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A Dynamic, Technology-based Air Transportacion Model: Description and Some Applications

EUR 22617 EN

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http://www.jrc.cec.eu.int

EUR 22617 EN

ISSN 1018-5593

Luxembourg: Office for Official Publications of the European Communities

Printed in Spain

European Commission

EUR 22617 EN – DG Joint Research Centre, Institute for Prospective Technological Studies
Title: A Dynamic, Technology-based Air Transportation Model: Description and Some Applications
Authors: Ignacio Hidalgo, Juan Carlos Ciscar, Antonio Soria
Luxembourg: Office for Official Publications of the European Communities
2006
EUR - Scientific and Technical Research series; ISSN 1018-5593

Abstract

Civil aviation produces around 3% of the global greenhouse gas emissions. The Commission has issued recently an initiative aiming at including this sector under the EU emission trading scheme. The lack of available tools has prompted the development of the IPTS Air Transport Model, described in this document. This new tool has been conceived as an extension of the POLES model, and it is aimed to project the global energy use and the corresponding emissions from the civil air transport sector during the period 2000-2050.

The IPTS Air Transport Model is fed with an extensive database built mainly from IATA's statistics, and complemented with other data from NASA, EUROCONTROL, Airbus and Boeing. The information has been structured in a way fully compatible with POLES.

This report describes the main hypothesis made, as well as the results of the reference scenario and four alternative scenarios. The results from the reference scenario are compared with those of other available studies in the literature. The four alternative scenarios focus on alternative schemes of emission trading that could potentially be implemented for the sector in the period 2013-2020.

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A Dynamic, Technology-based Air Transportation Model: Description and Some Applications

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Summary

Currently civil aviation produces around 3% of the global greenhouse gas emissions. It is expected that, following past trends, the sector will continue growing at a very high rate during the next years. In the EU, aviation-related emissions could offset a significant part of the emission reductions achieved in other sectors, hampering the compliance with the EU environmental targets for the first commitment period of the Kyoto Protocol. The Commission has issued recently a communication considering that the best way to address the environmental impacts of aviation is to include this sector under the EU emission trading scheme[1].

It is assumed that this amendment of the current EU legislation will produce diverse impacts on this and other sectors of the economy, which should be assessed quantitatively. The lack of available tools has prompted the development of the IPTS Air Transport Model, described in this document. This new tool has been conceived as an extension of the POLES[2] model, and it is aimed to project the global energy use and the corresponding emissions from the civil air transport sector during the period 2000-2050.

The IPTS Air Transport Model is fed with an extensive database built mainly from IATA's statistics, and complemented with other data from NASA, EUROCONTROL, Airbus and Boeing. The information has been structured in a way fully compatible with POLES.

The world is divided into 47 regions, according to the geographical breakdown used in POLES. These regions are grouped into twelve macro-regions. The model considers 78 regional markets defined as pairs of macro-regions.

Air transport capacity in each market is determined as a combination of aircraft fleet and use. Taking into account the different propulsion systems, sizes, and uses, the current aircraft models have been classified into ten groups of airplanes. The expected changes in supply determine the requirements of new aircrafts in the future. For each simulation period, the fleet is calculated from the balance between added, retired and remaining aircrafts.

Air transport demand, capacity constraints, and operating costs determine fleet use and air transport supply by each country in each market. Transport demand is represented as a function of GDP and price using the so-called gravity modelling approach.

Energy consumption in each of the regions is estimated from fleet use. Based on energy consumption and through the use of emission indexes for six gases, the model is also able to calculate the corresponding pollutant emissions.

In addition to this summary, section 1 describes the model in detail. Section 2 describes the main demographic and economic hypothesis used, as well as the results of the reference scenario and four alternative scenarios. The reference or "business as usual" scenario projects the evolution of the air transport sector when present conditions remain. The results from the reference scenario are compared with those of other available studies in the literature. The four alternative scenarios analyse the consequences of including civil aviation in the EU emission trading system for the period 2013-2020. The document concludes with the main findings outlined in section 3.

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[1] COM(2005) 459: http://europa.eu.int/eur-lex/lex/LexUriServ/site/en/com/2005/com2005_0459en01.pdf

[2] More information on the POLES model available at: http://energy.jrc.es.

1. Model description

1.1 Model overview

This document describes the first version of the IPTS Air Transport Model. The model has been conceived as an extension of the POLES model and is aimed to project the global energy use and the corresponding emissions from the civil air transport sector during the period 2000-2050.

The model is fed with an extensive database built mainly from IATA's statistics, and complemented with other data from NASA, EUROCONTROL, Airbus and Boeing. The information has been structured in a way fully compatible with POLES. To this purpose, the world is divided into 47 regions, according to the geographical breakdown used in POLES. These regions are grouped into twelve macro-regions. The model considers 78 regional markets defined as pairs of macro-regions.

The model is made up of four interconnected modules, as it is shown in Figure 1. Each of these parts deals with a specific problem, namely:

- Capacity planning
- Cost calculation
- Market clearing
- Energy use and emissions

Taking into account the different propulsion systems, sizes, and uses, the current aircraft models have been classified into ten groups of airplanes. In the capacity planning module, current fleet volumes and expected changes in transport supply are used to determine the requirements of new aircrafts for each region in the following simulation period. Expected supplies are obtained by linear regression from the past transport supplies. By means of a vintage model, which considers the past additions to the fleet and the survival rate of each aircraft group, the model establishes the amount of aircrafts still in service from each vintage. The current fleet by region is then calculated from the balance between added, retired and remaining aircrafts.

The cost calculation module takes fuel prices and fleet use in each of the regions, with the technical characteristics of the aircrafts, in order to determine the operating costs of each aircraft class. Fleet use is obtained as a function of fleet volume, transport supply and average load factor.

