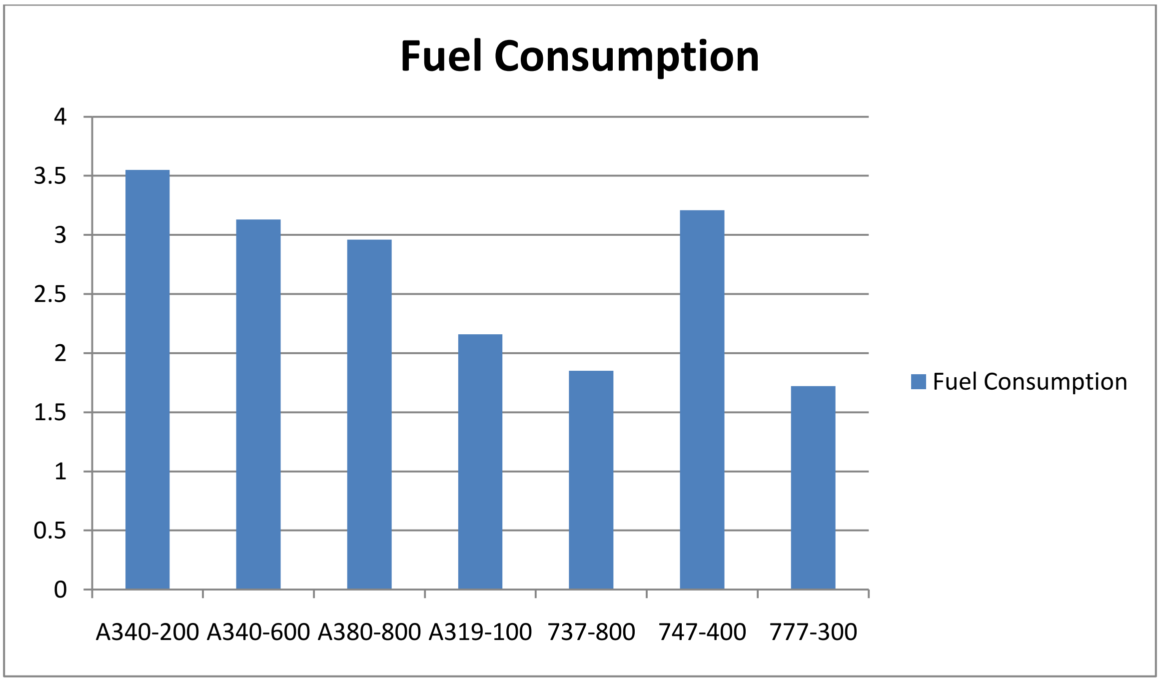

Fig 5.8 Fuel consumption of turbofan aircraft with estimated E in l/100pkm

Propeller Aircraft

$$E = \frac{R \cdot c_p \cdot g}{n_p} \cdot \frac{1}{ln \frac{M_{initial}}{M_{end}}} \tag{5.21}$$

Table 5.16 Estimation of minimum fuel weight on propeller aircraft with maximum payload

Aircraft Type	Maximum Take-off Weight (kg)	Maximum Operating Empty Weight (kg)	Maximum Payload Weight (kg)	Minimum Fuel Weight (kg)
ATR 72-500	22000	12950	7050	2000
ATR 42-500	18600	11250	5450	1900
DHC-8 Dash 8 Q-400	29256	17108	8747	3401
DHC-8 Dash 8 Q-300	19504	11791	6126	1587
DHC-8 Dash 8 Q-200	16465	10486	4211	1768
An-140	19150	11800	6000	1350
XAC MA60	21800	13700	5500	2600
IL-114	23500	15000	6500	2000

Table 5.17 Lift to drag ratio and Breguet factor of propeller aircraft with maximum payload

Aircraft Type	Engine Model	Specific fuel consumption, c ((kg/s)/N)	R (km)	Propeller's efficiency, η_P	M_{MTOW} (kg)	Minimum Fuel Weight	Lift to drag ratio, E	Breguet Factor
ATR 72-500	PW127F	7.80E-08	1322	0.85	22000	2000	12.49	13870502
ATR 42-500	PW127E	7.80E-08	1555	0.85	18600	1900	12.99	14431171
DHC-8 Dash 8 Q-400	PW150A	8.20E-08	2518	0.85	29256	3401	19.28	20375354
DHC-8 Dash 8 Q-300	PW123E	8.20E-08	1557	0.85	19504	1587	17.36	18345794
DHC-8 Dash 8 Q-200	PW123C	8.20E-08	1713	0.85	16465	1768	14.27	15080085
An-140	TV7-117VMA-SBM1	8.50E-08	900	0.85	19150	1350	12.08	12311184
XAC MA60	PW127J	7.80E-08	1600	0.85	21800	2600	11.34	12598456
IL-114	TV7-117	8.40E-08	1000	0.85	23500	2000	10.90	11242589

Table 5.18 Estimation of fuel consumption of propeller aircraft with maximum payload

Aircraft Type	R (km)	PAX (max)	Minimum Fuel Weight	Fuel Consumption (l/100PKM)
ATR 72-500	1322	68	2000	2.78
ATR 42-500	1555	48	1900	3.18
DHC-8 Dash 8 Q-400	2518	70	3401	2.41
DHC-8 Dash 8 Q-300	1557	50	1767	2.55
DHC-8 Dash 8 Q-200	1713	37	1768	3.49
An-140	900	52	1350	3.61
XAC MA60	1600	56	2600	3.63
IL-114	1000	64	2000	3.91

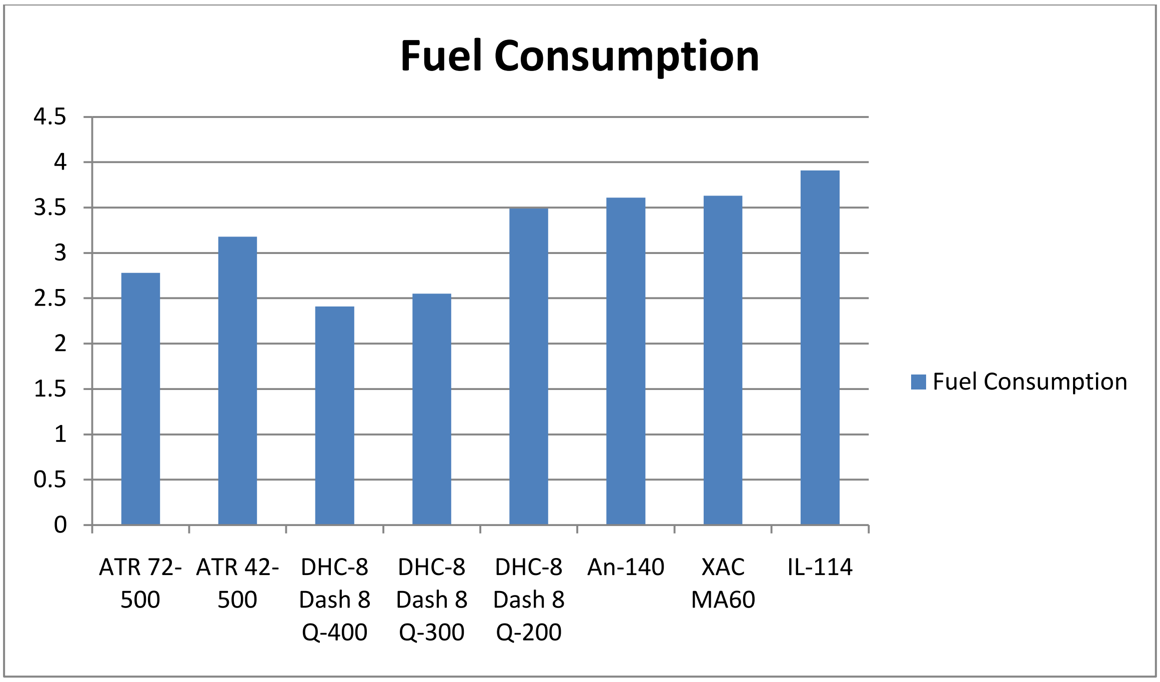

Fig 5.9 Fuel consumption of propeller aircraft with estimated E in l/100pkm

5.6 Fuel consumption with estimated E and maximum payload for different ranges

Table 5.19 Estimation of fuel consumption of short haul flight from Hamburg to Paris, ≈750km

Aircraft Type	B (m)	M_{MTOW} (kg)	R (km)	PAX (max)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A319-100	28182160	64000	750	124	1681	2.26
737-800	27502628	70535	750	162	1898	1.95
ATR 72-500	13870502	22000	750	68	1158	2.84
ATR 42-500	14431171	18600	750	48	942	3.27
DHC-8 Dash 8 Q-400	20375354	29256	750	70	1057	2.52
DHC-8 Dash 8 Q-300	18345794	18642	750	50	781	2.60
DHC-8 Dash 8 Dash Q-200	15080085	16465	750	37	799	3.60
An-140	12311184	19150	750	52	1132	3.63
XAC MA60	12598456	21800	750	56	1260	3.75
IL-114	11242589	23500	750	64	1517	3.95

