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“Analysis of evolution of commercial air traffic CO2 emissions in
the European Union”

-PhD Thesis-

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Abstract

The environmental sustainability of the air transport industry, as a key player in global social and economic development, has become a major issue in the agenda of the industry's stakeholders during the past decade. On both international and local levels, policy makers, scientists and environmentalists, manufacturers and airlines have begun to collaborate on fuel efficiency improvements and greenhouse gas emissions reductions in the sector.

This dissertation evaluates the structure and distribution of air traffic in European Union member states. The data presented here has been extracted from the statistical office of the European Union (Eurostat) and databases compiled by the The European Organization for the Safety of Air Navigation (EUROCONTROL). The focus of this study is on commercial air traffic and CO₂ emissions in the European Union in 2010 and its evolution through 2013.

The extracted data for all EU countries consist of variables such as: number of flights, number of passengers, freight tonnes, revenue passenger kilometers (RPKs) and revenue tonne kilometers (RTKs), fuel consumption and CO₂ emissions. The majority of EU air transport traffic is concentrated in six countries: France, Germany, Italy, The Netherlands, Spain and The United Kingdom, which in 2010 represented approximately two thirds of the total EU flights. The data is then segmented per distance bands, at intervals of 500 km to see the concentration of traffic in different distance bands and compare their share with other modes of transport. The fuel efficiency trend in the six largest EU aviation markets from 2010 to 2013 is analyzed and the potential reasons for the changes are investigated. The evolution in the airline fleet composition during the last decade is presented as one of the reasons for the improvement in fuel efficiency, measured by fuel efficiency parameter measuring fuel consumption per RTK (passengers + freight). Additionally, the differences in terms of fuel efficiency among the various airline business models (network carriers, low cost carriers, etc.) and aircraft types are studied. Moreover, future CO₂ emissions are projected, taking into consideration three different traffic growth and efficiency improvement scenarios.

The results of this analysis indicate a slight reduction in the traffic, both for passengers and freight about (-0.8%) but more importantly, a reduction in CO₂ emissions (-4.3%), which is the result of an improvement in fuel efficiency parameters (-3.5%) during these three years. There has been a relevant change in the fleet composition in the last ten years, with the replacement of older models for more efficient ones, and a shift to larger aircraft, particularly in the regional segment. Traffic has decreased in shorter distances (internal EU traffic), but increased in more efficient long-range flights (extra-EU traffic), resulting also in an improvement in the efficiency parameters as average aircraft size and stage length increases. This investigation concludes that technological efficiency increases do not seem to be enough to compensate for the rapid growth in air traffic and that implementing market-based measures is an effective and necessary complement to advances in technology.

Resumen

La sostenibilidad ambiental de la industria del transporte aéreo, como un actor clave en el desarrollo social y económico mundial, se ha convertido en un tema importante en la agenda de las participantes de la industria desde la última década. Tanto a nivel internacional como local, los responsables de la formulación de políticas, los científicos y los ambientalistas, los fabricantes y las compañías aéreas han comenzado a colaborar en la persuasión de las mejoras en la eficiencia del combustible y la reducción de las emisiones de gases de efecto invernadero en el sector.

Esta tesis evalúa la estructura y distribución del tráfico aéreo en los países de la Unión Europea. Los datos utilizados han sido extraídos de la oficina de estadística de la Unión Europea (Eurostat) y de la base de datos de la Organización Europea para la Seguridad de la Navegación Aérea (EUROCONTROL). El estudio se centra en el tráfico aéreo comercial y las emisiones de CO₂ en la Unión Europea en 2010 y su evolución hasta 2013. Los datos extraídos para todos los países de la UE consisten en variables como el número de vuelos, el número de pasajeros, los pasajeros por kilómetros transportado (RPKs, por sus siglas en inglés) y las toneladas por kilómetros transportadas (RTKs, por sus siglas en inglés), y consumo de combustible y emisiones de CO₂. La concentración del tráfico aéreo de la UE se encuentra en los seis países, Francia, Alemania, Italia, Países Bajos, España y Reino Unido, que en 2010 representan aproximadamente dos tercios del total de los vuelos de la UE. A continuación, los datos son segmentados por bandas de distancia, a intervalos de 500 km para ver la concentración de tráfico en diferentes bandas de distancia y comparar su cuota con otro modo de transporte. Se analiza la tendencia de la eficiencia del combustible en los seis mayores mercados de aviación de la UE de 2010 a 2013 y se investigan las posibles razones de los cambios. La evolución de la composición de la flota aérea durante la última década se presenta como una de las razones de la mejora en la eficiencia del combustible, medida por parámetros de eficiencia de combustible que miden el consumo de combustible por RTK (Pasajeros + carga). También se estudian las diferencias en términos de eficiencia de combustible entre los distintos modelos de negocio de la aerolínea (compañías de red, compañías de bajo coste, etc.) y el tipo de aeronave. Además, considerando tres diferentes escenarios de crecimiento del tráfico y mejora de la eficiencia, se proyectan futuras emisiones de CO₂.

Los resultados muestran una ligera reducción del tráfico, tanto para los pasajeros como para el transporte de carga (-0,8%), pero lo que es más importante, una reducción de las emisiones de CO₂ (-4,3%), resultado de mejorar del parámetro de eficiencia de combustible (-3,5 %) durante estos tres años. Ha habido un cambio relevante en la composición de la flota en los últimos diez años, con la sustitución de modelos más antiguos por otros más eficientes y un cambio hacia aeronaves más grandes, particularmente en el segmento regional. El tráfico ha disminuido en distancias más cortas (tráfico interno de la UE), pero ha aumentado en vuelos de largo alcance más eficientes (tráfico extracomunitario), lo que también ha permitido mejorar el parámetro de eficiencia a medida que aumenta el tamaño medio de la aeronave y la duración de la etapa. Esta investigación concluye que el aumento de la eficiencia tecnológica no parece suficiente para compensar el rápido crecimiento del tráfico aéreo y la aplicación de medidas basadas en el mercado es un complemento necesario.

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Chapter 1. Introduction

The air transport industry, as one of the main contributors to globalization and worldwide socioeconomic development, plays an important multidimensional role in the people's life today. Though the environmental impact of air transport had been neglected in the past, analysing and controlling its environmental costs has become increasingly topical. Despite the fast evolution of air transport and impressive technological improvements, the sector is still highly dependent on fossil fuels and. Consequently the growing rate of CO₂ emissions is an important challenge facing the industry today. The contribution of aviation to climate change is relatively small, constituting about 2% of global fossil fuel consumption and 12% of CO₂ emitted by the wider transport sector, including automobile and rail traffic. However, considering its fast expansion, CO₂ emitted by the air transport industry will grow a further 300-700% until 2050, calling for more environmental measures to be developed. This rapid growth of aviation emissions goes against the successful results of emissions reduction in the other sectors of the economy and has attracted the attention of environmentalists and policy makers to pursue more serious and practical actions. International air transport along with its important role in social, economic and political development has been a major CO₂ producer in the aviation sector. It is estimated that air transport emissions by 2020 will grow by 70% compared to its level in 2005¹ even if fuel efficiency in the whole system improves at 2% per year (European Commission, 2016).

Environmental concerns about the future growth of the aviation sector's CO₂ emissions led the industry to take additional measures to on one hand encourage efficiency improvements through innovation and technological developments and on the other hand to restrict market demands. The first international action to limit greenhouse gas emissions is the Kyoto Protocol, which was adopted in December 1997 and imposed mandatory targets to reduce emissions mainly from developed countries. International civil aviation, due to its characteristics, was not directly included in The Kyoto Protocol and the International Civil Aviation Organization (ICAO) was made responsible for controlling greenhouse gasses (GHGs) from aviation at a worldwide level. In addition to technical measures, international communities have suggested that air transport needs market based measures and a drastic reduction in the growth of air transport. Though global efforts for a worldwide Emissions Trading System (ETS) in 2007 weren't successful, in 2008, the European Union (EU) adopted Directive 2008/101/EC (European Commission 2009), to include aviation (for both EU and non-EU flights) in the EU ETS from the beginning of 2012 and to continue its investigations to adopt further environmental solutions (European Commission 2011a). Already, many European industries have experienced the trading of allowances through the EU ETS. Airlines have joined the same system by receiving tradable allowances, which permit airlines for a fixed level of CO₂ emissions per year.

¹ 2005 has been the reference year for the baseline of the European Union Emissions Trading System (EU ETS).

After the failed attempt to launch a worldwide emissions trading system in 2007, in 2013 ICAO agreed to develop a global market-based mechanism to address international aviation emissions by 2016 and apply it by 2020. Supporting the new negotiations of ICAO on a global ETS, the European Union decided to suspend the EU ETS requirements for flights, which departed to or arrived from non-European countries. According to this decision, in the period, 2013-2016, only emissions from intra-EU flights are covered in EU ETS. Additionally, some exemptions are considered for low-emission operators.

According to the European Commission (2016d), in comparison with other options such as a fuel tax system, “EU ETS is the most cost-efficient and environmentally effective option for controlling aviation emissions and provides the same environmental benefit at a lower cost to society”. However, market-based measures are not enough and should be complimented by global operational advancements in modernising and improving air traffic management systems (European Commission 2016d). The 39th Session of the ICAO Assembly, was an important step forward in the progress of each element of the so-called “basket of mitigation measures”. This basket comprises aircraft technology advancements, operational improvements, sustainable alternative fuels substitution and the global market-based measures (ICAO 2013c).

In early 2016, ICAO members reached a historic agreement on a market-based measure to offset CO₂ emissions in international aviation to achieve the ICAO global aspirational goals of 2% annual fuel efficiency improvement and carbon neutral growth from 2020. The agreed upon Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is the first global market-based measure that addresses CO₂ emissions from any industry sector. To date, 102 States, representing more than 90% of international aviation traffic, have voluntarily prepared and submitted their action plans on CO₂ emissions reduction activities for international aviation to ICAO. With the increasing engagement of member states and in close cooperation with the aviation industry and other international organizations, the sector will be led to reach the aspirational goals of ICAO (UNFCCC 2016).

Fuel has been and still is a major component of airlines cost structure, rising up to 36% of the airlines total expenses in 2008. Even after the recent drastic drop in global oil prices, fuel is forecasted to be 21% of total expenses in 2016 (IATA 2016c), as will be discussed in section 2.3.4 of this thesis. In the period between 2006 and 2014, the rising price of oil has been a driver for industry to improve the fuel efficiency of airlines and control costs, which in addition to environmental concerns and legislations resulted in important developments in fuel efficiency maximization. The emergence of entirely new generations of aircraft, such as the Airbus A350 XWB, the Boeing 787 Dreamliner and the Bombardier C Series and also improved versions of existing aircraft such as the A320neo and the Boeing 747-8 are the results of this fuel efficiency improvement trend. These new aircraft are built with about 70% advanced materials, including composite wings and parts of the fuselage, which results in an almost 15% weight reduction in this new level of technology. On average, introducing each new generation of aircraft to the

fleet means an improvement of approximately 20% of efficiency comparing with the previous generation (ICAO, 2010b; ATAG, 2016a).

Including the air transport industry in EU ETS along with the increasing demand of air travel has led to more investment in research and development programs targeting sustainable alternative fuels, more efficient airplanes and green technologies, and improvements in air traffic operations. For instance, broad implementation of advanced-generation of sustainable biofuels in aviation will play an important role in CO₂ emissions reduction (Blakey, Rye, and Wilson, 2011; Krammer, Dray, and Köhler, 2013; IATA, 2015b).

The study of Sgouridis, Bonnefoy, and Hansman (2011) suggest that the biofuel share of total fuel consumption in commercial aircraft's engines will rise to 15.5% in 2024 in a "moderate scenario", and to 30.5% in an "ambitious scenario" comparing to the 0.5% share in 2009. In the EU, policy makers, in collaboration with aircraft manufacturers, airlines and airport operators, and European biofuel producers, are supporting the development of sustainable biofuels through a program calling "European Advanced Biofuels Flightpath". The target of this program is to create a framework toward producing two million tonnes of sustainably produced biofuels suitable for aircraft engines until 2020 (European Commission 2011c).

Another factor which has been studied is the evolution of aircraft size and airlines strategies to deal with traffic growth and fuel efficiency (Paul Peeters, Rietveld, and Schipper, 2001; Babikian, Lukachko, and Waitz, 2002; Miyoshi and Mason, 2009; Lenoir, 2016). According to Peeters, Rietveld, and Schipper (2001), Moshe Givoni et al. (2009), Morrell (2009) and Moshe Givoni and Rietveld (2010), utilization of larger aircraft might reduce the airlines' overall emissions. The increase of load factor results in fuel efficiency improvement per available tonne kilometre (Kling and Hough, 2011; Mayer, Ryley, and Gillingwater, 2015). Some studies highlight the importance of operation efficiency improvement in fleets' CO₂ emissions reduction and believe that it can even bring greater efficiency improvements. According to ATAG (2016a), CO₂ emissions have been almost halved in the same flight between 1990 and the present. The industry needs to invest in the implementation of more modern ATM and operational systems during the flight and in the airport (Somerville, 2003; Reynolds, 2009).

Another influential factor in the fuel efficiency improvement is the wider and more intelligent integration of transport modes. For instance, particularly in EU, there is a new trend of supporting high-speed railways (HSR) to replace short-distance flights wherever possible considering the fact that HSR is the greenest available transport mode currently (European Commission, 2001; Brecher, Sposato, and Kennedy 2014). At the same time, air transport industry has revolutionized since the mid 1990's, through the emergence of low-cost carriers (LCCs). They led to an increase of air transport especially in short-haul and medium-haul distances where they compete strongly with HSR (Dobruszkes 2011b; Clewlow, Sussman, and Balakrishnan, 2014).

The introduction of the Internet and the rapid expansion of information and communication technology (ICT) have also impacted the air transport industry as in other industries. Moreover, the emergence of e-business models and Internet booking systems on one hand and the introduction of new facilities such as teleworking, mobile working and virtual meetings on the other hand have influenced air transport demand in different ways (Åkerman and Höjer, 2006; EEA, 2014; Achachlouei, 2015). Voluntary carbon markets, and some other voluntary strategies such as corporate social responsibility and green marketing have emerged for CO₂ emissions mitigation, implemented by some airlines in the sector.

The main aim of this doctoral thesis is to analyse the evolution of air traffic, CO₂ emissions and fuel efficiency in the European Union, from 2010 to 2013. To do so, the works published in Alonso et al. (2014) and Aminzadeh et al. (2016) that extrapolates possible scenarios of traffic and emissions in the EU, taking the year of 2010 as a starting point. In study of Alonso et al. (2014), the year 2010 is characterized and represents an important reference in the modern evolution of air traffic in Europe. This is due to the fact that 2010 was the first year of the recovery in airlines results following the 2008 crisis, and it was also the benchmark year for the allocation of free allowances to aircraft operators according to the civil aviation EU ETS. On the other hand, 2013 is the first year of growth (in yearly basis) in airlines results, after the decay in 2011 and 2012. The period of 2010 to 2013 covers the second part of the economic crisis initiated in 2008, a complicated business environment for airlines in Europe, with rising fuel costs and weakening demand.

The objective of this research is to analyse how the main air traffic indicators evolved during 2010-2013, reflecting how airlines adapted to the unstable environment, and resulting in the evolution of fuel efficiency parameters. The results may serve as a base for developing new potential scenarios and provide an orientation on how changes in relevant parameters affect airline behaviour and civil aviation emissions in the EU and some of its larger Member States.

In Chapter 3 of this thesis, the structure of air traffic evolution is investigated, both for passenger and cargo traffic, comparing the main indicators in 2013 with respect to their values in 2010. The evolution of traffic in the six largest European markets is compared, as well as the distribution of traffic in terms of flight distances and aircraft types. Chapter 4 analyses the evolution of CO₂ emissions for the same period, and from the same perspective: comparison of the evolution per country, per distance band, and per aircraft type. Then, an efficiency parameter is defined, in terms of kg CO₂/RTK, and its evolution analysed, trying to identify the potential reasons for the changes, particularly the fleet evolution along the last ten years, an expanded period (compared to the 2010 to 2013 reference period for the evolution of traffic, emissions and efficiency) because the effects of the changes in airlines' fleets usually take time to materialize. Finally, three different air transport growth scenarios are described and, based on them, the European air traffic evolution and CO₂ emissions until 2030 are projected.

1.1. Outline of the thesis

Current dissertation consists of five Chapters:

- Chapter 1, explains the motivation and overall intention of this study.
- Chapter 2, covers the research background and available literature and international reports.
- Chapter 3, describes the methods and their application in the current thesis.
- Chapter 4, presents and analyses the results and research findings.
- Chapter 5, summarises the whole research and presents general conclusions and recommendations for the future studies.

Chapter 2. Literature review

1.2. Global Aviation Industry

“If aviation were a country, it would rank 21st in size by GDP (similar in size to Sweden or Switzerland)”.

(ATAG 2016a)

“During the last four decades, air transport industry has been one of the fastest growing economic sectors” (IATA 2011b). In just four decades, passenger travels and air freight have expanded by ten and fourteen times, respectively (FAA 2015). Due to this broad growth, the impact of air transport on the global economic and social development has intensified. The significant growth of world economy during last decades along with the progress of technological innovations resulted in a huge expansion and improvement in air transport industry. According to (European Commission 2013c), it is expected that the share of air transport between transport modes will grow to 13% in 2050, from 8% in 2010, ranking the second most important passenger mode after road transport (European Commission 2013c). It is estimated that in 2016, 1% of world GDP (almost \$740 billion) is spent on air transport (IATA 2016b).

According to the International Air Transport Association (IATA), from 1945 until the first oil crisis in 1973, in about 30 years, the growth rate of international air transport doubled including both passenger travel and freight transport. The launches of aircraft such as turboprops and transatlantic jets in 1950s, and wide-bodied and high by-pass engines in 1970s, have been among the main innovations of that period. Thanks to technological evolutions, aviation industry experienced bigger airplanes; higher speeds and more advanced cost control systems, which resulted in lower real fares and rates. The growing availability of affordable air travels changed the aviation industry environment from a luxury industry with small target group to an essential transport mode, creating new potentials for trade and tourism over the globe (IATA 2016b). Since 1970, the real cost of air travel has declined by over 60%, impacted by the aviation market deregulation in the 1980s². The development of more fuel-efficient aeronautical technologies and emergence of low-cost carriers (LCCs) have been important outcomes of deregulation (ATAG 2014a). The development and impact of LCCs are studied in Section 2.3.7.

The global economic and social developments have changed widely the life style of people, and their interests and demands. The increase of overall incomes and leisure time of people have created new demands for tourism and air travel. At the same time, globalization has created new trading opportunities. Because of the unbalanced distribution of raw materials and market demands, air freight transport has grew even in

² The 1978 Airline Deregulation Act, shifted part of the air travel control from governments to the market (Fred et al. 2008).

a higher rate in comparison with passenger transport (Macintosh and Wallace, 2009; IATA, 2011; Tian et al., 2014; IATA, 2000; Senguttuvan, 2007; ATAG, 2014).

In 2008, global airlines were hit by international economic downturn, the sharp increase of oil price and drop of airlines' revenue. The Freight Tonne Kilometres (FTKs) and Revenue Passenger Kilometres (RPKs) both fell down respectively to 22% and 4.6% below 2007 amounts. After this shock, the industry in 2010 could recover by making \$19.2 billion profits and \$554 billion revenues (Li et al. 2016). Figure 1 illustrates the traffic trend between 2005 and 2014.

Figure 1. Total Scheduled Traffic 2005 to 2014

According to statistics provided by ICAO (2015) and IATA (2016), in 2014, RPKs of international scheduled passenger air traffic grew by 6% higher than its 5.7% growth rate in 2013. Europe, with the largest share of international RPKs (38%), and Asia and Pacific with the second largest share of international RPKs (28.1%) have had respectively 5.9% and 5.8% RPKs growth from 2013 to 2014. The fastest growth rate from 2013 to 2014, recorded for the Middle East with 11.5% and the slowest growth rate for Africa with 0.6% RPKs growth.

In terms of domestic passenger flights, the world market experienced 5.6% RPKs growth in 2014. North America as the largest domestic air traffic market by 44% share of total world domestic air travels, grew at 3.1% in 2014. The Asia and Pacific with 38% of total world domestic air travels, had a strong growth of 8.4% particularly because of the growth of domestic market in china (11.2%) and India (7.9%).

Part of this fast growth in air transport traffic is the result of growing share of low-cost carriers (LCCs). It is estimated that in 2014 around 900 million passengers, approximately 27% of the world total scheduled passengers, carried by LCCs. This means the number of LCCs' passengers have increase by 10.3% from 2013 to 2014. This number is 2 times of the average passenger growth rate in the world (ICAO, 2015; IATA, 2016).

The growth rate of international long-haul flights has been faster than domestic, and international short-haul flights. Boeing (2015) forecasts an annual 5% growth rate for

long-haul international traffic over the next tow decades; and Airbus (2015) estimates the share of international long-haul air traffic reaches to 45% by 2034.

The growth of air transport demand has been faster than capacity expansion, which has led to increase of average load factor. The overall air traffic load factor reached 79.7% in 2014. The load factor for international and domestic passenger air traffic is estimated 79% and 80.8% respectively (ICAO 2015c).

This tremendous development in air transport has made this industry a major player in globalization. Here economic impact and social impact of air transport industry are discussed:

- **Economic Impact:**

Air transport facilitates international trade and tourism, which are important drivers of economic growth, job creation, living standards improvement and worldwide communications. Due to abetter connection between cities, passenger travelling and freight transfer have become less costly and easier. Increase of export and import, expansion of supply and demand and easier distribution of products all around the world, transfer of technology and know-how, all together help communities to develop their business and industries. Air freight as a fast growing sector of civil aviation, has experienced a considerable growth in air express services, which compete with other shipping modes (WBCSD, 2001; Chapman, 2007). The share of tourism industry in the global economy is increasing very fast, partly due to the wide expansion of air transport (J Blanke and Chiesa, 2013; UNWTO, 2015).

The Air Transport Action Group (ATAG) in its reports categorizes economic impact of aviation to direct, indirect, induced impacts and tourism catalytic. The total global economic impact of aviation industry is expected to be about US\$2.7 trillion, which means 3.5% of the world gross domestic product (GDP). It should be taken into account that aviation's economic impact is even wider considering the creation of many jobs and businesses, which air travel makes them possible, or the creation of opportunities based on speed and level of connectivity that air transport provides. Currently the total fleet has over 25,000 aircraft, operating by 1,400 airlines, landing and taking off at around 4,000 airports, which means several million kilometres of network routs, which are managed by 173 air navigation service providers. The worldwide job opportunities provided by aviation industry and its related tourism, accounts for 62.7 million (ATAG 2016a).

As it is illustrated in Figure 2, aviation industry's job creation opportunities are divided to tourism catalytic jobs, induced jobs, indirect jobs and direct jobs in the aviation industry. The direct jobs are about 9.9 million jobs consist of 4.5% airport operations, 27% airlines related jobs (flight and cabin crew, management and administrative responsibilities, ground services, check-in, training, maintenance staff and etc.), 11% civil aerospace related jobs (engineers and designers of civil aircraft, engines and components), 2% air navigation service providers (air traffic controllers,

executives) and 55% other jobs which are created around airports (car rental, government agencies such as customs and immigration, freight forwarders and some catering).

The 11.2 million indirect jobs are those related to suppliers of the air transport industry. For example, aviation fuel suppliers; construction companies that build airport facilities; suppliers of sub-components used in aircraft; manufacturers of goods sold in airport retail outlets; and a wide variety of activities in the business services sector (such as call centres, information technology and accountancy) (ATAG 2016a).

Figure 2. Aviation's global employment and GDP impact in 2016

- **Social Impact:**

The social impact of air transport has been as impressive as its economic impact. Since affordability of air transport has been increased to the public, air transport has played a vital role in globalization by connecting communities around the world. The wider opportunities for air travelling provide a wider access to information and knowledge, intercultural communication and leisure tourism. Air transport is an essential transport mode of travelling in many remote areas and Islands where there are not enough railways and roads. In some cases, air transport plays an extremely important role in connecting these countries to the world, not just for tourism and business, but also for health care services in emergency situations caused by accidents, war or natural disasters (ATAG 2014a).

The global sustainable development needs more integration and worldwide social development. The opportunities which air travelling have brought to people such as the ability to travel to any other country for business, paying a visit to family members or friends, moving abroad for studying or working or spending leisure time are invaluable (ATAG 2016a).

Generally transport has a fundamental role in shaping the tourism by linking tourism demand and supply (Debbage 2002). The international tourism has expanded hugely. In 1950 the number of international tourists was 25 million, in 1980 278 million, in 1995 527 million and in 2014, 1,133 million, valuing about US\$ 1,245 billion. The estimations show a 3.3% yearly growth in tourist numbers (UNWTO 2015).

Human travel behaviour trend shows that faster transport modes, pioneering by aviation, are more attractive for people (Schafer and Victor, 2000; Clewlow, Sussman,

and Balakrishnan, 2014). Air transport expansion has changed tourism industry greatly. Tourism is not any more limited to traditional spots. The decrease of air travel costs and emergence of LCCs led to introduction of new destinations to the tourism industry. North America and Europe have grown at an average annual rate of 5.7% and 5.0% respectively over the last two decades and Asia-Pacific and Middle East have experienced an important growth (Sgouridis et al. 2011). According to UNWTO (2015), emerging economies are going to have a bigger market share from tourism in the future. While their share was about 30% in 1980, it grew to 45% in 2014, and is estimated to reach 57% by 2030, receiving over one billion international tourists.

2.1.1. Air Transport in The European Union

The European Union aviation sector is strategically an important sector for the union, which have been a successful economic contributor and leading industry in the world. Yearly, almost one third of global air passengers, 900 million, travel (domestic, intra- and extra- EU) in the European Union. European Union (EU) as a global aviation hub contributes to overall economic and social development through job creation, tourism, regional and cultural connectivity and integration. In 2014, air transport contributed US\$708 billion to EU GDP, supporting about 8.8 million jobs (ATAG, 2014; European Union, 2014; European Commission, 2015; Airbus, 2015; ACI, 2016; ATAG, 2016a). The EU air transport value chain has a high potential, covering all essential activities for flight operations. This value chain supports 1.9 million direct jobs, which around 1.4 million are high value-added jobs consisting of: 33% manufacturing and repairing of aircraft, 31% airlines, 18% airport operators and handling (which includes air navigation services), 18% tour operator and travel agencies and 20% include flying schools, renting and leasing of aircraft, and regulatory administration (European Commission 2015a). The contribution of EU air transport to GDP and employment is seen in Figure 3.

Figure 3. Air transport's contribution to EU GDP and job creation in 2016

The number of EU flights in 2014 was 80% higher than 1990, which means 879 million air passengers in 2014, 4.4 % more than 2013. The United Kingdom (UK) with 220 million air passengers in 2014 or an average of 3.4 passengers per inhabitant ranked the

first air transport market in EU (Pellegrini and Rodriguez, 2013; EASA, 2016; Eurostat, 2016). Also London Heathrow was the busiest EU airport in 2014, connecting 73 million passengers. Paris' Charles de Gaulle airport by connecting 64 million passengers in 2014, ranked the second busiest EU airport, followed by Frankfurt airport and Amsterdam's Schiphol airport connecting 59 million and 55 million passengers respectively. The majority of passengers in these four largest EU airports, at least 89 %, were travelling by international flights (Eurostat 2016b). It is expected that EU air traffic growth will continue at a high rate mainly for extra-EU trips. Considering the current economic situation of EU, it seems that long-haul leisure travels at low fares and intra-EU flights operating by LCCs are the most popular options (Aparicio 2016).

1.3. Aviation's Worldwide Contribution to GHGs

The main source of the current global warming is the expansion of greenhouse gas (GHG) emissions caused by human activities, particularly during the last decades. Accumulation of GHGs in the lower atmosphere prevents heat crossing subsequently resulted in the environmental unbalance (NASA 2015). Transport sector is one of the main producers of GHG emissions. Apart from all the positive socio-economic impacts of transport sector development in the world, this sector needs to take serious actions to decrease its negative impacts on the environment. Over 90% of the fuel used for transportation is petroleum based, including gasoline and diesel (EPA 2015). Currently transport sector is considered as the second-largest contributors of GHG emissions, after the power generation sector. Currently transport sector's emissions are about 23% of total global GHG emissions while this share is estimated to grow in the future (OECD, 2007; IEA, 2010; Chavez-Rodriguez and Nebra, 2010; Urry, 2012; Tian et al., 2014).

Scientists believe that carbon dioxide (CO₂) is one of the most influential greenhouse gas in the climate change, having a long lifetime (IPCC, 1999c; IPCC 2008; B. Daley, 2010; Kurniawan and Khardi, 2011). According to NASA (2016), the concentration of CO₂ has increased by third since the beginning of Industrial Revolution.

Aviation, with the highest growth rate among all transport modes, is the second-largest contributor of CO₂ emissions in transport sector, emitting 12% of all transport sector's CO₂ emissions (Chapman 2007). While air transport has experienced a broad expansion in a short time, its GHG emissions have increased also by 98% from 1990 to 2006. Currently, the total CO₂ emissions of global aviation industry are about 2% of all CO₂ emissions caused by humans. The total CO₂ emissions of global air traffic in 2015 was 770 million tonnes (ICAO, 2010b; Zhao, Yin, and Gao, 2014; UNFCCC, 2015; ATAG, 2016).

The CO₂ emissions generated by worldwide international aviation are growing rapidly to 70% higher amounts in 2050, comparing with 2005. The estimation is after considering 2% yearly fuel efficiency improvements (Kousoulidou and Lonza 2016; European Commission, 2016).

However, it should be taken into account that the development rate of aviation industry in different countries has not been the same. According to this fact, the responsibility of countries about the current level of total CO₂ emissions from aviation is not equal. “The carbon emissions per capita”, can be a factor to compare the environmental contribution of countries with each other (Feng-Cai et al. 2014). The growing environmental impact of aviation is considered both on a local scale including noise, air quality, and on a global scale which is resulted in global climate change and the depletion of the ozone layer (The European Commission, 2007; Graham, 2014; Evans, 2014). Dorbian, Wolfe, and Waitz (2011) highlight the importance of “the social cost of carbon” as a neglected issue, which should be calculated as the external cost of the industries, responsible for various social damages and health problems.

Although emissions by aircraft engines are similar to the other fossil fuel combustion, but as they generate contrails and occur in the climate-sensitive levels of atmosphere, since late 1960s, many studies have divided the environmental impacts of aviation to direct and indirect impacts (Kuhn, 1970; Anderson et al., 1998; Lee et al., 2010; Sgouridis, Bonnefoy, and Hansman, 2011; World Meteorological Organization, 2014). Also, as aviation emissions happen at high altitudes, their impacts are not limited to where they are released and can affect distances far away (FAA, 2015)

Between all environmental impacts of air transport, noise and CO₂ emissions have received more attentions until now. The aircraft emissions consist of almost 70% CO₂ and a little less than 30% H₂O. Less than 1% of the emitted GHGs are a combination of nitrogen oxides (NO_x), oxides of sulfur (SO_x), carbon monoxide (CO), partially combusted or unburned hydrocarbons (HC), particulate matter (PM), and other trace compounds. The impacts of aviation on climate change are not limited to CO₂ and non-CO₂ emissions should be considered too. Though, still most of studies concentrate on CO₂ impacts due to its long lasting impacts and also uncertainties surrounding the non-CO₂ emissions (Schipper, 2004; Lee, 2010; ICAO, 2010b; Stettler, Eastham, and Barrett, 2011; Sgouridis, Bonnefoy, and Hansman, 2011; Khodayari, Olsen, and Wuebbles, 2014; Graham, 2014). The environmental impacts of CO₂ emissions are expected to last for many hundreds of years whilst the impact of non-CO₂ emissions on temperature last for decades (Marais et al., 2008; J. J. Lee, 2010). The impacts of contrails and cirrus clouds on the climate change are still under investigation (Anger 2010).

The amount of GHG emissions generated by aircraft is dependent on various factors such as the type and efficiency of the aircraft engines; fuel type; the distance and duration of flight; type and frequency of aircraft operations; the duration of taxing, landing and take-off and cruise level of flight; the power setting; and, also to the altitude of flight operation (IPCC, 2006; Rypdal, 2009).

Aircraft operations are divided into:

- a. Landing/Take-Off (LTO) cycle;
- b. Cruise.

Normally around 10% of total aircraft GHG emissions (except CO and hydrocarbons) are generated at the ground operations and during the landing/take-off (LTO). This amount for CO₂ is 13% and for NO_x 11.6% (Kim et al., 2007; Dessens et al., 2014). Major aircraft emissions, about 90%, occur at cruise levels when aircraft is flying between 8 to 12 km in altitude (David S. Lee et al. 2009; Wasiuk et al., 2016). Between GHGs, hydrocarbons and CO are exceptions as their emissions happen in the low fuel efficiency levels of engine operations. Their emissions occur 30% local and 70% at higher altitudes (IPCC, 2006; FAA, 2015).

Two type of fuel are common to use in aircraft:

- Gasoline: just in small piston aircraft engines;
- Kerosene: in most of aircraft engines; and also in the bulk used for aviation.

Most of the transport modes have the potential to shift completely to other alternative fuels or electricity but air transport is always partly dependent to kerosene, either of fossil or renewable origin (Rypdal, 2009; Kurniawan and Khardi, 2011; Chiaramonti et al., 2014). There is a correlation between the aircraft engine's power and level of GHG emissions. The design of aircraft engines makes them capable for performing well at high cruise altitudes. Therefore, when they are operating on the airports (ground level), the engines are operating far from their optimal combustion efficiency (Whitefield et al., 2008; Kinsey et al., 2010; Masiol and Harrison, 2014; FAA, 2015). This fact shows how the air quality of airports is influenced by GHG emissions. Recently airports are receiving more and more attention from environmentalists and policymakers. Although the major emissions from the aviation industry happens as jet fuel is burning and is out of the control of individual airports, but taking into account the direct impacts of local emissions on the air quality and human health, nowadays airports are important targets of environmental improvements (B. Daley, 2010; BAA, 2010; Kurniawan and Khardi, 2011; Mahashabde et al., 2011; Volta, 2012; Adler, Martini, and Volta, 2013; ATAG, 2014; Monsalud, Ho, and Rakas, 2015). The role of airports as the global network connectors is very critical. Efficiency improvement in operation and maintenance of airports leads to greater environmental benefits throughout the industry (Monsalud, Ho, and Rakas, 2015).

During the take-off and climb segment of a flight, the engines use the highest quantity of fuel to produce power though generally LTO duration is not more than 8 to 15% of the total time of medium and long distance flights. Before the oil price significant increase in 2008, airlines didn't pay too much attention to this segment of flight but with the increase of oil price, saving the fuel burn at take-off and climb stage become an important strategy for airlines (Roberson & Johns 2008). This duration of LTO flight phase is almost similar in all kind of flights. This fact shows that short-haul flights are less efficient as their fuel burn per kilometre is more than longer flights. Anyway, there is an optimum distance for flight fuel efficiency. As the time of flights increase, aircraft need to carry more amount of fuel which itself add to the aircraft weight and fuel burn ratio (Chapman 2007).

International tourism as one of the main users of aviation with its high growth rate could become a leading contributor to global GHG emissions in the future (Scott, Peeters, and Gössling, 2010; Tang et al., 2014). At worldwide level, tourism contributes around 5% to the global CO₂ emissions. The share of transport in tourism sector's emissions is 75% while air transport, alone, is responsible for 50% of tourism sector's emissions. According to the International Energy Agency IEA (2009), air travel is expected to grow by four times between 2005 and 2050. This means that emissions induced by air travelling are growing dramatically and 80% of air travels is coming from tourism industry (Gössling, Scott, and Hall, 2015; Robaina-Alves, Moutinho, and Costa, 2015).