Table 5.20 Estimation of fuel consumption of medium haul flight from Hamburg to Athens, ≈2027km

Aircraft Type	B (m)	M_{MTOW} (kg)	R (km)	PAX (max)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A319-100	28182160	64000	2027	124	4442	2.21
737-800	27502628	70535	2027	162	5012	1.91
777-300	45749664	263080	2027	386	11402	1.82
DHC-8 Dash 8 Q-400	20375354	29256	2027	70	2770	2.44
An-140	12311184	19150	2027	52	2907	3.45

Table 5.21 Estimation of fuel consumption of long haul flight from Frankfurt to Kuala Lumpur, ≈10000km

Aircraft Type	B (m)	M_{MTOW} (kg)	R (km)	PAX (max)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A340-200	32585952	275000	10000	239	72672	3.80
A340-600	30886047	365000	10000	380	100953	3.32
A380-800	33928975	548000	10000	555	139888	3.15
747-400	27985172	362875	10000	416	109029	3.28

5.7 Fuel consumption with estimated E and 70 % load factor for different ranges

Table 5.22 Short haul flight from Hamburg to Paris, ≈750km with 70 % load factor

Aircraft Type	B (m)	M_{TO} (kg)	R (km)	PAX (70 % load factor)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A319-100	28182160	55537	750	87	1458	2.79
737-800	27502628	59479	750	113	1600	2.36
ATR 72-500	13870502	17359	750	48	914	3.17
ATR 42-500	14431171	15324	750	34	776	3.80
DHC-8 Dash 8 Q-400	20375354	24479	750	49	885	3.01
DHC-8 Dash 8 Q-300	18345794	16092	750	35	645	3.07
DHC-8 Dash 8 Dash Q-200	15080085	13940	750	26	676	4.34
An-140	12311184	15601	750	36	922	4.27
XAC MA60	12598456	17978	750	39	1039	4.44
IL-114	11242589	19132	750	45	1235	4.57

Table 5.23 Medium haul flight from Hamburg to Athens, ≈2027km with 70 % load factor

Aircraft Type	B (m)	M_{TO} (kg)	R (km)	PAX (70 % load factor)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A319-100	28182160	55537	2027	87	3854	2.73
737-800	27502628	59479	2027	113	4226	2.31
777-300	45749664	236736	2027	270	10260	2.34
DHC-8 Dash 8 Q-400	20375354	24479	2027	49	2318	2.92
An-140	12311184	15601	2027	36	2368	4.06

Table 5.24 Long haul flight from Frankfurt to Kuala Lumpur, ≈10000km with 70 % load factor

Aircraft Type	B (m)	M_{TO} (kg)	R (km)	PAX (70 % load factor)	M_{Fuel} (kg)	Fuel Consumption (l/100PKM)
A340-200	32585952	258688	10000	167	68361	5.12
A340-600	30886047	339065	10000	266	93780	4.41
A380-800	33928975	510121	10000	389	130219	4.18
747-400	27985172	334483	10000	291	100499	4.32