The environmental impacts of aviation industry has become under the spotlight. Policy makers and environmentalists in the last decades highlighted the fact that without any practical measures, aviation can devastate the environmental practices for CO₂ reductions in the other industries (Anable and Boardman, 2005; Simons, 2014).

2.1.2. Air Transport CO₂ Emissions in EU

Following the enormous growth of European air transport during last decades, the environmental impacts of air transport have increased too. CO₂ emissions have almost doubled between 1990 and 2014 (EEA 2015). The European aviation industry generates around 3% of total EU GHG emissions. The international flights, either between two EU members or between a EU member and a non-EU country, are responsible for the majority of air transport emissions. The international air transport emissions have risen by 87% since 1990 (European Commission 2006).

European Union has been successful in controlling the CO₂ emissions of some industries through implementing EU ETS. But without practical actions in limiting the CO₂ emissions of European air transport, environmental efforts of the other sectors may become meaningless. "As an example, someone flying from London to New York and back generates roughly the same level of emissions as the average person in the EU does by heating their home for a whole year" (European Commission 2006).

1.4. Reduction Strategies and Influential Factors on CO₂ Emission in Commercial Air Transport

As the result of growing environmental concerns of governments and general public, controlling the devastating impacts of aviation on climate change and CO₂ emissions reduction have become priorities for aviation sector (McDougall, G., Roberts, 2012; Monsalud, Ho, and Rakas, 2015). In the international market many discussions about the responsibility of international aviation in climate change started. The international air transport is the fastest growing segment of the industry, emitting more than 60% of total aviation GHG emissions (Macintosh & Wallace 2009). At the same time, the international nature of aviation industry makes adoption of new strategies to a lower carbon future difficult. Reaching international agreements for the emissions reduction in

aviation is very complicated as any measurement must deal with several important legal and policy issues which is not the same for domestic aviation (Macintosh & Wallace 2009). In addition, aviation industry's capital stock is exceptionally long-lived which make any radical shifts to more efficient technologies even harder (Dray 2014).

Any environmental movement needs long-term and gradual strategies. The first step is to identify the factors influencing the volume of air transport CO₂ emission to highlight the potential strategies in local and international environment. In this study, emissions of CO₂, the well-known greenhouse gas with a long atmospheric lifetime, as the major concern of global climate change is considered. CO₂ is one of the key contributors to aviation's environmental impacts and its emission to the atmosphere is proportional to fuel consumption (IPCC 1999).

Air transport industry is experiencing a vast evolution in various dimensions including aircraft internal developments, advancements in engine design and utilization, fleet renewal (very different rate in different countries) and development of external processes such as more environmental friendly business plans, more efficient air traffic control and sustainable alternative fuel substitution (IPCC, 2001; 2012). Reduction of CO₂ emissions from aviation demand a combination of operational, technological and economic measures which should be followed gradually with three approaches: short-term, medium-term and long-term goals (The World Bank, 2012; ATAG, 2013b; EEA, 2015).

Several environmental actions have taken place in air transport industry. Introduction of policies to penalize or even restrict the use of emission-intensive aircraft at many airports and in some geographic regions and deployment of European emission trading scheme (ETS) for CO₂ emissions have been great movements (J. D. Scheelhaase and Grimme, 2007; Girvin, 2009). Subsequently airlines need to demonstrate their environmental commitments and to build a greener image competing with other airlines and transport modes as environmental factors can become part of customer's decision making in future (Mayer, Ryley, and Gillingwater, 2012; Roskopf, Lehner, and Gollnick, 2014). Airlines have started to conclude environmental goals in their fleet planning. Some airlines have begun to go beyond minimum standards by investing on purchasing more efficient and less-polluting aircraft. Even using environmental reporting and green marketing have become part of some airlines' business plans (Lynes & Dredge 2006). Environmental benefits can be encouraged through increase of competition in the industry by improving efficiency in response to market forces (Mayer et al. 2015).

Analysing the fuel consumption of international aviation reveals the impact and influential depth of various factors in aviation fuel efficiency improvements. According to (Airbus 2007) the passenger transport fleets have reduced their fuel consumption by approximately 37% between 1987 and 2007, falling from 8 to 4.7 L/100RPK. According to international reports technological advancements such as enhancements in aircraft and engine design like using lighter weight materials and operational improvements such as air traffic management (ATM) upgrades, significant increase in aircraft load factors (carrying more passengers or freight on a given aircraft),

eliminating non-essential aircraft mass/weight, optimizing aircraft speed, limiting the use of auxiliary power units, and reducing taxiing have been the most important factors in fuel burn reductions (IPCC, 1999; ICAO, 2007a; Macintosh and Wallace, 2009; OECD, 2012). According to IPCC Special Report (IPCC 1999), ATM improvements and other operational procedures together have the potential of reducing aviation fuel burn by between 8 and 18%. The large majority of these efficiency improvements, 6 to 12% comes from ATM improvements. (Lee et al. 2009) pointed out that the most important factors that affect carbon intensity in air transportation are load factors, system efficiency of operations (avoidance of detours and delays), improvement of technology, and the rate of fleet renewal and the average size of an aircraft.

Besides the important improvements in the fuel efficiency of air transport, still the fast growth of this industry demands more effective regulations and policies to control its negative environmental impacts. In 2010, in the 37th session of the International Civil Aviation Organization (ICAO) Assembly, a set of environmental goals for the air transport industry were defined (ATAG 2013a):

- The global air transport industry has to improve its average fuel efficiency by 2% annually until 2020 and an aspirational global fuel efficiency improvement rate of 2% per annum from 2021 to 2050;
- Also air transport should keep its volume of CO₂ emissions from international aviation from 2020 at the same level.
- The air transport industry has the commitment of reducing its CO₂ emissions volume to 50% under the level of 2005 (IATA, 2009a; ATAG, 2013; European Commission, 2016a).

According to ATAG (2016a), the global air transport industry has been successful to reach to an overall fuel efficiency improvement of 2.4% per year between 2009 and 2014. Since 1990, more than 9 billion tonnes of CO₂ emissions has been avoided through the mentioned combination of new technologies, operational efficiencies and infrastructural improvements. Also airlines have spent US\$3 trillion on over 25,000 new aircraft to renew their fleets. Civil aerospace spends around US\$15 billion yearly investing on R&D programs related to aircraft efficiency. New advancements in deployment of sustainable aviation fuels are expected to have an important impact on aircraft environmental efficiency up to 80% emission reductions (ATAG 2016a). Load factors are specifically an important aspect in achieving carbon efficiency of airlines (Mayer et al. 2015). Regional jet operators continue to replace smaller regional jets with larger regional jets or small single-aisle commercial airplanes with better fuel economy and lower trip costs (Boeing 2014a).

Air transport industry is a global strategic sector today. Various factors are internationally impact growth rate and efficiency of this sector. Considering the interdisciplinary concept of air transport, this study is trying to analyse main influential factors, which define the environmental sustainability of air transport in the future.

These factors are highly dependent to each other and interconnected to macro and micro economic, social and political aspects in market.

- Policies and measures
- Technology Advancement
- Sustainable Alternative Fuels
- Fossil Fuel Prices
- Aviation Management and Operations
 - ✓ Air Traffic Management
 - ✓ The Single European Sky
 - ✓ Airport operations and management
- High-speed Rail
- Low-Cost Carriers
- ICT
- Voluntary carbon reduction by air transport industry

2.1.3. Policies and measures

"The willingness to take action has increased at national, transnational and individual levels, and the physical changes in climate and weather systems are more evident. What has yet to change is the willingness to take genuinely effective and substantive action in a coordinated way, at a global level, such that no government perceives its national economic interests to be threatened".

(Gössling, S., Upham 2009: 375)

The global air traffic and consequently its environmental impacts are growing rapidly. Now, more than ever, the necessity of effective policies toward emissions reduction and fuel efficiency improvements is felt. International entities, governments and other air transport stakeholders try to respond to this universal environmental concerns by (Eurocontrol 2016b):

- Optimizing the available capacity of air transport;
- The interdisciplinary collaboration of all sectors toward a more sustainable aviation industry;
- Optimizing the balance between social, economic and environmental essential requirements;
- Minimizing the adverse impacts of air transport by modernizing and renewing the operating facilities and ATM systems;
- Investing in R&D projects, trainings, educational programs and public awareness;
- Working on improvement and integration of international policies and regulations.

Reaching the goal of environmental sustainability without integrated legal frameworks and effective policies is impossible. Though technological improvements in aviation

industry have played the leading role in CO₂ emissions reduction during last decades, but industry's technological targets are highly influenced by international structures and policies. Global environmental players are emphasizing the need of an integrated international framework to maintain fuel efficiency improvements and expand them around the sector (Jillian Anable et al., 2012; Hill et al., 2012).

IPCC (2006) identified three categories for calculating the emissions from air transport:

- **Domestic aviation** represents the segment, which covers all emissions from civil passenger and freight air traffic departures and arrivals that occur in the same country. These domestic flights can be related to commercial, private, agriculture or etc. activities. "In this category journeys of considerable length between two airports in a country (for example San Francisco to Honolulu) may be included". The military aviation is totally excluded.
- **International aviation** represents all air traffic emissions from the flights, which their origins and destinations are in two different countries. "Emissions from international military aviation can be included as a separate sub-category of international aviation".
- **Military aviation** emissions are reported separately from civil aviation, or not reported at all.

In 1997, state members of the United Nations Framework Convention on Climate Change (UNFCCC) reached the world's first emission reductions agreement calling Kyoto protocol³. Kyoto protocol is the result of UNFCCC's aim to fight with global warming and climate change by reducing the concentrations of GHGs in the atmosphere to an acceptable level. The decided target of Kyoto Protocol was to reduce the emissions of all sectors of the economy by 8% between 2008-2012 compared to 1990 level (Lauge Pedersen, 2000; UNFCCC, 2010). "The domestic aviation emissions have been included in national emissions and addressed at the national level within the UNFCCC-Kyoto Protocol regime". But international aviation because of its characteristics, the UNFCCC greenhouse accounting framework and international aviation law was not covered by Kyoto Protocol; instead, article 2.2 of the Protocol assigned the responsibility of pursuing international aviation segment to reduce its GHG emissions to the International Civil Aviation Organization (ICAO) (Olsthoorn, 2001; IPCC, 2006; Macintosh and Wallace, 2009; United Nations, 1998; Gössling, 2013). In 1999 Intergovernmental Panel on Climate Change (IPCC) reported to ICAO the dangerous rapid growth of CO₂ emissions of aviation which has the potential to increase between 60% and 1000% during 1992 to 2050 (IPCC 1999). The national policies can control the impact of domestic air transport which is about 30–35% of total air transport (IPCC, 2014; ATAG, 2015b). More than 60% of total aviation emissions is caused by international air transport and policy makers proposed additional measures to

³ There are currently 192 parties (Canada withdrew effective December 2012) agreed to the Protocol.

control international emissions by optimizing demand and promoting technological advancements. Also various strategies have been promoted by governments to have a more efficient air transport such as “targeted taxation”, “improved pricing strategies” and “limited flight distances”.

Air transport sector needs to have long-term plans to satisfy the market demands, to keep the industry productive and profitable by attracting enough investors and by supporting the value chain. In addition to these regular economic practices, air transport industry is responsible to apply environmental measures and to plan for the efficiency improvements and sustainable development. Any effective legal scheme demands deep analyses of its effects on the environment, on national and international economic scales, on the airline industry, and on the travellers (Solomon and Hughey, 2007; Daley, 2010; Sgouridis, Bonnefoy, and Hansman, 2011; ACI, 2011; Monsalud et al., 2012).

Talking about the limiting emissions of aviation to achieve a fair allocation scheme also demands consideration of this fact that the level of aviation industry varies in different countries. According to the studies, the level of responsibility of countries for the total CO₂ emissions of international air transport varies with CO₂ emissions per capita of countries. Unfair allocation schemes can lead to market distortion and it’s a threat for sustainable development of the industry (ICAO, 2010b; McDougall, G., Roberts, 2012; Loo et al., 2014; Feng-Cai, Li-Gang, and Lan, 2014). According to Feng-Cai, Li-Gang, and Lan (2014) study, “there are huge differences in CO₂ emissions of different countries, especially between developed and developing countries”. The top 20 countries for CO₂ emissions in 2013 are listed in Table 1, which shows significant differences between the CO₂ emissions of different countries. For example, emissions per capita of the United States and European Union are respectively seven times and almost nine times of those of China. According to these differences, carbon allocation should be closely adopted to the development level of countries to give equal aviation carbon emission rights to all (Evans, 2014; Feng-Cai, Li-Gang, and Lan, 2014). Also Feng-Cai, Li-Gang, and Lan (2014) point out another factor defining as intra-generational fairness and inter-generational fairness, which should be considered in any legal scheme aiming to reach fair carbon allocations. Intra-generational fairness requires consideration of the fairness of international aviation emissions per capita, while inter-generational fairness includes the fairness of historical international aviation emissions. Countries’ accountability for CO₂ emissions requires analysing their historical impact on environment (He et al., 2009; Feng-Cai, Li-Gang, and Lan, 2014).

In 2010, the ICAO Assembly adopted new goals for aviation. Since then, aviation industry has to take action toward making annually 2% improvement in fuel efficiency by 2020 and an aspirational global fuel efficiency improvement rate of annually 2% from 2021 to 2050 (ICAO 2010b). Following this aspirational goal require a close collaboration between all public and private contributors of industry (ATAG 2013a). IPCC (2014b) has categorized the policy options to two groups: “Regulatory instruments such as fuel efficiency and emission standards at aircraft or system levels

and Market-based measures (MBM) such emission trading under caps, fuel taxes, emission taxes, subsidies for fuel efficient technologies”.

Many economic sectors prefer market-based measures because of they are economically more efficient at emissions reduction. Emissions trading as a market-based measure is widely accepted trying to reduce CO2 emissions under a cap and trade scheme (Lee et al. 2009).

Table 1. International Aviation CO2 emissions per capita in 2013 including the top 20 countries in 2013

Area	Emissions (Mtonnes Co2)	Population (millions)	Emissions per capita (tonnes CO2)	Ranking
EU28	130.09	508.5	0.26	7
United States	65.24	316.5	0.21	10
China*	38.48	1,367.20	0.03	19
Russia	18.18	143.00	0.13	13
Singapore	21.45	5.4	3.97	1
Japan	19.62	127.3	0.15	12
India	12.29	1,250.0	0.01	20
Thailand	11.63	67.0	0.17	11
Korea	12.80	50.2	0.25	8
Australia	10.09	23.3	0.43	5
United Arab	14.38	9.3	1.55	3
México	9.09	118.4	0.08	14
Malaysia	8.99	29.7	0.30	6
Saudi Arabia	5.96	28.08	0.21	9
Brazil	6.98	200	0.03	18
Qatar	6.34	2.2	2.88	2
Switzerland	4.61	8.1	0.57	4
Canada	2.47	35.2	0.07	15
Iran	3.91	77.4	0.05	16
Turkey	3.11	75.8	0.04	17

Data source: CO2 emissions from fuel combustion highlights edition 2015 (IEA 2015)

* The EU-28 members are as a whole;

** The data from China include Hong Kong and Macau, but not Taiwan.

In October 2010, the ICAO Assembly decided to develop a certification standard for CO2 emissions to ensure that new manufacturing lines of aircraft meet a baseline for CO2 emissions. With IATA’s full support, an important milestone was reached in July 2012 when ICAO’s Committee on Aviation Environmental Protection (CAEP) agreed on a metric for the new CO2 standard (ICAO, 2008; ICAO, 2011a; IATA, 2013). At the 38th ICAO Assembly in September 2013 reached some new advancement and agreed to develop a global market-based mechanism by 2016 to be implemented by 2020 that can be adopted at ICAO’s next Assembly in 2016. Also ICAO decided to develop, in the meantime, several milestones that could help build the foundation for a single global MBM, including:

- An ICAO standard for monitoring, reporting and verifying emissions from aviation;

- A mechanism to define the quality of verified offset types that could be used in a global MBM for aviation (ATAG 2013a).

Studies suggest that the potential for environmental policies is limited and they can just slow down the rate of emissions growth (Winchester et al. 2011). The trends show that aircraft CO₂ emissions are expected to continue to grow in the future, but at a slower rate than the growth in traffic. The new airplane CO₂ emissions Standard, the first global Standard for CO₂ emissions of any sector, will apply to new airplane type designs from 2020 and to airplane type designs that are already in production in 2023 (ICAO 2016e).

On the 39th ICAO Assembly in Montreal, Canada, ICAO's 191 member states agreed to implement a Carbon Offset and Reduction Scheme for International Aviation (CORSIA). According to Alexandre de Juniac, IATA's Director General and CEO: "The historic significance of this agreement cannot be overestimated. CORSIA is the first global scheme covering an entire industrial sector. The CORSIA agreement has turned years of preparation into an effective solution for airlines to manage their carbon footprint. Aviation is a catalytic driver of social development and economic prosperity—it is the business of freedom making our world a better place. This agreement ensures that the aviation industry's economic and social contributions are matched with cutting-edge efforts on sustainability. With CORSIA, aviation remains at the forefront of industries in combatting climate change". CORSIA has been set to have a voluntary period from 2021 to 2026 and after will become mandatory. As of 12 October 2016, 66 States, representing more than 86.5 % of international aviation activity, intend to voluntarily participate in the global MBM scheme from its outset (IATA, 2016a; ICAO, 2016a).

2.3.1.1. Policy and measures in EU

In the European Union, combating with the negative environmental impacts of aviation and integrating this goal into the other EU policies and activities have become a priority in the political agenda (European Commission 2015a). This goal has led EU to introduce the first real multilateral measure to control GHG emissions of aviation. European Commission adopted this measure through Directive 2008/101/EC to include aviation in the current European Union Emission Trading Scheme (EU ETS)⁴. According to this directive, the international aviation for all flights arriving and departing from EU airports, are included to EU ETS from the first of January 2012. The main target of inclusion of aviation to EU ETS is to reduce aviation CO₂ emissions by a cap system to 5% below the 2006 level, by 2020 (J. Scheelhaase, Grimme, and Schaefer, 2010; European Commission, 2013b; Hagmann, Semeijn, and Vellenga,

⁴ The European Union Emissions Trading System (EU ETS) is the first large greenhouse gas emissions trading scheme in the world. The implementation of EU ETS started since 2005 to combat with global warming. In 2013, "more than 11,000 factories, power stations, and other installations with a net heat excess of 20 MW in 31 countries, all 28 EU member states plus Iceland, Norway, and Liechtenstein" are covered by EU ETS.

2015). The EU ETS is a “cap and trade” scheme. These schemes set a ‘cap’ on total overall emissions by establishing a fixed number of emissions ‘allowances’, distribute these to industries according to a given benchmark, and permit industries to trade these allowances according to their needs. In the case of the EU ETS, the allowances are distributed initially by a combination of free allocation and auction (European Commission, 2009; Bartels, 2012).

According to (Vespermann and Wald (2011) and Anger (2010) inclusion of aviation in EU ETS has been costly for aviation industry though this cost for different airlines and in different periods is different. Anger (2010) indicates that this cost is directly related to the level of fuel efficiency of airlines, influenced by parameters such as the fleet age and advancement, operational management and load factor. This fact will encourage airlines to improve their fuel efficiency and manage their emissions in a cost-efficient way through EU ETS. Airlines can invest on their efficiency improvement and benefit from lowering their emissions, not just because of the less fuel consumption but also by being able to sell their extra allowances to the other airlines. Also as EU ETS is covered other industrial sectors, the allowances can be traded between different industries. This may result in more collaboration between industrial sectors to invest in mutual programs targeting sustainable development. For example investment on clean energy projects carried out in third countries under the Kyoto Protocol mechanisms such as Clean Development Mechanism (CDM)⁵ (European Commission, 2008).

In 2012 the European Union took action based on the European Commission Directive 2008/101. Since the start of 2012, emissions from all flights from, to and within the European Economic Area (EEA), the 28 EU Member States, plus Iceland, Liechtenstein and Norway - are included in the EU Emissions Trading System (EU ETS). Carriers awarded free permits based on their 2010 RTK data. Each year, the EU publishes a benchmark in units of allowances per ton-kilometre that is used to calculate how many free allowances each carrier will receive that year. Carriers that exceed their allotted allowances must either purchase allowances from other ETS participants, purchase approved emission-reduction credits, or pay a fine (European Commission 2016d). Between 2013 and 2016, the EU ETS covered emissions from flights performed by around 640 aircraft operators between airports located in the European Economic Area (EEA). The EU Member States are responsible for the implementation and enforcement of the EU ETS. This was a big and highly controversial step for the EU aviation industry and its deployment rescheduled to April 2013 and for the airlines out of EU, at least until 2014 (European Commission 2014). According to this adjustment:

⁵ The Clean Development Mechanism (CDM) is called to a series of projects, which have been defined in Article 12 of the Kyoto Protocol and enable countries with commitment for emissions reduction to implement an emission-reduction project in developing countries. Such projects can earn saleable certified emission reduction (CER) credits, each equivalent to one ton of CO₂, which can be counted towards meeting Kyoto targets.

- The emissions generated from flights inside European Economic Area (EEA) remained under coverage of the scheme.
- Emissions from flights to and from non-EEA countries were fully excluded until 2013.
- From January 2014, for the flights with the arrival or departure outside EEA, just emissions generated during the proportion of flights within EEA are covered.
- The especial treatment is considered for the flights between a country in EEA and some of the developing countries.

According to (European Commission 2015a), verified CO₂ emissions from aviation activities carried out in the EEA amounted to 53.4 million tonnes of CO₂ in 2013 and 54.9 million tonnes of CO₂ in 2014, which represents an increase of 2.8 % in 2014 compared to 2013. Overall figures in EU show around 32m tons of emission reductions in 2013 and 2014. The relation between this reduction and EU ETS obligations are very high, affecting more than 99.5% of emissions covered by the EU ETS, including from more than 100 third country commercial operators (European Commission 2015a).

In a more global scale, ICAO's triennial assembly in 2016 supposed to agree on a global market-based measure, to be implemented from 2020 (Robaina-Alves et al. 2015). Based on the outcome of the assembly, the Commission may propose policies for 2017 onwards that is appropriate considering the international developments. The EU initiative has opened international discussion and may lead to a global response to the problem of CO₂ emissions from aviation. Meanwhile, the EU ETS itself need reforming in order to increase market stability. In recent years mainly due to economic downturn, the functioning of the system has been challenged by a growing surplus of allowances (EEA 2015).

In EU, other types of economic measurements exist which can be operated alongside EU ETS (Cairns & Newson 2006) such as:

- Taxation of aviation fuel;
- Taxing passengers depending on their destination;
- Air passenger duty;
- Introducing airport slot auctions;
- Obligation of replacement of older aircraft with newer;
- Airport taxes for airlines;

Taxation of aviation fossil fuel is an unpopular option among many members of ICAO, but in some EU countries, taxation of Kerosene is working very well. At the regional level there are doubts about effectiveness of taxation as may cause competitive distortions but it is implemented in some counties as a local measure to reduce the level of fuel consumption and instead, invest the tax revenues in the development of aviation industry (Ron Wit et al., 2004; Kahn Ribeiro et al., 2007; David S. Lee et al., 2009).

Analysis of Fukui and Miyoshi (2017) suggests that fuel taxation has a limited and small impact with unpromising effectiveness as a policy tool for CO₂ emissions reduction. Besides, the impact of fuel tax differs depending on the size of carriers. The financial impact of fuel taxation for low cost carriers and regional airlines are significantly greater than for network carriers (Scheelhaase & Grimme 2007). Another practice, which by UK and the Netherlands implemented, is taxing passengers depending on their destination. Different levels of tax and the way destinations are grouped have different consequences. There are on-going debates to decide to add this tax to passengers' tickets or to the flight operators. But these measurements are very critical as may lead to decrease of load factor, which has negative environmental impact (Mayor & Tol 2008). One important action to reduce the industry's CO₂ emissions is to renew the fleets by removing the old and less efficient aircraft. Studies show that airlines' decision for investing on purchase of new airplanes is so dependent on oil price and carbon price under EU ETS (Girardet and Spinler, 2013; Malavolti and Podesta, 2015).

According to European Commission (2015a), European Emission Trading System (EU ETS) has been among the most cost-efficient and environmentally effective options for controlling aviation emissions in comparison with other optional measurements such as fuel tax. Anger (2010) and Venmans (2012) in their studies analysed EU ETS an effective measurement for emissions reduction in EU. Some studies suggest that the deployment of measurements such as the EU ETS are not enough for the CO₂ reduction in the sector, and combining them with other measures such as fuel taxing will make the whole emission reduction strategies more effective (Carlsson and Hammar, 2002; Fukui and Miyoshi, 2017).

According to Anger (2010), depending on the different allowance prices, even up to 7.4% in CO₂ emitted by the air transport industry is possible. More recent studies about the impact of EU ETS system show changes in airlines' behaviour. It has led airlines to increase their load factor and efficiency or in case of less efficient aircraft, they have decreased their activities which both approaches resulted in less emissions (Malavolti & Podesta 2015).

2.1.4. Technology Advancement

In terms of the engine/airframe, and what can be done from an engineering point of view to mitigate against aviation's climate impacts, this largely comes down to the combustion/propulsion system in terms of atmospheric science questions, other than small incremental improvements from aerodynamics to fuel burn rate and more radical new airframe configurations such as the blended wing body.

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The most promising way to reach a more sustainable aviation sector is to invest in steady technological improvements, the fleet modernization through deployment of

most efficient available aircraft and utilization of advanced operational systems (IATA, 2009a; ATAG, 2010).

Fuel still is considered the largest component of airline cost structure, though depending on the price of oil; its share in the total operating costs is changed. Table 2 presents the oil price fluctuation during last 4 years and its impact on the airlines' total operating costs. The forecasts of IATA (2016b) show that the airlines' fuel expenses in 2016 fall to US\$127 billion which is less than 20% of the total operating costs of airlines. Since 2004, this is first time the industry experiences a sharp decline of oil price.

Table 2. The last four years trend of fuel price and fuel efficiency in global airline industry
(The information of this table has been extracted from (IATA 2014a, 2015a, 2016b))

Worldwide airline Industry	2013	2014	2015	2016
Fuel spend, \$billion	208	226	180	124
% change over year	0.40%	-1.80%	-19.90%	-31.20%
% operating costs	30.10%	31.60%	27.30%	19.20%
Fuel use, billion litres	261	278	307	323
% change over year	1.60%	4.20%	5.60%	5.10%
Fuel efficiency, litre fuel/100atk	24.10%	24.30%	23.90%	23.70%
% change over year	-1.90%	-1.10%	-0.70%	-1.00%
CO2 million tonnes	693	739	775	814
% change over year	1.60%	4.20%	5.60%	5.10%
Fuel price, \$/barrel	124.50%	115	66.7	52.1
% change over year	-3.90%	-7.80%	-41.90%	-21.90%

*Note: ATK = Available Tonne Kilometres.

Data related 2016 are estimation.

Fuel efficiency improvements in aircraft engines have been always a key subject in research and development (R&D) programs of the sector as the rate of fuel burn in aircraft, directly impacts the financial and environmental sustainability of flights (IPCC 2007). In 2010, ICAO decided to lead the industry toward 2% a year fuel efficiency improvement until 2050 (ICAO 2011b). Aircraft and engine manufacturers invest about US\$15 billion annually on R&D programs targeting the efficiency improvements of airlines' fleets. The technological improvements in aviation emissions reduction have been successful but not enough to meet the needs of this fast growing industry. David S. Lee et al. (2009) explain that: "Technological improvements usually involve aerodynamic changes, weight reductions, more fuel- efficient engines, and increased operational efficiency". Operational advancements have an important impact on aviation fuel efficiency improvement, which are discussed in section 2.3.5. According to Joosung J. Lee et al. (2001), the fuel efficiency improvements between 1959 and 1998 were mainly related to: utilization of more fuel-efficient engines (57%), improvements in aerodynamic efficiency (22%), increase of load factor (17%) and increase of aircraft size and other factors (4%). Technological evolution of air transport sector in different dimensions has been impressive. Utilizing "carbon fibre composites" in the aircraft wings to reduce the overall weight or "ceramic-matrix composites" in aircraft engines to improve the engine efficiency by enabling the engine to operate at a higher temperatures are some of the recent technological advancement (ATAG 2016a).

Morrell (2009) argues that increase of overall aircraft size results in 1% a year improvements in fuel efficiency during the next two decades. International reports indicate that the average rate of efficiency improvements has fallen from yearly 2.5% fuel efficiency improvement in 1983-1990 period to 2.2% in 1994-2003 period (Janić, 1999; DG Energy and Transport, 2007; Morrell, 2009b; European Commission, 2010). It is partly due to the fact that technological advancements are not unlimited and have an optimum level. Morrell (2009) identifies two main trends in the aviation fuel efficiency improvements:

- a) Applying new technologies in the aircraft with the same size
- b) Utilizing larger aircraft adjusted to the existing technology and benefiting from economy of scale in the rate of fuel burn.

The latter approach is seen particularly in short- and medium-haul routes.

According to a study by Air Transport Department of Cranfield University (2010), replacement of older aircraft with 20-25 years of operation can result in 20 to 25% fuel efficiency improvement which means 1% fuel saving annually. "On average, each new generation of aircraft is roughly 20% more efficient than the previous generation" (ATAG, 2016a). There are different factors influencing the decisions of airlines about fleet renewing including leasing opportunities, operating costs, flexibility of capacity configuration and new aircraft availability. Environmental goals of ICAO strongly encourage airlines to use best-available technology aircraft (highest fuel efficiency rate) both regarding capacity and range in the specified flight segment (OAG 2009). According to IATA (2009), about US\$1.5 trillion will be invested on fleet renovations to replace 5,500 aircraft (27% of the total fleet) by 2020. This fleet renovation results in 21% CO₂ emissions reduction. Some new aircraft types such as the Airbus A350-900, the Boeing 787 Dreamliner and the Bombardier C Series, or re-modelled versions of existing aircraft such as the A320neo and the Boeing 747-8 have already joined the fleet. Manufacturers such as CFM International, Pratt & Whitney, GE Aviation and Rolls Royce introduce these new aircraft with high fuel-efficiency to market. Also the completely new fuel-efficient aircraft types such as the Embraer E2, Airbus A330neo and Boeing's 777X and 737MAX are expected to join the fleet by 2020 (ATAG 2016a). Referring to Frederick (1961), Peeters, Middel, and Hooijmans (2005) and Ryerson and Hansen (2010), environmental costs of turboprop aircraft are smaller than jet engines aircraft.

The growth of air travel demands is responded by airlines with two different approaches: a. Increasing the size and capacity of aircraft b. Increasing services frequency (M. Givoni, 2005; Pai, 2010). Airlines try to expand their capacity focusing on cost optimization by reduction of fuel consumption and trade-off between different choices. Though from environmental point of view these options are not the same. As discussed previously, the major part of flight's fuel burn occurs in the take-off, which means more flight frequency results in more GHG emissions. Besides, studies of Peeters, Rietveld, and Schipper (2001) and Moshe Givoni et al. (2009) show that larger aircraft

are more environmental friendly and have less passenger-kilometres costs comparing with smaller aircraft.

During the last two decades, the average size of aircraft in short-haul, medium-haul and long-haul regional routes has been showing a tendency towards 160 seats per aircraft. For the longer-haul regional routes like transcontinental paths, the aircraft size has been steadily at 160 seats utilizing airplanes such as Boeing 737-800, which are capable of point-to-point services and greater frequencies for passengers. Increased payload capability has provided airlines with the opportunity to carry additional passengers and cargo (Boeing 2014a). Due to the expected annual growth rate of air traffic, nearly 5% a year, the airline industry needs to expand its capacity by approximately 4% a year (Boeing 2015).

In the new approach to aircraft design, manufacturers consider the capacity of aircraft and its flying range and potential routes. This approach helps airlines to choose the most compatible aircraft with the routes and reduce their environmental costs. For instance, in the large airports with high demands, airlines can use large wide-body aircraft, which are designed for short distances instead of increasing their flight frequency (Moshe Givoni and Rietveld, 2010; Yongha Park and O'Kelly, 2014). Williams and Noland (2006) also suggest that long-haul flights are per kilometer more fuel-efficient than short-haul flights.

Besides, the increase of aircraft load factor have reduced the total fuel burn (Kling and Hough, 2011; Mayer, Ryley, and Gillingwater, 2015). Steven and Merklein (2013) in their study indicate "Airlines aim to minimize non-essential weight and maximize load factors by carrying more passengers or freight on given distances". Currently maximizing the load factor is one of the important targets of airlines to decrease their negative environmental impacts (Moshe Givoni et al., 2009; Arul, 2014). Airlines' strategies for increasing load factor are to utilize larger aircraft or to configure the aircraft cabins to add more seats. The relationship between fuel efficiency and aircraft size is stronger in single-aisle aircraft while for larger aircraft is not considerable (Morrell 2009). The best results have been achieved by those airlines, which are using modern aircraft, with high seating density and high rates of passenger occupancy and load factor. David S. Lee et al. (2009) point out the importance of load factor increase in the decline of air transport CO₂ emissions and indicate that the worldwide average of airlines' load factor has risen from 68% in 1989 to 76% in 2006. The study of Morrell (2009) also shows that the average load factor of international scheduled flights has increased from approximately 67% in the early 90s to around 80% in 2006.

According to Atmosfair Airline Index (Atmosfair 2015) as is illustrated in Figure 4, currently, the load factor is the leading parameter and aircraft type is the second parameter in controlling aircraft CO₂ emissions.

Figure 4. Atmosfair Airline Index 2015 showing various factors' impact on airline energy optimization (Source: Atmosfair 2015)

The feasibility and cost of efficiency improving tools for airlines are different. The priority of airlines like any other economic sector is their financial sustainability. Morris et al. (2009) in their study introduce a concept calling “marginal abatement costs” which is used to determine the most cost effective measures for aviation emissions reduction. The “marginal abatement costs” can guide airlines to choose cost effective strategies to increase their fuel efficiency. Figure 5 illustrates the “marginal abatement costs” curve prepared Morris et al. (2009). This figure shows the cost of per unit of CO₂ emissions reduction for airlines (\$/tCO₂) during one year. It seems that improvement of efficiency in operational activities of airlines is the most cost efficient action. As it has been illustrated, the fleet renewal has a major impact in CO₂ emissions reduction but is the most expensive action.

Figure 5. “Marginal Abatement Costs” by Morris et al. (2009)

Sometimes airlines need to make strategic plans such as joining a business partner to increase their opportunity to invest while decreasing their risk. Steven and Merklein (2013) explain that airlines with business alliance are more are about 1.7% more productive comparing with airlines without partners. Airlines can increase their productivity by joining more business alliances. For example for big investments like

substituting younger fleets, airlines need investment cooperation between business alliances.

Applying advanced technologies is important for fuel saving in aviation. Though the cost and duration of introducing these new technologies in different countries with different economic situation are different (Dray et al. 2014). If it was possible to replace entire old fleets by the most fuel-efficient aircraft, 10% of air transport CO₂ emissions could be avoided. Though according to the long life of aircraft which is about 30 years, replacing old aircraft by new technology aircraft is a time consuming process (Dray 2014). According to (IPCC 1999) the average lifetime of aircraft are expected between 25 to 35 years. Airplanes before being removed completely from the industry, experience several owners and the decision for scrapping them is affected by various economic factors. Generally due to the high growth rate of air traffic, in most cases new aircraft are acquired in response to new demands not as substitution for old aircraft. Therefore the fleet renovations and new technology introductions are highly impacted by the increase of market demand. Policy makers should consider these market variables in their decision makings (Dray 2014).

“There is no “one technology solution fits all.” The best design depends strongly on the aircraft mission and the market niche at which it is aimed. The quantitative value of new technologies can only be accurately judged during the complex process of aircraft design optimization”.

(The World Bank 2012)

Some technological improvements in aviation are not any more optional and will be applied to all new aircraft (Lee 2000). Introducing more radical configurations, such as the flying wings, have the great potential for fuel efficiency improvements, but these radical shifts normally are involved with large uncertainty for operators. Bringing radical changes to the industry takes more time to be commercially accepted (Åkerman 2011). Some other radical innovative designs such as open rotor engines or aircraft with blended wing body are expected to increase aircraft fuel efficiency greatly but they are more expensive in comparison with small technological improvements (Dray et al. 2014). For instance, about 31-45% CO₂ emissions can be saved through replacement of turbofan engines by open rotor engines (Vera-Morales et al., 2011; Schäfer et al., 2011). Boeing is going to introduce new blended wing body aircraft in future which are expected to be 15% lighter during take-off and burn 27% less fuel per seat kilometres (Liebeck 2004). Biofuel commercial use is another important new-technology option considered which high capacity for aviation emissions reduction. This subject is discussed in section 2.3.3.

2.3.2.1. EU Technology Advancement

In The European Union, aerospace equipment manufacturing has been an important economic contributor, which stands as the second largest transport equipment-manufacturing subsector. Besides, the investments in aerospace R&D programs has

been the second largest R&D investments in transport sector (Eurostat 2014). The total R&D investments in European civil aeronautics in 2008 was Euro 6.9 billion and in 2015 about Euro 8.2 billion (ASD, 2008&2015). The major R&D investments in European civil aeronautics, about 66% in 2015, has been made by the nineteen largest companies based in EU such as Airbus Group, Finmeccanica, Rolls Royce and Safran (ASD, 2015; Wiesenthal, Condeco-Melhorado, and Leduc, 2015).

The statistics show the importance given to technological improvements in EU air transport sector. The European Union in cooperation with private sector has launched different R&D projects targeting fuel efficiency and CO₂ reductions in transport sector. TOSCA is one the EU projects aiming to investigate opportunities for promising technology advancements to mitigate GHG emissions caused by transport sector until 2050. Under the umbrella of TOSCA program, many projects regarding air transport fuel efficiency are conducted (Graham et al. 2014). EU ambitious goal of an overall fuel efficiency improvement of 50% by 2020 is following by ACARE (the Advisory Council for Aeronautics Research in Europe) to provide strategic advisory in the sector on the way of achieving this goal (European Commission 2011b). This 50% cut in aviation CO₂ emissions is achievable by improvements in the following areas (Airbus, 2007; Nygren, Aleklett, and Höök, 2009):

- 20 to 25% through technological advancements in mechanical structure of aircraft and airframe;
- 15 to 20% through technological advancements in aircraft engine;
- 5 to 10% through air traffic management improvements.

As it has been discussed in the previous section, increasing the load factor is a strategy toward CO₂ emissions reduction in EU. According to EASA, EEA, and EUROCONTROL (2016), from 2005 to 2014, the average number of passengers per flight has risen from 87 to 113 and average load factor of passenger flights from 70.2% to 76.7%. To increase each airplane capacity, the aircraft seats have become slimmer and lighter. Besides, during the same period, the average of flight distance has grown from 1,480 km to 1,650 km. These changes together have brought about 19% reductions to CO₂ emissions per passenger kilometre. In the segment of EU air freight the similar trend is seen too. While the volume of air freight increased about 30% during 2005-2014, the number of freight flights decreased by 4%. Particularly, the number of freight aircraft carrying less than 50 tonnes of take-off weight has declined sharply. Analysis of Lenoir (2016) reveal that load factor has been evolving at a steady rate in EU. Over the past twenty years, load factor has increased by 1.46 % per year in the EU.

2.1.5. Sustainable Alternative Fuels

Global concerns about limited sources of fossil fuels, challenges of fuel price instability and supply and demand; and international aim to reduce greenhouse gas emissions of air transport sector, all together led the industry to invest on R&D projects to explore sustainable alternative jet fuels and adopt available or in production aircraft for utilizing them (D. S. Lee et al., 2009; J. Scheelhaase, Grimme, and Schaefer, 2010; Boeing, 2014). Sustainable alternative jet fuels have been identified by the industry as one of the

key elements in the green path to a more sustainable aviation industry (Gökalp and Lebas, 2004; Blakey, Rye, and Wilson, 2011; IATA, 2015b). Expansion of alternative aviation jet fuels utilization in the air transport resulted in less dependency on fossil fuels. This trend provide the sector with a more diverse geographic supply chain as alternative fuels opposite to fossils fuels are not limited to especial locations. At the same time many shipments related to fossil fuel transfer will be avoided and maybe local smaller scale supply chains will be built (ATAG 2009).

In current work, just the impact of biofuels as the most sustainable alternative fuels is studied. Until now, biofuels has been categorized to three generations (OECD/IEA, 2008; ATAG, 2009b; Eisentraut, 2010; EBTP-SABS, 2015):

- **First-generation biofuels** are produced from sources such as sugar, starch, vegetable oil and animal fats. Typical first-generation biofuels are sugarcane ethanol, starch-based or corn ethanol, biodiesel and Pure Plant Oil (PPO). This biofuel generation has some negative sides as competes with food resources and causes deforestation. Besides, the first-generation biofuels including ethanol and biodiesel are not appropriate for civil aircraft engines.
- **Second-generation biofuels** are made from sustainable sources of biomass like as remainders of forests, industries, household and city wastes and sustainable grown biomass. Second-generation biofuels are considered the best alternative for jet fossil fuels regarding the following points (ATAG 2009):
 - They are based on sustainable sources not any valuable resources;
 - They have the potential of being produced in any location around the world, even in deserts and salt water;
 - The producers of **second-generation biofuels** can deliver sufficient amount of sustainable fuel for aviation at more stable prices.

The second-generation biofuels are include bio-derived oil, sourced from feedstocks such as jatropha, camelina, algae and halophytes; They can be “Fischer-Tropsch Synthetic Paraffinic Kerosene” derived from “Biomass to Liquid” processes or “Hydrotreated Renewable Jet” produced as “Hydroprocessed Esters and Fatty Acids (HEFA)”. Both fuels are approved by ASTM International⁶ for use in jet engines, at blend rates up to 50% with petroleum jet fuel (McCollum, Gould, and Greene, 2010; IATA, 2011a; EIA, 2016a). As both fuels are pure hydrocarbons, they can theoretically be used in any mixing ratio with each other and with conventional fossil jet fuel (Köhler et al. 2014).

- **Third-generation biofuels** are made from sustainable biomass sources such as algae, babassu, jatropha, switch grass and halophytes.

According to Sgouridis, Bonnefoy, and Hansman (2011), second-generation and third-generation of biofuels are capable of CO₂ emissions reduction by 70% and 20%

⁶ ASTM International is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services.

respectively comparing with the fossil jet fuels. IATA's focus is on biofuels sourced from second or new generation biomass (IATA 2014b).

After years of various R&D projects invested by public and private air transport stakeholders, technological advancements and strategic cooperation between airlines and fuel producers, now sustainable aviation biofuels have been accepted as a feasible way to reduce emissions from the aviation sector. The first successful biofuel flight was in 2011 (IATA, 2013; ICAO, 2016b). This success was followed by more commercial airlines carrying on successful tests and using sustainable alternative jet fuels. Currently over 2,500 commercial flights powered by blends of up to 50% biojet fuel from used cooking oil, jatropha, camelina, algae and sugarcane, operated by 23 airlines across the globe (IATA, 2015a; ICAO, 2016b; IATA, 2016c).

The number of flights operates using blends of biofuels and conventional kerosene is increasing and it has been proved that alternative fuels are safe and technically compatible with aircraft systems. However, production of aviation biofuels is still far from the industrial scale and the high quality requirements for the commercial aviation fuels limit the broad application of current alternative fuels for all exiting aircraft (Waynick, 2001; Daggett et al., 2008; Nygren, Aleklett, and Höök; 2009; Lee, 2010; Gupta, Rehman, and Sarviya, 2010). To promote sustainable alternative aviation fuels, support of governments and policy makers is essential. Aviation industry needs to invest to develop a long-term production plan for sustainable alternative fuels which is cost competitive (IATA 2015c). The ICAO Sustainable Alternative Fuels (SUSTAF) Experts Group started working on long-term planning. They focused on the identification of the major challenges for the deployment of sustainable alternative fuels for aviation and on possible solutions to overcome them. Their strategies consist of (ICAO 2016c):

- Establishing robust biomass feedstock supply chains;
- Ensuring that the biomass feedstock is produced in an environmentally, socially and economically sustainable manner;
- Supporting necessary investments to build the production facilities;
- Developing policies that promote the use of Sustainable Aviation Biofuels;
- Improve fuel production technologies by continues investment in R&D projects.

Currently, 5 biofuel production lines are technically certified and 16 more are on the process. The airlines which are involved are: KLM, Lufthansa, Finnair, Interjet, Aeromexico, Iberia, Thomson Airways, Air France, United Airlines, Alaska Airlines, Thai Airways, LAN, Qantas, Jetstar, Porter, Gol, Air Canada, bmi, Nextjet, SAS, Norwegian and Hainan Airlines (IATA 2016d). Since beginning of 2016, a forward step in development and commercialization of biofuels has happened by introducing Oslo Airport as the first international hub to offer sustainable alternative fuel to all airlines flying in and out of the Norwegian capital. An important challenge now is to provide enough biofuels (at a cost-effective price) to as many airlines as possible around the

world (ATAG 2016a). The current challenges of market are commercial and political challenges not technical. Still biofuel productions are more expensive than fossil Jet fuel. At the same time more investment in biofuel productions seems risky especially to private sector, as still the broad demand is low; therefore, carefully designed policy is needed to promote investment and development of biofuel production capacity (IATA 2016d). A study by Noh, Benito, and Alonso (2016) suggest that learning from other transport modes, biofuel subsidizing through advanced tax management or offset mechanisms in combination with obligation for minimum level of biofuel in blending with jet fuels are some options for policy makers which in future should be studied. According to the aviation industry's development plan by the end of 2016, about 5,500 flights will have taken place using sustainable alternative fuels. The capability of CO₂ emissions reduction by biofuel substitution is estimated up to 80% (ATAG, 2016a; IATA, 2016c).

2.3.3.1. Alternative Fuels in EU

In 2011, the European Commission in partnership with Airbus, and in cooperation with leading European Airlines (Lufthansa, Air France/KLM, and British Airways) and biofuel producers (Choren Industries, Neste Oils, Biomass Technology Group, and UOP) launched the "European Advanced Biofuels Flightpath" (European Commission 2016c). This initiative "European Advanced Biofuels Flight path" is a shared and voluntary commitment by its members to support and promote the production, storage and distribution of sustainable production of aviation biofuels. It also targets the establishment of appropriate financial mechanisms to support the construction of industrial biofuel production plants. This roadmap has clear milestone to achieve an annual production of two million tonnes of sustainably produced biofuel for aviation by 2020 (European Commission, 2011b, 2013b; Sanz et al., 2014). Continued growth in biofuel consumption needs new production lines and the scale-up of production facilities to reach a more competitive price comparing with fossil jet fuels (European Commission 2016b). More specifically, the EU actions focus on the following issues (ICAO, 2011c; FOCA, 2012; IATA, 2012):

- Facilitate the development of standards for drop-in biofuels and their certification for use in commercial aircraft;
- Work together with the full supply chain to further develop worldwide accepted sustainability certification frameworks;
- Agree on biofuel take-off arrangements over a defined period of time and at a reasonable cost;
- Promote appropriate public and private actions to ensure the market uptake of paraffinic biofuels by the aviation sector;
- Establish financing structures to facilitate the realization of second-generation biofuel projects;
- Accelerate targeted Research and Innovation (R&I) for advanced biofuel technologies, and especially algae;

- Take concrete actions to inform the European citizen of the benefits of replacing kerosene by certified sustainable biofuels.

2.1.6. Fossil Fuel Prices

Oil price fluctuation in the last decades has been an important concern of air transport industry due to its impact on airline's business plans and cost structure. The volatility of fuel price makes the profitability of airlines very difficult (J. Hansman et al., 2014; Kristjanpoller and Concha, 2016). One of the major problems for industries dependent on oil price is the fact that forecasting fossil fuel prices far into the future is extremely challenging as oil price is impacted by a large number of factors. Worldwide political instabilities, economic growth rates across the world, development of new technologies, global climate change policies and strategies, all affect oil price (DECC, 2015; EIA, 2016). The aviation industry is very dependent on oil products and consumes almost 6.3% of world refinery productions including both jet fuel and aviation gasoline (Nygren et al. 2009). According to Becken and Lennox (2012) in the short term a large number of factors influences the price of oil, while long-term prices are driven by world oil demand and supply, which is ultimately limited by resources. According to J. Hansman et al. (2014), fuel price increase can provide a cost motivation for operational efficiency improvements. By adopting strategies that improve fuel efficiency, airlines can reduce their unit fuel cost, prevent airfare rise and maintain financial return. Oil price can impact tourism as the main customer of civil aviation. Some studies discuss that countries reaction to oil price fluctuation is different depending on various factors including the share of oil costs in their GDP (Blanke and Chiesa, 2011; Becken and Lennox, 2012). For example in oil producers countries in Middle East, lower oil revenues make air travelling less attractive though can create new opportunities like LCC development (Morrison and Mason 2016). Analyses show that even if the price of oil is increasing much higher than the 2008 record, just the ratio in which air traffic is growing will decline or it may become a luxury product again (Eurocontrol 2008).

Fuel cost is a major part of airlines' operating expenses and depends on fuel price and aircraft fuel burn (Eurocontrol 2008). The global airline industry's fuel bill is estimated to total \$181 billion in 2015 which means about 27% of its operating costs at \$54/barrel Brent of oil. This is a decrease of -20.5% over 2014's fuel bill and is over 4 times 2003's bill of \$44 billion. In 2016 the fuel bill is forecasted at \$127 billion accounting for 20% of operating costs at \$45 per barrel Brent (IATA 2016c). The lower price of oil on 2015, about 50% lower than in 2014, resulted in a huge rise in airlines' profitability. Net profits reached around US\$35 billion in 2015 (Boeing, 2016; Macquarie Research Group, 2016). The International Air Transport Association (IATA) has forecast that due to oil price decline, the profit of European carriers will rise by 23% in 2016 which will result in a recovery in the EU economy and strong business travel on North Atlantic routes (Macquarie Research Group 2016). Table 2 shows how the fluctuation of oil price can affect airline's operating cost structure and threaten their financial sustainability.

Table 2. Oil price and aviation fuel share of operating cost

Year	% of Operating Costs	Average Price Per Barrel of Crude (US\$)	Total Fuel Cost (US\$ billion)
2003	1.6	28.8	44
2004	17.3	38.3	65
2005	22.2	54.5	91
2006	28.1	65.1	127
2007	29.8	73	146
2008	35.7	99	204
2009	28.3	62	134
2010	28.3	79.4	152
2011	30.8	111.2	191
2012	33.1	111.8	228
2013	33.1	108.8	230
2014	31.6	99.9	226
2015	27.5	53.9	181
2016	19.7	45	127

*Source: Industry Economics Performance – Forecast Table (IATA Economics) 06/2016

Low prices may bring short-term gains to consumers, but can have negative long-term impacts such as ignoring future risks related to energy security and environmental sustainability. Policy makers have to consider that lower energy prices can slow down energy efficiency efforts. Oil price reduction can slow down the development of biofuel advancement and its commercialization too. Taking into account different scenarios about oil price in the world, aviation industry cannot rely just on a finite resource like oil and should work on its independency and efficiency improvements constantly (OECD/IEA 2016). Another negative impact of lower oil price is that airlines may postpone their fleet renewing and older aircraft become increasingly competitive with new planes. It has become attractive to airlines to extend the use of older aircraft or lease older airplanes. Even considering the more fuel burn and maintenance expenses of older aircraft, they are still more attractive for many airlines (Tipping, Schmahl, and Duiven, 2015; Saketa, 2016).

2.1.7. Operational developments

Aviation operational activities consist of business processes, fleet planning and operational procedures of flights. The opportunities for operational efficiency improvements are usually win-win solutions for airlines as they are dealing with fleet's cost reduction which most of the time results in less fuel consumption and less emissions. Besides, operational improvements do not always require huge investments for newer technologies or fleet renovations. Optimization of operational procedures to use available equipment and resources more efficiently can reduce airlines' costs significantly. Policy makers have started to point out the importance of operational developments in the sector. In 2001, International Civil Aviation Organization (ICAO) started supporting of operational improvements by promoting "new communication, navigation, surveillance and air traffic management (CNS/ATM) systems" to reduce

fuel consumption and GHG emissions. ICAO in February 2004 published “Operational Opportunities to Minimize Fuel Use and Reduce Emissions” to support operational improvements in air transport industry (ICAO, 2007a; 2016c). IATA also has started a program called “Fuel Action Campaign” to encourage airlines to improve the efficiency of their operational activities by strategies such as “opening new and more direct routes (shortening and optimizing the routes as much as possible), eliminating inefficient routes, and improving ground traffic flows” (IATA, 2013b; Guo, Zhang, and Wang, 2014). Steven and Merklein (2013) suggest that “avoiding unnecessary distance-related activities, cancelling low demand flights and reducing detours and holding patterns” should be implemented by airlines to save fuel consumption.

Guaranteeing the operational safety and improving their efficiency is one of the main challenges of the sector. According to ICAO reports, there are four interrelated grounds for continuous universal improvement: a. Airport Operations; b. “Globally Interoperable Systems and Data; refers to applying the full potential of Flight & Flow Information for a Collaborative Environment (FF-ICE)” and to enhance data and information management. c. Optimum Capacity and Flexible Flights; refers to applying the full potential of a global integrated ATM system. d. Efficient Flight Path; refers to applying the full potential of Trajectory-Based Operations (TBO) (ICAO 2013a). Any improvements in these grounds such as optimization of aircraft speed, limiting utilization of auxiliary power, which is used for heating, ventilation and etc., just in time fuelling and reducing taxiing time have a considerable impact on fuel consumption reduction. As it has been discussed in section 2.3.2, optimizing flights’ capacity and increasing the load factor and eliminating non-essential weights are very important in reduction of fuel burn too. The average efficiency improvement in result of these operational measures is about 2 to 6% (IPCC 1999). David S. Lee et al. (2009) in their study discuss the impact of optimization of aircraft size and capacity rate on air transport fuel efficiency. As it has been discussed in previous sections, during last years the tendency of aircraft size has been to larger aircraft, as in some routes they are more cost-effective.

2.3.5.1. Air Traffic Management

Air traffic management (ATM) is about the dynamic and integrated operating procedures, technology, and human resources responsible for the safety and efficiency of air transport system. ATM in one hand is responsible for guiding the aircraft safe through the flight and take-offs and landings and, on the other hand is responsible to provide the changing needs of air traffic over time.

Air Traffic Management originally deals with three distinct areas (ICAO, 2005; Eurocontrol, 2016b):

2. Air Traffic Control (ATC)

ATC refers to the services operated by ground-based authorities, which are responsible of the safe, orderly and expeditious flow of air traffic.

3. Air Traffic Flow Management (ATFM)

ATFM refers to an activity that is done before airplane starting to fly. The flow management process should monitor available capacity and demands at the airports and in the terminals and in airspace routes. Based on this monitoring will ATFM providers, implement appropriate strategies to protect ATC from overloads and to provide an optimal flow of traffic by making best use of available airspace capacity. All operating aircraft, from a business airplane to an airliner, use ATC and files a flight plan and sends it to a central repository.

4. Aeronautical Information Services

These services are responsible to gather and circulate all necessary aeronautical information to all airspace users. This information consists of safety, navigation, technical, administrative or legal matters and their updates. The information can take the form of maps showing the air routes and ATC centres and the areas that they are responsible for; or it can be notices, information circulars or publications.

While air traffic is growing continuously, management of operating processes related to capacity limitations, airline and airport security, planning and scheduling of flights, are getting more complicated. To deal with this growing travel demand, airlines need a more efficient and accurate ATM system. Aviation industry has identified ATM improvements a fundamental parameter to conduct air transport system toward sustainable goals. The Intergovernmental Panel on Climate Change (IPCC) estimated the potential of improvements in air traffic management and other operational procedures on CO₂ reduction around 8 to 18%, which 6 to 12% of this amount per flight, is related to ATM improvements (IPCC, 1999a; AEA, 2001; Somerville, 2003; Reynolds, 2009). Schäfer et al. (2011) estimate that efficient ATM systems can reduce CO₂ emissions of all aircraft designs about 5- 11%. According to ICAO (2007a), advanced ATM systems enable aircraft to choose a more direct route and optimize its flight conditions by selecting optimum altitude and speed which results in considerable emissions mitigation. If operators could implement a 100% efficient ATM system, aircraft was able to fly point to point while using the entire flight time the optimum route between airports. But facing an amount of inefficiency is unavoidable as ATM providers have to deal with various factors such as safety, capacity, weather, noise, airline practices and institutional and military airspace exist (IPCC, 1999c; CANSO and The Boeing Company, 2012; The World Bank, 2012).

Concerning the safety, many times aircraft has to deviate from its ideal route to maintain a secure distance with other aircraft. Concerning the weather, there are always some uncertainties in the forecasts. ATM providers should ensure safe and smooth flights and stop flying in adverse weathers. The capacity management is a complicated issue for operators to manage as both airspace and airports have limited capacity. Sometimes aircraft is required to wait before landing or departing. ATM technological advancements have made analysing and optimizing the civil airspace capacity easier but ATM systems don't have any control on airport capacity management. Concerning the

noise, operators have to respect especial limitations around the airports to avoid noise pollutions. In some cases they have to choose a route, which is less efficient or fly in an altitude, which is not ideal. “Flight-planning systems” play an important role and as much as they are more flexible, they are more capable to benefit from the available optimal routes. Sometimes civil aircraft are asked to avoid military airspace zones or other types of airspace restrictions. Also aircraft may take less optimal routes due to fragmented airspace. Different regions/countries may have different operating procedures, charging mechanisms and require specific protocols that may lead to a less fuel-efficient routing (The World Bank 2012).

According to (Canso 2012), half of ATM inefficiencies are related to interdependencies but the other half still have the potential for improvement. The report prepared by Canso (2012) is called “ATM Global Environment Efficiency Goals for 2050”, indicate currently the global level of ATM fuel efficiency is between 92% to 94%. The CANSO goal is to save 79 million tonnes of CO₂ emissions per year and 4% increase in ATM fuel efficiency by 2050. European Union and US are following their regional ATM system improvement by SESAR and NextGen programs respectively. Both programs have set targets for environmental improvements. SESAR is targeting a 10% reduction in environmental impact by 2025 relative to 2006. NextGen is persuading a 12% reduction of environmental impacts by 2025.

Operational measures for ATM improvements by implementing SESAR in EU results in 70% cut in route extension and by implementing NextGen in US results in 57% reduction in delays (IATA 2009). A Study by Dray et al. (2014), explains that both programs are expected to be fully applied during 2015–2025 as many current potential improvements are not any more optional and will cover all the sector. One of the challenges ahead of achieving more efficient ATM is that the main suppliers of ATM are governmental entities (there are just a few notable exceptions)⁷. As in most of governmental entities happen, many civil aviation authorities are not enough motivated to face difficulties of reaching a more efficient system and this approach in many highly utilized systems leads to a mismatch between supply and demand (McDougall, G, Roberts, 2008; 2012).

To have a more efficient ATM system we need a global integrated ATM system. An integrated ATM enables aircraft operators to meet flight plans and departure and arrival timings, to follow optimized flight profiles with minimum constraints and no safety risk. This integration increase the flight flexibility and efficiency in high-density traffic areas (IPCC 1999a).

⁷ These expectations consist of NavCanada, where this control is now in the hands of a not-for-profit agency and NATS, a public-private partnership in the United Kingdom.

Aircraft have an optimal cruise altitude that minimizes the rate of fuel burn and CO₂ emissions (Canso 2012). According to Williams and Noland (2005), reducing cruise altitude reduces contrails and limits the negative impacts of NO_x emissions on Ozone while increases fuel burn. Williams and Noland (2005) suggest that a restricting cruise altitude policy should be applied to optimize the altitude restrictions to improve contrail reduction while is lowering the rate of increase in CO₂ emissions. At the same time reducing the cruise altitude decrease the journey time and consequently fuel burn in the climb and descent phases whereas flying in a limited cruise altitude has negative impacts of air space capacity reduction and journey time increase (Williams, Noland, and Toumi, 2002; Chapman, 2007). More recent studies discuss that by applying new technological improvements in ATM, aircraft can operate without altitude restrictions during departure or arrival phases to optimize the flight profile for less fuel burn and CO₂ emissions (ICAO 2015a). According to (Canso 2012), until 2002, aircraft flew in altitude bands separated by 2000 feet intervals. Due to technological improvements in aircraft fleet and ATM systems, now by deployment of Reduced Vertical Separation Minima (RVSM), aircraft can reduce their altitude bands to 1000 feet without compromising safety. This enables aircraft to fly closer to their optimal altitudes. Referring to Malwitz et al. (2007), RVSM alone have the capability of about 1.8% improvement in fuel efficiency.

A Eurocontrol study by Jelinek, F., Carlier, S., Smith, J., Quesne (2002) shows that the introduction of RVSM over Europe can lead to 1.6–2.3% fuel burn reduction. More advanced World Area Forecast Systems (WAFS) has been introduced which provide information on cumulonimbus clouds, icing, volcanic ash and turbulence as well as reference to Internet-based services. These system upgrades, enhance safety and fleet planning which increase the fuel efficiency of system (ICAO 2016e).

Continues air traffic growth results in more complex planning and significant growth in delays. Air traffic delays impose unnecessary costs to airlines, passengers, and other indirect stakeholders in addition to their environmental costs. Congestion forces aircrafts to flight in cruise altitude and/or the cruise speed other than optimized ones results in extra fuel burn and GHG emissions globally and locally at airports (Joosung Joseph Lee, 2000; Clarke et al., 2008). According to a report prepared by The World Bank (2012), updating the old air traffic control systems, which are based on 1950s-era technology can banish 12% CO₂ emissions of commercial air transport. Shortening the average length of commercial flight by one minute can save 4.8 million tonnes CO₂ emissions per year.

Predictability is highlighted in air transport literature as a crucial parameter in air transport efficiency. Poor predictability imposes excessive costs to operators. Predictability in the context of weather forecasts and traffic flow (Cook et al. 2015), better “collaborative decision-making”, better “management of reaction to bad weather conditions” and better “control of take-off times” (Desart et al. 2010), or more efficient planning for flights and preventing extra fuel loading before the departure (Hao, Hansen, and Ryerson 2016), are have been related to flight predictability which its improvement reduces costs and fuel burns of aircraft. According to Hao, Hansen, and

Ryerson (2016), a 1 minute deviation from flight's standard schedule can cause 1.66 minutes rise in the total contingency and alternate fuel loading. Hao, Hansen, and Ryerson (2016) explains that extra fuel loading results in more fuel consumption. "You burn fuel to carry fuel. In the industry, this is known as cost to carry". It shows that how time deviation due to lack of predictability led to more fuel burn and CO2 emissions. In their study they found that the forecasted weather at destination airport, comparing with all weather factors, has the greatest influence in fuel loading. Improvement in predictability helps operators to define their cost structure in a more efficient way, planning the flights in with optimum situation. This prevents flight and network overloads (Eurocontrol 2016c). Traffic variability is another factor affecting the ATM performance. Traffic demand variability impacts on productivity, cost-efficiency, service quality and predictability of operations. Variability can be categorized to seasonal variability (difference in preferability of various times of year), temporal variability (difference in traffic in daily various times), and spatial variability (difference in demand within a given airspace) (Eurocontrol 2015). Infrastructure improvements by making efficient use of limited airspace and airport resources while ensuring high levels of safety is the major responsibility of ATM system. This demands integrated cooperation for planning and operations among all stakeholders including regulators, service providers, and users in international and national levels (IPCC 1999). A point that some studies highlighted is that optimization of ATM systems to their maximum potential is a one-off saving activity and yet, considering the fast growth of air traffic, policy makers should think about other CO2 reduction alternatives while they are fostering ATM improvements (R. Wit et al., 2005; Forster, Shine, and Stuber, 2006; David S. Lee et al., 2009).

2.3.5.1.1. The Single European Sky

The aim of the European Union to reach a more sustainable and fuel efficient air transport industry led the European Commission to launch "the Single European Sky (SES) program" on 1999. The Single European Sky is promoting improvement and technological modernization of safety, network capacity, effectiveness and environmental impacts which are major concerns of European air transport (IATA 2013a; Pellegrini and Rodriguez, 2013). In 2004, The Single European Sky ATM Research (SESAR) program has started as the technological pillar of the SES targeting the enhancement of The European ATM system to respond effectively to the three-fold increase of air transport capacity in EU. SESAR program is following SES goals (IATA 2013a):

- A three-fold increase in capacity to respond to growing demand effectively;
- Improve safety performance by 10%;
- Reduction of environmental impacts by 10%;
- Reduce the cost of ATM services by at least 50%.

It is estimated that EU air traffic will grow from 9.5 million flights in 2012 to around 14.4 million in 2035. The goal of SESAR program is to find effective solutions for

improvement of fuel efficiency and safety. Following some solutions of SESAR are explained (ICAO 2016c):

- Delivering “High-Performing Aviation for Europe”;
- The performance targets are to reduce fuel burn by between 250 and 500 kg per flight by 2035.
- Integrating Airports and Optimizing Operations on the Ground;
- Developing solutions, for efficient taxiing schedule, which allow aircraft to move more smoothly, and efficiently from the terminal to the runway, without unnecessary queuing or stops. Taxiing can represent almost one third of total fuel burn for a short haul flight if waiting in queue adds to the time on the ground.
- Flying the Optimum Route;
- The concept of free routing (flying the most efficient route between departure and destination) provides important fuel savings by reducing flown distance and flight time in all en-route airspace categories and allowing carrying less fuel.
- Creating Fewer Delays and Optimizing in Departures and Arrivals;

2.3.5.2. Airport operations and management

Airports are known as the bottlenecks of air transport systems. The safety, quality and fuel efficiency of ground operations including take-offs and landings, and taxiing are among responsibilities of airport operators. Airport operations require accurate data input and efficient cooperation of five main stakeholders: airport authorities, pilots, air traffic control (ATC) system, ground handling providers and regulators (Wilke et al. 2014). Approximately 10% of fuel burn occurs in the Landing/Take-off (LTO) cycle of each flight which is below the altitude of 1km (Rypdal, 2000; Simone, Stettler, and Barrett, 2013) with small deviation in fuel burn ratio depending on engine type, thrust setting and airport location (Ashok et al. 2014).

The air quality of an airport is impacted by two factors: a. the level of LTO emissions from each operating aircraft and also b. the number of LTO cycles (number of flights) which take place in the given airport (Čokorilo 2016). In addition to aircraft emissions, other sources such as the ground support equipment, the auxiliary power units, and vehicular traffic contribute to airport air pollutions (Masiol & Harrison 2014). Also handling equipment is another contributor of CO₂ emissions at airports. They provide facilities for operations such as refuelling, cleaning, catering, baggage/staff/crew transfer. Depending on the flight and passenger numbers and freight volume, their impacts differ. As in study of Postorino and Mantecchini (2014) and other literature has been noticed, as much the number of LTO which happens in an airport increases, total fuel burn related to aircraft and land vehicles operating increase. Therefore, one of the best strategies to face increasing demand of passenger and freight air transport is to increase the aircraft load factor as a solution toward the sector’s environmental improvements. Also using larger aircraft instead of increasing the flights frequency can reduce environmental impacts (Graham 2014). Due to the direct and local scale impact

of airport GHG emissions, they are the important targets of CO₂ mitigation policies. With the continues growth of air traffic many airports have become busier which means that mainly during peak hours, delays related to arrival and departure queuing, and consequently taxiing duration increase which lead to unnecessary fuel burn and CO₂ emissions (Simić et al. 2014).

An empirical study by Grampella et al. (2017) estimate that 1% annual rise in flight operations on airports causes 1.05% increase in total environmental impacts including noise and GHG emissions. According to the projections of Eurocontrol (2013c), by 2035, airport delays will rise from around 1 minute per flight in 2012 to 5.6 minutes per flight in 2035. Gillen, Jacquillat, and Odoni (2016) in their study highlight three options for air transport sector to deal with the fast growth of demand at airports: a. capacity expansion; operational upgrade, and demand management. According to literature, the potential for airport capacity expansion is very limited. The two latter options seem more practical opportunities. The optimization of operational procedures seems the most important environmental solution, at least in the short-term perspective (Ravizza et al. 2014).

Study of Schmidt et al. (2016) suggest improvement in airport infrastructure utilization, better monitoring of operating processes and data sharing enhancement as key potentials for efficiency improvement in airports. Ahn and Min (2014) by the results of their research, emphasize the importance of more efficient management system considering privatization and public-private partnerships as more effective options for efficiency improvements in airports in future. Adler, Ülkü, and Yazhensky (2013) consider outsourcing of part of services at airports as a potential solution for efficiency improvement. Their analysis show in those cases with in-house services of ground-handling or fuelling are on average 3% to 6% less efficient in comparison with the cases which have outsourced the same activities. Adler, Ülkü, and Yazhensky (2013) by referring to “World Development Report (1994): Infrastructure for Development” point out some elements which may improve the performance of airport as an infrastructure.

- Considering infrastructure as a commercial sector, which can use innovative management tools in market to, makes more diversity possible in the supply of services in more efficient ways.
- Utilizing public-private partnership is highlighting new ways to increase efficiency and expand services. Also shift in the role of government rather than provider to regulator.
- Competition makes infrastructure providers more accountable and increase efficiency of systems while provides clients with more opportunities to choose.

Gillen, Jacquillat, and Odoni (2016) discuss about “demand management” as an important strategy to cope with the growing demand of air travelling and to prevent overscheduling at busy airports. As it is estimated, the contrast between available airport capacity and demand will grow in the future and the sector need to implement more measurements related to economic and market sphere such as slot control,

congestion pricing, slot auctions and etc. to control the demand. S Ravizza et al. (2013) and Lordan, Sallan, and Valenzuela-Arroyo (2016) in their study highlight the necessity of more accurate airport taxi time estimation to reduce delays and environmental impacts of airport operations. According to CODA (Central Office for Delay Analysis) (Eurocontrol 2016a), delay causes are categorized to airline (e.g. mismanagement of passenger and baggage handling), airport (e.g. damages in airport facilities), en-route causes (e.g. en-route equipment problems), governmental (e.g. problem regarding security and immigration), weather, miscellaneous, reactionary (e.g. late arrival of crew, passengers, baggage or etc.). Due to the close connection of all these activities and considering the central role of airports in air transport, it is clear that how even slight deviation in flight schedules due to inefficient airport operations can lead to a chain of inefficiencies along the system (Atkin, Burke, and Greenwood 2011; Simić and Babić, 2015). These inefficiencies become even more problematic in hub airports, where many landings and take-offs occur at the same time and operators have to deal with more interconnected variables.