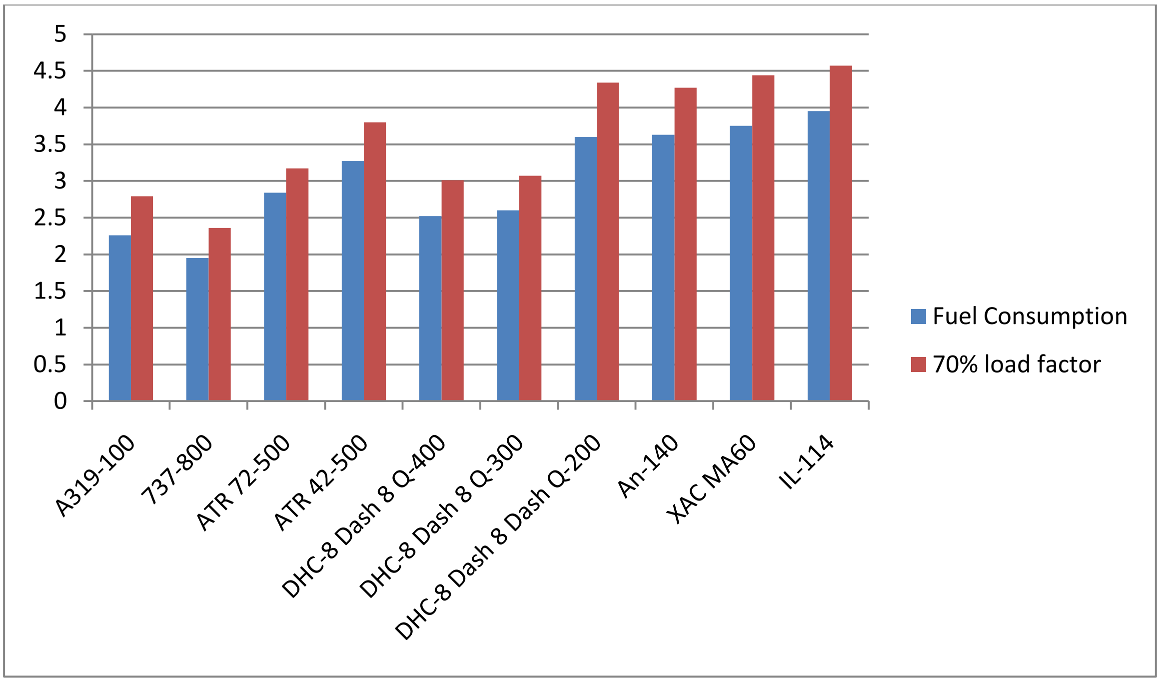

Fig 5.10 Fuel consumption of short haul flights with estimated E in l/100pkm

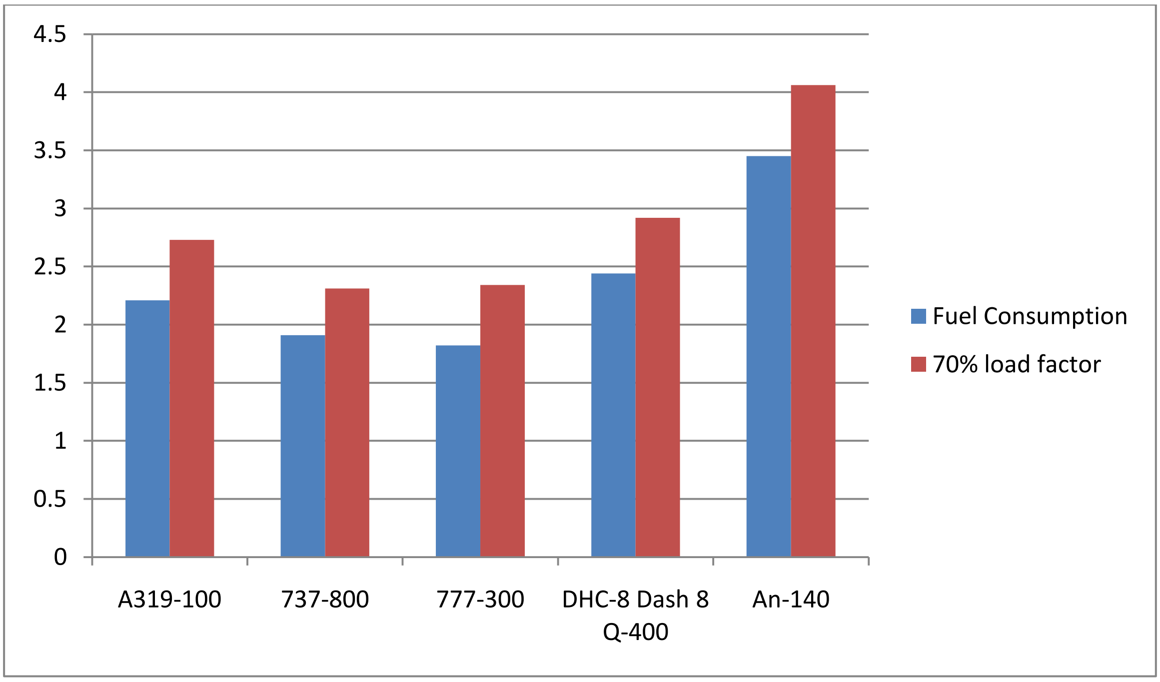

Fig 5.11 Fuel consumption of medium haul flights with estimated E in l/100pkm

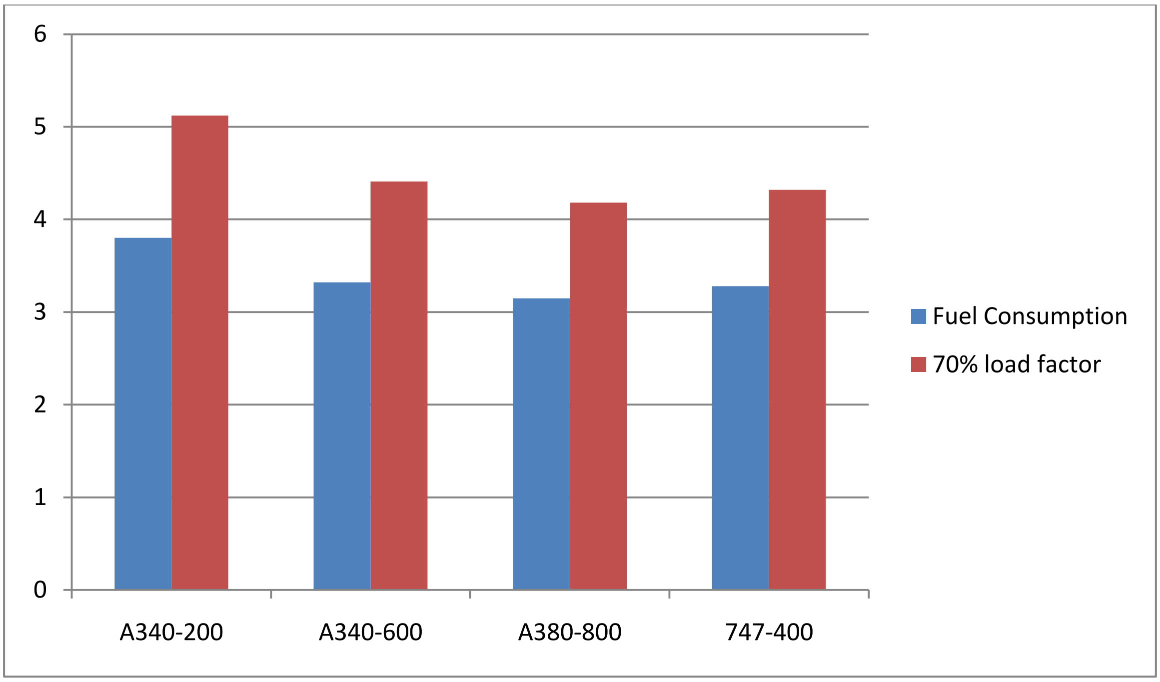

Fig 5.12 Fuel consumption of long haul flights with estimated E in l/100pkm

6 Life cycle assessment (LCA)

LCA is a method used to quantitatively assess a product's impacts on the environment throughout its total life cycle. The life cycle of a product includes manufacture, raw materials extraction, distribution, repair and maintenance, infrastructure, disposal and recycling etc. LCA can be used to ensure that environmental impacts are considered in design and implementation decisions, identify which part of the cycle has high potential in damaging the environment.

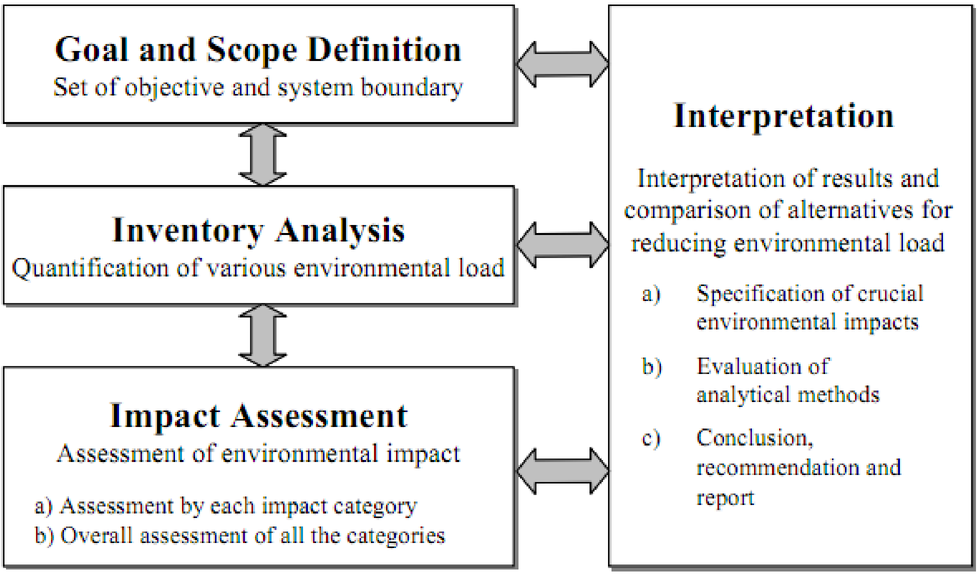

Fig 6.1 The process of LCA standardized by ISO 14040's (**Kato 2005**)

6.1 LCA of Air Transport

<u>Manufacture of aircraft</u>

There are basically three types of commercial aircraft, which are designed for specific travel distances and passenger loads will be discussed, which are small, medium and large aircraft. Small aircraft (Embraer 145), medium aircraft (Boeing 737, Airbus 300s) and large aircraft (Boeing 747) are used for short, medium and long haul respectively. The manufacture of an aircraft is divided into two categories, manufacture of the aircraft body and manufacture of the aircraft engine (**Chester 2008**).

Table 6.1 Energy consumption and emissions of aircraft engines manufacturing

	Energy	GHG	SO2	CO	NOx	VOC	PM
Small aircraft	63	5.1	13	51	11	8.4	3.1
Medium aircraft	213	17	45	171	38	28	11
Large aircraft	775	63	164	625	137	103	38
Units	*TJ/plane*	*mt/plane*	*mt/plane*	*mt/plane*	*mt/plane*	*mt/plane*	*mt/plane*
Small aircraft engine	7	592	1.7	5	1.3	0.8	0.4
Medium aircraft engine	14	1140	3.2	10	2.5	1.5	0.7
Large aircraft engine	27	2192	6.2	19	4.9	2.8	1.4
Units	*TJ/eng.*	*mt/eng.*	*mt/eng.*	*mt/eng.*	*mt/eng.*	*mt/eng.*	*mt/eng.*

Operation of aircraft

Operation of aircraft includes all the processes from start-up, taxi out, take off, climb out, cruise, approach, taxi in. Evaluations during LTO and cruise are made differently due to different engine performance; hence different rate of emissions will be produced. The emissions during the stationary phase at the gate are also not to be neglected. Auxiliary power units of aircraft are still running during this phase to provide electricity and hydraulic pressure to some components of the aircraft.

Table 6.2 Energy consumption and emissions of small aircraft during operation

	Energy	GHG	SO2	CO	NOx	VOC	PM
APU operation	70	4645	4.3	28	20	2.6	-
Startup	-	-	-	-	-	69	-
Taxi out	884	58793	26	315	74	43	2.9
Take off	230	15302	6.7	4	103	1.2	1.3
Climb out	606	40302	17.6	10	232	3.2	3.1
Approach	411	27365	11.9	26	70	5.1	1.9
Taxi in	325	21629	9.4	116	27	15.9	1.1
Units	*TJ/LTO*	*mt/LTO*	*mt/LTO*	*mt/LTO*	*mt/LTO*	*mt/LTO*	*mt/LTO*
Cruise	49.07	3.29	1.06	1.43	8.07	0.19	0.06
Units	*MJ/VKT*	*kg/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*

Table 6.3 Energy consumption and emissions of medium aircraft during operation

	Energy	GHG	SO2	CO	NOx	VOC	PM
APU operation	105	6977	2.5	45	12	2.6	-
Startup	-	-	-	-	-	47	-
Taxi out	756	50302	21.9	535	65	33.6	3.9
Take off	212	14120	6.2	4	82	0.2	1.0
Climb out	560	37264	16.3	11	190	0.5	2.2
Approach	376	25006	10.9	29	68	0.6	1.6
Taxi in	278	18552	8.1	197	24	12.4	1.4
Units	*TJ/LTO*	*mt/LTO*	*mt/LTO*	*mt/LTO*	*mt/LTO*	*mt/LTO*	*mt/LTO*
Cruise	138.51	9.32	2.98	5.16	32.30	0.31	0.12
Units	*MJ/VKT*	*kg/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*

Table 6.4 Energy consumption and emissions of large aircraft during operation

	Energy	GHG	SO2	CO	NOx	VOC	PM
APU operation	146	9728	0.7	12	2	1.1	-
Startup			-	-	-	5	-
Taxi out	200	13336	5.8	48	22	2.6	1.3
Take off	88	5877	2.6	0	63	0.2	1.0
Climb out	225	14984	6.5	1	121	0.6	2.6
Approach	135	8953	3.9	2	34	0.7	0.9
Taxi in	74	4910	2.1	18	8	0.9	0.5
Units	*TJ/LTO*	*mt/LTO*	*mt/LTO*	*mt/LTO*	*mt/LTO*	*mt/LTO*	*mt/LTO*
Cruise	486.34	32.67	10.37	10.00	128.57	2.55	0.43
Units	*MJ/VKT*	*kg/VKT*	*kg/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*

Maintenance of aircraft

Aircraft need to undergo maintenance after a certain flight hours to ensure safety during flights. Maintenance of an aircraft consists of lubricant and fuel changes, battery repair and replacement, chemical milling and application, parts cleaning, metal finishing, coating application, de-painting and painting. The costs of all types of maintenance are assumed to be averagely distributed besides painting, which costs around 30 % more than other type of maintenance (**Chester 2008**). Insurance of an aircraft consists of pilot and flight crew benefits and vehicles' casualty and liability. The costs of insurance are determined by the airline's financial status, aircraft type and aircraft total flight hours.