Any operational inefficiency might involve many other airports and airlines and impose substantial direct and indirect costs to operators, airlines and customers in addition to its environmental cost (Schmidt et al. 2016). According to Loo et al. (2014), in international hub airports, because of air traffic congestion, the concentration of CO2 emissions are higher; therefore hub airports should implement more environmental and efficiency improvement measurements. At the same time study of Scotti et al. (2014) show that on the whole larger airports are more efficient due to the existence of scale economies at the airport level.

2.3.5.2.1. Airport Operations in European Union

Airports play a crucial role in the air transport sector of EU. The fast expansion of EU air transport and market demands has created new challenges for airports to deal with. Passenger numbers just at EU airports grew by 23% between 2004 and 2013. In 2014, the number of carried air passengers in EU reached 879 million, which had 4.4% growth from 2013. The share of EU air passenger traffic is approximately one third of total global air traffic (European Parliament 2016). Figure 6 shows an overview of air transport traffic in EU28 in 2015. According to Eurostat, 45% of total EU28 air passengers travelled within EU countries in 2015 and 38% travelled to or from outside EU. The number of Intra-EU passengers has increased by 303% and Extra-EU by 165% from 2002 to 2015 (Eurostat 2016a).

Figure 6. The distribution of EU28 air passenger traffic in 2015 estimated by Eurostat (2016a)

Among all EU28 airports, London Heathrow has the highest number of travelled air passengers with 73 million passengers in 2014. The second, third and fourth airports in the terms of travelled air passengers are Paris Charles de Gaulle airport with 64 million, Frankfurt Main airport with 59 million and Amsterdam Schiphol airport with 55 million passengers in 2014. Figure 7 illustrates the top 10 airports in EU28 countries in terms of carried passenger in 2015.

Figure 7. The top 10 EU28 airports in terms of carried passengers in 2015
Source: (Eurostat (avia_paoa) 2015)

In the freight and mail transport segment, growths of 6.4 % and 3.3 % respectively were recorded for international intra-EU and extra-EU freight and mail transport in 2014 compared with 2013. In contrast, domestic freight and mail transport recorded a decrease of 0.2% over the same period. Figure 8 shows the top 15 airports in terms of freight and mail air traffic in EU28 (eurostat 2016).

Figure 8. Top 15 EU28 Airports in terms of freight and mail air traffic
Source: (Eurostat (avia_paoa) 2015)

The projected fast growth of about 50% from 2012 to 2035, creates two main challenges for EU airports:

1. Managing the future growth of air traffic;
2. Maintaining high quality standards.

The current airports' capacity is limited and seems unlikely to be able to receive more flights in the future. The estimated potential for airport capacity increase is just about 17% by 2035. The estimations indicate that at least 60 EU airports will be very crowded until 2025 and the 20 busiest airports will be full over 8-10 hours a day. As a consequence, the increase of congestions at airports, will impact the fuel efficiency and safety negatively as more delays and queuing are expected. In response to these challenges and the need for practical actions and measurements, the European Commission started promotion of five key strategies (Eurocontrol 2013a):

- Optimizing the current airports' capacity;
- Stabilizing the air safety operations at airports;
- Developing and implementing cost-efficient technological solutions;
- Fostering "co-modality" which means a better integration between different modes of transport;
- "Maximising the environmental capacity of airports" (Upham et al. 2004) and better planning for airports' new infrastructures.

The European Commission has financed several R&D projects regarding above issues. SESAR is one of these projects targeting the increase of safety and efficiency of airport operations (European Commission 2007). One of the measures, which has been

implemented in the EU airports, is called “The Airport Carbon Accreditation” program, introduced by “the Airports Council International Europe” in 2009 and has now expanded globally. The goal of this program is to provide an integrated framework and standard for carbon and energy management to encourage and enable airports to implement best practices. In the latest 2014-2015 period of “The Airport Carbon Accreditation” application, about 168,000 tonnes of CO₂ emissions in all airports was cut. The most common actions for CO₂ emissions offset in airports is to optimize energy consumption, to use electric-powered ground equipment, and to use less energy consuming lighting systems (EASA et al. 2016).

In 2011, European Union launched a new strategy calling “Roadmap to a Single European Transport Area, towards a competitive and resource efficient transport system”. This roadmap created to make transport sector responsive to the constant growth of demands. One of the main goals of this framework is to make main airports more connected to rail network particularly to high-speed railways by 2050. Also they are promoting a wide range of initiatives, including the revision of the Slot Regulation to favour the more efficient use of airport capacity; Implementing financial measures such as pricing and taxiing strategies to internalize the costs of local pollution and noise at airports, from 2016 to 2020; Improving conditions to enter and provide quality services, including ground handling: ensure that all actors in an airport system meet minimum quality standards (European Commission, 2011d; European Parliament, 2016).

Janic (2011) analyses the environmental and social benefits of connecting airports to other transport modes. For instance the integration of airports into HSR networks can lead to replacement of some short-haul flights by HSR services. Environmental EU policies are promoting HSR services as the greenest available transport mode. Janic (2011) argues that even a small rate of short-haul flights replacement by HSR services with the equivalent, up to 2%, can have a significant contribution to air transport delay reductions, up to 20%. This means that airlines can save 17% in related costs. This important reduction of delays, can lead to better fuel efficiency at aircraft and airports and save considerable amounts of CO₂ emissions in transport sector.

2.3.6. High-speed Rail

One of the important solutions for traffic efficiency and transport GHGs reduction is introduction of more integrated transport system. European Commission supports co-modality and developing of new infrastructures in EU to make air and rail transport more complementary (European Commission 2007). Improving and optimizing the link between air and rail transport system could be one the important CO₂ reduction strategies in the future. Considering the characteristics of routes and especial distances, sometimes the best option for CO₂ emissions reduction is to promote alternative and greener transport modes. This is just possible by creating an integrated transportation

system which encourages people to use more efficient and cost-effective modes of transport (FAA 2015).

According to EEA (2013), “Rail transport is the most energy efficient mode of passenger transport and the second most energy efficient mode of freight transport (after maritime)”. The CO₂ emissions of passenger rail transport fell by 24 % during 1995 to 2011 mostly because of replacement of diesel trains by electric trains. Rail transport is a popular mode of transport in many countries. The rail industry trend is to replace fossil fuels (diesel and coal) by electricity. In some regions like EU and Japan electricity has become the main source of energy in railways.

The technological advancements in rail transport resulted in the expansion of high-speed rail (HSR) which are up to eight times more energy efficient than commercial aircraft over the same distances (Brecher, Sposato, and Kennedy 2014). HSR are generally based on low-emission electricity sources and by attracting passengers from the other transport modes, can have positive impacts on overall CO₂ emissions reduction (Tarpey et al. 2010).

According to the estimations of European Commission (2013d), the rail passengers increase by 1.5% annually from 2010 to 2050. Besides, the share of rail transport from all transport modes will rise from 8% in 2010 to 10% in 2050. The plan of EU is to shift 37% of passenger rail traffic to HSR by 2050.

In the European Union, expansion of HSR is seen as a strategy to cover part of the increasing demands for air transport in the future (European Commission, 2011; Åkerman, 2011). Givoni and Banister (2006) suggest that air transport and rail operators should look for integration opportunities and route optimization programs instead of competition. Although in the recent years, in EU and USA have been a tendency to promote HSR as a most environmental friendly transport mode (European Commission, 2008; FRA, 2009). European Commission clearly has welcomed the shift from air transport to high-speed railways wherever is possible. In a white paper on 2001, European Commission (2001) indicates: “We can no longer think of maintaining air links to destinations for where there is a competitive high-speed rail alternative. In this way, capacity could be transferred to routes where no high-speed rail service exists”. One of the European Union environmental plans is to increase the financial support of HSR and to encourage passengers to travel by trains (Adler et al. 2010). However in some routes and distances, preferability of one mode to the other one is unavoidable (Dobruszkes et al. 2014).

HSR particularly in medium and short distances can be a strong competitor of air transport with less environmental costs. But in long distances, when travel time is the most important variable in decision making, air transport is estimated to remain major transport mode (Pellegrini & Rodriguez 2013). Janić (1993) explains that HSR potential to compete with air transport is relatively high “in a large range of distances from 400 to over 2000 km” while Rothengatter (2011) argues that HSR has the potential to compete

with air transport on routes below 1000 km, particularly between 400 and 800 km. According to IPCC (2014a), the investment and development in HSR can have a negative impact on the demands for flights in short and medium distances in Europe and some other countries. Moshe Givoni and Banister (2006) with reference to reports of Eurostar (2005), the HSR operator in the London-Paris and London-Brussels routes, introduce HSR as the winner of competition between air transport and rail transport. Eurostar (2005) explains punctuality of HSR services in comparison with air transport an influential factor in their success, which attracted some business travellers from short from short-haul airlines. Behrens and Pels (2012) discusses that after operation of HSR route of London–Paris, network carriers have lost an important share of market. Although LLCs’ situation is a bit better but HSR may attract their leisure passengers. Park and Ha (2006) on their study about HSRs impact in South Korea, explain the decline of domestic air transport passengers.

With reference to GAO (2009) report, HSR are capable of being the “most time-competitive” transport mode in the distances below 800 kilometres. In the distances from 200 to 800 km HSR can beat air transport particularly because rail passengers get to their train faster, avoiding the required time to get to airport, regular checking and security, waiting time and queuing in airports. In most of the cases HSR terminals are inside cities and easily accessible.

Some articles argue that HSRs have not been enough successful in expanding the market share and competing with the other transport modes especially LLCs. “Lack of competition among rail operators” and intense price competition with LLCs are among the most important reasons of this argument (The Economist 2015).

Investing in HSR infrastructure, demand a large fixed capital. Regarding to this fact, the success of HSR is highly dependent to the density of cities and governmental financial supports. Before investment, feasibility of the HSR services should be studied as in some countries with a very scattered population and with low density like the case of Sweden, HSR investments don’t seem to have sufficient outcome (Åkerman 2011). “Travel by rail is more competitive in areas of higher population density” (Clewlow, Sussman, and Balakrishnan 2014). In many middle-sized cities, investments in HSR infrastructure are too costly and air transport remains the main option. In these cases turboprop aircraft with high efficiency seem a good option. About 83% of turboprop aircraft operate in the destination below 500 kilometres (ATAG 2014b).

Studies explain price, frequency and total travel distance and duration as the main parameters influencing decision-making behaviour of customers to choose between different modes of transport. Gonzalez-Savignat (2004) describes that HSR has been successful to compete with air traffic in many routs mainly due to the total travelling time, including the time of reaching to the rail stations in comparison with airports. According to Dobruszkes (2011), “in addition to travel time, some other variables also affect competition between the two modes including frequencies, fares, airlines’ hubs, geographical structures of urban regions”. Yang and Zhang (2012) and Behrens and

Pels (2012) in their studies explain that generally the influential factors on the decision of business passengers are different with tourists and leisure passengers. Behrens and Pels (2012) found more diversity regarding average fares in leisure passengers compared with business passengers. Yang and Zhang (2012) found that price sensitivity of business passengers are less than leisure passengers. Considering the far distance of many airports from city centres and the time that passengers have to spent for flight standard procedures (Shiomi 1999), the advantages of air travel can be seen in long distances and in short distances they lose their time advantages. At the same time rail transport is less sensitive to weather fluctuations which increase its punctuality (Givoni & Banister 2006).

“HSR investment is a complex decision that includes technical, social, economic, and environmental trade-off considerations” (Chester and Horvath, 2010).

2.3.7. Low-Cost Carriers

In the late 1970s, following the first waves of air transport liberalization, a new era in this industry started. The economic liberalization and deregulation of many industries, dramatically changed air transport sector from a very conservative and governmental industry to a more flexible and market-based sector. The privatization of industries generally is one the consequences of deregulation as happened in air transport sector and caused a paradigm shift in the airline business models (Fred et al. 2008). The liberalization of air transport market started in several countries following “the US Deregulation Act of 1978” (Gudmundsson 2011). In the European Union, air transport liberalization occurred in a gradual process between 1987 and 1997 (O’Reilly and Stone Sweet, 1998; Jiang and Li, 2016).

The liberalization allowed new firms to enter the market and resulted in more competition among airlines and subsequently growth of innovation and efficiency in the industry. Airlines started reconfiguration of their routes and equipment while optimizing their capacity utilization. These efficiency improvements changed the approach of airlines to their operating expenses and enabled them to lower air traveling costs (Bailey, 1992; B. Graham, 1998; Fragoudaki, 2000; Fu, Oum, and Zhang, 2010; Gudmundsson, 2011) and led to the introduction of new business models to the market (ICAO 2016b). These new business models targeted new challenges and demands of the market such as the early 2000s recession (Franke & John 2011) and started to cope with new terms such as clients’ price sensitivity, more frequency and connectivity needs, market volume growth, interlaced networks and enhanced services (Costantino et al. 2016).

The emergence of low-cost carriers (LCCs) is the result of this evolution in air transport sphere and airlines’ business models. LCCs have revolutionized air travel by making it more accessible and affordable for general public around the world (Schlumberger and Weisskopf 2014; Jiang and Li, 2016). By offering a lean and convincing business model targeting budget travellers, LCCs are competing strongly with network carriers (Franke

and John, 2011; A. Graham, 2013; Schlumberger and Weisskopf, 2014). LCCs have created new market demands and have attracted passengers from network carriers and also other transport modes.

The competitive advantage of LCC business plan is in their cost structure, which enables them to reflect more effectively to the market dynamic environment and allow them to reduce their costs and offer flights to the routes with lower density which are not possible for network carriers (J. G. de Wit and Zuidberg, 2012; Costantino et al., 2016).

Some of the core characteristics of LCCs are similar in most of the low-cost business models, which enable them to lower their costs. LCCs are based on high aircraft utilization (average load factor of about 80%); operational efficiency; fleet standardization; choice of secondary airports; point-to-point services; mostly short-haul flights without connections; lower-density routes; adoption of strict yield management techniques; short ground turn-around times; one class of seating (no business class in most cases); Limited cargo carried; a limited portfolio of services (removing luxury and non-basic services); no frills; minimum cabin crew; lower fixed costs related to staff; Internet booking (avoiding part of the costs related to travel agency services); E-ticketing and etc. (C. a. Piga and Filippi, 2002; Vidović, Steiner, and Babić, 2006; European Parliament, 2007; Costantino et al., 2016). All the mentioned features can finally result in about 40% lower operation costs in comparison with the network airlines (Vidović et al. 2006). Having higher load factors is one of the major attributes of low-cost carriers which gives airlines the opportunity to offer lower prices (Aomo et al. 2016). Another important characteristic of LCCs is that they usually provide “a single-type fleet”. Operating just one type of aircraft facilitates the fleet maintenance and also human resource management including cabin crew and pilots (ICAO 2003). Another vital feature of LCC business model is to utilize secondary airports instead of main airports which help them to reduce their operating costs significantly (ICAO, 2003; C. A. Piga and Bachis, 2007; Gillen and Gados, 2009; Laurino and Beria, 2014; Dzedzic and Warnock-Smith, 2016). LCCs benefit from utilizing secondary airports due to two reasons: First, secondary airports have lower service charges for the airlines; Second, as secondary airports are usually less crowded, airlines benefit from quick turnaround times and face less delays and queuing (K. J. Mason, 2000; ICAO, 2003). To attract passengers to these secondary airports, which are normally remote and far from city centres, airlines should offer reasonably low fares. Studies show that these low fares are more attractive for leisure travellers as they are more “price-sensitive” than “time-sensitive” (Pantazis and Liefner, 2006; Pita, Adler, and Antunes, 2014). In contrary, business travellers prefer to spend less time to reach an airport even if they have to pay more. Therefore, secondary airports have been attractive option for “time-sensitive” passengers (C. a. Piga and Filippi, 2002; Humphreys and Morrell, 2009; J. G. de Wit and Zuidberg, 2012). LCCs have created new approaches to tourism and enabled travellers to benefit from low fares to travel to vocational residential or second home, to travel for city tourism, or family and friends visiting over the weekend. Also they have provided facilities for more cultural and academic collaborations in national and

international levels. Besides, LCCs have introduced new tourist destinations to the market. Many smaller or less famous cities have become important tourism destinations thanks to LCCs (Bieger and Wittmer, 2006; Olipra, 2012; J. G. de Wit and Zuidberg 2012; Dobruszkes, 2013). Some studies suggest that LCCs' successful outcome is very dependent on the growing middle class population (Schlumberger and Weisskopf, 2014; Morrison and Mason, 2016).

Introduction of "Internet" has been a game changer in air transport industry. Internet influenced the pricing structure of airlines and created online sales and distribution system, which resulted in removal of travel agencies and other indirect players. This paradigm shift led to faster and cheaper air travelling options. The popularity and accessibility of online booking is growing very fast which will result in faster growth of LCCs (Morrison & Mason 2016).

LCCs were first introduced in the US and pioneered by Southwest Airlines in the early 1970s. The spread of LCCs around the world was relatively slow. It was in the mid-1990s when this phenomenon was ultimately implemented in Europe and some other countries. LCCs became more popular, with the birth of Ryanair in 1992 and EasyJet in 1995 (Costantino et al. 2016). The major success of low-cost carriers is seen in short-haul routes where significantly have been impacted by the introduction of LCCs (Bhadra, 2003; Whyte and Lohmann, 2015). The impact of LCCs on the long-haul routes has not been homogeneous. For instance, LCCs in European long-haul market have not showed very positive results though since 2013 the low-cost carrier, Norwegian Airline, began operating long-haul services. In some Asian long-haul routes, LCCs such as Jetstar Asia Airways⁸ and AirAsia X⁹ started operation and have shown some positive results under certain conditions (De Poret et al. 2015).

In 2013, the share of LCCs from total global flight seats was 26.3% (Pearson et al. 2015) which increased to about 28% of total scheduled passengers (950 million passengers) in 2015. The share of Asia Pacific from the total LCC passengers was 31%, the share of EU was 30% and North America, 26%. One the interesting trends is seen in the emerging economies where LCCs are growing fast. The sharp decline of oil price in 2015, approximately 40%, has made the cost structure of airlines more flexible (Delaplace and Dobruszkes, 2015; ICAO, 2015a). LCCs have started operation in developing countries, especially in Asia and Latin America. This new carriers can make air travel affordable for larger number of people while contributes to the economy of these countries widely. Also thanks to emergence of LCCs, many isolated islands and cities in developing countries are receiving more tourists (Schlumberger & Weisskopf 2014).

Before 2013, the competition between LCCs and network carriers was not direct as they were mostly operating in different routes and airports. Now, this image has changed and

⁸ Jetstar Asia Airways Ltd. is a low-cost carrier based in Singapore.

⁹ AirAsia X, is a long-haul low-cost carrier based in Malaysia.

LCCs have expanded their operations to some of the main routes, using primary hub airports (Burghouwt & de Wit 2015).

In the European Union, the market liberalization suspended the majority of commercial limitations for EU airlines by giving them more freedom on route configurations and setting of flights and airfares which led to a single EU aviation market (ICAO 2016b). This market liberalization resulted in emergence of LCCs in the late 1990's in EU. Introduction of LCCs to EU happened simultaneously with emergence of Internet. This coincidence brought new business models and commercial tools to the air transport market. The LCCs and Internet together have changed the EU aviation market to a much more dynamic market. An important impact of Internet was a great cost reduction for both passengers and airlines. It has facilitated considerably the process of expansion by the airlines into new geographical markets and resulted in creation of new destination spots, new workplaces in less important regions and new travelling demands in EU (C. a. Piga and Filippi, 2002; Starkie, 2012). LCCs introduced large number of new routes to the network. LCCs were able to provide a price-service quality combination that consumers found very attractive for short-haul flights (Mason et al. 2011).

In the European Union, the rise of LCCs has changed air transport market broadly. While only 1.5% of passenger seats were sold by LCCs and 65% by network air carriers in 1992, in 2011 LCCs exceeded the market share of network carriers for the first time with 42.2% versus 42.4%. In 2015, LCCs represented 48% of total passenger capacity of EU (European Parliament 2016).

According to ICAO definition of LCCs, 19 carriers are in Europe with various strategies and states (ICAO, 2014; Dziedzic and Warnock-Smith, 2016). The three biggest LCC players in Europe until 2013, are Ryanair, EasyJet and Air Berlin together supplied over half of the seats (Lenartowicz et al. 2013). Ryanair is the largest low-cost carrier in Europe, operates a fleet of 328 latest generations of Boeing B737-800 aircraft, and the age of its fleet is about 6.7 years. According to Boeing statement, this new aircraft are lighter with improved aerodynamics and new engine design and are able to save about 8% fuel consumption comparing with similar narrow body aircraft. The second largest low-cost carrier in Europe is easyJet, which operates a relatively young fleet of Airbus A319 and A320 aircraft on average 6.2 year old. EasyJet has 130 new A320 and is waiting for operation of new engine aircraft between 2017 and 2022 and 56 normal A320 aircraft. According to Airbus, its new generation of aircraft are 13% to 15% more fuel-efficient than the previous models (Budd & Suau-Sanchez 2016). De Poret, O'Connell, and Warnock-Smith (2015) indicate that utilizing advanced and more fuel-efficient aircraft such as Boeing B787-8, provide opportunities to make long-haul LCC operations economically feasible taking into account their seat, range and payload capabilities. As previously mentioned, long-haul LCCs have not been very successful due to some of their features such as "no frills service", single class, limited cargo and etc. which are generally incompatible with long-haul services. But recently both Air Berlin and Norwegian Air Shuttle started serving long-haul transatlantic routes between

Europe and North America using new Airbus A330–200 and Boeing 787 Dreamliner aircraft, respectively (Budd & Suau-Sanchez 2016).

LCCs have various important socio-economic impacts. Apart from removing monopoly of big cities and big airports business and tourism, LCCs started to compete with network carriers, which resulted in improvement of service quality (Bubalo and Gaggero 2015). Despite the fact that LCCs have played an important role in globalization and democratization of air transport sector, their contribution to GHG emissions should not be neglected. There are many discussions about the impact of LCC expansion and their emissions on the environment. Some studies believe low-cost airlines environmental impact is more controlled as they are using more efficient and modern aircraft, consume less fuel and consequently produce less GHG emissions (Vidović et al. 2006). Also based on their cost structure, LCCs need to increase their load factor as much as possible (ICAO 2003) and usually their load factors are higher than network carriers. LCCs normally achieve on average at least a 10% higher load factor in comparison with network airlines, which means the average energy use per passenger in the LCCs is approximately 25% lower than network airlines (ELFAA 2004). Macário, Viegas, and Reis (2008) argue that LCCs are more energy efficient per passenger as they benefit from utilization of newer aircraft and more efficient cabin configuration with a higher load factor.

Meanwhile the negative impacts of LCCs should be studied. For example the competition between LCCs and HSRs has increased in domestic and short-haul markets in many countries. Clewlow, Sussman, and Balakrishnan (2014) discuss that “There were significantly more medium-haul flights added to the system than short-haul flights removed”. As the promotion of HSR in many regions like EU has been a decision to decrease the negative impacts of transport sector, this competition between LCCs and HSRs can be in contrary with environmental policies (Dobruszkes 2011a).

2.3.8. Information and Communication Technologies (ICTs)

Information and communication technology (ICT) advancements have enhanced safety, efficiency, capability and affordability of air transport industry broadly. Providing the industry with new business solutions, advanced cost modelling systems, advertisement and marketing strategies, new tourism and travelling approaches, travel booking

systems, modern communication equipment, more efficient air traffic control and ATM systems with the capability of measuring environmental impacts are some of the major contributions of ICTs to air transport industry.

The fast and continues growth of air transport system creates new challenges concerning “system capacity, financial stability and environmental impacts” which can be managed by ICTs (Hansman 2005). Many studies believe that digitalization and ICT enhancements have a positive impact on economic, social, and environmental sustainability of air transport, although some literatures express concerns about the expansion of ICT-induced travel demand.

The fact that ICTs have become an integral part of daily life highlights the importance of their environmental impacts. Johnson, Perkins, and Arkko (2004), Berleur, Hercheui, and Hilty (2010) and Achachlouei (2015) in their studies describe ICT environmental impacts through three main categories:

- First-order or direct effects of ICT:
This category covers the environmental impacts caused by ICT hardware during its whole life cycle. In the case of air transport, the total life cycle of ICT hardware related to intelligent transport system can be analysed.
- Second-order or enabling effects of ICT:
Implementing ICT in a system has an effect on the other processes such as traffic management, manufacturing processes and distribution systems, which influence their environmental impacts indirectly. In the case of air transport, the improvement of fuel efficiency by applying an intelligent transport system (ITS) can be explained.
- Third-order or systemic effects of ICT:
Today, people’s lifestyle and social and economic structures are widely influenced by the broad application of ICTs. For example the ICT-induced demands for travelling is an indirect result of modern lifestyles.

ICT applications in passenger transport such as intelligent transport system (ITS) have made transport more time efficient which on one hand results in more traffic and ICT-induced transport demands, and on the other hand results in more fuel efficiency and less delays. Overall, studies indicate that ICTs have made transport more cost and time efficient (Achachlouei 2015).

In this dissertation, some of the direct and indirect environmental impacts of ICT applications in air transport industry are explained:

1. **New air transport business models:** Implementation of e-business models have provided new opportunities such as “new models of value chains, value webs and models of remote diagnostics and monitoring” (Black and Geenhuizen, 2006). For instance ICTs have introduced new booking systems which have resulted in the

direct connection between customers and operators (EEA 2014). Internet booking systems, optimize time and money that people spend on planning and buying tickets for travelling while decrease unnecessary city travels.

2. Teleworking, mobile working and virtual meetings (dematerialization):

European Union has encouraged the replacement of unnecessary business trips, which are just some hours of meeting, by virtual meetings and teleconferences. ICT development during last decades has encouraged teleworking and more autonomous working conditions for many jobs and positions, which are not based on physical presence. The growing awareness about the potential cost savings through using ICT applications has increased their popularity. It is expected that by 2050 virtual meetings and teleconferences become more common around the world (Eurocontrol, 2013d; EEA, 2014). These changes on one hand decrease the number of unnecessary business trips, while on the other hand through creation of new leisure time and capacities by teleworking and teleconferencing, increase the number of leisure trips (Åkerman and Höjer 2006). People's time management and dependency to traditional offices have changed. This has created new approaches to spend free time such as travelling to new touristic destinies, weekend trips and using LCCs. Though broad utilization of ICTs have increased the transport demands, yet teleworking is considered as an important way to save emissions by reducing the number of business trips and daily commutes (Black and Geenhuizen, 2006).

3. Intelligent Transport Systems (ITSs): According to definition of European Union (2010), "ITSs are advanced applications which aim to provide innovative services relating to different modes of transport and traffic management and enable various users to be better informed and make safer, more coordinated and smarter use of transport networks". Regarding postnote (2008), ITSs by deployment of advanced sensors, analytical models and wide integrated communications can facilitate less polluting forms of transport. Intelligent transport systems are applicable in all transport modes (road, rail, air, water) for both passenger and freight services. ITS applications in aviation include professional services such as navigation and air traffic control systems, and also services for passengers, such as on-board telephony (ETSI 2016). Intelligent transport systems play a vital role to deal with Europe's growing emissions and congestion problems. They can make transport safer, more efficient and more sustainable by applying various information and communication technologies to all modes of passenger and freight transport (European Commission 2016a).

4. Airline planning and ground operations: ICTs are applicable in all segments of airline planning cycle. Airline planners and ground operation suppliers can take advantage of new technologies that allow airlines to react quickly to ever-changing situations, including crew legality, weather, and airport traffic congestion. IT solutions help airlines to optimize activities in real time as the operational environment changes. "Mobile solutions that connect applications that assist baggage handlers, gate agents, caterers, fuel providers, and passengers on

the ground will become more important as airlines strive to reduce flight disruptions and maximize airplane utilization to gain the greatest return on their investment” (Boeing 2014a).

5. **In-flight operations:** The tendency to in-flight connectivity is rapidly increasing as using mobile devices such as tablets and smart phones become more common among the flight and cabin crew. “Electronic flight bags have been in use for decades, but improved connectivity now allows pilots to quickly upload the latest navigation charts to their devices and monitor weather in flight, adjust flight plans to optimize fuel use, use moving runway and taxiway maps for improved situational awareness, and use a wide variety of applications to improve crew productivity and enhance safety. Cabin crew use mobile devices with in-flight connectivity for on-board sales (including verification of credit cards to eliminate fraud), passenger services, and crew communication and to access crew reporting tools” (Boeing 2014b).

The ICT role in ATM enhancement has been discussed in Section 2.3.5. The main target of the current section was to cover the indirect “Third-order or systemic effects” of ICTs on the environmental impacts of air transport.

2.3.9. Air Transport Voluntary Carbon Mitigation

To complement technological and legal frameworks for CO₂ emission reductions in the aviation industry, voluntary actions of airlines and airport operators are highly encouraged. IATA supports implementation of voluntary initiatives to point out environmental concerns and necessity of energy efficiency improvements in the industry. Currently some airlines and airports have started offering voluntary carbon offsetting schemes to air travellers (IATA 2016e). These schemes are called voluntary as they are not mandatory through environmental legislations, rather they are applicable within “corporate social responsibility (CSR) policy, efforts to improve brand image or individual ethical motivations” (Gössling & Upham 2009). Voluntary emissions reduction in air transport is partly a consequence of public environmental awareness about the negative impacts of air transport industry. This growing awareness has led to changes in consumer behaviour and perception about environmental responsibility. Encouraging purchase of carbon credits by travellers needs an appropriate marketing strategy and clear data distribution to highlight the impacts of customers’ collaboration on emissions reduction (Becken, 2007; McLennan et al., 2014). Observing the willingness of air transport passengers to contribute to CO₂ emissions offsetting plans, shows positive results but still there is a gap in converting concerns into actual behaviour (Brouwer, Brander, and Van Beukering, 2008; Araña and León, 2013). In practice, carbon credit purchasing by tourists is still low, with the participation of just 2-10% of air passengers (Mair 2011). Becken (2007), argues the main reasons for the unambitious voluntary participation of passengers is related to the absence of clear information and transparency about the carbon offsetting schemes. At the same time there is not an integrated and comprehensive system of carbon offsetting in the industry

and operators use different carbon calculating systems which sometimes create ambiguity (Gössling et al., 2007; Eisenkopf and Knorr, 2009).

ICAO (2007) has encouraged airlines to provide sufficient information and facilities to their customers enabling them to participate in voluntary offsetting schemes regarding their air travel emissions through:

- a) Selecting the most effective carbon offset schemes and providers;
- b) Certifying the voluntary contribution of air passengers to the rate of flights' fuel consumption and CO₂ emissions reduction;
- c) Facilitating the evaluation of customer contributions to the emissions reduction schemes;
- d) Launching effective promoting programs by operators to highlight the environmental benefits of passengers' contribution. Besides, governmental supports are always very effective in the success of voluntary emissions reduction schemes (ICAO 2007c).

Studies of Hagmann, Semeijn, and Vellenga (2015) show that almost every other passenger is interested in paying more for a more “eco-friendly flight”. This recent analysis can encourage airlines to be more active in implementation of green initiatives and carbon offsetting schemes. Mayer, Ryley, and Gillingwater (2015) explain that “eco-positioning of airlines” and “green marketing” are effective win-win strategies. Airlines can work on their green image and use it as competitive advantage. Airlines should try to benefit from passengers participation by applying innovative carbon offsetting initiatives (Hagmann et al. 2015). For instance an innovative proposal by British Conservative Party was “Green Miles Scheme” to offer a “Green Air Miles Allowance” within this framework people get an allowance for a short-haul flight a year and for longer trips they will be charged by higher tax rates (Mayor & Tol 2008). Gössling and Buckley (2016) discuss the utilization of “carbon labels” as a voluntary action towards CO₂ emissions reduction in different transport modes. Airlines can use “carbon labels” as a green marketing tool, which help passengers to distinguish and choose more environmentally sustainable flights. Carbon labels explain the volume of CO₂ emissions of flights through understandable methods for passengers to attract them for more collaboration towards a more sustainable future. The non-profit carbon offset organization (Atmosfair 2015) evaluates airlines and classify them based on carbon efficiency and their actual fuel consumption in the available routs. In each rout the fuel efficiency of each flight is compared to the best possible option and is ranked by efficiency class of A to G. According to Gössling and Buckley (2016), British carrier called Flybe (2007) has started to use an “eco-label” for its aircraft since June 2007. This “eco-label” illustrates different environmental impacts of each aircraft type, which are available in their online booking system. At the same time some online booking platform have started to use “a Carbon Friendly Flight Search” enabling customers to compare the environmental impacts of different flights. Among 235 member of IATA in 2013, just 14.5% gave passengers the opportunity to contribute to carbon offsetting (Hall, B., and Wilson, 2015; Gössling, Scott, and Hall, 2015). MacKerron et al. (2009)

in their study explains voluntary carbon offsetting as a diverse market, which can engage passengers to contribute to a wide range of projects with co-benefits to support socio-economic development programs.

Chapter 3. Method

This dissertation has been developed through a variety of methods and results which have been already published in Alonso et al., (2014) and Aminzadeh et al., (2016).

4.2. Traffic data

The main idea of this study is to collect and classify air transport data to analyse air traffic in 2010 and 2013 and its evolution during this period in EU27+2. Based on this air traffic data and by analysing the past trends, air transport CO₂ emissions are projected. In the current study, air transport data have been collected from the European Commission's Air Transport Statistics (Eurostat)¹⁰ for EU27+2 countries, which means all the present EU members except Croatia, plus Norway and Switzerland¹¹.

Based on the method which has been published in Alonso et al. (2014), For each country the following information has been extracted:

- Air passenger transport between the main airports of country xx and their main partner airports (routes data) [avia_par_xx database]: total commercial passenger flights, total passengers on board and total passenger seats available.
- Freight and mail air transport between the main airports of country xx and their main partner airports (routes data) [avia_gor_xx database]: total freight and mail air flights and total freight and mail on board in tonnes.

All the above-mentioned information was obtained for each airport pair, between the main airports of country xx and their main partner airports and the following parameters were derived:

- Passenger transport: number of RPKs (revenue passenger kilometres¹²) and ASKs (available seat kilometres).
- Freight and mail transport: number of RTKs (revenue tonne kilometres).

Figure 9 shows inputs, operations and results of the model. Using latitude and longitude of each airport, the model is calculating the distance which aircraft flies between two

¹⁰ Short Description: The indicator shows the total number of passengers carried in Europe (arrivals plus departures), broken down by country and by year. Passengers carried:

- Are all passengers on a particular flight (with one flight number) counted once only and not repeatedly on each individual stage of that flight;
- Are all revenue and non-revenue passengers whose journey begins or terminates at the reporting airport and transfer passengers joining or leaving the flight at the reporting airport;
- Excludes direct transit passengers.

¹¹ The number of EU Countries has been 27 countries until 2013, before joining of Croatia. The EU countries until 2013 are: Austria, Belgium, Bulgaria, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the UK.

¹² RPKs (revenue passenger kilometers) are measures of traffic for an airline flight by multiplying the number of revenue-paying passengers aboard the airplane by the distance traveled. Revenue passenger kilometers can be considered the basic amount of "production" that an airline creates. The revenue passenger kilometers can be compared to the available seat kilometers over an airline's system to determine the overall passenger load factor.

airport pair. The distances between each pair of airports has been calculated for the shortest (orthodromic) routes between each pair of airports and cannot be directly compared with ground transportation distances. These differences can be seen for instance in Spain, between road distances or high speed train tracks between two cities which are about 25% longer than air distances as an average (conventional railways are 35% longer in distances) (Alonso et al. 2014). Finally, the extracted data were segmented, for each country between the reference countries, the EU27+2 countries and the non-EU countries. The data were also segmented per distance bands, at intervals of 500 km, which is the EU scale for classifying the activities of the different transportation modes.

Figure 9. The model and its Inputs and outputs

4.3. Emissions data

As mentioned before, available information extracted from Eurostat databases on the number of flights and both passenger and freight payload, and also on the airport pairs to evaluate RPKs or RTKs and classify per distance bands. However aircraft type information is not available for airport pairs to classify this information according to aircraft types and evaluate fuel consumption and subsequently CO₂ emissions. Instead,

there is another relevant source of data, which is the EUROCONTROL Data Demand Repository (DDR) where information from the flight plans in EUROCONTROL countries is stored. Data gathering for all flights in 365 days of year is possible but as the amount of data is huge; therefore, in this study a sample of data from two weeks (central week of June and central week of September) was downloaded and then averaged for the overall year. This is a standard practice in the airline industry to evaluate yearly data, considering the variation in flight schedules between the high peak and other times (Garrow 2010). The reference year for the study database was 2010 but data for the years 2011, 2012 and 2013 were used as well. The data extracted for each flight consisted of the departure airport, the arrival airport, the type of aircraft and the type of flight. Hence Eurostat data were used to derive traffic volume (flights, passengers, RPKs or RTKs) and EUROCONTROL data were used to evaluate fuel consumption and CO₂ emissions. The extracted data from EUROCONTROL DDR were processed and segmented.

First, through a distance calculator, the distance between each airports pairs was evaluated.

Second, flights were filtered per type and only scheduled and non-scheduled flights were included (military, customs or police flights, general aviation flights and others have been excluded).

Third, The fuel consumption for every flight was evaluated with reference to EMEP/CORINAIR Emission Inventory Guidebook (EEA 2007), which defines fuel consumption as a function of the distance which is flown per aircraft type in per flight phase. According to EMEP/CORINAIR Emission Inventory Guidebook (EEA 2007) air traffic as a source of combustion emissions will depend on the:

- Type of aircraft;
- Type of engines and fuel used;
- Emission characteristics of the engines (emissions per unit of fuel used depending on engine load);
- Location (altitude) of operation;
- Traffic volume (number of flights and distance travelled).

With reference to Olivier (1991), generally the specific fuel consumption of airplanes decreases at higher flying levels and lower thrusts. As the weight of the aircraft varies during the flight, the optimum cruise level also varies. Since engine types are regularly modified and improved with the aim firstly to reduce the specific fuel consumption and secondly to reduce the major emissions, the emission factors in the cruise mode depend on the performance of the actual engine type in use, which has improved substantially in time. The proportion of fuel used in a mission, which is attributed to LTO, decreases as mission distance increases. Thus a substantial part of the fuel consumption takes place outside the LTO-cycle. Studies indicate that the major part CO₂ (80-90%) is emitted at altitudes above 1000 m (EEA 2007).

The effect of engine ageing on emissions is not taken into account. It is, however, generally assumed that this effect is of minor importance compared with the total emissions since aircraft engines are continuously maintained to tighter standards than the engines used for instance in automotive applications. Emissions come from use of kerosene and aviation gasoline that are used as fuel for the aircraft. Gasoline is used in small (piston engine) aircraft only. This is, of course, a simplified procedure for the evaluation of fuel consumption, as it does not take into account the dependence of the fuel consumption of a given flight on the flight actual data such as take-off weight, trajectory, altitude, speed, and meteorological conditions. Also not all aircraft types are represented, and therefore assumptions were made in order to estimate the fuel consumption of certain aircraft types based on the CORINAIR fuel consumption of similar types. The impact of these simplifications could be relevant in the evaluation of the fuel consumption or CO₂ emissions of a particular flight, but are far less important when we are estimating aggregated data involving thousands of flights, and furthermore if we are using this data for comparative purposes.

CO₂ emissions are directly related to fuel consumption and therefore can be estimated accurately. Regarding the analysis, emissions of CO₂ are proportionally related to fuel consumption (kerosene) by a factor of ~3.15 which is the value selected for the EU ETS Directive (Olivier, 1991; IATA, 2008; European Commission, 2008; Moshe Givoni and Rietveld, 2010; ICAO, 2010a; Grote, Williams, and Preston, 2014). Therefore, the information for each flight was: departure airport, arrival airport, type of aircraft, fuel consumption in LTO cycle (approach, landing, taxiing, take-off and climb, below 3000 feet over the airport), fuel consumption in climb/cruise/descent, total flight fuel consumption, and total flight CO₂ emissions. This was segmented for the EU27+2 countries plus the non-EU countries and presented by pairs for every country (departure) and the rest of the countries (destination). Figure 10 shows the model's framework, which has been used in this study for calculation of fuel combustion and CO₂ emissions.

The data were segmented according to the same distance bands, at 500 km intervals, and per aircraft type, taking into account the MTOW (Maximum Certified Take-off Weight) and the propulsion type. The following aircraft type categories were considered:

- MTOW less than 7 tonnes (aircraft typically up to 19 seats in passenger configuration)
- MTOW between 7 and 136 tonnes:
 - Turboprops
 - Turbofans
- MTOW larger than 136 tonnes (aircraft larger than 240 seats)

Table 3 shows the classification, which has been used in the study. The objective is to evaluate CO₂ emissions in 2010 as the baseline and 2013 to compare these emissions with the traffic structure and evolution from 2010.

Figure 10. The utilized model's framework

Table 3. The classification, which has been used in this thesis

		Distance Band (Km)	Number of flights				Total Band
			Aircraft type (MTOW range in tonnes)				
			< 7	7-136		> 136	
			Small	Turboprop	Jet	Wide	
Departure Country	Destination Country	< 500					
		500 - 1000					
		1000 - 1500					
		1500 - 2000					
		2000 - 2500					
		> 2500					
		Total type					

Chapter 4. Results and Analysis

4.1. Traffic Data Results

The data of commercial passenger flights for 2010, as the baseline year, is gathered and analysed. The results are illustrated in Table 4, segmented by per 500 km distance bands. Figure 11 shows the distribution of passenger flights for each distance band.

Table 4. Commercial passenger flights' data for the baseline year 2010 in EU27+2

Distance Band (km)	Flights (10 ³)	Passengers (10 ⁶)	RPKs (10 ⁹)	Seats (10 ⁶)	ASKs (10 ⁹)	L/F	Seats /Flights
<500	2,360	174	64	262	98	65%	111
500-1000	2,877	271	197	380	278	71%	132
1001-1500	1,479	176	220	230	291	76%	156
1501-2000	796	106	182	129	231	79%	162
2001-2500	340	46	103	52	132	78%	152
>2500	933	195	1,160	234	1,416	82%	251
Total	8,785	968	1,926	1,287	2,446	75%	146

Figure 11. The distribution of commercial air passengers per distance band in 2010

Analysing the illustrated data in Table 4 and Figure 11 shows that almost 60% of passenger flights and 46% of passengers belong to distances below 1000 km (<1000 km). As discussed in the Section 2.3.6, flights below 1000 Km (<1000 km), excluding islands and remote areas, are likely to compete with high-speed railways (Correnti et al., 2007; Duarte, A., Silla, A., Selmi, H., Coelho, 2008; European Commission, 2010b; Albalade, Bel, and Fageda, 2015). Though it should be considered that HSR needs a very high initial investment, which requires cost-effectiveness analysis. To invest in HSR infrastructures, a minimum level of demand is necessary and they are feasible in the more populated regions (Rus and Nombela, 2007; De Rus, 2008; Albalade and Bel, 2010; Ruiz-Rúa and Palacín, 2013; D'Alfonso, Jiang, and Bracaglia, 2015). As data

shows, the segment below 1000 km (<1000 km) has a much smaller share of total RPKs, just about 13%. While 20% of the passengers fly distances longer than 2500 km (>2500 km), representing 60% of the total RPKs.

It is noticeable that there are a small number of flights in the distance interval between 1500 and 2500 km, 13% of the total. The number of average seats per flight in the distance interval below 500 km (<500 km) is 111, which indicates that an important number of these short range flights are performed using aircraft with more than 100 seats, and therefore are at least medium range aircraft. As previously in Section 2.3.2 discussed, referring to various studies (Joosung J. Lee et al., 2001; Pm Peeters, Middel and Hoolhorts, 2005; Morrell, 2009; Moshe Givoni and Rietveld, 2010; Singh and Sharma, 2015), long-haul aircraft are more fuel efficient per passenger kilometres. Therefore the fuel efficiency in the segment of flights below 500 km (<500 km) is low. The same consideration can be applied to the distance interval from 500 to 1000 km, with just 132 seats per flight. At intermediate distances, from 1000 to 2500 km, the seat per flight value is very similar, around 150-160 seats per flight. The average aircraft size grows significantly at distances beyond 2500 km (>2500 km), 251 seats per flight, which indicates a mixed fleet of single-aisle and wide-body jets. The average load factor grows steadily with the distance of the flight, from a minimum value of 64.7% for distances below 500 km (<500 km), to a maximum value of 82.0% for distances larger than 2500 km (>2500 km). The average load factor for all flights is 79%.

Table 5. Freight flights data for the baseline year 2010 in EU27+2

Distance Band (km)	Flights (10³)	Freight (Tonnes × 10⁶)	RTKs (10⁶)	Tonnes /Flights
<500	119	1,077	399	9
500-1000	112	1,703	1,176	15
1001-1500	38	625	731	16
1501-2000	22	372	635	17
2001-2500	12	385	773	31
>2500	67	9,183	60,586	138
Total	370	13,345	64,301	36

In Table 5, data of total commercial freight flights are represented, segmented per distance band. Although most of the freight flights, 62%, take place with distances below 1000 km (<1000 km), it is significant that 94% of the RTKs are flown in distances larger than 2500 km (>2500 km). These figures confirm the intense competition that air cargo suffers from surface transport modes in the intra-EU market, because of the short-medium distances involved. It is in the long distance range where air transport competes much better with other modes. The average load factor per flight grows steadily with the distance flown, but with generally small values up to 2500 km. For distances longer than 2500 km the average load factor per flight changes order of magnitude to 138 tonnes.

In Table 6, the distribution of commercial passenger flights among the EU27+2 countries is shown. Looking over this data, concentration of traffic in six countries, France, Germany, Italy, Spain, The Netherlands and UK, is clear. The share of these six countries is approximately two thirds of the total EU27+2 flights and passenger traffic and about 82% of total RPKs.

Table 6. Distribution of commercial passengers flights per country of EU27+2, 2010

Country	Flights (10 ³)		Passengers (10 ⁶)		RPKs (10 ⁹)		L/F	Passenger /Flight
Austria	229	2.6%	19.9	2.1%	27.0	1.4%	75.7%	87
Belgium	172	2.0%	16.8	1.7%	31.1	1.6%	75.2%	97
Bulgaria	45	0.5%	4.7	0.5%	7.2	0.4%	75.8%	104
Cyprus	38	0.4%	5.2	0.5%	12.5	0.6%	83.1%	137
Denmark	217	2.5%	20.4	2.1%	29.2	1.6%	77.5%	94
Estonia	19	0.2%	1.1	0.1%	1.1	0.1%	71.6%	60
Finland	148	1.7%	12.2	1.3%	25.2	1.3%	76.1%	82
France	987	11.2%	109.1	11.3%	261.1	13.6%	78.9%	111
Germany	1,315	15.0%	141.9	14.7%	306.9	15.9%	80.9%	108
Greece	230	2.6%	24.0	2.5%	37.3	1.9%	74.2%	104
Hungary	65	0.7%	6.0	0.6%	6.9	0.4%	73.9%	91
Ireland	154	1.8%	19.7	2.0%	26.9	1.4%	79.4%	128
Italy	1,065	12.1%	115.8	12.0%	144.4	7.5%	75.9%	109
Latvia	52	0.6%	3.9	0.4%	4.8	0.2%	77.4%	75
Lithuania	29	0.3%	2.2	0.3%	2.8	0.1%	74.4%	75
Luxembourg	30	0.3%	1.3	0.1%	1.1	0.1%	68.8%	44
Malta	20	0.2%	2.3	0.2%	3.8	0.2%	74.9%	115
Norway	292	3.3%	24.7	2.6%	22.3	1.2%	66.2%	85
Poland	159	1.8%	14.1	1.5%	19.6	1.0%	74.7%	88
Portugal	159	1.8%	17.7	1.8%	30.7	1.6%	76.7%	111
Romania	73	0.8%	6.3	0.7%	8.6	0.4%	79.1%	86
Slovakia	17	0.2%	1.6	0.2%	2.0	0.1%	80.4%	93
Slovenia	22	0.2%	1.1	0.1%	0.9	0.0%	69.8%	49
Spain	1,050	12.0%	130.2	13.5%	237.7	12.3%	77.1%	124
Sweden	226	2.6%	22.2	2.3%	30.6	1.6%	77.7%	99
Switzerland	323	3.7%	33.0	3.4%	59.4	3.1%	81.5%	102
The Netherlands	370	4.2%	45.0	4.7%	134.9	7.0%	83.1%	122
UK	1,279	14.6%	164.9	17.1%	499.9	23.4%	79.9%	129
Total EU+2 (2010)	8,785	100%	967.3	100%	1,925.7	100%	78.8%	110

In Figure 12, the air passenger traffic of 2010 in the six EU largest air transport markets is illustrated. The share of Spain, France and Germany in the number of flights, passengers and value of RPKs are almost consistent respectively about 13%, 15% and 12% though this is different in case of Italy, UK and The Netherlands. Italy with 12% share of flights and passengers accounts for just 7% of the RPKs, while The Netherlands and UK, on the contrary, with respectively 4% and 15% of flights and almost 5% and 17% of total passengers account for 7% and 23% of the RPKs.

Figure 12. Air passenger traffic in the six EU largest air transport markets and total EU27+2, 2010

About the freight traffic in EU27+2, Table 7 shows a different distribution. The share of Italy and Spain in Freight traffic is smaller than passenger traffic while countries such as Belgium have 8% share of total freight flights and 7% of total freight tonnes. For instance, Luxemburg, which has a small share of freight flights, with 5% of RTKs, stands higher than Italy and Spain. The six countries, France, Germany, Italy, Spain, The Netherlands and UK, with 82% of RPKs stand for the same share of total RTKs in EU27+2. This shows the importance of specific airports such as Paris Charles de Gaulle, Frankfurt, Schiphol and London Heathrow airports as worldwide freight and cargo hubs. Figure 13 shows the air freight traffic in the six mentioned countries and total EU27+2 in 2010.

Table 8 and Figure 14 illustrates the relationship between the number of passengers per citizen and the country's GDP per capita. The average for the EU27+2 countries is almost 2 passengers per citizen, well above the world average of approximately 1.4. The well-known relationship between the two variables is apparent, with the passengers per citizen growing with the GDP per capita almost linearly. Remarkable exceptions are Luxembourg, with the largest by far GDP per capita but an average value of flights per citizen, or on the other side Malta and Cyprus, with poor GDP per capita but around 6 passengers per citizen, showing the important contribution of air transport to their tourism industry for these small countries. This is also noticeable in the case of Ireland, again showing an above-average number of passengers per citizen and a GDP per capita in line with the EU average, emphasizing the significance of air transport for an island.

Table 7. Distribution of freight flights in per EU27+2 country, 2010

Country	Flights (10 ³)		Freight (10 ³)		RTKs (10 ⁶)		Tonnes /Flight
Austria	5.2	1.4%	234.2	1.8%	1,118	1.7%	45
Belgium	30.6	8.3%	975.6	7.3%	1,746	2.7%	32
Bulgaria	2.4	0.6%	17.5	0.1%	23	0.0%	7
Cyprus	1.1	0.3%	35.8	0.3%	76	0.1%	31
Denmark	4.9	1.3%	149.2	1.1%	672	1.0%	31
Estonia	1.5	0.4%	8.9	0.1%	11	0.0%	6
Finland	7.3	2.0%	158.2	1.2%	764	1.2%	22
France	39.4	10.7%	1,399.4	10.5%	7,989	12.4%	36
Germany	68.9	18.6%	3,677.0	27.6%	17,142	26.7%	53
Greece	10.2	2.8%	82.5	0.6%	188	0.3%	8
Hungary	4.2	1.1%	44.4	0.3%	155	0.2%	10
Ireland	4.7	1.3%	110.4	0.8%	263	0.4%	23
Italy	25.9	7.0%	748.5	5.6%	2,967	4.6%	29
Latvia	0.5	0.1%	10.3	0.1%	15	0.0%	19
Lithuania	2	0.5%	7.3	0.1%	7	0.0%	4
Luxembourg	6.9	1.9%	536.5	4.0%	3,235	5.0%	78
Malta	0.7	0.2%	14.8	0.1%	25	0.0%	21
Norway	9.2	2.5%	46.3	0.3%	115	0.2%	5
Poland	8	2.2%	54.4	0.4%	151	0.2%	7
Portugal	8.8	2.4%	95.4	0.7%	308	0.5%	11
Romania	29	7.8%	19.2	0.1%	21	0.0%	1
Slovakia	1.1	0.3%	17.2	0.1%	22	0.0%	15
Slovenia	0	0.0%	6.9	0.1%	4	0.0%	6851
Spain	26.2	7.1%	549.7	4.1%	2,573	4.0%	21
Sweden	15.6	4.2%	174.6	1.3%	510	0.8%	11
Switzerland	3.5	0.9%	369.3	2.8%	1,976	3.1%	106
The Netherlands	17.3	4.7%	1,518.1	11.4%	9,842	15.3%	88
UK	34.8	9.4%	2,284.1	17.1%	12,382	19.3%	66
Total	370	100%	13,345.4	100%	64,301	100%	36

Figure 13. Air freight traffic in the six EU largest air transport markets and total EU27+2, 2010

Table 8. Passengers per inhabitant (capita) as a function of country's GDP per capita

Countries	GDP Per Capita (Euro)	Passenger Per Capita
Austria	34,100	2.4
Belgium	32,700	1.5
Bulgaria	4,800	0.6
Cyprus	21,000	6.3
Czech Republic	14,300	0.0
Denmark	42,600	3.7
Estonia	10,700	0.8
Finland	33,300	2.3
France	29,900	1.7
Germany	30,500	1.7
Greece	19,600	2.1
Hungary	9,700	0.6
Ireland	35,000	4.4
Ireland	35,000	4.4
Italy	25,700	1.9
Latvia	8,600	1.7
Lithuania	8,900	0.7
Luxembourg	78,600	2.6
Malta	15,200	5.5
Norway	65,000	5.1
Poland	9,200	0.4
Portugal	16,200	1.7
Romania	5,800	0.3
Slovakia	12,100	0.3
Slovenia	17,400	0.5
Spain	22,800	2.8
Sweden	37,300	2.4
Switzerland	53,400	4.2
The Netherlands	35,400	2.7
UK	27,500	2.6
Average	26,114	1.9

Figure 14. Passengers per inhabitant (capita) as a function of country's GDP per capita

After analysing the air traffic of EU27+2 in 2010, Table 9 shows the results of year 2013, and their evolution compared to the 2010 corresponding to number of flights, passengers, RPKs, Load Factor and the average number of passengers per flight.

Table 9. Air passenger traffic of six biggest air transport markets of EU27+2 in 2013 with their evolution from 2010 to 2013 (showing in parentheses)

Country	Flights (10 ³)	Passengers (10 ⁶)	RPK (10 ⁹)	Load Factor (%)	Passengers per flight
Germany	1,462 (+11%)	165 (+16%)	320 (+4%)	80 (-2%)	113 (+5%)
Spain	1,118 (+6%)	138 (+6%)	230 (-3%)	78 (+2%)	124 (+0%)
France	1,108 (+12%)	128 (+18%)	284 (+9%)	74 (-6%)	116 (+4%)
Italy	883 (-17%)	104 (-10%)	116 (-19%)	75 (-2%)	118 (+8%)
The Netherlands	348 (-6%)	44 (-1%)	125 (-7%)	85 (+2%)	128 (+5%)
UK	1,435 (+12%)	179 (+8%)	445 (-1%)	79 (-2%)	124 (-3%)
Total Six Countries	6,353 (+5%)	758 (+7%)	1,520 (-1%)	78 (-2%)	119 (+2%)

Analysing the results, it is seen that UK remains the largest market by far in terms of RPKs, representing 29% of the total for the six countries, followed by Germany (21%), France (19%) and Spain (15%). The share of Italy and The Netherlands is smaller, almost 8% of total RPKs. With the exception of Italy and The Netherlands, both the number of flights and the number of passengers grew in all countries, resulting in an overall increase in the number of flights (5% more in 2013 than in 2010) and in the number of passengers (7% more in 2013 than in 2010). Despite of the growth in terms of flights and passengers, there is a reduction in the number of RPKs (1% less in 2013 than in 2010) indicating a slight average stage length decrease. Only in Germany and France there is growth in terms of RPKs but lower than the growth in passengers, with the corresponding reduction of the average flight length as well. It is interesting to note that the 2010 traffic was affected by the air space closure following the eruption of the Eyjafjallajökull volcano in Iceland, but the 2013 traffic is still slightly lower in terms of RPKs, indicating that the effects of the difficult economic conditions in Europe have had a greater impact on air traffic. There is a slight reduction in the average Load Factor (2% less), indicative of the commercial difficulties of airlines, and an increase in the number of passengers per flight (2% more). Both the reduction in the average Load Factor and the increase in the number of passengers per flights, together with the reduction in terms of RPKs can be explained by an increase in the average size of the aircraft used by airlines, as it can be seen later in Table 14 and it will be discussed in the section 4.3.

The distribution of commercial passenger traffic in the six biggest EU27+2 air transport market, segmented per distance band, is presented in Table 10. One of the interesting points in this table is how the average load factor grows with the distance, from the 67% for distances below 500 km (<500 km), where there is a high presence of regional aviation flights, to the 80% for distances longer than 2500 km (>2500 km). It is also noticeable the average number of seats per flight is 123 for distances less than 500 km (<500 km). It means that an important part of these low range flights are performed by

single aisle jets, instead of smaller regional jets or more efficient turboprops due to the fact that airlines try to simplify their fleet composition reducing the number of different aircraft types, selecting models capable to operate in a variety of routes. As it is seen the concentration of flight and the passenger numbers of each segment is similar to 2010. The distance range below 1000 km (<1000km) represents 64% of total passenger flights and 51% of the total passengers. This segment as it has been discussed previously, includes intra-EU flights, which are highly competitive with surface modes, particularly HSR. However, most of the RPKs are in distances longer than 2500 km (>2500 km) about 75% of the total, while just 17% for the range below 1000 km (<1000km). The interval between 2000 km and 2500 km shows the smallest number of flights (3%), passengers (also 3%) and even RPKs (4%).

Table 10. Air passenger traffic in 2013 in the six countries with greatest air traffic in EU27+2

Distance Band (km)	Flights (10 ³)	Passengers (10 ⁶)	RPK (10 ⁹)	Seats (10 ⁶)	ASK (10 ⁹)	Load Factor (%)	Seats per flight
< 500	1,863	153	57	229	85	67	123
500 - 1000	2,205	233	166	316	224	74	143
1000 - 1500	939	123	153	162	200	77	172
1500 - 2000	471	68	118	87	150	79	184
2000 - 2500	177	25	56	32	71	79	180
> 2500	698	155	970	195	1218	80	279
Total	6,353	758	1,520	1,020	1,948	78	119

In terms of freight air traffic, Table 11 Shows the distribution of freight traffic in 2013 in the six countries with the greatest overall air traffic, also the evolution from 2010 to 2013. Except UK and The Netherlands, other countries have had growth in their freight revenue tonne kilometre (FRTK). Germany, UK, The Netherlands and France have the majority of air freight traffic. Airports in The Netherlands move more cargo than airports in Spain and Italy, which have more passenger traffic. This result is consistent with the ranking of European airports in terms of air freight traffic leading by Frankfurt, Paris Charles de Gaulle, Amsterdam Schiphol and London Heathrow airports (ACI 2015).

Table 11. Air freight traffic of six biggest air transport markets of EU27+2 in 2013 with their evolution from 2010 to 2013 (showing in parentheses)

Country	Flights (10 ³)	Tonnes (10 ³)	FRTK (10 ⁶)	Tonnes per flight
Germany	77 (+12%)	3,925 (+7%)	18,235 (+6%)	51 (-4%)
Spain	33 (+26%)	576 (+5%)	2,584 (+4%)	17 (-19%)
France	51 (+30%)	1,609 (+15%)	8,001 (0%)	32 (-11%)
Italy	24 (-7%)	726 (-3%)	3,265 (+10%)	30 (+3%)
The Netherlands	14 (-19%)	1,308 (-14%)	8,710 (-11%)	94 (+7%)
UK	50 (+44%)	2,245 (-2%)	11,974 (-3%)	45 (-32%)

Table 12 presents the distribution of air freight traffic per distance band in the six countries with greatest air traffic in EU27+2. The results support the conclusions from studying the year 2010. Most of freight flights (66%) correspond to short distances, with less than 1000 km (<1000 km), typical of courier services and feeders of large cargo hubs. The bulk of the cargo (68%) is transported to long distances, larger than 2500 km (>2500 km), but those flights only represent 19% of the total. This is due to the much larger size of these aircraft transporting cargo to long distances (average 151 tonnes per flight). In fact, 94% of the FRTKs correspond to distances longer than 2500 km (>2500 km).

Table 12. Distribution of air freight traffic in 2013
in the six countries with the greatest air traffic in EU27+2

Distance Band (km)	Flights (10 ³)		Tonnes (10 ³)		FRTK		Tonnes per flight
< 500	87	35%	1,030	10%	389	1%	12
500 – 1000	78	31%	1,293	12%	925	2%	17
1000 – 1500	22	9%	413	4%	508	1%	19
1500 – 2000	11	4%	266	3%	471	1%	24
2000 – 2500	5	2%	307	3%	654	1%	61
> 2500	47	19%	7,079	68%	49,822	94%	151
Total	250	100%	10,388	100%	52,769	100%	42

Finally, as it is seen in Table 13, the distribution in terms of distance band and aircraft type of all flights in the EUROCONTROL airspace has been analysed, with the intention of deriving conclusions on the evolution of the airlines industry in Europe. The study covers the so-called EU27+2 countries, including all the present EU members but Croatia, plus Norway and Switzerland. The distribution of flights given in Table 13 has been obtained from EUROCONTROL DDR (2013) data, which allows this classification per aircraft type. Observing the Table 13, it is seen that about 78% of the flights are performed with short and medium range jets. This percentage has increased with respect to 2010 figures (75.6%), reflecting the progression of the development of the low-cost model in Europe, which, as a reference, has passed from a 20% market share in 2008 to a 26% in 2013 (EUROCONTROL 2014).

According to OAG (2015) the number of seats offered by low-cost carriers (LCCs) in Europe has increased by an average of 14% per year over the last decade, currently providing 45% of capacity in EU. LCCs are exclusively operating medium range aircraft and their growth has influence in this size of aircraft inventory. There is a reduction in the number of flights in the short range distance, below 500 km (<500 km), and also in the range between 500 km and 1000 km, compatible with the already mentioned intensification of the competition with surface modes, like HSR, and consistent also with the decrease in the domestic traffic consequence of the economic crisis, especially acute in some countries like Greece or Spain.

Table 13. Number of flights in EU27+2 classified per distance band and per aircraft type in 2010 and 2013 (Number of flights less than 500 are given the value "0")

Distance Band (Km)	Aircraft type (MTOW range in tonnes)								Total Band			
	< 7		7-136				> 136		Total flights	% of total	Total flights	% of total
	Small		Turboprop		Jet		Wide					
	2013	2010	2013	2010	2013	2010	2013	2010	2013	2010		
< 500	50	64	671	866	1,436	1,487	26	28	2,182	25.3 %	2,445	29.0 %
500-1000	12	12	154	214	2,013	2,010	31	27	2,209	25.6 %	2,263	26.8 %
1000-1500	2	2	20	16	1,243	1,163	26	23	1,290	15.0 %	1,204	14.3 %
1500-2000	1	0	4	3	886	827	25	19	916	10.6 %	850	10.1 %
2000-2500	0	0	1	1	518	427	37	17	556	6.5 %	445	5.3 %
> 2500	0	0	0	1	608	470	852	761	1,461	17.0 %	1,232	14.6 %
Total	64	78	850	1,100	6,705	6,384	996	876	8,614	100 %	8,439	100 %
% of total flights	0.7 %	0.9 %	9.9 %	13.0 %	77.8 %	75.6 %	11.6 %	10.4 %				

Also, in support of this conclusion, a large reduction in the number of flights with turboprop is seen in Table 13. On the other hand, there is an increase in the number of flights in the medium range (from 1000 km to 2500 km), which can be explained again by the continuous development of the LCCs, with routes of 2 to 3 hours of flight, concentrated in the intra-EU network, a liberalized area with no need of bilateral agreements for traffic rights. The number of long-range flights, distances longer than 2500 km (>2500 km), has increased as well, indicating the air traffic growth outside the EU (extra-EU) to and from countries less affected by the financial crisis (ICAO, 2014a; EASA, EEA, and EUROCONTROL, 2016). Again, this conclusion is supported by the growth in the number of flights performed with jets (single aisle) and wide bodies (see Table 13). It is worth noting (thinking of CO₂ emissions) that there are more wide body flights than turboprops ones.

Overall, there is an increase of 2.1% in the total number of flights in the EU27+2 perimeter in 2013 compared to 2010. This increase is larger, 5%, for the total flights in the six largest markets EU27+2 (Table 9).

4.2. Emissions data Results

By implementing the processes before illustrated in Figure 10, CO₂ emissions for 2010 in EU27+2 were calculated. The results are shown in Table 14. The total CO₂ emissions in 2010 are 216 million tonnes which can be compared with the reference value used by

the European Commission in the inventory performed to implement the emissions trade scheme (ETS) in the aviation sector. The average value for the period of 2004 to 2006 period was also 216 million tonnes (Benito et al. 2010). The difference is to be found in the flight inventory as for the purpose of the ETS other non-airline flights (business flights, sport aviation, utility, general aviation) have been included. The emissions from this sector are about 22 million tonnes, accounting roughly for the emissions growth from commercial flights between 2005 and 2010, thus showing a good consistency. The distribution of CO₂ emissions shows most of the CO₂ emissions, 67.5%, correspond to flights longer than 2500 km (>2500 km) while as it has been seen in Table 4 and Figure 11, this segment just carry 20% of total air passengers. In the contrary, while short-range flights, with less than 1000 km (<1000 km), transport almost half of the total passengers (46%), emit just 13% of the total CO₂.

Table 14. CO₂ emissions distribution per distance band and aircraft type;
Emissions lower than 0,1Mtons are given the value 0 in this table.

CO2 total (Mtonnes)							Total RTK (Passengers + Freight)
Distance Band (Km)	Aircraft type (MTOW range in tonnes)				Total Band		
	< 7	7-136		> 136			
	Small	Turboprop	Jet	Wide			
< 500	0	1.2	8.3	286.3	9.9	4.6%	2.6%
500-1000	0	0.6	17.0	507.4	18.1	8.4%	8.1%
1000-1500	0	0	15.4	665.3	16.2	7.5%	8.8%
1500-2000	0	0	14.7	679.3	15.4	7.1%	7.3%
2000-2500	0	0	9.6	975.1	10.6	4.9%	4.3%
> 2500	0	0	16.1	129.4	145.6	67.5%	68.7%
Total	0	2.0	81.2	132.5	215.8	100.0%	100%

The percentage of total RTKs (passenger flights plus freight flights) per distance band is also shown in Table 14, in order to be compared with the distribution of emissions per distance band. There is a direct correlation between both measures at distance bands. Longer distances flights (>2500 km) are by far the largest contributors to RTKs and emissions, representing approximately 68% of both total RTKs and CO₂ emissions. It is remarkable the relevance of the segment between 500 and 1000 km in the EU with more RTKs and CO₂ emissions than larger distances, notably more than the segment 2000 to 2500 km which represents less than 5%. The significance of the 500 to 1000 km segment is also observed in Table 4, where it can be seen that the largest number of passengers (28% of the total) are in this segment. In addition, the efficiency of turboprops in terms of fuel consumption and therefore CO₂ emissions is apparent, representing less than 1% of the total CO₂ emissions, having 13% of the flights. This is due to the dual effect of a better fuel efficiency and shorter distances flown. Fuel consumption or CO₂ emissions efficiency is measured using the standard parameter of the kilograms of fuel burnt or CO₂ emitted per total RTK (ICAO 2011d). The CO₂ emissions per total RTK values are shown in Figure 15, classified per distance band. In Figure 15, RTKs correspond to all flights (passenger and freight). The fuel efficiency of

short flights (<500 km) is very poor, about 1.48 kg/RTK. This efficiency improves to 0.87 kg/RTK with the distance up to 1500 km. From 1500 km the efficiency declines somehow, showing the poor efficiency of the mixed fleet used in these distances. It was shown in Table 13 that for distances between 1500 and 2500 km, there is a certain portion of the flights flown by wide-body jets, clearly operating far from their maximum range (much longer than 2500 km) and therefore also far from their optimum energetic efficiency.

Figure 15. CO2 emissions per RTK (passenger and freight)

The distributions of the fuel consumption and CO2 emissions per country, together with the values of the intensity parameter are given in Table 15. This again shows a large concentration of the CO2 emissions in a few countries, with the outstanding case of the UK emitting 22.5% of the total EU27+2 air transport CO2. Again, the correlation between the emissions and the production parameter is observed, because in Table 6 it can be seen that UK represents also 23.4% of the total RPKs. This correlation appears for most of the countries, comparing the RPKs for each country as a percentage of the total was shown in Table 6 and the CO2 emissions for that country as a percentage of the total is shown in Table 15. The six largest markets of EU27+2, France, Germany, Italy, Spain, The Netherlands and UK, account for more than two thirds of the EU27+2 CO2 emissions as with the traffic. The CO2 efficiency values which are presented in Figure 15 and Table 15, are comparable with the 0.896 kg/RTK value obtained from worldwide CO2 emissions and RTK data, in the ICAO Environmental Report (ICAO 2013a).

Table 15. CO2 emissions and efficiency per country 2010

Country	Fuel Consumption (Mtonnes)	CO2 (Mtonnes)		CO2 (kg) /RTK
UK	15.43	48.61	22.50%	0.85
Germany	12.46	39.25	18.20%	0.82
France	8.93	28.14	13.00%	0.83
Spain	6.27	19.76	9.20%	0.75
The Netherlands	5.14	16.21	7.50%	0.69
Italy	4.99	15.73	7.30%	0.9
Switzerland	1.91	6.02	2.80%	0.76
Belgium	1.8	5.66	2.60%	1.17
Greece	1.48	4.66	2.20%	1.19
Portugal	1.34	4.21	2.00%	1.25
Austria	1.05	3.31	1.50%	0.87
Denmark	1.04	3.26	1.50%	0.91
Sweden	0.98	3.08	1.40%	0.86
Norway	0.87	2.75	1.30%	1.17
Ireland	0.83	2.61	1.20%	0.88
Finland	0.77	2.42	1.10%	0.74
Poland	0.72	2.26	1.00%	1.07
Czech Republic	43	1.36	0.60%	???
Luxembourg	0.41	1.29	0.60%	0.39
Cyprus	0.35	1.11	0.50%	0.83
Romania	0.3	0.94	0.40%	1.07
Hungary	0.28	0.87	0.40%	1.02
Bulgaria	0.27	0.86	0.40%	1.16
Latvia	0.13	0.42	0.20%	0.84
Malta	0.11	0.33	0.20%	0.83
Lithuania	0.06	0.2	0.10%	0.69
Slovakia	0.06	0.2	0.10%	0.9
Slovenia	0.05	0.16	0.10%	1.72
Estonia	0.04	0.12	0.10%	1.01
Total	68.5	215.79	100.00%	0.84

This study continues with the evaluation of CO2 emissions growth from 2010 to 2013. The CO2 emissions in the 29 countries in 2013 are presented in Table 16, together with the evolution from 2010. Overall, there is a reduction of 3.1%, 209.1 million tonnes of the CO2 emissions in 2013 compared to 2010, which means slightly more than a 1% average yearly decrease in the period. Referring to Alonso et al. (2014), from 2005

(reference year for the EU ETS) to 2010 the overall increase in CO₂ emissions was 10% which means about 2% average yearly increase.