Table 6.5 Emissions of aircraft maintenance

	Energy	GHG	SO2	CO	NOx	VOC	PM
Aircraft maintenance	25	1762	3.1	7.9	2.1	2.3	0.6
Units	*TJ/$M*	*mt/$M*	*mt/$M*	*mt/$M*	*mt/$M*	*mt/$M*	*mt/$M*
Engine Maintenance	5.1	411	1160	3500	912	527	256
Crew health and benefits	1.0	84	207	934	233	173	44
Aircraft liability	1.0	84	207	934	233	173	44
Units	*TJ/$M*	*mt/$M*	*kg/$M*	*kg/$M*	*kg/$M*	*kg/$M*	*kg/$M*

Different from fuel used for other vehicles like cars and trucks, jet fuel is used in aircraft. Jet fuel is a mixture of different hydrocarbons. The most widely used type of jet fuel is Jet A-1, which is suitable for most turbine engine aircraft. However, during the production of jet fuel, the emissions emitted into the atmosphere contribute to part of the emissions of aircraft in the entire life cycle.

Table 6.6 Emissions of aircraft fuel production

	Energy	GHG	SO2	CO	NOx	VOC	PM
Fuel production	25	2200	4220	6020	2460	2730	436
Units	*TJ/$M*	*mt/$M*	*kg/$M*	*kg/$M*	*kg/$M*	*kg/$M*	*kg/$M*

Infrastructure of air transport

The main infrastructure built for aircraft is airport. Airports serve 2 basic purposes, which are passenger facilities and aircraft facilities. Examples for passenger facilities are shops, gates, check-in desks etc. Examples for aircraft facilities are runway and taxiway etc. The size of airports is built according to the amount of passengers and the aircraft type. The runways of an airport are designed to accommodate the most demanding aircraft. Heavier, larger aircraft need longer and wider runways to perform landings and take-offs. Besides that, materials used for the runways are higher graded to be able to sustain higher impact on the runways during landings. Components like lighting, de-icing fluid production and ground support equipment are included to operate an airport. During the production of the de-icing fluid, GHG and CAP are emitted. Moreover, ground support services contribute to a significant amount of emissions at airports. Various kind of GSE vehicles are used in airport. Typical examples of GSE vehicles are fuel truck, ground power unit, bus, and aircraft pushback tractor. Insurance of airports consists of non-flight crew personnel and non-vehicle casualty and liability.

Emissions of Air Transport in the entire life cycle

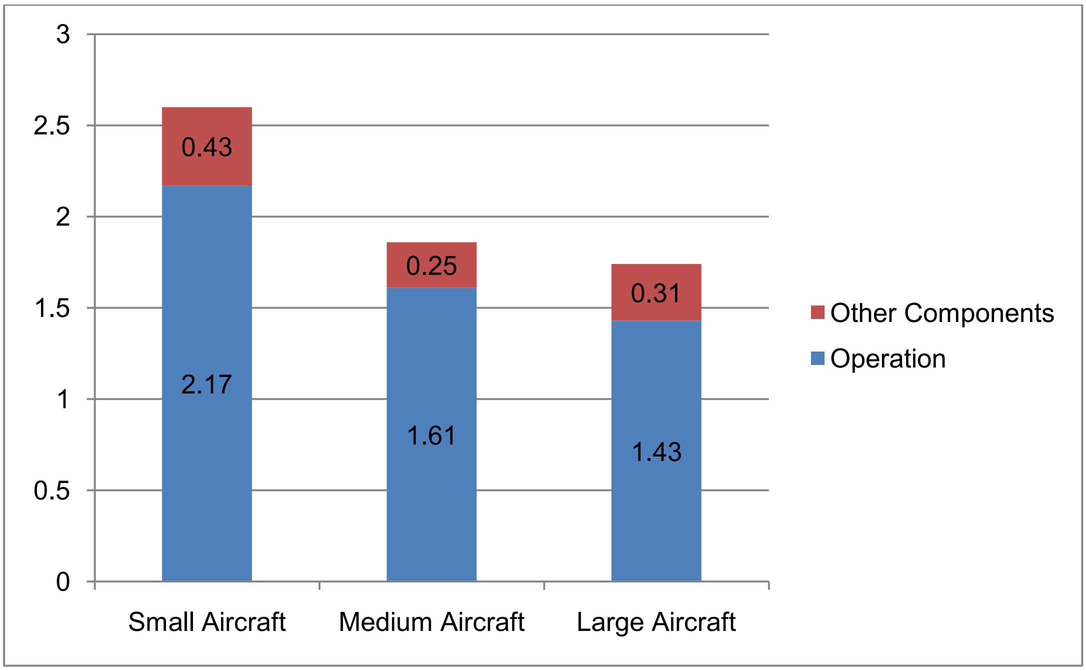

Fig 6.2 Energy consumption of air transport in the entire life cycle in MJ/pkm

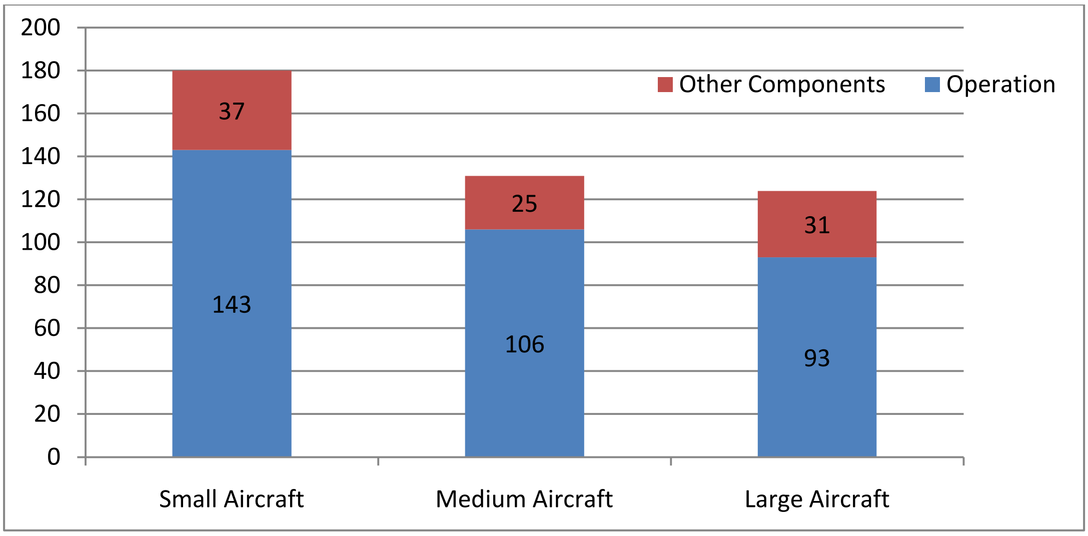

Fig 6.3 GHG Emissions of air transport in the entire life cycle in g/pkm

In the entire life cycle, operation of aircraft dominates the total GHG emitted during the whole life cycle. The percentage of GHG emitted during operation of aircraft is as much as 80 % in all sizes of aircraft as shown in Fig 6.3. The GHG emissions of fuel products are approximately 10 % for all type of aircraft (**Chester 2008**). The rest of the GHG emissions are emitted during activities like aircraft maintenance, construction of airports and airport facilities etc. It is to be noted that all commercial carry other payload besides passengers like freight and mail. Larger aircraft are usually not 100 % dedicated to passengers but carry a significant amount of freight and mail.

6.2 LCA of road transport

Manufacture of automobiles and urban buses

Automobiles can be divided into 3 categories, which are sedan, sport utility and pickup. A sedan car is a typical car with 3 separate compartments for engine, passengers and cargo. Sedan is among the categories, the lightest and most fuel efficiency car. Examples for sedan are Toyota Camry, Toyota Corolla and Honda Accord. In comparison, a sport utility car/vehicle (SUV) is known for its off-road ability. A SUV has poor fuel efficiency in comparison to sedan and is the heaviest among the categories. For examples, Mercedes M-class and Chevrolet Trailblazer are among the popular SUV. A pickup is a utility vehicle which has an open area for cargo and loads. Examples for this category of automobiles are Nissan Frontier and Ford F-series. All these 3 categories will be discussed in terms of their fuel efficiency and emission factor later on. Besides automobiles, buses will also be included in our discussion. In this paper, a 40-feet long bus will be chosen as representative. To assess the life cycle of all the on road vehicles, a few parameters have been set. The parameters are shown in Table 6.7.