Table 16. CO₂ emissions in EU27+2 countries in 2013 compared to 2010

	Country	CO ₂ emissions 2013 (Mtonnes)	Changes from 2010 (%)
1	UK	47.36	-2.60%
2	Germany	37.62	-4.20%
3	France	26.92	-4.30%
4	Spain	17.49	-11.50%
5	The Netherlands	16.12	-0.60%
6	Italy	15.05	-4.30%
7	Switzerland	6.56	9.00%
8	Belgium	5.38	-4.90%
9	Greece	4.69	0.60%
10	Portugal	4.21	0.00%
11	Denmark	3.44	5.50%
12	Norway	3.26	18.50%
13	Sweden	3.16	2.60%
14	Austria	2.99	-9.70%
15	Ireland	2.85	9.20%
16	Finland	2.56	5.80%
17	Poland	2.07	-8.40%
18	Czech Republic	1.3	-4.40%
19	Cyprus	1.14	2.70%
20	Bulgaria	1.03	19.80%
21	Luxembourg	0.9	-30.20%
22	Romania	0.84	-10.60%
23	Hungary	0.59	-32.20%
24	Latvia	0.49	16.70%
25	Malta	0.37	12.10%
26	Lithuania	0.24	20.00%
27	Estonia	0.17	41.70%
28	Slovakia	0.17	-15.00%
29	Slovenia	0.14	-12.50%
	Total EU27+2	209.1	-3.10%

At it is seen clearly from Table 16, again there is a big concentration of CO₂ emissions in the selected six countries, consistent with the concentration in the traffic distribution among these countries. These six countries together are responsible for 76.8% of

EU27+2 air transport CO₂ emissions. Respectively UK with 22.6%, Germany with 18%, France with 12.9%, Spain with 8.4%, and The Netherlands with 7.7% and Italy with 7.2% of the total EU27+2 CO₂ emissions are the major air transport CO₂ contributors.

The evolution of the CO₂ emissions per distance band is analysed in Table 17 referring to Table 14. The results show that except the interval of 1500 to 2500 km, in all the distance ranges have been a reduction in CO₂ emissions from 2010 to 2013. The largest reduction, -20.2%, has happened in the short-range interval (<500 km) and a significant increase of 6.6% occurred in the range between 2000 km and 2500 km. The evolution of emissions classified per distance has a different trend comparing with the evolution of traffic already described in Section 4.1. It is especially relevant to the emissions reduction in the largest distances interval (>2500 km), responsible for the most of air transport CO₂ emissions in EU, because the number of flights grew in that band.

Table 17. CO₂ emissions in EU27+2 countries in 2013 classified per distance band

Distance Band	CO ₂		Growth % 2010 to 2013
	Mtonnes	% of Total	
< 500	7.9	3.8	-20.2%
500 - 1000	16.3	7.8	-9.2%
1000 - 1500	15.7	7.5	-3.1%
1500 - 2000	15.5	7.4	0.6%
2000 - 2500	11.3	5.4	6.6%
> 2500	142.3	68.1	-2.3%
Total	209.1	100%	-3.1%

The distribution of the CO₂ emissions per aircraft type and distance band is shown in Table 18. As it could be expected, most of the CO₂ emissions (73%) correspond to long distance flights (>2500 km). It is worthwhile highlighting again the relevance of the long-range traffic in the six largest markets analysed, comparing the results in Tables 17 and 18. It can be observed in Table 18 that the distribution of the share of the six selected countries varies between 58% and 70%, depending on the distance band, except in the category of more than 2500 km (>2500 km) band, where the share reaches 83%. This fact has an impact on the efficiency figures, as will be shown in Section 4.3, because long-range flights are usually more efficient in terms of fuel consumption.

Table 18. CO2 emissions in the six largest EU27+2 aviation markets in 2013
classified per distance band and aircraft type

CO2 emissions (Mtonnes)					
Distance Band (Km)	Aircraft type (MTOW range in tonnes)				Total Band
	< 7	7-136		> 136	
	Small	Turboprop	Jet	Wide	
< 500	-	0.5	4.6	0.2	5.2
500-1000	-	0.2	10.7	0.4	11.4
1000-1500	-	0	10	0.5	10.5
1500-2000	-	0	9	0.5	9.5
2000-2500	-	0	6.1	0.5	6.6
> 2500	-	0	10.7	106.7	117.4
Total	-	0.7	51.1	108.7	160.8

4.3. Fuel Efficiency Evolution

After analysing the evolution of the air traffic and CO2 emissions, the fuel efficiency (or CO2 emissions efficiency) is investigated. The evolution of the efficiency parameter, measured in terms of emitted CO2 per RTK (or burnt fuel per RTK) is shown in Table 19 for the six largest EU aviation markets. There is a reduction of 4.3% in the CO2 emissions, only partly explained by a modest decrease in the traffic (0.8% in terms of RTK). Overall, there is a 3.5% improvement in the efficiency parameter, which corresponds to an average 1.2% yearly improvement between 2010 and 2013. The reduction in the CO2 emissions for the six largest countries (-4.3%) is larger than for the whole EU27+2 (-3.1%), in the three years period.

Table 19. Efficiency parameter per country; Comparison between 2013 and 2010

Country	RTK (10 ⁶) passengers + freight			CO2 (Mtonnes)			kg CO2 /RTK		
	2013	2010	Var. (%)	2013	2010	Var. (%)	2013	2010	Var. (%)
Germany	50,235	47,842	+5.0	37.92	39.25	-4.20	0.75	0.82	-8.70
Spain	25,584	26,373	-3.0	17.49	19.76	-11.5	0.68	0.75	-8.8
France	36,401	34,089	+6.8	26.92	28.14	-4.3	0.74	0.83	-10.4
Italy	14,865	17,367	-14.4	15.05	17.73	-4.3	1.01	0.91	+11.8
The Netherlands	21,210	23,342	-9.4	16.12	16.21	-0.6	0.76	0.69	+9.1
UK	56,474	57,382	-1.6	47.36	48.6	-2.6	0.84	0.85	-1.0
Total six	204,769	206,395	-0.8	160.56	167.69	-4.3	0.78	0.81	-3.5

From data in Table 20, it can be seen that longer distance routes (>2500 km) account for 73% of total CO2 emissions, consistent with carrying 72% of the RTKs. Shorter distances (<500 km) are responsible for just 3.3% of the CO2 emissions, but move 20%

of the passengers. Most of the efficiency gain comes from the shorter distance range below 1000 km (<1000 km) and especially from the long distance range larger than (>2500 km). The methodology that has been followed to analyse the evolution of traffic and CO₂ emissions is also useful to derive the same type of information at airline level, and investigating for instance the differences in terms of energy efficiency among the various airline business models. The results are shown in Table 21 and Figure 16, where the average efficiency is presented for a subset of network carriers (Lufthansa, 1st European airline and 6th of the world in terms of traffic, Air France, KLM, British Airways, Iberia, SAS and Alitalia), low-cost carriers (Ryanair, largest European low cost carrier and 2nd of the world in this category, Easyjet, Air Berlin, Norwegian, Vueling and Wizz), Regionals (Air Nostrum, Air Dolomiti and BEE) and Inclusive Tour (IT) or charter carriers (TUI, Thomas Cook and Monarch), a category still important in the intra-European traffic. According to this analysis, the average efficiency of the low-cost carriers represents 78% of the value for the network carriers, a very important difference that explains partly the cost advantage of this type of companies. IT's or charter carriers are even more efficient (60% of the efficiency of the network carriers).

Table 20. Efficiency parameter for the six largest EU aviation markets in 2013 classified per distance band. In brackets, percentage with respect to the total.

Distance Band (km)	RTK (10 ⁶) passengers + freight	CO ₂ (Mtonnes)	Kg CO ₂ /RTK	
			2013	Change w.r.t 2010
< 500	6,089 (3%)	5.24 (3.3%)	0.86	-14.0%
500 - 1000	17,525 (9%)	11.37 (7.1%)	0.65	-11.0%
1000 - 1500	15,808 (8%)	10.54 (6.6%)	0.67	1.5%
1500 - 2000	12,271 (6%)	9.48 (5.9%)	0.77	8.5%
2000 - 2500	6254 (3%)	6.57 (4.1%)	1.05	19.3%
> 2500	146,822 (72%)	117.36 (73.1%)	0.80	-1.3%
Total	204,769	160.56	0.78	-3.5%

Table 21. Airlines emissions and efficiency

Airline type	Average efficiency (kg Co ₂ /RTK)	Difference w.r.t. Network Carriers (=100)
Network carriers	1.06	100
Low-cost carriers	0.83	78
Regionals	1.84	1.73
IT's or charter	0.6	57

On the other hand, Regional routes show the worst behaviour, with efficiency 73% less than that of the network carriers. These results are consistent with the analysis of Miyoshi and Mason (2009) for the period 1997 to 2006. In order to investigate the reasons of those differences in the efficiency for each airline business model, the

efficiency of the various aircraft types, depending on how they are utilized by each airline, have also been analysed. The results are shown in Table 22 and Figure 17.

Figure 16. Efficiency of different aircraft type and airline business model

Figure 17. Efficiency of different aircraft type and airline business model

As the “Corinair database” has a relatively wide definition of aircraft type, putting together models with different weights and engines, these figures should be considered as approximate but give a good first order of magnitude of the comparative results. A relevant aspect of this comparison is the higher efficiency (in terms of kg CO2/RTK) of the low cost carriers compared with the traditional airlines when operating the same type of aircraft (Airbus A320 or B737NG family aircraft). Analysing Table 22, the dependency of the efficiency parameter with the average stage length, it can be appreciated how the improvement in the efficiency parameter of the low cost carriers compared to the network carriers flying the same type of aircraft is larger for longer values of the average stage length, but it is also the case even for smaller values of the average stage length, as a proof of a more modern fleet composition in the case of the low-cost carriers.

Another interesting output of this analysis is the different aircraft utilization that airlines obtain from the aircraft they operate. It can be observed from data in Table 23, how the daily utilization of the same aircraft type is quite higher for low-cost companies compared to network carriers due to the differences between their network structure (point to point instead of hub & spoke) and operation procedures (short time airport turnaround, no connections, no cargo).

Table 22. Efficiency of aircraft operated in 2013

Family	Model	Network carriers		Low-cost carriers	
		Mean leg (km)	Kg CO2/RTK	Mean leg (km)	Kg CO2/RTK
A320	A318	590	1.13		
	A319	966	1.12	862	1.12
	A320	1,034	0.95	1261	0.76
	A321	1,247	0.78	1419	0.68
Single aisle Airbus		959	0.99	1181	0.86
B737-classic	B737-300	592	1.2	868	1.04
	B737-400	1,117	1.08		
	B737-500	532	1.47		
B737-NG	B737-600	657	1.18		
	B737-700	785	1.13	507	1.33
	B737-800	2,000	0.73	1253	0.69
	B737-900	2,108	0.75		
Single aisle Boeing		1,113	1.08	876	1.02
Total single aisle		1,057	1.05	1028	0.94
A330	A330-200	5,548	1.1		
	A330-300	5,514	0.99		
A340	A340-300	6,416	1.05		
	A340-600	7,984	0.94		
A380	A380	8,462	0.78		
Wide body Airbus		6,794	0.97		
B767	B767-300	3,760	0.82		
B777	B777-200	8,020	1.04		
	B777-LR	6,327	0.78		
	B777-W	8,400	0.84		
B747	B747-400	7,592	1.09		
Wide body Boeing		8,004	0.99		
Total wide body		7,284	0.98		
Regionals		588	1.61		

Table 23. Aircraft utilization

Model	Airline	Daily Utilization
		(Block Hours)
A319	British Airways	6.3
	Iberia	9
	Easyjet	10.1
A320	British Airways	7.1
	Iberia	8.3
	Easyjet	10.4
	Wizz	10.2
B737-800	KLM	9.5
	Ryanair	11.5

4.4. Fleet evolution 2004-2013

In order to explain the improvement in the efficiency previously shown, the evolution of the fleet composition of airlines operating in the EUROCONTROL airspace has been performed for the last decade. The evolution of the number of aircraft of each category is shown in Figure 18, where the percentage of the number of flights operated by each aircraft type referring to the total number of flights is shown from 2004 to 2013. Although the period covered by this investigation of traffic and efficiency evolution is 2010 to 2013, but the changes in airlines' fleet composition are analysed for a longer time frame to show the trend in this important parameter for the airlines efficiency. The share of flights operated by wide bodies is relatively stable, being the same at the end of the period than at the beginning (12%), with a slight decrease during 2008 (10%) and the interval 2009-2012 (11%). Probably the most relevant result is the sustained increase in the share of the single aisle type, growing almost continuously from 62% in 2004 to 67% in 2013. This increase matches very well with the reduction in the share of regional aircraft, decreasing from a 26% share in 2004 to a 22% in 2013, where the decrease in the smaller segment (<50 seats), from 16% to 5% does not compensate the increases in the 70 seats category (from 8% to 10% and in the more than 90 seats category (from 2% to 7%).

The results show an overall increase in the average size of the aircraft flying these routes, where regional models are reducing their participation in the total of the flights, while larger jets, both single aisle and wide body, are increasing theirs. These figures are consistent with the results of the traffic evolution described in Section 4.1, and with the changes in the business model of the airline industry in Europe in the last decade, with the continued growth of low-cost carriers, typical users of single aisle aircraft, and the difficulties of regional airlines caused at a great extent by the poor economy of small size jets in an expensive fuel environment and the competition of fast surface transportation modes. The improvement in the industry fuel efficiency shown previously can be partly explained by the evolution of the number of flights operated by aircraft of each category shown in Figures 19, 20, 21 and 22, where the percentage of flights

operated by each aircraft model with respect to the total of the corresponding category is plotted. Concerning single aisle aircraft, the replacement of the classic B737 family by the newer B737 NG family is clearly appreciated in Figure 19 as well as the reduction in the share of the B757 and the practical disappearance of the MD80/MD90 series, both replaced by a mix of B737NG and A320 families. All replacements are made with more energetic efficient models and collaborate to reduce CO2 emissions per RTK.

Figure 18. Fleet evolution 2004 to 2013 per aircraft category

Figure 19. Fleet evolution 2004 to 2013, total single aisle

Concerning wide bodies, as it is shown in Figure 20, there is a continuous increase in the share of the two most modern long range twin types, the A330 and the B777, reaching each of them 25% of the total number of flights of this category in 2013, starting in both cases also with a 13% in 2004. Only the A340-500/600 and the newest A380, B747-8 and B787 increase their share. There is a strong reduction in the relative number of flights of old models such as the A300/A310, the DC10/MD11 and the older versions of the B747 and A340-200/300, all of them out of production nowadays. The share of the B767 shows a slow decline from 18% to 16%. It can be concluded that along the full period 2004 to 2013 (and also between 2010 and 2013), there has been an

important renovation in the commercial jet (single aisle and wide bodies) fleet operating in the EUROCONTROL airspace. This fleet renewal can explain the improvement in fuel efficiency described in Section 4.3.

Figure 20. Fleet evolution 2004 to 2013. Wide bodies

Figure 21. Fleet evolution 2004 to 2013 in the segment of regional aircraft with up to 50 seats (<50 seats)

In the regional aircraft segment with up to 50 seats (<50 seats) (Figure 21), there has been a strong increase in the share of turboprops, from 38% in 2004 to 49% in 2014, reflecting the need for efficiency improvement of regional airlines during the decade. It is particularly noticeable the increase in the share of the Dash8 family and the strong decrease of the share of the CRJ100/200, good example of jet-powered aircraft with 50 seats, affected by the high price of fuel and being partially replaced by more fuel efficient turboprop models. The share of turboprops in regional aircraft segment with 70

seats, as it is seen in Figure 22, has remained more stable varying around 70% for the whole period (adding the ATR42 and Dash8-400Q). From the jet side, there is a replacement of the CRJ700 and especially the older Fokker F70 by the Embraer E170.

Figure 22. Fleet evolution 2004 to 2013 in the segment of regional aircraft with 70 seats

Figure 23. Fleet evolution 2004 to 2013 in the segment of regional aircraft with more than 80 seats (>80 seats)

Finally, in Figure 23 the larger regional jets segment (>80 Seats) (8%). All of them replace the old (and far less efficient in terms of fuel consumption) Fokker F100, which had 100% of the share in terms of number of flights in 2004, and keeps just 11% in 2013. Summarizing, there has also been an improvement in fuel efficiency in the regional segment, coming from different sides:

- Replacement of jets by turboprops in the smaller segment (less than 50 seats).
- Replacement of old models (Fokker F70 and F100) by newer models (E170/190, CRJ900/1000) in the large regional aircraft segment.

- Overall, an increase in the aircraft size, with a net reduction in the number of flights operated by aircraft with less than 50 seats and an increase in the flights with aircraft with more than 90 seats.

4.5. CO₂ emissions projection

Considering 2010 as the baseline, traffic activity, fuel demand and emissions have been projected on an annual basis up to 2030. In this study, 2010 is considered as the reference year, but verified data of 2011 and 2012 are also available and actual growth rates for these years are included in all scenarios and projections start from 2013 onwards. This section of current thesis is based on a projection research project, which have been started in 2013. Therefore, updated data for 2013 will be compared with the results of projection to show the accuracy of current model. For this data projection, three different growth scenarios have been used.

Historical air traffic growth After the Second World War, air transport experienced a fast and continuous growth in every geographical area, at rates dictated by the prevalent socio-economic conditions in each country. In the 50s and 60s decades, growth rates were double digit. The oil price shocks of the 70s and 80s tempered the air transport increase and aligned it to the cyclic fluctuations of the world economy, with a typical elasticity (Air transport growth/world GDP growth) between 1.5 and 2 (Benito 2007). In spite of many contingencies, all specialized forecasts (ICAO, 2007b; EUROCONTROL, 2010; IATA, 2012a; Boeing, 2012; Airbus, 2012) extrapolate the idea of a growing industry in the coming years, based on a number of related socio-economic trends that explain the direct relationship between air transport and the economy, both in international trade patterns and in the leisure travel sectors. There are negative factors as well, that are becoming more significant as the dimension and repercussions of commercial aviation gain importance. The most relevant ones are likely to be:

- The cost of the kerosene fuelling commercial aircraft. Until alternative fuels are developed, air transport suffers from a strong dependence on the oil price that is expected to increase again in the coming years.
- The maturation of the air travel market in the most developed countries.
- Public opinion worries about environmental conditions, which may impact air transport development.

The different evolution of the above-mentioned factors in the European Union and in other parts of the world seems to recommend using different growth scenarios for the traffic growth within European borders and the flights beyond them. This is the philosophy adopted in this study in order to evaluate the evolution of air transport in the European Union. Long-term scenarios, covering the period 2013 to 2030, have been prepared. A central or most likely scenario is followed by two additional ones, the first assuming a number of credible negative trends that may appear during that period and the second following the hypothesis of more optimistic conditions. A survey of available forecast by specialized bodies has been performed, including international organizations

(ICAO, 2007b; EUROCONTROL, 2010; IATA, 2012a; Boeing, 2012; Airbus, 2012). As the aim of this research project is to choose the most likely scenario as the baseline, the mentioned international sources (ICAO, Eurocontrol, IATA, ACI, Airbus and Boeing) have been compared, taking out the highest and lowest value and adopting the statistical mode of the other four. The baseline of this scenario considers the (2013-2016) as the beginning period of slow economic growth within the European Union countries followed by a gradual recuperation in the (2017-2020) period and a steady growth in the following decade (2021-2030). As the air transport demand varies in parallel to the economy growth, traffic to and from EU is assumed to have different levels of development in each decade, but in any case higher than domestic EU demand, due to integrating the higher developing pace of emerging economies (Table 24).

Table 24. Central Scenario traffic growth

Period	2013-2016	2017-2020	2021-2030
EU traffic	2.80%	3.20%	3.50%
Non EU traffic	4.00%	4.00%	4.50%

The application of these values to the traffic is not immediately translated to the fuel consumption because there are several factors improving the energetic efficiency of air transport:

- Fleet replacement, substituting some aircraft models by new, more efficient ones as they enter into the market.
- Use of larger aircraft, as the average commercial aircraft size is continuously increasing.
- Increased density seating inside the aircraft. With the development of low cost carriers, the number of seats has been rising, not only with these airlines but also with the incumbents.
- Air traffic control and navigation system improvements, allowing the optimization of flight profiles and trajectories.

Calculating the practical impacts of all these advancements is rather complicated. During the last 15 years IATA has been comparing the values of the RTKs with fuel consumption. The results show an average annual improved efficiency, measured in tonnes of fuel per RTK, of around 1.9% (IATA, 2013) for the IATA members, although other studies indicate lower figures. A good recollection of different analysis in the 1997 to 2012 period can be found in Peeters (2013). Meanwhile ICAO, in its climate change mitigation program, has set an aspirational target for the world air transport sector of 2.0% annual improvement until 2020, with a possible stretch until 2030 if the national action plans prepared by contracting States prove to be adequate (ICAO, 2011). In addition, IATA has considered an efficiency improvement of 1.5% per year in future years and adopted this as a voluntary commitment. Considering that information, the annual figure of 1.5% efficiency improvement has been used in the Central Scenario for

the full 2013 to 2030 period. The appearance of a number of new more efficient models in all size and range categories (A350, B777X, A320NEO, B737MAX, C919, MS21, C-Series, E2Jet and CRJ re-engined) in the next five years and the promised improvements in the use of the air space (SESAR, NextGen) seem to support the credibility of this number. With respect to the biofuel usage, most of the specification and operational questions have been already answered and no technological showstopper seen in the considered period. However, the economic viability is still far from being made secure. For this study, an assumption has been used that up to 2017 the introduction of biokerosene is 1% of the total fuel usage, with this percentage progressively increasing, achieving 5% in 2021 and remaining at this level until 2030. In the projections made, the CO₂ emissions coming from biokerosene are not included. This decision of taking a zero emission factor for aviation biofuels is congruent with the European ETS Directive (EC, 2008) although assessments of life-cycle CO₂ emissions typically show a reduction potential compared to fossil jet fuel in the order of 30-90%, depending on the feedstock and production processes (Stratton et al. 2010).

Alternative scenarios The Pessimistic Scenario (Table 25) is based on the hypothesis of a prolongation of the EU economic crisis until the end of the present decade with a dual situation of high-deficit countries sunk in the economic recession or its sequels, and better-off countries carefully moving their budget control with strong limitations on expenditure. This bleak forecast would be improving at a slow pace during the second decade. Moderate US economic recovery, inflationist pressures in China and fast rising oil prices would reduce by a couple of percentage points the demand growth for air traffic outside the EU.

Table 25. Pessimistic Scenario traffic growth

Period	2013-2016	2017-2020	2021-2025	2026-2030
EU traffic	0.80%	1.00%	1.50%	2.00%
Non EU traffic	2.00%	2.00%	2.50%	2.50%

Table 26. Optimistic Scenario traffic growth

Period	2013-2016	2017-2020	2021-2025	2026-2030
EU traffic	2.8 – 3.0	3.4 – 3.6	4	4
Non EU traffic	4.50%	5.00%	5.50%	5.50%

Figure 24. CO2 emissions projections in the three scenarios

The Optimistic Scenario as is seen in Table 26, assumes a fast and robust recovery of the EU economy, returning to pre-crisis growth rates in the middle of the present decade, partially thanks to the stabilization of oil prices. International markets would gain from a high consumer expenditure increase in the United States and a soft landing of the overheated Chinese economy. Intra-EU demand will always increase less than external traffic. In both alternative scenarios, the efficiency improvement and the percentage of bio-kerosene usage are kept at the same levels than in the Central Scenario. The projections for CO2 emissions in all three scenarios are shown in Figure 24. CO2 emissions in 2030 result in a baseline value of 293 million tonnes, ranging between 207 and 334 million tonnes respectively for the pessimistic and optimistic scenarios. These projections result in average annual growth rates of CO2 emissions of 1.8% in the Central Scenario, -0.2% in the Pessimistic Scenario and 2.7% in the Optimistic Scenario. Similar growth rates are given in (Chèze et al. 2013). In terms of total fuel consumption (including bio-kerosene), the projections give values for 2030 of 93, 66 and 106 million tonnes respectively for the baseline, pessimistic and optimistic scenarios (Figure 25).

Figure 25. Total fuel consumption projections in the three scenario

Chapter 5. Conclusions and future works

During last decades the tendency to choose between transports modes has been toward faster transport modes, which resulted in the air travel fascinating growth in passenger and freight segments. Though air transport development has contributed to multidimensional development of countries, but its environmental impact has become a major challenge for the industry. This thesis started out of the idea to explore influential factors toward a more sustainable air transport industry. This idea developed into studying air transport fuel efficiency and its growth rate in the European Union by analysing the structure of domestic and international air traffic and its distribution among the European Union member states.

The findings of current research will be useful for researchers and decision makers in their evaluation of different strategies aiming sustainable air transport. The analysis of passenger flights in 2010 shows that the traffic is very concentrated on short distances below 1000 km (almost 60% of the flights and 46% of the passengers), despite the broad availability of surface transport alternatives. This distance segment is highly competitive with HSR which is highly supported by the EU policy makers referring to the report of European Commission (2001), “We can no longer think of maintaining air links to destinations for where there is a competitive high-speed rail alternative. In this way, capacity could be transferred to routes where no high-speed rail service exists”.

Air freight transport is concentrated on long distances, with 69% of the cargo tonnes and 94% of the RTKs flown in distances larger than 2500 km. The concentration of passenger flights is seen in the six larger air transport markets of the EU such as France, Germany, Italy, Spain, The Netherlands and UK. Approximately two thirds of the total flights and passenger traffic in EU27+2 and about 82% of total RPKs are belonging to these six countries. The distribution of cargo flights is different showing an even larger concentration. France, Germany, The Netherlands and the UK represent together 74% of the total RTKs of the EU27+2. In 2010, air transport CO₂ emissions accounted for a total value of 216 million tonnes. Again, a large concentration of emissions is seen in a few countries leading with UK with 22.5% of the total CO₂ emissions generated by air transport in EU27+2. The parameter, CO₂ emissions per RTK, varies with the distance band, and therefore with the fleet composition used per distance band.

The investigation about the traffic evolution in the six EU largest markets (representing some 80% of the total EU RTKs) shows that the number of air passenger traffic has declined slightly, almost 1% from 2010 to 2013. This reduction is mainly consequence of the financing crisis in Europe. This is unevenly distributed according to the evolution of the local economies in those years: growth in Germany and France, decrease in the UK, Spain, Italy and The Netherlands. Most of the flights are operated in the distance range below 1000 km, although most of the RPKs are flown in distances longer than 2500 km. The number of flights performed with short and medium range jets (78% of total flights) have increased with respect to 2010 figures (75.6% of total flights), as well as the number of flights in the medium range (from 1000 km to 2000 km), reflecting the

progression in the development of the LCC in Europe. There is on the other side a reduction (in relative terms) in the number of flights performed with turboprop and in the number of flights in the short-range distance (below 500 km). It corresponds to the reduction in the domestic traffic and may be also an indication of an escalation of the competition with surface modes, like HSR. Largest growth in traffic comes in the long range (distances longer than 2500 km), and in the number of flights performed with single aisle and wide body jets, indicating the air traffic growth outside the EU, less affected by the weak economy. The CO₂ emissions have been reduced by 4.3% in the three years period considering only the six largest markets. Considering the overall EU27+2 perimeter, the reduction in the CO₂ emissions is smaller, 3.1%, corresponding to lower levels of fleet renewal in less wealthy economies. The reduction in the CO₂ emissions is larger than the decrease in traffic (RTKs), resulting therefore in a 3.5% improvement in efficiency (kg of CO₂ per RTK), coming from efficiency improvements in shorter-range flights (less than 1000 km) and long-range flights (longer than 2500 km). This latter segment explains the overall improvement in the efficiency parameter, as it accounts for 73% of the total CO₂ emissions. That global figure for the three-year period (2010-2013) is 3.1% and represents a 1.2% average efficiency improvement per year. Yet, this number is lower than the 1.5% voluntary commitment adopted by IATA and much lower than the 2% aspirational target established by ICAO (2013b). However, it is in line with the recent analysis by Kharina and Rutherford (2015), which have found an annual improvement of 1.1% after 2010, considering only the evolution of the world fleet composition. As the calculation in the present investigation covers fleet composition but also real operation and network evolution, the 10% difference may be considered acceptable for those two additional factors. Taking a representative sample of airlines from the different business models (network, low-cost, regionals, Inclusive Tour), the differences in their corresponding efficiencies are highlighted, with important efficiency variations among them. Charter type carriers with high density interior configuration, medium to long range routes, high load factors and large aircraft are the most efficient, while regional carriers, with standard interiors, medium to short range routes, modest load factors and small aircraft are the worst. The results show that Inclusive Tour operators are three times more efficient than regionals in CO₂ emissions. A clear consequence is that fuel efficiency increases as load factor and seating density get higher and an advanced policy of emissions reduction should make clear distinction among different passenger accommodation and on the cargo effect as well.

An additional conclusion may lead us to show that the freighter version of a passenger aircraft is always more energetically efficient than the original, at similar load factor. In order to try and explain the improvement in the efficiency parameter, an analysis of the fleet composition has been performed, showing an important fleet renewal in the last ten years, implying the replacement of old models by newer ones and an increase of the average size of aircraft, especially in the regional routes segment. While passenger preference leans towards high frequency service with small aircraft, from the point of view of environmental economics and airport capacity management, low frequency

with larger aircraft is much more energy-efficient. As the technological efficiency increase does not seem enough to compensate the traffic growth, the only way of stabilizing air transport CO₂ emissions (as it is planned, starting in 2020) seems to be the application of MBMs. This may have a dual effect: moderate the demand growth by doing the flight more expensive (an effect to be compared with the fuel price evolution) and collect money to apply compensatory mechanisms, investing in reducing CO₂ emissions in other sectors with a more affordable cost per suppressed tonne.

The future research can follow decision-making methods to develop a model to calculate effectiveness of each influential factor on air transport CO₂ reduction. For example one interesting area of research is to analyse how geopolitical situation of countries, impact creation of airport hubs and deviations from optimal routs, which are an important parameters in fuel efficiency.

Chapter 6. Bibliography

- Achachlouei, M.A., 2015. *Exploring the Effects of ICT on Environmental Sustainability : From Life Cycle Assessment to Complex Systems Modeling*.
- ACI, 2011. *ACI GUIDANCE MANUAL : AIRPORT GREENHOUSE GAS EMISSIONS MANAGEMENT*,
- ACI, 2015. *ACI World releases preliminary world airport traffic and rankings for 2014*, Available at: <http://www.aci.aero/News/Releases/Most-Recent/2015/03/26/ACI--World-releases-preliminary-world-airport-traffic-and-rankings-for-2014--DXB-becomes-busiest-airport-for-international-passenger-traffic->.
- ACI, 2016. AIRPORTS COUNCIL INTERNATIONAL EUROPE.
- Adler, N., Martini, G. & Volta, N., 2013. Measuring the environmental efficiency of the global aviation fleet. *Transportation Research Part B: Methodological*, 53(September 2010), pp.82–100. Available at: <http://dx.doi.org/10.1016/j.trb.2013.03.009>.
- Adler, N., Pels, E. & Nash, C., 2010. High-speed rail and air transport competition: Game engineering as tool for cost-benefit analysis. *Transportation Research Part B: Methodological*, 44, pp.812–833.
- Adler, N., Ülkü, T. & Yazhemsky, E., 2013. Small regional airport sustainability: Lessons from benchmarking. *Journal of Air Transport Management*, 33, pp.22–31. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2013.06.007>.
- AEA, 2001. Yearbook 2001. , (July). Available at: <http://europa.eu.int/comm/agriculture/>.
- Ahn, Y.H. & Min, H., 2014. Evaluating the multi-period operating efficiency of international airports using data envelopment analysis and the Malmquist productivity index. *Journal of Air Transport Management*, 39, pp.12–22.
- Air Transport Department of Cranfield University, 2010. *Fuel and air transport (A report for the European Commission)*,
- Airbus, 2007. *Flying by Nature: Global Market Forecast 2007–2026*,
- Airbus, 2015. *Global Market Forecast: Flying By Numbers 2015-2034*,
- Airbus, 2012. *Global Market Forecast 2012-2031*,
- Åkerman, J., 2011. *Transport systems meeting climate targets – A backcasting approach including international aviation*. Available at: <http://kth.diva-portal.org/smash/get/diva2:396982/FULLTEXT01.pdf>.
- Åkerman, J. & Höjer, M., 2006. How much transport can the climate stand?-Sweden on a sustainable path in 2050. *Energy Policy*, 34, pp.1944–1957.
- Albalade, D. & Bel, G., 2010. ‘High-Speed Rail: Lessons for Policy Makers from Experiences Abroad’. *Institut de Recerca en Economia Aplicada Regional i Pública, Universitat de Barcelona*, (3). Available at: http://www.ub.edu/irea/working_papers/2010/201003.pdf.
- Albalade, D., Bel, G. & Fageda, X., 2015. Competition and cooperation between high-speed rail and air transportation services in Europe. *Journal of Transport of Geography*, 42, pp.166–174. Available at: <http://dx.doi.org/10.1016/j.jtrangeo.2014.07.003>.