Table 6.7 Parameters of automobiles and urban buses

	Weight (kg)	Lifetime (Years)	PAX
Sedan	3200	16.9	1.58
SUV	4600	15.5	1.74
Pickup	5200	15.5	1.45
Bus	25000	12	10.5

Automobiles manufacturing is a complex process and is one of the world's most important economic sectors. To estimate the average production costs for each of the categories stated in Table 6.7, the price which the manufacturers sell to the car dealers is used. Energy used and the pollutants produced during the manufacturing processed are being tabulated in Table 6.8.

Table 6.8 Energy consumption and emissions of automobiles and urban buses during manufacture

	Energy	GHG	SO2	CO	NOx	VOC	Pb	PM
Sedan	121	10	23	124	23	23	32	7
SUV	103	9	20	105	20	21	27	6
Pickup	146	12	28	149	28	29	39	8
Bus	114	129	1.6	302	392	0.3	87	162
Units	*GJ/veh.*	*mt/veh.*	*mt/veh.*	*mt/veh.*	*mt/veh.*	*mt/veh.*	*mt/veh.*	*mt/veh.*

Operation of automobiles and urban buses

The energy consumed and pollutants produced during different phases of driving are running, start-up, brake wear, tire wear and evaporative losses. Pollutants are including CO2, CO, NOx etc under various conditions. However, it is to be noted that in different temperature, the pollutants emitted by vehicles vary. For example, during winter, more emissions are recorded due to more energy needed hence more combustions for process like start-up. Therefore, two scenarios have been done and the average amount of each of the pollutants is taken. The pollutants are recorded in the Table 6.9 to Table 6.12.

Table 6.9 Energy consumption and emissions of sedan during operation

	Energy	GHG	SO2	CO	NOx	VOC	PM
Running	3.0	228	0.07	6.8	0.53	0.19	0.07
Start-up	-	-	-	4.35	0.12	0.25	-
Brake wear	-	-	-	-	-	-	0.01
Tire wear	-	-	-	-	-	-	0.01
Evaporative	-	-	-	-	-	0.37	-
Units	*MJ/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*

Table 6.10 Energy consumption and emissions of SUV during operation

	Energy	GHG	SO2	CO	NOx	VOC	PM
Running	4.84	297.52	0.02	7.45	0.50	0.25	0.07
Start-up	-	-	-	5.59	0.12	0.31	-
Brake wear	-	-	-	-	-	-	0.01
Tire wear	-	-	-	-	-	-	0.01
Evaporative	-	-	-	-	-	0.31	-
Units	*MJ/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*

Table 6.11 Energy consumption and emissions of pickup during operation

	Energy	GHG	SO2	CO	NOx	VOC	PM
Running	5.16	296.27	0.02	7.45	0.68	0.25	0.07
Start-up	-	-	-	6.21	0.12	0.31	-
Brake wear	-	-	-	-	-	-	0.01
Tire wear	-	-	-	-	-	-	0.01
Evaporative	-	-	-	-	-	0.31	-
Units	*MJ/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*

Table 6.12 Energy consumption and emissions of urban buses during operation

	Energy	GHG	SO2	CO	NOx	VOC	PM
Running	13.66	1473.91	0.46	2.48	11.06	0.37	0.02
Start-up	-	-	-	-	-	-	-
Brake wear	-	-	-	-	-	-	0.01
Tire wear	-	-	-	-	-	-	0.01
Evaporative	-	-	-	-	-	0	-
Units	*MJ/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*
Idling	65	4.614	-	80	121	8.2	2.8
Units	*MJ/hr*	*g/hr*	-	*g/hr*	*g/hr*	*g/hr*	*g/hr*

Maintenance of automobiles and urban buses

Automobiles and buses maintenance is basically split into two categories, which are vehicle maintenance and tire maintenance. Tires, which carry the vehicles, have to be changed quite often and different tires are used in different seasons. Moreover different tires are used in different categories of automobiles and buses. Therefore, maintenance costs and lifetime of tires of different type of vehicles are to be calculated separately. Other equipment, which are used to maintain the performance of the vehicles, like choke cleaners and engine degreasers are to be included into calculations of the total pollutant emissions. Cars and buses insurance indirectly cause more pollutants emitted to the atmosphere by setting up facilities such as offices.

Table 6.13 Energy consumption and emissions of automobiles and urban buses during maintenance

	Energy	GHG	SO2	CO	NOx	VOC	PM
Vehicle maintenance	5.2	423	1090	4340	994	1260	214
Tire maintenance	15.1	1090	1960	15200	2030	2600	1140
Vehicle Insurances	1.0	84	207	934	233	173	44
Units	*TJ/$M*	*mt/$M*	*kg/$M*	*kg/$M*	*kg/$M*	*kg/$M*	*kg/$M*

Infrastructure of road transport

Without infrastructure, automobiles and buses are not able to function. Roadway is among the most important infrastructures for on-road vehicles. Different materials are used for different kind of road constructions. For example, highways need higher graded materials compared to normal roadway. Maintenance jobs have to be done on these infrastructures to keep them in a good condition. The frequency for roadway maintenance does not depend on the number of vehicles but the weight and the impact on the roadway itself. In general, roadway damages are caused by heavy vehicles such as buses and trucks. In other words, the heavier the vehicle is, the more damage it does to the roadway. For instance, a SUV does four to seven times more damage than a sedan. Comparatively, buses and heavy-loaded trucks do approximately 3500 times more damages to a roadway compared to a sedan. Other roadway facilities are like parking lots, roadway lightings etc. Although all these infrastructures are not mega structures like highway, their emissions of pollutants are not to be neglected.

Table 6.14 Energy consumption and emissions of road transport infrastructure

	Energy	**GHG**	**SO2**	**CO**	**NOx**	**VOC**	**Pb**	**PM**
Construction	63	4	8	13	25	45	0.4	85
Maintenance	1.3	65	18	236	1.0	-	10	309
Parking	42	2.6	27	13	32	36	85	0.6
Garage parking	8	53	222	380	465	36	84	0
Units	*MJ/ft^2*	*g/ft^2*	*g/ft^2*	*g/ft^2*	*g/ft^2*	*g/ft^2*	*g/ft^2*	*g/ft^2*

Table 6.15 Energy consumption and emissions of road transport fuel product

	Energy	**GHG**	**SO2**	**CO**	**NOx**	**VOC**	**PM**
Gasoline	19	1.7	3.2	4.6	1.9	2.1	0.33
Diesel	18	1.6	3.0	4.3	1.8	2.0	0.31
Units	*MJ/gal*	*kg/gal*	*g/gal*	*g/gal*	*g/gal*	*g/gal*	*g/gal*

Energy consumption and emissions of road transport in the entire life cycle

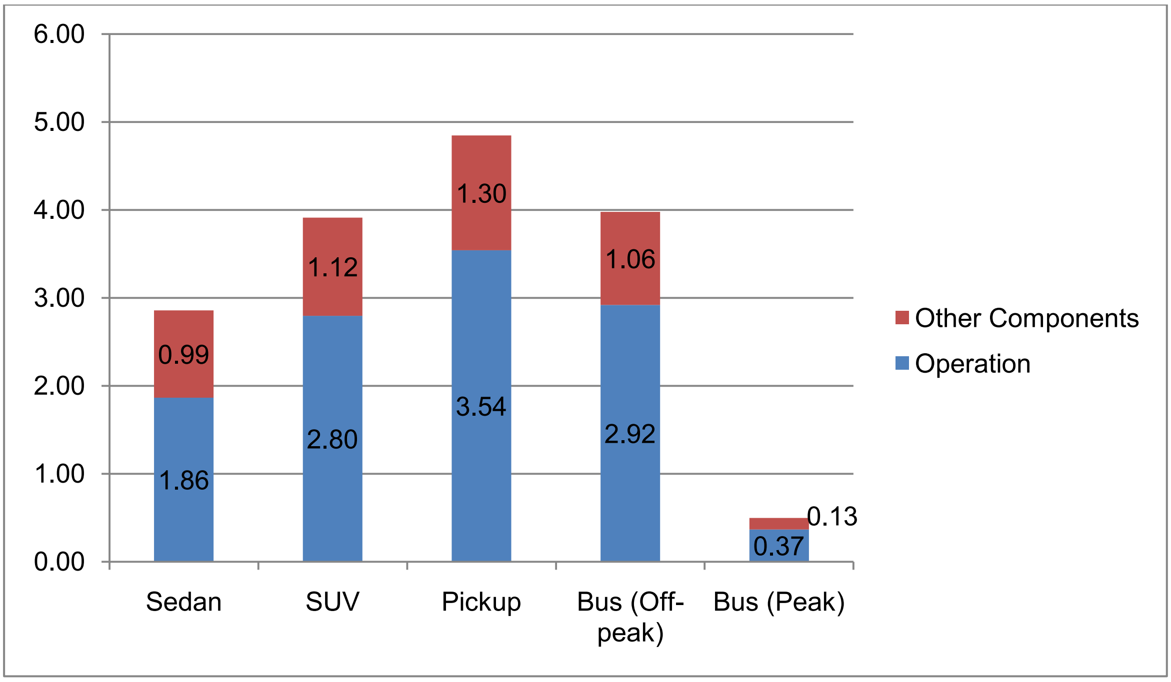

Fig 6.4 Energy consumption of road transport in the entire life cycle in MJ/pkm

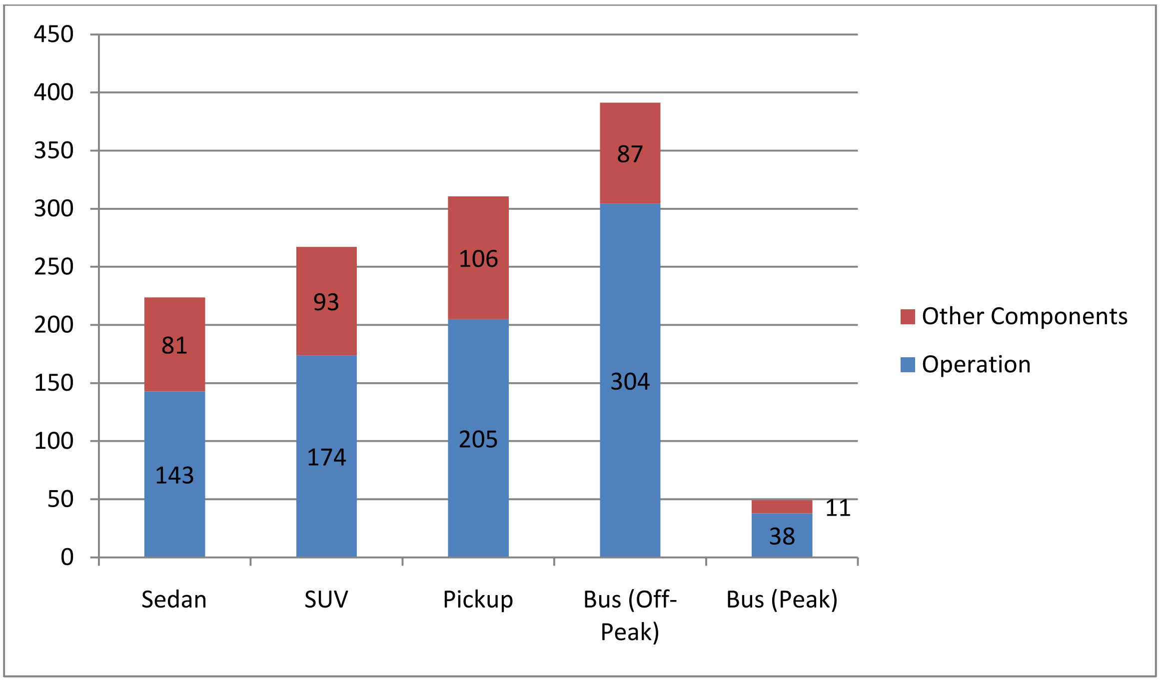

Fig 6.5 GHG emissions of road transport in the entire life cycle in g/pkm

The emissions of GHG of automobiles are more evenly distributed in compared to the emissions of GHG of aircraft. The percentage of operational GHG emissions to the total GHG emissions of sedan, SUV, pickup, bus (off-peak) and bus (peak) is 64 %, 65 %, 66 %, 78 % and 77 % respectively as shown in Fig 6.5. The maintenance of on road vehicles also releases a significant amount of GHG to the atmosphere. Besides that, roadway construction and operation is one of the most significant contributors to the GHG inventory, especially for automobiles. The main source of the GHG emissions is due the material production and transportation from production site to construction site. Parking lots raise the amount of GHG emitted during the life cycle of automobiles. However the parking requirements for buses are negligible. Emissions of fuel products burden pickup the most due to its low fuel efficiency. Additionally, manufacture of both the automobiles and buses, accounts for roughly 10 % of the total GHG emissions in the life cycle. There is a stark difference between buses during peak and off-peak due to the huge difference in load factor during off peak and peak hours.

6.3 LCA of Rail Transport

Manufacture of rail transport

Rail transit systems are basically divided into 3 categories, which are light rail transit, high speed rail and long distance rail. Most of the railway systems are powered by electricity but some of them are powered directly by diesel fuel. Light rail transits carry and transport passengers within the city. On the other hand, long distance rails and high speed rails connect passengers and loads from one city to another.

A lifespan of train is around 30 years. The emissions produced during manufacture of trains are based on the weight of the trains. The weight of the trains includes the loads that the trains carry especially goods and passengers. Number of passengers of each train is 54, 146 and 263 for LRT, long distance trains and high speed trains respectively.

Table 6.16 Energy consumption and emissions during manufacture

	Energy	**GHG**	**SO2**	**CO**	**NOx**	**VOC**	**Lead**	**PM**
LRT	7	373	1.9	2.8	1.1	0.3	6.7	0.7
Long Distance Train	30	1841	6.9	2.1	3.8	1.0	8.0	1.9
High Speed Train	44	2127	10	8.4	5.6	1.7	25	3.1
Units	*TJ/Train*	*mt/train*	*mt/train*	*mt/train*	*mt/train*	*mt/train*	*mt/train*	*mt/train*

Operation of rail transport

The operational energy consumption and emissions are disaggregated into three categories, which are propulsion, idling and auxiliaries. The energy consumption and emissions of propulsion mode are calculated when the trains are moving and accelerating. The trains are in idling mode when they reach their destinations or the end of their lines. Another component to consider during idling mode is when the trains heat up before they start running. Lighting and Heating, Ventilation and Air-conditioning (HVAC) are essentials for trains operation and they take up a small part of total emissions during operation of trains. In this paper, only trains powered by electricity are discussed. Electricity generation emissions are different from places to places.

Table 6.17 Energy consumption and emissions of LRT during operation

	Energy	GHG	SO2	CO	NOx	VOC	PM
Propulsion	4.91	3.11	20.50	4.29	4.84	0.25	0.20
Idling	2.48	1.55	10.56	2.17	2.42	0.12	0.10
Auxiliaries	0.75	0.50	3.11	0.62	0.75	0.06	0.03
Units	*kWh/VKT*	*kg/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*

Table 6.18 Energy consumption and emissions of long distance train during operation

	Energy	GHG	SO2	CO	NOx	VOC	PM
Propulsion	17.39	6.21	50.31	4.22	4.66	0.68	0.37
Idling	8.70	3.11	25.47	2.17	2.36	0.37	0.19
Auxiliaries	2.42	0.62	6.83	0.56	0.62	0.12	0.05
Units	*kWh/VKT*	*kg/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*

Table 6.19 Energy consumption and emissions of high speed train during operation

	Energy	GHG	SO2	CO	NOx	VOC	PM
Propulsion	18.01	6.21	51.55	4.35	4.78	0.75	0.38
Idling	0.87	0.31	2.61	0.19	0.25	0.06	0.02
Auxiliaries	0.99	0.31	2.80	0.25	0.25	0.06	0.02
Units	*kWh/VKT*	*kg/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*	*g/VKT*

Maintenance of rail transport

The maintenance of trains is divided into three categories, which are routine maintenance, cleaning and flooring replacement. Examples for components which are included in routine maintenance are material replacement, wheel grinding, lubrication, brake parts replacement and inspection. These jobs have to be done constantly to make sure that the trains are in good condition.

Table 6.20 Energy consumption and emissions of rail transport routine maintenance

	Energy	GHG	SO2	CO	NOx	VOC	Lead	PM
LRT	1.4	68	0.2	0.2	0.2	0.1	1.4	0.1
Long Distance Train	25	1128	3.1	2.8	2.6	4.1	11	0.8
High speed train	28	1329	1	2.6	2.5	4.0	2	0.4
Units	*TJ/life*	*mt/life*	*mt/life*	*mt/life*	*mt/life*	*mt/life*	*mt/life*	*mt/life*

Insurances for operation crew and vehicles casualty and liability make up a significant portion of the total operating costs. To provide this service, offices and buildings are built. Hence energy is consumed throughout the process.