- Alonso, G. et al., 2014. Investigations on the distribution of air transport traffic and CO₂ emissions within the European Union. *Journal of Air Transport Management*, 36, pp.85–93. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2013.12.019>.
- Aminzadeh, F. et al., 2016. Journal of Air Transport Management Analysis of the recent evolution of commercial air traffic CO₂ emissions and fleet utilization in the six largest national markets of the European Union. *Journal of Air Transport Management*, 55, pp.9–19. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2016.04.006>.
- Anable, J. et al., 2012. Modelling transport energy demand: A socio-technical approach. *Energy Policy*, 41, pp.125–138. Available at: <http://dx.doi.org/10.1016/j.enpol.2010.08.020>.
- Anable, J. & Boardman, B., 2005. *Transport and CO₂*,
- Anderson, B.E. et al., 1998. Airborne observations of aircraft aerosol emissions II: Factors controlling volatile particle production. *Geophysical Research Letters*, 25(10), p.1693.
- Anger, A., 2010. Including aviation in the European emissions trading scheme: Impacts on the industry, CO₂ emissions and macroeconomic activity in the EU. *Journal of Air Transport Management*, 16, pp.100–105. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2009.10.009>.
- Anon, 1999. Aviation and the Global Atmosphere. , pp.2–6.
- Aomo, M.O., Oima, D.O. & Oginda, M.N., 2016. An Empirical Investigation into the Effect of Enhancing Airline Capacity on Load Factor: A Case of Kenya's Low-Cost Carriers. *American Journal of Industrial and Business Management*, 6, pp.717–731. Available at: <http://www.scirp.org/journal/PaperDownload.aspx?DOI=10.4236/ajibm.2016.66066>.
- Aparicio, A., 2016. Exploring Recent Long-distance Passenger Travel Trends in Europe. *Transportation Research Procedia*, 14, pp.3199–3208. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S235214651630268X>.
- Araña, J.E. & León, C.J., 2013. Can Defaults Save the Climate? Evidence from a Field Experiment on Carbon Offsetting Programs. *Environmental and Resource Economics*, 54, pp.613–626.
- Arul, S.G., 2014. Methodologies to monetize the variations in load factor and GHG emissions per passenger-mile of airlines. *Transportation Research Part D: Transport and Environment*, 32, pp.411–420. Available at: <http://www.sciencedirect.com/science/article/pii/S1361920914001199> [Accessed May 16, 2015].
- ASD, 2015. *AEROSPACE AND DEFENCE INDUSTRIES FACTS & FIGURES*,
- ASD, 2008. *Facts & Figures 2008*,
- Ashok, A. et al., 2014. Quantifying the air quality-CO₂ tradeoff potential for airports. *Atmospheric Environment*, 99, pp.546–555. Available at: <http://dx.doi.org/10.1016/j.atmosenv.2014.10.024>.
- ATAG, 2016a. *Aviation Benefits Beyond Borders*,
- ATAG, 2014a. *Aviation benefits beyond borders*, Available at: <http://www.atag.org/facts-and-figures.html>.
- ATAG, 2014b. Aviation benefits beyond borders. *Atag*, (April), p.72. Available at: http://aviationbenefits.org/media/26786/ATAG__AviationBenefits2014_FULL_LowRes.p

df.

- ATAG, 2015. *Aviation Climate Solutions*, Available at: WWW.ENVIRO.AERO/CLIMATESOLUTIONS.
- ATAG, 2009. Beginner's Guide to Aviation Biofuels. *Air Transport Action Group*, (May). Available at: WWW.enviro.aero.
- ATAG, 2010. Beginner 's Guide to Aviation Efficiency. *Aviation*, (November).
- ATAG, 2016b. Facts & FIGURES - Air Transport Action Group (ATAG). , (May).
- ATAG, 2013a. *Reducing emissions from aviation through carbon neutral growth from 2020*, Available at: <http://www.iata.org/policy/environment/Documents/atag-paper-on-cng2020-july2013.pdf>.
- ATAG, 2013b. *THE GLOBAL FLIGHTPLAN: REDUCING EMISSIONS FROM THE INTERNATIONAL AVIATION SECTOR THROUGH CARBON-NEUTRAL GROWTH FROM 2020*,
- Atkin, J.A.D., Burke, E.K. & Greenwood, J.S., 2011. A comparison of two methods for reducing take-off delay at London Heathrow airport. *Journal of Scheduling*, 14(5), pp.409–421.
- Atmosfair, 2015. Atmosfair Airline Index 2015. *atmosfair, Berlin 2011*. Available at: https://www.atmosfair.de/portal/documents/10184/43549/AAI_Broschuere_2013_DE.pdf/fd98f702-32c9-4785-85a1-e281c0194591.
- BAA, 2010. Towards a sustainable Heathrow Aviation and climate change Emissions from flights : technology and emissions trading. *Heathrow Airport Report*. Available at: http://www.heathrow.com/file_source/Company/Static/PDF/Communityandenvironment/LHR_Climate_brochure.pdf.
- Babikian, R., Lukachko, S.P. & Waitz, I.A., 2002. The historical fuel efficiency characteristics of regional aircraft from technological, operational, and cost perspectives. *Journal of Air Transport Management*, 8, pp.389–400.
- Bailey, E.E., 1992. Airline Deregulation Confronting the Paradoxes. *CATO Review of Business & Government*, (Summer).
- Bartels, L., 2012. The Inclusion of Aviation in the EU ETS: WTO Law Considerations. *International Centre for Trade and Sustainable Development (ICTSD)*, April(6). Available at: <http://papers.ssrn.com/abstract=1959981>.
- Becken, S., 2007. Tourists' Perception of International Air Travel's Impact on the Global Climate and Potential Climate Change Policies. *Journal of Sustainable Tourism*, 15(4), pp.351–368.
- Becken, S. & Lennox, J., 2012. Implications of a long-term increase in oil prices for tourism. *Tourism Management*, 33(1), pp.133–142.
- Behrens, C. & Pels, E., 2012. Intermodal competition in the London-Paris passenger market: High-Speed Rail and air transport. *Journal of Urban Economics*, 71(3), pp.278–288. Available at: <http://dx.doi.org/10.1016/j.jue.2011.12.005>.
- Benito, A., 2007. Climate change impact as a constraint to the air transport growth, The European Case. In *11th World Conference on Transport Research Berkeley*. pp. 1–35.

- Benito, A., Blanch, A. & Herranz, R., 2010. Estimation of Historical Aviation CO2 Emissions. In *12th World Conference for Transportation Research*. Lisbon, Portugal, pp. 1–22.
- Berleur, J., Hercheui, M.D. & Hilty, L.M., 2010. What Kind of Information Society? Governance, Virtuality, Surveillance, Sustainability, Resilience. In *9th IFIP TC 9 International Conference, HCC9 2010 and 1st IFIP TC 11 International Conference, CIP 2010 Held as Part of WCC 2010 Brisbane, Australia, September 20-23, 2010 Proceedings*. Available at: <http://www.springerlink.com/content/3w1j288007704185/>.
- Bhadra, D., 2003. Demand for air travel in the United States: Bottom-up econometric estimation and implications for forecasts by origin and destination pairs. *Journal of Air Transportation*, 8(2).
- Bieger, T. & Wittmer, A., 2006. Air transport and tourism - Perspectives and challenges for destinations, airlines and governments. *Journal of Air Transport Management*, 12, pp.40–46.
- Black, W. & Geenhuizen, M. Van, 2006. ICT innovation and sustainability of the transport sector. *European Journal of Transport and Infrastructure Research*, 1(6), pp.39–60.
- Blakey, S., Rye, L. & Wilson, C.W., 2011. Aviation gas turbine alternative fuels: A review. *Proceedings of the Combustion Institute*, 33(2), pp.2863–2885. Available at: <http://dx.doi.org/10.1016/j.proci.2010.09.011>.
- Blanke, J. & Chiesa, T., 2011. *The Travel & Tourism Competitiveness Report 2011*,
- Blanke, J. & Chiesa, T., 2013. *The Travel & Tourism Competitiveness Report 2013*, Available at: <http://www.fitzroy.cl/wp-content/uploads/2013/05/Travel-and-Tourism-Competitiveness-2013-Fuente-WEF.pdf>.
- Boeing, 2012. *Current Market Outlook 2012-2031*,
- Boeing, 2014a. *Current Market Outlook 2014-2033*,
- Boeing, 2014b. *Current Market Outlook 2014–2033*,
- Boeing, 2015. *Current Market Outlook 2015-2034*, Available at: http://www.boeing.com/resources/boeingdotcom/commercial/about-our-market/assets/downloads/Boeing_Current_Market_Outlook_2015.pdf.
- Boeing, 2016. *Current Market Outlook 2016-2035*, Available at: http://www.boeing.com/resources/boeingdotcom/commercial/about-our-market/assets/downloads/Boeing_Current_Market_Outlook_2015.pdf.
- Boeing & CANSO, 2012. *Accelerating Air Traffic Management Efficiency: A Call to Industry*, Available at: [http://www.faa.gov/nextgen/media/newsletter/Accelerating ATM Call to Industry.pdf](http://www.faa.gov/nextgen/media/newsletter/Accelerating%20ATM%20Call%20to%20Industry.pdf).
- Brecher, A., Sposato, J. & Kennedy, B., 2014. *Best Practices and Strategies for Improving Rail Energy Efficiency*, Available at: <http://www.fra.dot.gov/Elib/Document/3547> \n <http://ntl.bts.gov/lib/51000/51000/51097/DOT-VNTSC-FRA-13-02.pdf> \n <http://trid.trb.org/view/1290855>.
- Brouwer, R., Brander, L. & Van Beukering, P., 2008. ‘A convenient truth’: Air travel passengers’ willingness to pay to offset their CO2 emissions. *Climatic Change*, 90(3), pp.299–313.
- Bubalo, B. & Gaggero, A.A., 2015. Low-cost carrier competition and airline service quality in

- Europe. *Transport Policy*, 43, pp.23–31. Available at: <http://dx.doi.org/10.1016/j.tranpol.2015.05.015>.
- Budd, T. & Suau-Sanchez, P., 2016. Assessing the fuel burn and CO2 impacts of the introduction of next generation aircraft: A study of a major European low-cost carrier. *Research in Transportation Business & Management*, 21, pp.68–75. Available at: <http://dx.doi.org/10.1016/j.rtbm.2016.09.004>.
- Burghouwt, G. & de Wit, J.G., 2015. In the wake of liberalisation: Long-term developments in the EU air transport market. *Transport Policy*, 43, pp.104–113. Available at: <http://dx.doi.org/10.1016/j.tranpol.2015.05.006>.
- Cairns, S. & Newson, C., 2006. *Predict and decide: aviation, climate change and UK policy*, Available at: <http://discovery.ucl.ac.uk/1310984/>.
- Canso, 2012. *ATM Global Environment Efficiency Goals for 2050*,
- Carlsson, F. & Hammar, H., 2002. Incentive-based regulation of CO2 emissions from international aviation. *Journal of Air Transport Management*, 8, pp.365–372.
- Chapman, L., 2007. Transport and climate change: a review. *Journal of Transport Geography*, 15, pp.354–367.
- Chavez-Rodriguez, M.F. & Nebra, S. a., 2010. Assessing GHG emissions, ecological footprint, and water linkage for different fuels. *Environmental Science and Technology*, 44(24), pp.9252–9257.
- Chester, M. & Horvath, A., 2010. Life-cycle assessment of high-speed rail: the case of California. *Environmental Research Letters*, 5.
- Chèze, B., Chevallier, J. & Gastineau, P., 2013. Will technological progress be sufficient to stabilize CO2 emissions from air transport in the mid-term? *Transportation Research Part D: Transport and Environment*, 18, pp.91–96.
- Chiaromonti, D. et al., 2014. Sustainable bio kerosene: Process routes and industrial demonstration activities in aviation biofuels. *Applied Energy*, 136, pp.767–774. Available at: <http://www.sciencedirect.com/science/article/pii/S0306261914008769> [Accessed December 18, 2014].
- Clarke, J. et al., 2008. *En Route Traffic Optimization to Reduce Environmental Impact En Route Traffic Optimization to Reduce Environmental Impact*,
- Clewlow, R.R., Sussman, J.M. & Balakrishnan, H., 2014. The impact of high-speed rail and low-cost carriers on European air passenger traffic. *Transport Policy*, 33, pp.136–143. Available at: <http://dx.doi.org/10.1016/j.tranpol.2014.01.015>.
- Čokorilo, O., 2016. Environmental Issues for Aircraft Operations at Airports. *Transportation Research Procedia*, 14, pp.3713–3720. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S2352146516304987>.
- Cook, A. et al., 2015. Applying complexity science to air traffic management. *Journal of Air Transport Management*, 42, pp.149–158. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S0969699714001331>.
- Correnti, V. et al., 2007. The potential of rotorcraft for intercity passenger transport. *Journal of Air Transport Management*, 13, pp.53–60.
- Costantino, F. et al., 2016. Evolution of the intellectual structure of research on pricing strategy

- of low cost carriers. *Research in Transportation Business & Management*, 21, pp.99–116. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S2210539516300748>.
- D'Alfonso, T., Jiang, C. & Bracaglia, V., 2015. Would competition between air transport and high-speed rail benefit environment and social welfare? *Transportation Research Part B: Methodological*, 74, pp.118–137.
- Daggett, D.L. et al., 2008. *Alternate Fuels for use in Commercial Aircraft*,
- Daley, B., 2010. *Air Transport and the Environment*,
- Debbage, K.G., 2002. Airport runway slots: Limits to growth. *Annals of Tourism Research*, 29(4), pp.933–951.
- DECC, 2015. *DECC 2015 Fossil Fuel Price Assumptions*, Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/212521/130718_decc-fossil-fuel-price-projections.pdf.
- Delaplace, M. & Dobruszkes, F., 2015. From low-cost airlines to low-cost high-speed rail? The French case. *Transport Policy*, 38, pp.73–85. Available at: <http://dx.doi.org/10.1016/j.tranpol.2014.12.006>.
- Desart, B., Gillingwater, D. & Janic, M., 2010. Capacity dynamics and the formulation of the airport capacity/stability paradox: A European perspective. *Journal of Air Transport Management*, 16, pp.81–85. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2009.10.006>.
- Dessens, O. et al., 2014. Aviation and climate change. *Transport Policy*, 34, pp.14–20. Available at: <http://www.sciencedirect.com/science/article/pii/S0967070X14000456> [Accessed March 24, 2015].
- DG Energy and Transport, 2007. *AIR TRANSPORT: QUARTERLY REPORT NO . 16 3rd QUARTER 2007 (July to September)*,
- Dobruszkes, F., 2011a. High-speed rail and air transport competition in Western Europe: A supply-oriented perspective. *Transport Policy*, 18, pp.870–879.
- Dobruszkes, F., 2011b. High-speed rail and air transport competition in Western Europe: A supply-oriented perspective. *Transport Policy*, 18, pp.870–879.
- Dobruszkes, F., 2013. The geography of European low-cost airline networks : a contemporary analysis. *Journal of Transport Geography journal*, 28, pp.75–88.
- Dobruszkes, F., Dehon, C. & Givoni, M., 2014. Does European high-speed rail affect the current level of air services? An EU-wide analysis. *Transportation Research Part A: Policy and Practice*, 69, pp.461–475.
- Dray, L. et al., 2014. Airline fleet replacement funded by a carbon tax: An integrated assessment. *Transport Policy*, 34, pp.75–84. Available at: <http://dx.doi.org/10.1016/j.tranpol.2014.02.021>.
- Dray, L., 2014. Time constants in aviation infrastructure. *Transport Policy*, 34, pp.29–35. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S0967070X1400047X>.
- Duarte, A., Silla, A., Selmi, H., Coelho, P., 2008. Competition between High Speed Trains (HST) and Airplanes e Limits and Prospects. *ResearchGate*.
- Dziedzic, M. & Warnock-Smith, D., 2016. The role of secondary airports for today's low-cost

- carrier business models: The European case. *Research in Transportation Business and Management*, 21, pp.19–32. Available at: <http://dx.doi.org/10.1016/j.rtbm.2016.07.002>.
- EASA, EEA & EUROCONTROL, 2016. *European Aviation Environmental Report 2016*,
- EBTP-SABS, 2015. *Report on Barriers to Biofuels Deployment in Europe*,
- EEA, 2007. *EMEP/CORINAIR Emission Inventory Guidebook (Air Traffic)*, Available at: <http://www.eea.europa.eu/publications/EMEPCORINAIR5/page017.html>.
- EEA, 2013. *Energy efficiency and specific CO2 emissions*, Available at: <http://www.eea.europa.eu/data-and-maps/indicators/energy-efficiency-and-specific-co2-emissions/energy-efficiency-and-specific-co2-3>.
- EEA, 2015. *Evaluating 15 years of transport and environmental policy integration TERM 2015: Transport indicators tracking progress towards environmental targets in Europe*,
- EEA, 2014. *Focusing on environmental pressures from long - distance transport*,
- EIA, 2016a. *International Energy Outlook 2016*,
- EIA, 2016b. Short-Term Energy Outlook (STEO). Available at: DECC Fossil Fuel Price Projections.
- Eisenkopf, A. & Knorr, A., 2009. Voluntary Carbon Offsets in the Airline Industry. *Working Paper*, (January). Available at: C:\libs2\Airline_Carbon_Offsets.pdf.
- Eisentraut, A., 2010. Sustainable Production of Second- generation Biofuels (Potential and perspectives in major economies and developing countries). *International Energy Agency (iea)*, (February).
- ELFAA, 2004. *Liberalisation of European Air Transport: The Benefits of Low Fares Airlines to Consumers , Airports, Regions and the Environment*,
- EPA, 2015. Sources of Greenhouse Gas Emissions. *EPA United States Environmental Protection Agency*.
- ETSI, 2016. Intelligent Transport Systems. *he European Telecommunications Standards Institute*.
- Eurocontrol, 2008. *Challenges of Air Transport 2030: Survey of experts' views*,
- Eurocontrol, 2013a. *Challenges of Growth 2013 (Task 4: European Air Traffic in 2035)*,
- Eurocontrol, 2013b. *Challenges of Growth 2013 (Task 6: The Effect of Air Traffic Network Congestion in 2035)*,
- Eurocontrol, 2013c. *Challenges of Growth 2013 (Task 7: European Air Traffic in 2050)*,
- Eurocontrol, 2016a. *Coda Digest 2016 (All-Causes Delay and Cancellations to Air Transport Europe – Q2 2016)*, Available at: <http://www.eurocontrol.int/publications/coda-digest-2015>.
- Eurocontrol, 2016b. Environmental issues for aviation. *Eurocontro*. Available at: <http://www.eurocontrol.int/articles/environmental-issues-aviation>.
- EUROCONTROL, 2010. *EUROCONTROL Long-Term Forecast (Flight Movements 2010 - 2030)*,

- Eurocontrol, 2016c. Improving Predictability. *Eurocontrol*.
- EUROCONTROL, 2014. Market Segments in European Air Traffic 2013. *European Organisation for the Safety of Air Navigation (EUROCONTROL)*.
- Eurocontrol, 2015. *Performance Review Report: An Assessment of Air Traffic Management in Europe during the Calendar Year 2014*,
- Eurocontrol, 2016d. What is Air Traffic Management? *Eurocontrol*. Available at: <http://www.eurocontrol.int/articles/what-air-traffic-management>.
- EUROCONTROL DDR, 2013. *Demand Data Repository (DDR)*, Available at: <http://www.eurocontrol.int/ddr>.
- European Commission, 2013a. 2 million tons per year: A performing biofuels supply chain for EU aviation August 2013 Update. , (August). Available at: http://ec.europa.eu/energy/renewables/biofuels/doc/20130911_a_performing_biofuels_supply_chain.pdf.
- European Commission, 2016a. A European Strategy for Low-Emission Mobility. , (20.7.2016).
- European Commission, 2016b. *Alternative fuels and infrastructure in seven non-EU markets - Final report*,
- European Commission, 2007. An action plan for airports in Europe: The ‘airport package’. *European Commission- EUR-Lex*. Available at: <http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=URISERV:l24467&qid=1433511982446&from=EN>.
- European Commission, 2015a. *An Aviation Strategy for Europe*,
- European Commission, 2013b. *Annual Analyses of the EU Air Transport Market 2012*,
- European Commission, 2016c. Biofuels for Aviation. *European Commission Webpage*. Available at: <http://ec.europa.eu/energy/en/topics/biofuels/biofuels-aviation>.
- European Commission, 2006. *Climate change: Commission proposes bringing air transport into EU Emissions Trading Scheme*,
- European Commission, 2009. *Directive 2008/101/EC of the European Parliament and of the Council*, Available at: <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0101&from=EN>.
- European Commission, 2013c. *EU Energy, Transport and GHG Emissions: Trends to 2050 - Reference Scenario 2013*, Available at: <http://ec.europa.eu/transport/media/publications/doc/trends-to-2050-update-2013.pdf>.
- European Commission, 2013d. *EU energy, transport and GHG emissions trends to 2050*,
- European Commission, 2001. *European transport policy for 2010: time to decide*,
- European Commission, 2011a. *Flightpath 2050 Europe’s Vision for Aviation*, Available at: <http://ec.europa.eu/transport/modes/air/doc/flightpath2050.pdf>.
- European Commission, 2011b. *Flightpath 2050 Europes Vision for Aviation (Maintaining Global Leadership & Serving Society’s Needs)*, Available at: <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Flightpath+2050+Europe+’s+Vision+for+Aviation#0>.

- European Commission, 2010. High-speed Europe: A sustainable link between citizens. *European Union*, pp.1–26.
- European Commission, 2011c. *Launch of the European Advanced Biofuels Flightpath*, Available at:
http://ec.europa.eu/energy/sites/ener/files/20110622_biofuels_flight_path_launch.pdf.
- European Commission, 2016d. Reducing emissions from aviation. *Climate Action*.
- European Commission, 2014. Reducing emissions from aviation - European Commission. *European Commission*. Available at:
http://ec.europa.eu/clima/policies/transport/aviation/index_en.htm.
- European Commission, 2011d. *Roadmap to a Single European Transport Area—Towards a competitive and resource efficient transport system*, Available at:
<http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Roadmap+to+a+Single+European+Transport+Area+?+Towards+a+competitive+and+resource+efficient+transport+system#0>.
- European Commission, 2015b. What Do We Want to Achieve? *European Commission Transport*.
- European Commission, 2011e. *WHITE PAPER, Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system*,
- European Parliament, 2016. *Airports in the EU, Challenges ahead*,
- European Parliament, 2007. The Consequences of The Growing European Low-cost Airline Sector. *Directorate-General for Internal Policies of the Union*, (December). Available at:
<http://www.europarl.europa.eu/activities/expert/eStudies.do?language=EN>.
- European Union, 2014a. Conclusions and recommendations. *Official Journal of the European Union*.
- European Union, 2010. DIRECTIVE 2010/40/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 7 July 2010 on the framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport. *Official Journal of the European Union*, (7 July). Available at: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:207:0001:0013:EN:PDF>.
- European Union, 2014b. *Guidelines on State aid to airports and airlines*,
- Eurostar, 2005. Eurostar achieves record market shares despite difficult summer period.
- Eurostat, 2014. Aerospace equipment production statistics. Available at:
http://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Aerospace_equipment_production_statistics_-_NACE_Rev._1.1&oldid=197544.
- Eurostat, 2016a. Air transport statistics. *Eurostat*, (November). Available at:
http://ec.europa.eu/eurostat/statistics-explained/index.php/Air_transport_statistics.
- eurostat, 2016. Air transport statistics. *European Commission*, (November).
- Eurostat, 2016b. Passenger transport statistics. , (October).
- Eurostat (avia_paoa), 2015. *Air passenger transport by main airports in each reporting country*, Available at:

- http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=avia_paoa&lang=en.
- Evans, A.D., 2014. Comparing the impact of future airline network change on emissions in India and the United States. *Transportation Research Part D: Transport and Environment*, 32, pp.373–386. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S1361920914001102>.
- FAA, 2015. *FAA - Aviation Emissions, Impacts & Mitigation: A Primer*, Available at: http://www.faa.gov/regulations_policies/policy_guidance/envir_policy/media/Primer_Jan2015.pdf.
- Feng-Cai, Z., Li-Gang, Y. & Lan, G., 2014. Establishing the fair allocation of international aviation carbon emission rights. *Advances in Climate Change Research*, 5(3), pp.142–148. Available at: <http://www.sciencedirect.com/science/article/pii/S1674927814000082> [Accessed May 20, 2015].
- Flybe, 2007. Eco-labelling scheme. Available at: http://www.flybe.com/corporate/sustainability/carbon_offset_scheme.htm.
- FOCA, 2012. ICAO Action Plan on CO 2 Emission Reduction of Switzerland. *Federal Office of Civil Aviation (FOCA)*, (June).
- Forster, P.M.D.F., Shine, K.P. & Stuber, N., 2006. It is premature to include non-CO2 effects of aviation in emission trading schemes. *Atmospheric Environment*, 40(6), pp.1117–1121.
- FRA, 2009. April 2009 High-Speed Rail Strategic Plan. *u.S. Department of Transportation*, (April).
- Fragoudaki, A., 2000. Greek domestic air transport-industry and policy developments from post-World War II to post-liberalization. *Journal of Air Transport Management*, 6(4), pp.223–232.
- Franke, M. & John, F., 2011. What comes next after recession? - Airline industry scenarios and potential end games. *Journal of Air Transport Management*, 17, pp.19–26. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2010.10.005>.
- Fred, L., Smith, J. & Cox, B., 2008. Airline Deregulation. *The Concise Encyclopedia of Economics*, (August 18).
- Frederick, J.H., 1961. *Commercial Air Transportation*, Chicago: R.D. Irwin Inc. Available at: <file://catalog.hathitrust.org/Record/001039246>.
- Fu, X., Oum, T. & Zhang, A., 2010. Air transport liberalization and its impacts on airline competition and air passenger traffic. *Transportation journal*, 49(7), pp.24–41.
- Fukui, H. & Miyoshi, C., 2017. The impact of aviation fuel tax on fuel consumption and carbon emissions: The case of the US airline industry. *Transportation Research Part D: Transport and Environment*, 50, pp.234–253. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S1361920915300134>.
- GAO, 2009. *High speed passenger rail, Future Development Will Depend on Addressing Financial and Other Challenges and Establishing a Clear Federal Role*,
- Garrow, L.A., 2010. *Discrete Choice Modelling and Air Travel Demand - Theory and Applications*,
- Gillen, D. & Gados, A., 2009. Airlines within airlines: Assessing the vulnerabilities of mixing business models. *Research in Transportation Economics*, 24, pp.25–35.

- Gillen, D., Jacquillat, A. & Odoni, A.R., 2016. Airport demand management: The operations research and economics perspectives and potential synergies. *Transportation Research Part A: Policy and Practice*, 94, pp.495–513. Available at: <http://dx.doi.org/10.1016/j.tra.2016.10.011>.
- Girardet, D. & Spinler, S., 2013. Does the aviation Emission Trading System influence the financial evaluation of new airplanes? An assessment of present values and purchase options. *Transportation Research Part D: Transport and Environment*, 20, pp.30–39. Available at: <http://www.sciencedirect.com/science/article/pii/S1361920913000060> [Accessed August 17, 2015].
- Girvin, R., 2009. Aircraft noise-abatement and mitigation strategies. *Journal of Air Transport Management*, 15, pp.14–22. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2008.09.012>.
- Givoni, M., 2005. *Aircraft and high speed train substitution: The case for airline and railway integration*.
- Givoni, M. et al., 2009. Airline's choice of aircraft size – Explanations and implications. *Transportation Research Part A: Policy and Practice*, 43, pp.500–510. Available at: <http://dx.doi.org/10.1016/j.tra.2009.01.001>.
- Givoni, M. & Banister, D., 2006. Airline and railway integration. *Transport Policy*, 13(5), pp.386–397.
- Givoni, M. & Rietveld, P., 2010. The environmental implications of airlines' choice of aircraft size. *Journal of Air Transport Management*, 16, pp.159–167. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2009.07.010>.
- Gökalp, I. & Lebas, E., 2004. Alternative fuels for industrial gas turbines (AFTUR). *Applied Thermal Engineering*, 24(11–12), pp.1655–1663.
- Gonzalez-Savignat, M., 2004. Competition in air transport - The case of the high speed train. *Journal of Transport Economics and Policy*, 38(January), pp.77–108. Available at: internal-pdf://63_gonzalez-0120574208/63_gonzalez.pdf.
- Gössling, S., Upham, P., 2009. *Climate Change and Aviation. Issues, Challenges and Solutions*, London and Sterling, VA.
- Gössling, S., 2013. National emissions from tourism: An overlooked policy challenge? *Energy Policy*, 59, pp.433–442. Available at: <http://dx.doi.org/10.1016/j.enpol.2013.03.058>.
- Gössling, S. et al., 2007. Voluntary Carbon Offsetting Schemes for Aviation: Efficiency, Credibility and Sustainable Tourism. *Journal of Sustainable Tourism*, 15(3), pp.223–248.
- Gössling, S. & Buckley, R., 2016. Carbon labels in tourism: Persuasive communication? *Journal of Cleaner Production*, 111, pp.358–369.
- Gössling, S., Scott, D. & Hall, C.M., 2015. Inter-market variability in CO2 emission-intensities in tourism: Implications for destination marketing and carbon management. *Tourism Management*, 46, pp.203–212.
- Gössling, S. & Upham, P., 2009. *Climate Change and Aviation (Issues, Challenges and Solutions)*, London and Sterling, VA.
- Graham, A., 2014. *Managing Airports: An international perspective (Fourth edition)*, London and Sterling, VA.
- Graham, A., 2013. Understanding the low cost carrier and airport relationship: A critical analysis of the salient issues. *Tourism Management*, 36, pp.66–76. Available at: <http://dx.doi.org/10.1016/j.tourman.2013.03.001>.

- <http://dx.doi.org/10.1016/j.tourman.2012.11.011>.
- Graham, B., 1998. Liberalization, regional economic development and the geography of demand for air transport in the European Union. *Journal of Transport Geography*, 6(2), pp.87–104.
- Graham, W.R., Hall, C. a. & Vera Morales, M., 2014. The potential of future aircraft technology for noise and pollutant emissions reduction. *Transport Policy*, 34, pp.36–51. Available at: <http://dx.doi.org/10.1016/j.tranpol.2014.02.017>.
- Grampella, M. et al., 2017. Determinants of airports' environmental effects. *Transportation Research Part D: Transport and Environment*, 50, pp.327–344.
- Grote, M., Williams, I. & Preston, J., 2014. Direct carbon dioxide emissions from civil aircraft. *Atmospheric Environment*, 95, pp.214–224. Available at: <http://dx.doi.org/10.1016/j.atmosenv.2014.06.042>.
- Gudmundsson, S.V., 2011. Liberalization of air transport. *International Handbook of Network Industries: The Liberalization of Infrastructure*. Edward Elgar Publication, pp.234–251.
- Guo, R., Zhang, Y. & Wang, Q., 2014. Comparison of emerging ground propulsion systems for electrified aircraft taxi operations. *Transportation Research Part C: Emerging Technologies*, 44, pp.98–109. Available at: <http://dx.doi.org/10.1016/j.trc.2014.03.006>.
- Gupta, K.K., Rehman, a. & Sarviya, R.M., 2010. Bio-fuels for the gas turbine: A review. *Renewable and Sustainable Energy Reviews*, 14(9), pp.2946–2955. Available at: <http://dx.doi.org/10.1016/j.rser.2010.07.025>.
- Hagmann, C., Semeijn, J. & Vellenga, D.B., 2015. Exploring the green image of airlines: Passenger perceptions and airline choice. *Journal of Air Transport Management*, 43, pp.37–45. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2015.01.003>.
- Hall, C.M., B., Z. & Wilson, S., 2015. Case study: Carbon Offsetting and CSR in the Aviation Industry. In C. M. Hall, S. Gössling, & D. Scott, eds. *The Routledge Handbook of Tourism and Sustainability*. Routledg, pp. 511–514.
- Hansman, J. et al., 2014. *The Impact of Oil Prices on the Air Transportation Industry (Final Report)*,
- Hansman, R.J., 2005. The Impact of Information Technologies on Air Transportation. *American Institute of Aeronautics and Astronautics*, pp.1–12.
- Hao, L., Hansen, M. & Ryerson, M.S., 2016. Fueling for contingencies : The hidden cost of unpredictability in the air transportation system. *Transportation Research Part D*, 44, pp.199–210. Available at: <http://dx.doi.org/10.1016/j.trd.2016.02.016>.
- Hill, N. et al., 2012. *EU Transport GHG: Routes to 2050 II Developing a better understanding of the secondary impacts and key sensitivities for the decarbonisation of the EU ' s transport sector by 2050*,
- Humphreys, B. & Morrell, P., 2009. The potential impacts of the EU/US Open Sky Agreement: What will happen at Heathrow after spring 2008. *Journal of Air Transport Management*, 15(2), pp.72–77. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2008.09.020>.
- IATA, 2013a. *A Blueprint for the Single European Sky*,
- IATA, 2009. *A global approach to reducing aviation emissions First stop: carbon-neutral growth by 2020*,

- IATA, 2012a. *Airline Industry Forecast 2012-2016*,
- IATA, 2016a. Airlines Hail Historic ICAO Carbon Agreement. *IATA*. Available at: <http://www.iata.org/pressroom/pr/Pages/2016-10-06-02.aspx>.
- IATA, 2008. Aviation carbon offset programmes IATA guidelines and toolkit. , (May).
- IATA, 2016b. *Economic Performance of the Airline Industry*, Available at: www.iata.org/economics.
- IATA, 2014a. *Economic Performance of the Airline Industry*,
- IATA, 2015a. *Economic Performance of the Airline Industry*, Available at: <http://www.iata.org/whatwedo/Documents/economics/IATA-Economic-Performance-of-the-Industry-end-year-2015-report.pdf>.
- IATA, 2016c. *Fact Sheet-Fuel*,
- IATA, 2016d. *Fact Sheet: Alternative Fuels*, Available at: https://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-alternative-fuels.pdf.
- IATA, 2000. Growth and development. , 36(159), pp.37–39.
- IATA, 2011a. *IATA 2011 Report on Alternative Fuels 6th Edition*, Montreal — Geneva.
- IATA, 2012b. *IATA 2012 Report on Alternative Fuels (7th Edition)*,
- IATA, 2014b. *IATA 2014 Report on Alternative Fuels, 9th Edition*,
- IATA, 2015b. *IATA 2015 Report on Alternative Fuels 10th Edition*,
- IATA, 2015c. *IATA Sustainable Alternative Fuel — Advocacy*,
- IATA, 2016e. Improving Environmental Performance. Available at: <http://www.iata.org/whatwedo/environment/Pages/index.aspx>.
- IATA, 2013b. Responsibly Addressing Climate Change. , (February), pp.2012–2014.
- IATA, 2011b. *Vision 2050*, Available at: <http://www.wbcsd.org/pages/edocument/edocumentdetails.aspx?id=219&nosearchcontextkey=true>.
- ICAO, 2015a. *Air Navigation Report*, Available at: http://www.icao.int/airnavigation/Documents/ICAO_Air_Navigation_Report_2015_Web.pdf.
- ICAO, 2014a. Air Navigation Report. *International Civil Aviation Organization*. Available at: <http://www.icao.int/Pages/default.aspx>.
- ICAO, 2011a. *Airport Air Quality Manual*,
- ICAO, 2010a. *Aviation's Contribution To Climate Change*,
- ICAO, 2011b. *Aviation & Sustainability*, Available at: http://www.icao.int/publications/journalsreports/2011/6606_en.pdf.
- ICAO, 2016a. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). *ICAO*. Available at: <http://www.icao.int/environmental-protection/Pages/market-based->

measures.aspx.

ICAO, 2015b. *Continuing Traffic Growth and Record Airline Profits Highlight 2015 Air Transport Results*, Available at:
<http://www.icao.int/Newsroom/NewsDoc2015/COM.72.15.EN.pdf>.

ICAO, 2016b. Economic Development of Air Transport / Low Cost Carriers (LCCs). *ICAO*, p.2030. Available at: <http://centreforaviation.com/profiles/hot-issues/low-cost-carriers-lccs>.

ICAO, 2008. *Environmental Protection, Volume II, Aircraft Engine Emissions*,

ICAO, 2007a. *Environmental Report 2007*,

ICAO, 2011c. European Advanced Biofuels Flight Path. Available at:
<http://www.icao.int/environmental-protection/GFAAF/Pages/Project.aspx?ProjectID=9>.

ICAO, 2005. *Global Air Traffic Management Operational Concept*,

ICAO, 2011d. *Guidance Material for the Development of States' Action Plans (Towards the Achievement of ICAO's Global Climate Change Goals)*, Available at:
http://www.icao.int/environmental-protection/Documents/GuidanceMaterial_DevelopmentActionPlans.pdf.