Table 6.21 Energy consumption and emissions of rail transport insurance

	Energy	GHG	SO2	CO	NOx	VOC	Lead	PM
Insurance	1.0	84	207	934	233	173	0	44
Units	*TJ/$M*	*mt/$M*	*kg/$M*	*kg/$M*	*kg/$M*	*kg/$M*	*kg/$M*	*kg/$M*

Infrastructure of rail transport

Rail systems will not function properly without infrastructures like stations and tracks. Requirements for railway tracks are based on the train type and the loads. Heavier loaded trains deal more impact to the tracks and hence better graded materials are required. Underground tracks increase the energy consumed and the emissions. Facilities in stations are also included in the calculation. Facilities in train stations are like escalators, train control, parking lighting etc. To keep up with the good conditions of both tracks and stations, maintenances have to be done consistently. This is part of the emission factors. Construction material products like concrete and steel have a significant impact on the environment as well. The emissions and energy consumed during production and transportation are included in to the calculation. Infrastructure insurances cover the health and benefits of non-vehicle personnel.

Table 6.22 Energy consumption and emissions of rail transport infrastructure materials production

	Energy	GHG	SO2	CO	NOx	VOC	Lead	PM
Concrete Production	6500	809	1900	5100	2400	1700	0	309000
Concrete placement	5.7	35	82	241	312	12	0	35
Steel Production	5.9	0.54	0.9	5.0	0.9	0.5	0	0.5
Units	*MJ/yd^3*	*kg/yd^3*	*g/yd^3*	*g/yd^3*	*g/yd^3*	*g/yd^3*	*g/yd^3*	*g/yd^3*

Table 6.23 Energy consumption and emissions of LRT infrastructure

	Energy	GHG	SO2	CO	NOx	VOC	PM
Station lighting	2628	632	4.3	867	979	52	40
Station escalators	4.7	632	4.2	867	979	52	40
Train control	52132	632	4.2	867	979	52	40
Station Parking	43	2.9	27	12	27	36	81
Miscellaneous	159747	632	4.2	867	979	52	40
Units	*kWh/yr*	*g/kWh*	*g/kWh*	*mg/kWh*	*mg/kWh*	*mg/kWh*	*mg/kWh*

Table 6.24 Energy consumption and emissions of long distance train infrastructure

	Energy	GHG	SO2	CO	NOx	VOC	PM
Station lighting	448578	351	2.9	243	267	40	21
Station escalators	275642	351	2.9	243	267	40	21
Train control	191929	351	2.9	243	267	40	21
Station Parking	37	2.9	27	12	27	36	81
Parking lighting	0.9	351	2.9	243	267	40	21
Miscellaneous	47410	351	2.9	243	267	40	21
Units	*kWh/yr*	*g/kWh*	*g/kWh*	*mg/kWh*	*mg/kWh*	*mg/kWh*	*mg/kWh*

Table 6.25 Energy consumption and emissions of high speed train infrastructure

	Energy	GHG	SO2	CO	NOx	VOC	PM
Station lighting	115440	351	2.9	243	267	40	21
Station escalators	4.7	351	2.9	243	267	40	21
Train control	2760714	351	2.9	243	267	40	21
Station parking	37	2.9	27	12	27	36	81
Parking lighting	0.9	351	2.9	243	267	40	21
Miscellaneous	26640	351	2.9	243	267	40	21
Units	*kWh/yr*	*g/kWh*	*g/kWh*	*mg/kWh*	*mg/kWh*	*mg/kWh*	*mg/kWh*

Power supply of rail transport

Unlike other mode of transportation, rail requires electricity as main power input. The energy to produce a unit of electricity varies from city to city. Electricity is produced by power plants through combustion of fuels. The energy produced by power plants need to be transmitted and distributed to the railway systems. Along the transmissions and distributions, there are energy looses. The energy looses vary from places to places.

Table 6.26 Emissions of electricity production

	GHG	**SO2**	**CO**	**NOx**	**VOC**	**Lead**	**PM**
Electricity production	351	2910	243	267	40	-	21
Units	*g/kWh*	*mg/kWh*	*mg/kWh*	*mg/kWh*	*mg/kWh*	*mg/kWh*	*mg/kWh*

Energy consumption and emissions of rail transport in the entire life cycle

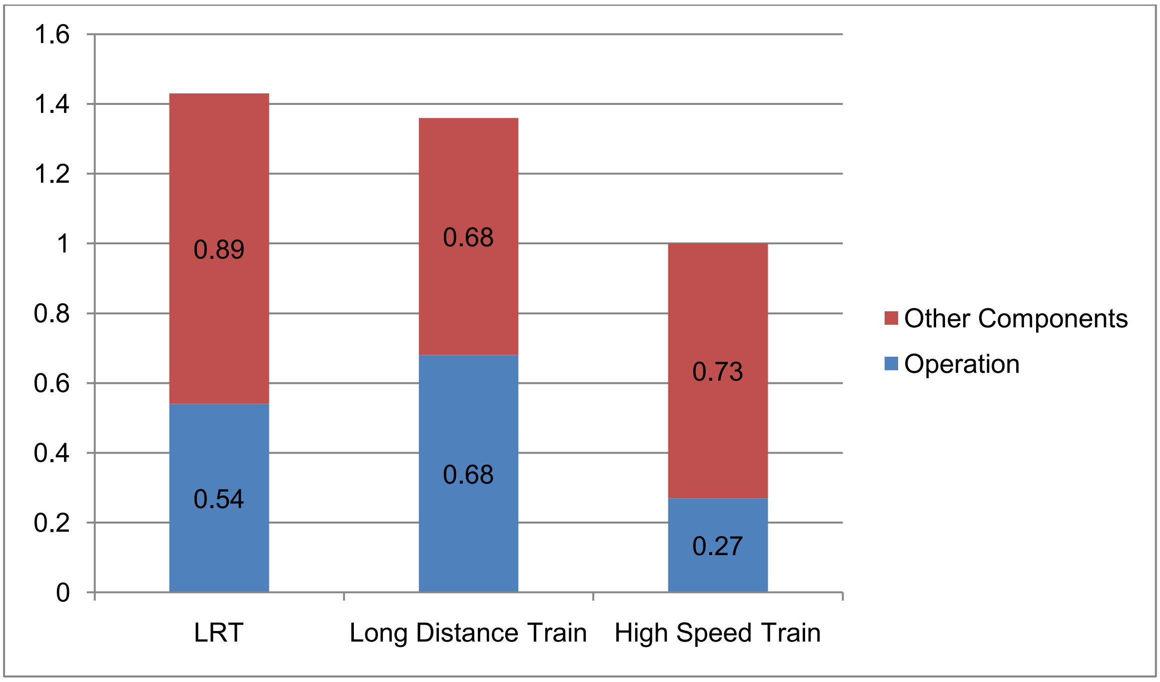

Fig 6.6 Energy consumption of rail transport in the entire life cycle in MJ/pkm

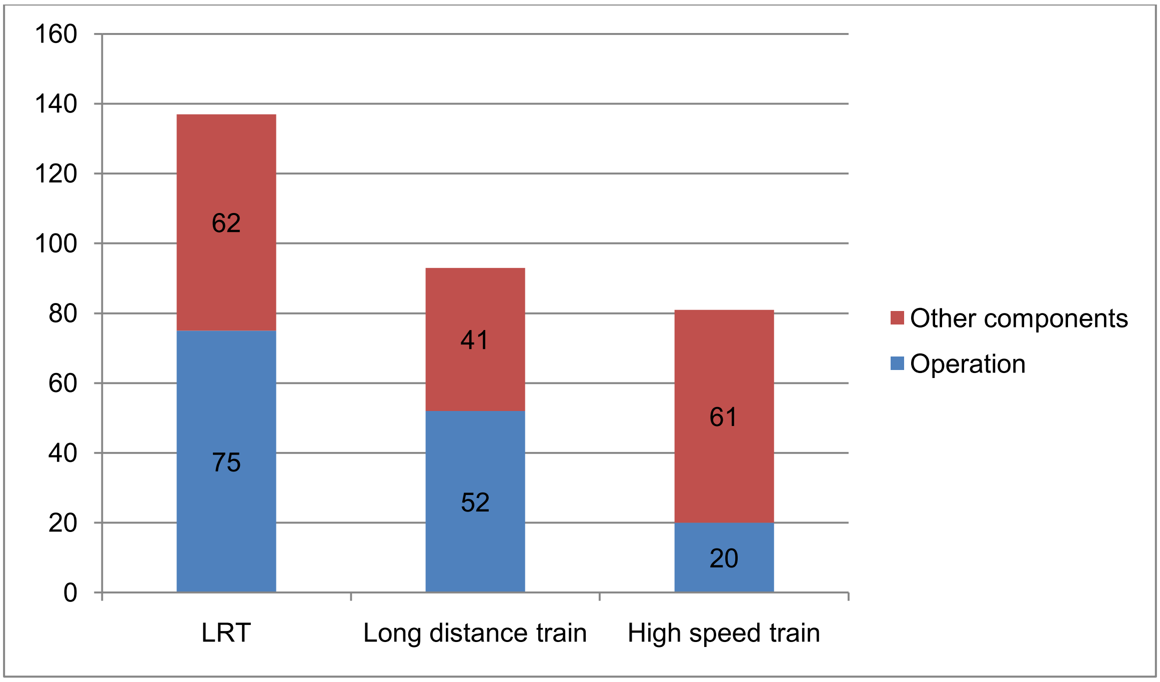

Fig 6.7 Emissions of rail transport in the entire life cycle in g/pkm

As we can see in Fig 6.7, LRT emits the highest amount of GHG compared to long distance train and high speed train. High speed train has the lowest GHG emissions during operation as well as the whole life cycle. Station construction is one of the main reasons for the high emissions of train life cycle due to the release of CO2 in cement production. For every kg of cement produced, near to half a kg of CO2 is produced. For stations and tracks which are built underground, higher energy is consumed for station lighting. Stations which operate more hours also emit more GHG gases and consume more energy.

7 Discussion of the results

As mentioned in this thesis above, all the results are only estimations. The results do not reflect the actual fuel consumption and emissions of aircraft. The results enable us to get a rough overview about the fuel consumption and its emissions of an aircraft during operation as well as in the entire life cycle. This enables us to determine the spaces of improvements that could be done in air transport. There are many manipulative variables in the reality that cause the fuel consumption and emissions of aircraft to sway from the estimated values stated in this thesis. Some examples of variables are listed below:

Load factor

Load factor of passengers or in other words the number of passengers in an aircraft strongly affects the values of fuel consumption per pkm. Fuel consumption per pkm is inversely proportionate to the number of passengers. In general, more passengers in the aircraft lead to lower fuel consumption per pkm.

Aircraft configurations

The configurations of an aircraft, for example the aircraft speed also determines the amount of fuel consumed during a flight. Basically an accelerated aircraft consumes more fuel than an aircraft, which flies at economic speed. Besides that, the seat capacity in an aircraft is also one of the major factors that manipulate the fuel consumption per pkm. An Airbus A380 is taken for example, an all-economy-class A380 can sit up to more than 800 passengers as stated in **Jane's 2001**, whereas a normal 3-classes A380 can only fit about 555 passengers. An additional of more than 245 passengers can be carried in an all-economy-class A380. However, when it comes to purchasing aircraft, seat capacities do not come into the very first considerations of the airlines. Due to economic considerations, airlines purchase aircraft that are divided into 3 travel classes, which are first class, business class and economy class (**Wikipedia 2011**). A combination of different travel classes enables airlines to sell their tickets at different prices to maximize their profitability.

Fuel type

As discussed above, jet fuel is the current fuel type used in aircraft. In chapter 6, it is mentioned that the production of jet fuel accounts up to 10 % of the total GHG emissions in the entire life cycle of aircraft. In the future, there are high possibilities of biofuel taking over jet fuel as the main fuel. For example, Lufthansa has carried out tests on regular flights for six months for better understandings about the effectiveness and properties of biofuels under the conditions of routine operations (**Lufthansa 2011**). With the replacement of jet fuel with biofuel, GHG emissions of fuel production will be reduced, as well as the GHG emissions during operation of aircraft.

Aircraft material

Lighter materials are always preferred in air industry. About 50 % of a Boeing 787's structure weight consists of composite materials (**Hawk 2005**). In general, lighter aircraft consume less fuel than heavier ones. However, the emissions during the production of the materials, as well as the emissions during disposal are not to be neglected. In a whole life cycle, some lighter materials may emit more emissions than the fuel saved during operation of the aircraft. This defeats the purpose of having lighter aircraft. Therefore, materials choices in building an aircraft are to be taken into consideration as a whole life cycle.

Fleet condition

Fleet condition will also affect the fuel consumption of aircraft. An aircraft with a smooth surface produces less skin friction drag. In cruise condition, the drag is equal to the thrust produced by the engines. Accumulative of dirt, dusts etc will result in a higher skin friction drag hence more thrust need to be produced by the engines to move the aircraft. In other words, more thrust means higher fuel consumption. On the other hand, aircraft's age is also a determining factor that leads to uncertainties in fuel consumption of an aircraft in a specific range. With an average of about 5 years, Emirates claim that their fuel efficiency and emissions performance is 30 % ahead of the global fleet average (**Emirates 2011**).

8 Summary

This thesis deals with the environmental aspects of current air transport and the air transport in the future, particularly in year 2020 and year 2050. The environmental impacts of the air transport have been treated more and more seriously, especially in Europe and in North America due to increased awareness towards the environment. Many projects are being undertaken to achieve the goals set by ACARE, IATA and other related organizations and associations. The global and local environmental impacts are discussed in this thesis. The environmental impacts are compared to road and rail transport. Individual comparisons are made to compare the energy consumption and emissions of different types of transportation during cruise and in the whole life cycle. Energy consumption is used to compare different types of transportation due to the difference of fuel. For air transport, jet fuel is chosen as the default fuel for aircraft; For road transport, gasoline and diesel are the two default fuels chosen for Sedan, SUV and pickup whereas for urban buses, diesel is chosen; For rail transport, electricity is chosen as the power supply for LRT, long distance trains and high speed intercity trains. In life cycle assessment, the manufacture of vehicles, the infrastructure built for different vehicles, insurances and maintenance of vehicles are taken into consideration. Besides that, the efforts taken by aircraft manufacturers are included in this thesis. Airbus and Boeing are the two main aircraft manufacturers in the world. Initiatives taken by major airlines from different world regions are discussed in this paper. Major airlines that are chosen in this thesis are Southwest Airline, China Southern Airline, Air France and Lufthansa with Southwest Airline representing North America, China Southern Airline representing Asia, and Air France and Lufthansa representing Europe. On the other hand, calculations of the fuel consumption of aircraft during different conditions are included. The aircraft type is separated into turbofan aircraft and propeller aircraft. The calculations are based on simplified Breguet range equation. The results of my calculations are tabulated and discussed in this thesis. With the same concepts, the calculations are done with two different assumptions. The first one is by substituting the maximum lift to drag ratio; the second one is by calculating the lift to drag ration from other parameters. The values for my calculations are from **Jane's 2001**. The calculations are performed for short, medium and long haul flights with 70 % and 100 % load factor.

9 Conclusion

To achieve the goals of air transport in year 2020 and year 2050, breakthrough technologies have to be introduced. The current trend of gaseous and noise emissions reduction will not lead to the goals set in year 2020. One of the most radical changes that we might see in the future is the total remake of the aircraft design. Blended wing body (BWB) aircraft will stand its chance to replace the conventional design of aircraft. BWB with significantly reduced wetted area and weight will result in a tremendous drop in drag. This new design is believed to reduce the fuel consumption by 50 %. Besides that, new materials like GLARE and CRFP will be more widely used in aircraft structure in the future. These materials are lighter than aluminium and are suitable for certain parts of the aircraft. GLARE and CFRP are used in construction of Airbus A380 and Boeing 787. Furthermore, these materials enable one-piece fuselage that can be seen in Boeing 787. This new method of constructing fuselage eliminates the need of fasteners to hold sheets of Aluminium together. In general, the fuel consumption per pkm during operation of short-range aircraft is higher than medium range and long range aircraft. Operation of aircraft includes LTO cycle and cruise. One of the main reasons of the higher fuel consumption per pkm is because of the low number of passengers in short-range aircraft. As discussed in the thesis, the fuel consumption per pkm is inversely proportionate to the number of passengers. Moreover, larger aircraft benefit from lesser LTO cycles. In general, air transport consumes less fuel per pkm than road transport, which includes automobiles and urban buses. On the other hand, air transport consumes more fuel than rail transport, which includes LRT, long distance train and high speed train. The high fluctuation in fuel consumption of urban buses is due to its high fluctuation of load factor during peak and non-peak hours. During off-peak hours, urban buses release the highest emissions into the environment. Huge amount of NOx is produced by operation of air transport due to incomplete combustions, particularly during take-off. Rail transport indicates relatively low values on all gaseous emissions except SO2. Different from air and road transport, which power supply is fuel-based, operation of train is powered by electricity. The conversion of coals to electricity releases a high amount of SO2 due to the sulphur substances contained in coals. According to the calculation made in chapter 5, where only cruise phase is taken into account, long range aircraft consume more fuel per pkm than short and medium range aircraft. There is a noticeable increase in fuel consumption per pkm when a reduction in load factor of 30 % is applied. In the case of life cycle, operation of air transport accounts to the majority source of its GHG emissions; whereas other components of the life cycle of rail transport accounts to the majority source of its GHG emissions.

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Appendix: Compact disc

The compact disc contains following documents:

- Bachelor thesis in Word 2007
- Bachelor thesis in PDF
- Abstract in Word 2007
- Abstract in PDF
- References