ICAO, 2010b. *ICAO Environmental Report 2010*,

ICAO, 2013a. *ICAO Environmental Report 2013*, Available at:
<http://www.icao.int/environmental-protection/Pages/EnvReport13.aspx>.

ICAO, 2016c. *ICAO ENVIRONMENTAL REPORT 2016 (AVIATION AND CLIMATE CHANGE)*,

ICAO, 2014b. List of LCC based on ICAO definiton. , (October 24th).

ICAO, 2016d. Operational measures. *ICAO*.

ICAO, 2007b. *Outlook for Air Transport to the Year 2025*, Available at:
http://www.icao.int/sustainability/Documents/C313_Outlook_En.pdf.

ICAO, 2007c. *Report on Voluntary Emissions Trading for Aviation (VETS Report)*,

ICAO, 2013b. Resolutions adopted by the Assembly Assembly 38th Session. , (November).

ICAO, 2015c. *State of Air Transport - 2014*, Available at:
http://www.icao.int/ads/Documents/SAT_2014_Web.pdf.

ICAO, 2016e. SUPPLEMENTARY REPORT ON ACTIVITIES OF THE ORGANIZATION IN THE FIRST HALF OF 2016 AND 38th SESSION OF THE ASSEMBLY. In *39th Triennial Assembly*. Montreal.

ICAO, 2003. The Impact Of Low Cost Carriers in Europe. , (February).

ICAO, 2013c. *The Thirty-ninth Session of the UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA39)*, Warsaw, Poland. Available at:
http://www.icao.int/environmental-protection/Documents/STATEMENTS/SBSTA39_ICAO_submission.pdf.

IEA, 2015. *CO2 EMISSIONS FROM FUEL COMBUSTION Highlights*,

- IEA, 2009. *Energy Policies of IEA Countries - Portugal Review 2009*, Available at: http://www.oecd-ilibrary.org/energy/energy-policies-of-iea-countries-portugal-2009_9789264060388-en.
- IEA, 2010. Transport Energy Efficiency. *Policy*, p.60. Available at: http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=2287.
- IPCC, 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories (Chapter 3: Mobile Combustion)*,
- IPCC, 2001. Climate Change 2001: The Scientific Basis. *Climate Change 2001: The Scientific Basis*, p.881.
- IPCC, 2007. *Climate Change 2007 Mitigation*,
- IPCC, 2008. *Climate Change 2007 Synthesis Report*,
- IPCC, 2014a. *Climate Change 2014: Mitigation of Climate Change*, Available at: <http://www.ipcc.ch/report/ar5/wg3/>.
- IPCC, 1999. *IPCC Special Report: Aviation and the Global Atmosphere*, Available at: <http://books.google.com/books?id=JgphajrWfOsC&printsec=frontcover\papers2://publication/uuid/9E05EEA8-894A-47FE-9C27-96F5A5B9D387>.
- IPCC, 2012. *Renewable energy sources and climate change mitigation: special report of the Intergovernmental Panel on Climate Change*, Available at: http://srren.ipcc-wg3.de/report/IPCC_SRREN_Full_Report.pdf.
- IPCC, 2014b. *Working Group III Report 'Climate Change 2014: Mitigation of Climate Change'*, Available at: <https://www.ipcc.ch/report/ar5/wg3/>.
- Janic, M., 2011. Assessing some social and environmental effects of transforming an airport into a real multimodal transport node. *Transportation Research Part D: Transport and Environment*, 16(2), pp.137–149. Available at: <http://dx.doi.org/10.1016/j.trd.2010.10.002>.
- Janić, M., 1993. A model of competition between high speed rail and air transport. *Transportation Planning and Technology*, 17(1), pp.1–23. Available at: <http://dx.doi.org/10.1080/03081069308717496>.
- Janić, M., 1999. Aviation and externalities: The accomplishments and problems. *Transportation Research Part D: Transport and Environment*, 4(3), pp.159–180.
- Jelinek, F., Carlier, S., Smith, J., Quesne, A., 2002. The free route project : Environmental Benefit Analysis. *Eurocontrol*, pp.324–386.
- Jiang, C. & Li, X., 2016. Low cost carrier and high-speed rail: A macroeconomic comparison between Japan and Western Europe. *Research in Transportation Business & Management*. Available at: <http://dx.doi.org/10.1016/j.rtbm.2016.05.006>.
- Johnson, D., Perkins, C. & Arkko, J., 2004. *Mobility Support in IPv6*,
- Kahn Ribeiro, S. et al., 2007. Transport and its infrastructure. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Available at: <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Transport+and+its+infrastructure#0>.
- Kharina, A. & Rutherford, D., 2015. *Fuel efficiency trends for new commercial jet aircraft*:

1960 to 2014,

- Khodayari, A., Olsen, S.C. & Wuebbles, D.J., 2014. Evaluation of aviation NO_x-induced radiative forcings for 2005 and 2050. *Atmospheric Environment*, 91(x), pp.95–103. Available at: <http://dx.doi.org/10.1016/j.atmosenv.2014.03.044>.
- Kim, B.Y. et al., 2007. System for assessing Aviation's Global Emissions (SAGE), Part 1: Model description and inventory results. *Transportation Research Part D: Transport and Environment*, 12(5), pp.325–346.
- Kinsey, J.S. et al., 2010. Physical characterization of the fine particle emissions from commercial aircraft engines during the Aircraft Particle Emissions eXperiment (APEX) 1-3. *Atmospheric Environment*, 44(17), pp.2147–2156. Available at: <http://dx.doi.org/10.1016/j.atmosenv.2010.02.010>.
- Kling, M. & Hough, I., 2011. Air Travel Carbon and Energy Management Plan. *Brighter Planet*.
- Köhler, J. et al., 2014. Lead markets in 2nd generation biofuels for aviation: A comparison of Germany, Brazil and the USA. *Environmental Innovation and Societal Transitions*, 10, pp.59–76. Available at: <http://dx.doi.org/10.1016/j.eist.2013.10.003>.
- Kousoulidou, M. & Lonza, L., 2016. Biofuels in aviation: Fuel demand and CO₂ emissions evolution in Europe toward 2030. *Transportation Research Part D: Transport and Environment*, 46, pp.166–181. Available at: <http://dx.doi.org/10.1016/j.trd.2016.03.018>.
- Krammer, P., Dray, L. & Köhler, M.O., 2013. Climate-neutrality versus carbon-neutrality for aviation biofuel policy. *Transportation Research Part D: Transport and Environment*, 23, pp.64–72. Available at: <http://www.sciencedirect.com/science/article/pii/S136192091300062X> [Accessed August 17, 2015].
- Kristjanpoller, W.D. & Concha, D., 2016. Impact of fuel price fluctuations on airline stock returns. *Applied Energy*, 178, pp.496–504.
- Kuhn, P.M., 1970. Airborne Observations of Contrail Effects on the Thermal Radiation Budget.
- Kurniawan, J.S. & Khardi, S., 2011. Comparison of methodologies estimating emissions of aircraft pollutants, environmental impact assessment around airports. *Environmental Impact Assessment Review*, 31(3), pp.240–252. Available at: <http://dx.doi.org/10.1016/j.eiar.2010.09.001>.
- Lauge Pedersen, S., 2000. The Danish CO₂ Emissions Trading System. *RECIEL*, 9(3).
- Laurino, A. & Beria, P., 2014. Low-cost carriers and secondary airports: Three experiences from Italy. *Journal of Destination Marketing and Management*, 3, pp.180–191. Available at: <http://dx.doi.org/10.1016/j.jdmm.2014.05.001>.
- Lee, D.S. et al., 2009. Aviation and global climate change in the 21st century. *Atmospheric Environment*, 43, pp.3520–3537. Available at: <http://dx.doi.org/10.1016/j.atmosenv.2009.04.024>.
- Lee, D.S. et al., 2010. Transport impacts on atmosphere and climate: Aviation. *Atmospheric Environment*, 44, pp.4648–4734. Available at: <http://dx.doi.org/10.1016/j.atmosenv.2009.06.005>.
- Lee, J.J., 2010. Can we accelerate the improvement of energy efficiency in aircraft systems? *Energy Conversion and Management*, 51(1), pp.189–196.

- Lee, J.J. et al., 2001. Historical and Future Trends in Aircraft Performance, Cost, and Emissions. *Annual Review of Energy and the Environment*, 26, pp.167–200.
- Lee, J.J., 2000. *Historical and Future Trends in Aircraft Performance, Cost, and Emissions*.
- Lenartowicz, M., Mason, K. & Foster, A., 2013. Mergers and acquisitions in the EU low cost carrier market. A Product and Organisation Architecture (POA) approach to identify potential merger partners. *Journal of Air Transport Management*, pp.1–9.
- Lenoir, N., 2016. *Airport slots and aircraft size at EU airports*,
- Li, Y., Wang, Y.Z. & Cui, Q., 2016. Has airline efficiency affected by the inclusion of aviation into European Union Emission Trading Scheme? Evidences from 22 airlines during 2008–2012. *Energy*, 96, pp.8–22.
- Liebeck, R.H., 2004. Design of the Blended Wing Body Subsonic Transport. *Journal of Aircraft*, 41(1), pp.10–25.
- Loo, B.P.Y. et al., 2014. CO2 emissions associated with hubbing activities in air transport: an international comparison. *Journal of Transport Geography*, 34, pp.185–193. Available at: <http://www.sciencedirect.com/science/article/pii/S0966692313002433> [Accessed April 22, 2015].
- Lordan, O., Sallan, J.M. & Valenzuela-Arroyo, M., 2016. Forecasting of taxi times: The case of Barcelona-El Prat airport. *Journal of Air Transport Management*, 56, pp.118–122. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2016.04.015>.
- Lynes, J.K. & Dredge, D., 2006. Going Green: Motivations for Environmental Commitment in the Airline Industry. A Case Study of Scandinavian Airlines. *Journal of Sustainable Tourism*, 14(2), pp.116–138.
- Macário, R., Viegas, J.M. & Reis, V., 2008. Impact of Low Cost Operation in the Development of Airports and Local Economies. *1st Workshop APDR - Impacto dos Aeroportos no Desenvolvimento Regional Nov 2008, Lisbon, Portugal*. Available at: http://www.mitportugal.org/index.php?option=com_docman&task=cat_view&gid=135&Itemid=1.
- Macintosh, A. & Wallace, L., 2009. International aviation emissions to 2025: Can emissions be stabilised without restricting demand? *Energy Policy*, 37, pp.264–273. Available at: <http://www.sciencedirect.com/science/article/pii/S0301421508004217> [Accessed August 19, 2015].
- MacKerron, G.J. et al., 2009. Willingness to pay for carbon offset certification and co-benefits among (high-)flying young adults in the UK. *Energy Policy*, 37(4), pp.1372–1381.
- Macquarie Research Group, 2016. Impact of crude oil price on indian economy. *Macquarie Group*, (29 Feb.). Available at: <http://www.macquarie.com/sg/about/newsroom/2016/jet-fuel-price-risk>.
- Mahashabde, A. et al., 2011. Assessing the environmental impacts of aircraft noise and emissions. *Progress in Aerospace Sciences*, 47, pp.15–52. Available at: <http://dx.doi.org/10.1016/j.paerosci.2010.04.003>.
- Mair, J., 2011. Exploring air travellers' voluntary carbon-offsetting behaviour. *Journal of Sustainable Tourism*, 19(2), pp.215–230.
- Malavolti, E. & Podesta, M., 2015. Strategic Reactions of Airlines to the European Trading Scheme. *Transportation Research Procedia*, 8, pp.103–113. Available at:

- <http://www.sciencedirect.com/science/article/pii/S2352146515001222> [Accessed August 17, 2015].
- Malwitz, A. et al., 2007. *Assessment of the impact of reduced verticle separation on aircraft-related fuel burn and emissions for the domestic United States*,
- Marais, K. et al., 2008. Assessing the impact of aviation on climate. *Meteorologische Zeitschrift*, 17(2), pp.157–172.
- Masiol, M. & Harrison, R.M., 2014. Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: A review. *Atmospheric Environment*, 95, pp.409–455. Available at: <http://www.sciencedirect.com/science/article/pii/S1352231014004361> [Accessed July 9, 2014].
- Mason, K., Morrison, W.G. & Stockman, I., 2011. Liberalization of Air Transport in Europe nad the Evolution of ‘Low-cost’ Airlines. *Liberalization in Aviation: Competition, Cooperation and Public Policy*, (May).
- Mason, K.J., 2000. The propensity of business travellers to use low cost airlines. *Journal of Transport Geography*, 8, pp.107–119.
- Mayer, R., Ryley, T. & Gillingwater, D., 2015. Eco-positioning of airlines: Perception versus actual performance. *Journal of Air Transport Management*, 44–45, pp.82–89. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S0969699715000253>.
- Mayer, R., Ryley, T. & Gillingwater, D., 2012. Passenger perceptions of the green image associated with airlines. *Journal of Transport Geography*, 22, pp.179–186. Available at: <http://www.sciencedirect.com/science/article/pii/S0966692312000117> [Accessed August 11, 2015].
- Mayor, K. & Tol, R.S.J., 2008. *Working Paper No . 241*,
- McCollum, D., Gould, G. & Greene, D., 2010. *Greenhouse Gas emissions from aviation and marine transportation: mitiGation potential and policies*, Available at: <papers2://publication/uuid/F9055029-159A-4979-9DC0-34F7223716BF> \ <papers2://publication/uuid/C5730912-E249-4D18-80AE-38C86144FF44>.
- McDougall, G, Roberts, A., 2008. Commercializing air traffic control: Have the reforms worked? *Canadian Public Administration*, 51(1), pp.45–69. Available at: file:///Media/2011/Unknown/2011_Screen_shot_2011-05-07_at_16.32.25.png.
- McDougall, G., Roberts, A.S., 2012. Strategies for managing risk in a changing aviation environment. *Journal of Air Transport Management*, 21, pp.24–35. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2011.12.014>.
- McLennan, C.L.J. et al., 2014. Voluntary carbon offsetting: Who does it? *Tourism Management*, 45, pp.194–198. Available at: <http://dx.doi.org/10.1016/j.tourman.2014.04.009>.
- Miyoshi, C. & Mason, K.J., 2009. The carbon emissions of selected airlines and aircraft types in three geographic markets. *Journal of Air Transport Management*, 15, pp.138–147. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2008.11.009>.
- Monsalud, A. et al., 2012. Sustainability Feasibility: Framework for Greenhouse Gas Emissions Mitigation for Midsized U.S. Airports. *ICSDEC*, pp.214–221.
- Monsalud, A., Ho, D. & Rakas, J., 2015. Greenhouse gas emissions mitigation strategies within

- the airport sustainability evaluation process. *Sustainable Cities and Society*, 14, pp.414–424. Available at: <http://www.sciencedirect.com/science/article/pii/S2210670714000894> [Accessed January 28, 2015].
- Morrell, P., 2009. The potential for European aviation CO2 emissions reduction through the use of larger jet aircraft. *Journal of Air Transport Management*, 15, pp.151–157.
- Morris, J. et al., 2009. *A Framework for Estimating the Marginal Costs of Environmental Abatement for the Aviation Sector. OMEGA Project 14 – Final Report*,
- Morrison, W.G. & Mason, K., 2016. Low cost carriers in the Middle East and North Africa: Prospects and strategies. *Research in Transportation Business & Management*, 21, pp.54–67. Available at: <http://dx.doi.org/10.1016/j.rtbm.2016.09.005>.
- NASA, 2016. A blanket around the Earth. *Nasa*. Available at: <http://climate.nasa.gov/causes/>.
- NASA, 2015. Global Climate Change, Vitar Signs of the Planet. *NASA*. Available at: <http://climate.nasa.gov/causes/>.
- Nations, U., 1998. Kyoto Protocol To the United Nations Framework Kyoto Protocol To the United Nations Framework. *Review of European Community and International Environmental Law*, 7, pp.214–217. Available at: <http://unfccc.int/resource/docs/convkp/kpeng.pdf>.
- Noh, H.M., Benito, A. & Alonso, G., 2016. Study of the current incentive rules and mechanisms to promote biofuel use in the EU and their possible application to the civil aviation sector. *Transportation Research Part D*, 46, pp.298–316. Available at: <http://dx.doi.org/10.1016/j.trd.2016.04.007>.
- Nygren, E., Aleklett, K. & Höök, M., 2009. Aviation fuel and future oil production scenarios. *Energy Policy*, 37, pp.4003–4010.
- O'Reilly, D. & Stone Sweet, A., 1998. The liberalization and reregulation of air transport. *Journal of European Public Policy*, 5(3), pp.447–466.
- OAG, 2009. Aviation Link Fleet Database. *OAG Aviation Solutions*.
- OAG, 2015. *Routes Europe briefing*, Available at: <http://www.oag.com>.
- OECD, 2007. *CUTTING TRANSPORT CO2 EMISSIONS: WHAT PROGRESS?*, Available at: <http://www.internationaltransportforum.org/Topics/pdf/07CO2summary.pdf>.
- OECD, 2012. Green growth and the future of aviation. *27th Round Table on Sustainable Development to be held at OECD Headquarters 23-24 January 2012*, (January). Available at: <http://www.oecd.org/sd-roundtable/papersandpublications/49482790.pdf>.
- OECD/IEA, 2016. Energy Efficiency: Market Report 2016. *International Energy Agency*, pp.1–250.
- OECD/IEA, 2008. From 1st to 2nd Generation Bio Fuel Technologies (An overview of current industry and RD&D activities). *IEA Bioenergy*, (November), pp.1–124.
- Olipra, L., 2012. The impact of low-cost carriers on tourism development in less famous destinations. *Referred Electronic Conference Proceeding*, pp.41–56.
- Olivier, J., 1991. Inventory of aircraft emissions; a review of recent literature.
- Olsthoorn, X., 2001. Carbon dioxide emissions from international aviation: 1950-2050. *Journal*

- of *Air Transport Management*, 7(2), pp.87–93. Available at: <http://www.sciencedirect.com/science/article/pii/S0969699700000314> [Accessed February 18, 2015].
- Pai, V., 2010. On the factors that affect airline flight frequency and aircraft size. *Journal of Air Transport Management*, 16, pp.169–177. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2009.08.001>.
- Pantazis, N. & Liefner, I., 2006. The impact of low-cost carriers on catchment areas of established international airports: The case of Hanover Airport, Germany. *Journal of Transport Geography*, 14(4), pp.265–272.
- Park, Y. & Ha, H.K., 2006. Analysis of the impact of high-speed railroad service on air transport demand. *Transportation Research Part E: Logistics and Transportation Review*, 42, pp.95–104.
- Park, Y. & O’Kelly, M.E., 2014. Fuel burn rates of commercial passenger aircraft: variations by seat configuration and stage distance. *Journal of Transport Geography*, 41, pp.137–147. Available at: <http://www.sciencedirect.com/science/article/pii/S0966692314001793> [Accessed April 14, 2015].
- Pearson, J. et al., 2015. The strategic capability of Asian network airlines to compete with low-cost carriers. *Journal of Air Transport Management*, 47, pp.1–10.
- Peeters, P., Middel, J. & Hoolhorts, A., 2005. Fuel efficiency of commercial aircraft: An overview of historical and future trends. *National Aerospace Laboratory NLR*, pp.1–37. Available at: <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Fuel+efficiency+of+commercial+aircraft:+An+overview+of+historical+and+future+trends#4>.
- Peeters, P., Rietveld, P. & Schipper, Y., 2001. Environmental impacts of hub and spoke networks in European aviation. *Vrije Universiteit, Amsterdam*, (September), pp.1–16.
- Pellegrini, P. & Rodriguez, J., 2013. Single European Sky and Single European Railway Area: A system level analysis of air and rail transportation. *Transportation Research Part A: Policy and Practice*, 57, pp.64–86. Available at: <http://dx.doi.org/10.1016/j.tra.2013.09.004>.
- Piga, C.A. & Bachis, E., 2007. *Hub Premium, Airport Dominance and Market Power in the European Airline Industry*.
- Piga, C. a. & Filippi, N., 2002. Booking and Flying with Low Cost Airlines. *International Journal of Tourism Research*, (May). Available at: <http://doi.wiley.com/10.1002/jtr.379>.
- Pita, J.P., Adler, N. & Antunes, A.P., 2014. Socially-oriented flight scheduling and fleet assignment model with an application to Norway. *Transportation Research Part B: Methodological*, 61, pp.17–32.
- De Poret, M., O’Connell, J.F. & Warnock-Smith, D., 2015. The economic viability of long-haul low cost operations: Evidence from the transatlantic market. *Journal of Air Transport Management*, 42, pp.272–281. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2014.11.007>.
- postnote, 2008. *ICT and CO2 Emissions*, Available at: www.parliament.uk/parliamentary_offices/post/pubs2008.cfm.
- Postorino, M.N. & Mantecchini, L., 2014. A transport carbon footprint methodology to assess

- airport carbon emissions. *Journal of Air Transport Management*, 37, pp.76–86. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2014.03.001>.
- Ravizza, S. et al., 2013. A combined statistical approach and ground movement model for improving taxi time estimations at airports. *Journal of the Operational Research Society*, 64, pp.1347–1360. Available at: <http://dx.doi.org/10.1057/jors.2012.123>.
- Ravizza, S., Atkin, J.A.D. & Burke, E.K., 2014. A more realistic approach for airport ground movement optimisation with stand holding. *Journal of Scheduling*, 17(5), pp.507–520.
- Reynolds, T.G., 2009. Development of Flight Inefficiency Metrics for Environmental Performance Assessment of ATM. *Europe Air Traffic Management Research and Development Seminar*, (July), pp.1–10.
- Robaina-Alves, M., Moutinho, V. & Costa, R., 2015. Change in energy-related CO₂ (carbon dioxide) emissions in Portuguese tourism: a decomposition analysis from 2000 to 2008. *Journal of Cleaner Production*. Available at: <http://www.sciencedirect.com/science/article/pii/S0959652615002401> [Accessed May 14, 2015].
- Roberson, W. & Johns, J., 2008. Fuel Conservation Strategies: Takeoff and Climb. *Aero Quarterly*, (4), pp.25–28.
- Roskopf, M., Lehner, S. & Gollnick, V., 2014. Economic-environmental trade-offs in long-term airline fleet planning. *Journal of Air Transport Management*, 34, pp.109–115. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2013.08.004>.
- Rothengatter, W., 2011. Competition between airlines and high-speed rail. In *Critical Issues in Air Transport Economics and Business*. Routledge, Oxford, UK.
- Ruiz-Rúa, A. & Palacín, R., 2013. Towards a liberalised European high speed railway sector: Analysis and modelling of competition using Game Theory. *European Transport Research Review*, 5, pp.53–63.
- De Rus, G., 2008. The Economic Effects of High Speed Rail Investment. In *OECD/ITF*. Available at: files556/Transport - 2012 - Discussion Paper No . 2008-16 revised May 2012 The Economic Effects of.pdf.
- Rus, G. de & Nombela, G., 2007. Is Investment in High Speed Rail Socially Profitable? *Journal of Transport Economics and Policy*, (January). Available at: <http://florio.economia.unimi.it/Materiali/MEEW5/deRus.pdf> <http://www.eco.uc3m.es/temp/gderus.pdf>.
- Ryerson, M.S. & Hansen, M., 2010. The potential of turboprops for reducing aviation fuel consumption. *Transportation Research Part D: Transport and Environment*, 15(6), pp.305–314. Available at: <http://dx.doi.org/10.1016/j.trd.2010.03.003>.
- Rypdal, K., 2000. Aircraft Emissions. *Good Practice Guidance and Uncertainty Measurement in National Greenhouse Gas Inventories*, pp.93–102. Available at: http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/2_5_Aircraft.pdf.
- Saketa, S., 2016. Impact Analysis: The Adverse Effects of Falling Oil Price in the Airline Industry | Surafel Saketa | LinkedIn. *Linkedin*. Available at: <https://www.linkedin.com/pulse/impact-analysis-adverse-effects-falling-oil-price-airline-saketa>.
- Sanz, M.T. et al., 2014. Economic assessment of CO₂ emissions savings in Spain associated

- with the use of biofuels for the transport sector in 2010. *Utilities Policy*, 29(December 2012), pp.25–32. Available at: <http://dx.doi.org/10.1016/j.jup.2014.04.002>.
- Schäfer, A. et al., 2011. *TOSCA Project Final Report : Description of the Main S & T Results / Foregrounds*, Available at: http://www.toscaproject.org/FinalReports/TOSCA_FinalReport.pdf.
- Schafer, A. & Victor, D.G., 2000. The future mobility of the world population. *Transportation Research Part A: Policy and Practice*, 34(3), pp.171–205.
- Scheelhaase, J., Grimme, W. & Schaefer, M., 2010. The inclusion of aviation into the EU emission trading scheme – Impacts on competition between European and non-European network airlines. *Transportation Research Part D: Transport and Environment*, 15(1), pp.14–25. Available at: <http://www.sciencedirect.com/science/article/pii/S1361920909000844> [Accessed August 17, 2015].
- Scheelhaase, J.D. & Grimme, W.G., 2007. Emissions trading for international aviation-an estimation of the economic impact on selected European airlines. *Journal of Air Transport Management*, 13(5), pp.253–263.
- Schipper, Y., 2004. Environmental costs in European aviation. *Transport Policy*, 11(2), pp.141–154.
- Schlumberger, C.E. & Weisskopf, N., 2014. *Ready for Takeoff? The Potential for Low-Cost Carriers in Developing Countries*.
- Schmidt, M. et al., 2016. Challenges for ground operations arising from aircraft concepts using alternative energy. *Journal of Air Transport Management*, 56, pp.107–117. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2016.04.023>.
- Scott, D., Peeters, P. & Gössling, S., 2010. Can tourism deliver its ‘aspirational’ greenhouse gas emission reduction targets? *Journal of Sustainable Tourism*, 18(3), pp.393–408.
- Scotti, D. et al., 2014. Incorporating negative externalities into productivity assessments of US airports. *Transportation Research Part A: Policy and Practice*, 62, pp.39–53. Available at: <http://dx.doi.org/10.1016/j.tra.2014.02.008>.
- Senguttuvan, P.S., 2007. *Principles of Airport Economics*, Available at: <https://books.google.se/books?id=oQN4SZSbBsoC&pg=PA13&lpg=PA13&dq=Aviation+industry+is+one+of+the+world%E2%80%99s+fastest+growing+industries+closely+following+development+of+economic+activities.&source=bl&ots=rAzktrziK5&sig=uhb9yw3fvPPxJOuYhqw6rkOIInyo&hl=>.
- Sgouridis, S., Bonnefoy, P. a. & Hansman, R.J., 2011. Air transportation in a carbon constrained world: Long-term dynamics of policies and strategies for mitigating the carbon footprint of commercial aviation. *Transportation Research Part A: Policy and Practice*, 45, pp.1077–1091. Available at: <http://dx.doi.org/10.1016/j.tra.2010.03.019>.
- Shiomi, E., 1999. Do Faster Trains Challenge Air Carriers? *Japan Railway & Transport Review*, (March).
- Simić, T.K. & Babić, O., 2015. Airport traffic complexity and environment efficiency metrics for evaluation of ATM measures. *Journal of Air Transport Management*, 42, pp.260–271.
- Simić, T.K., Babić, O. & Andrić, V., 2014. Influence of Airport Operations Management on Traffic Complexity and Efficiency. In *6th ICRAT Conference, Istanbul, Turkey, 2014 -*

- Simone, N.W., Stettler, M.E.J. & Barrett, S.R.H., 2013. Rapid estimation of global civil aviation emissions with uncertainty quantification. *Transportation Research Part D: Transport and Environment*, 25, pp.33–41. Available at: <http://www.sciencedirect.com/science/article/pii/S1361920913001028>.
- Singh, V. & Sharma, S.K., 2015. Fuel consumption optimization in air transport: a review, classification, critique, simple meta-analysis, and future research implications. *European Transport Research Review*, 7(12). Available at: <http://dx.doi.org/10.1007/s12544-015-0160-x>.
- Solomon, D.S. & Hughey, K.F.D., 2007. A proposed Multi Criteria Analysis decision support tool for international environmental policy issues: a pilot application to emissions control in the international aviation sector. *Environmental Science and Policy*, 10, pp.645–653.
- Somerville, H., 2003. *Handbooks in Transport, Chapter 14 Transport Energy and Emissions: Aviation*,
- Starkie, D., 2012. European airports and airlines: Evolving relationships and the regulatory implications. *Journal of Air Transport Management*, 21, pp.40–49. Available at: <http://dx.doi.org/10.1016/j.jairtraman.2011.12.016>.
- Stettler, M.E.J., Eastham, S. & Barrett, S.R.H., 2011. Air quality and public health impacts of UK airports. Part I: Emissions. *Atmospheric Environment*, 45(31), pp.5415–5424. Available at: <http://dx.doi.org/10.1016/j.atmosenv.2011.07.012>.
- Steven, M. & Merklein, T., 2013. The influence of strategic airline alliances in passenger transportation on carbon intensity. *Journal of Cleaner Production*, 56, pp.112–120. Available at: <http://dx.doi.org/10.1016/j.jclepro.2012.03.011>.
- Stratton, R.W., Min Wong, H. & Hileman, J.I., 2010. *Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels*, Available at: <http://web.mit.edu/aeroastro/partner/reports/index.html>.
- Tang, Z. et al., 2014. Decoupling indicators of CO2 emissions from the tourism industry in China: 1990–2012. *Ecological Indicators*, 46, pp.390–397. Available at: <http://www.sciencedirect.com/science/article/pii/S1470160X14003021> [Accessed May 14, 2015].
- Tarpey, L. et al., 2010. *Emerging High-Speed Rail Initiative in the Midwest A Case Study of the St. Louis-Chicago Line*,
- The Economist, 2015. High-speed rail in Europe Problems down the line. *The Economist*, (Jan 10th).
- The European Commission, 2007. *Integrating the environment into aerial transport*,
- The World Bank, 2012. *Air Transport and Energy Efficiency*, Available at: <http://siteresources.worldbank.org/INTAIRTRANSPORT/Resources/TP38.pdf>.
- Tian, Y. et al., 2014. Analysis of greenhouse gas emissions of freight transport sector in China. *Journal of Transport Geography*, 40, pp.43–52. Available at: <http://www.sciencedirect.com/science/article/pii/S0966692314000891> [Accessed March 27, 2015].
- Tipping, A., Schmahl, A. & Duiven, F., 2015. The Impact of Reduced Oil Prices on the Transportation Sector. *Strategy+Business*, (Online February 19, 2015). Available at:

- <http://www.strategy-business.com/article/00312?gko=ae404>.
- UNFCCC, 2015. Highlights of 82nd meeting of the CDM Executive Board. Available at: https://cdm.unfccc.int/press/newsroom/latestnews/releases/2014/0213_index.html.
- UNFCCC, 2016. *Information relevant to emissions from fuel used for international aviation and maritime transport*,
- UNFCCC, 2010. *Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009*,
- UNWTO, 2015. 2015 Edition UNWTO.
- Upham, P. et al., 2004. Environmental capacity and European air transport: Stakeholder opinion and implications for modelling. *Journal of Air Transport Management*, 10(3), pp.199–205.
- Urry, J., 2012. Changing transport and changing climates. *Journal of Transport Geography*, 24, pp.533–535. Available at: <http://www.sciencedirect.com/science/article/pii/S0966692312001469> [Accessed August 10, 2015].
- Venmans, F., 2012. A literature-based multi-criteria evaluation of the EU ETS. *Renewable and Sustainable Energy Reviews*, 16(8), pp.5493–5510. Available at: <http://www.sciencedirect.com/science/article/pii/S136403211200370X> [Accessed August 17, 2015].
- Vera-Morales, M. et al., 2011. *Techno-Economic Analysis of Aircraft*,
- Vespermann, J. & Wald, A., 2011. Much ado about nothing? - An analysis of economic impacts and ecologic effects of the EU-emission trading scheme in the aviation industry. *Transportation Research Part A: Policy and Practice*, 45(10), pp.1066–1076. Available at: <http://dx.doi.org/10.1016/j.tra.2010.03.005>.
- Vidović, A., Steiner, S. & Babić, R.Š., 2006. Impact of low-cost carriers on the european air transport market. In *10th International Conference on Traffic Science ICTS 2006: Globalization and Transportation*. Available at: http://bib.irb.hr/datoteka/260325.ICTS_06_vidovic.pdf.
- Volta, N., 2012. *Efficiency and Environment in the Aviation Sector*. UNIVERSITY OF BERGAMO.
- Wasiuk, D.K. et al., 2016. A Commercial Aircraft Fuel Burn and Emissions Inventory for 2005–2011. *Atmosphere*, 7(6), pp.1–14.
- Waynick, J.A., 2001. The Development and Use of Metal Deactivators in the Petroleum Industry: A Review. *Energy & Fuels*, 15(6), pp.1325–1340. Available at: <http://pubs.acs.org/doi/abs/10.1021/ef010113j>.
- WBCSD, 2001. *Mobility 2001 - World mobility at the end of the twentieth century and its sustainability*, Available at: <http://www.wbcd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=MTg1>.
- Whitefield, P.D. et al., 2008. *Summarizing and Interpreting Aircraft Gaseous and Particulate Emissions Data - ACRP REPORT 9*,
- Whyte, R. & Lohmann, G., 2015. Low-cost long-haul carriers: A hypothetical analysis of a ‘Kangaroo route’. *Case Studies on Transport Policy*, 3(2), pp.159–165. Available at: <http://dx.doi.org/10.1016/j.cstp.2015.01.003>.

- Wiesenthal, T., Condeco-Melhorado, A. & Leduc, G., 2015. Innovation in the European transport sector: A review. *Transport Policy*, 42, pp.86–93.
- Wilke, S., Majumdar, A. & Ochieng, W.Y., 2014. Airport surface operations: A holistic framework for operations modeling and risk management. *Safety Science*, 63, pp.18–33. Available at: <http://dx.doi.org/10.1016/j.ssci.2013.10.015>.
- Williams, V. & Noland, R.B., 2006. Comparing the CO₂ emissions and contrail formation from short and long haul air traffic routes from London Heathrow. *Environmental Science & Policy*, 9, pp.487–495.
- Williams, V. & Noland, R.B., 2005. Variability of contrail formation conditions and the implications for policies to reduce the climate impacts of aviation. *Transportation Research Part D: Transport and Environment*, 10(4), pp.269–280.
- Williams, V., Noland, R.B. & Toumi, R., 2002. Air Transport Cruise Altitude Restrictions to Minimize Contrail Formation. In *The 82nd Annual Meeting of the Transportation Research Board*.
- Winchester, N. et al., 2011. The Impact of Climate Policy on U.S. Aviation. *MIT Joint Program on the Science and Policy of Global Change*, Report No1(May). Available at: <http://mit.dspace.org/handle/1721.1/29790>.
- Wit, J.G. de & Zuidberg, J., 2012. The growth limits of the low cost carrier model. *Journal of Air Transport Management*, 21(July), pp.17–23.
- Wit, R. et al., 2004. *Climate impacts from international aviation and shipping*,
- Wit, R. et al., 2005. Giving wings to emission trading. , (July), p.245.
- World Bank, 1994. *World Development Report 1994, Infrastructure for Development*,
- World Meteorological Organization, 2014. *SCIENTIFIC ASSESSMENT OF OZONE DEPLETION : 2014*,
- Yang, H. & Zhang, A., 2012. Effects of high-speed rail and air transport competition on prices, profits and welfare. *Transportation Research Part B: Methodological*, 46(10), pp.1322–1333. Available at: <http://dx.doi.org/10.1016/j.trb.2012.09.001>.