The market match module computes the amount of air transport supplied by each country in each market. Transport supply curves by country and aircraft in each market are defined as a function of aircraft operating costs and transport capacity constraints within the market. Air transport capacity constraints are determined as a certain combination of aircraft fleet, use, range, and carrying capacity. Transport supply curves are added in order to estimate the aggregated transport supply curve of each market. The intersection between transport demand and aggregated supply produces the market equilibrium price. Transport supplies are given by the intersection between the market equilibrium price and the corresponding transport supply curves by country and aircraft. Transport demand has been represented using the so-called gravity modelling approach. Transport demand in each market depends on GDP and transport price.

Finally, the module devoted to energy use and emissions takes fleet use and aircraft technical features in order to estimate the energy consumption in each of the regions. Based on energy demand and through the use of emission indexes for six gases, this module is also able to calculate the corresponding pollutant emissions.

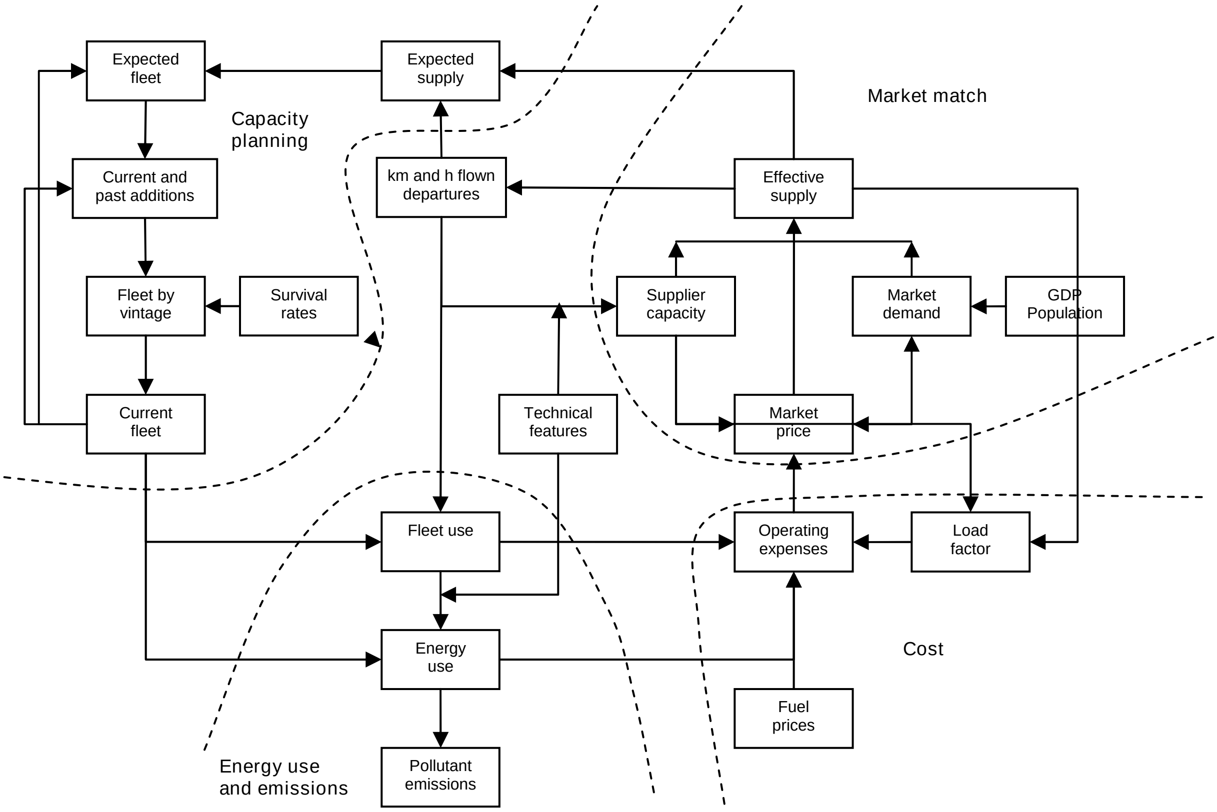

Figure 1: model diagram

1.2 Model database

The bulk of the information required by the model has been obtained from IATA (2004). IATA currently represents over 270 airlines[3] in 144 countries, comprising 95% of international scheduled air traffic, and 86.6% of the total world revenue passenger-kilometres flown in 2002.

This information has been reorganised in order to be able to distinguish between passenger and freight traffic. All-cargo flights have been subtracted from scheduled services figures, and the remaining scheduled services have been aggregated to charter services. Finally, airline figures have been aggregated depending on their flag and according to the geographical coverage used by POLES (shown in Table 1).

Table 1: geographical coverage of POLES

Europe		Rest of the World	
Acronym	Region	Acronym	Region
AUT	Austria	CAN	Canada
BLX	Belgium and Luxembourg	USA	United States
DNK	Denmark	MEX	Mexico
ESP	Spain	RCAM	Rest of Central America
FIN	Finland	BRA	Brazil
FRA	France	RSAM	Rest of South America
GBR	United Kingdom	CHN	China
GRC	Greece	COR	South Korea
IRL	Ireland	JPN	Japan
ITA	Italy	NDE	India
PRT	Portugal	RSAS	Rest of South Asia
NLD	Netherlands	RSEA	Rest of South East Asia
RFA	Germany	RJAN	Rest of Pacific OECD
SWE	Sweden	RUS	Russia
SMC	Slovenia, Malta and Cyprus	UKR	Ukraine
CZE	Czech Republic	RFSU	Rest of Former Soviet Union
HUN	Hungary	SSAF	Sub-Saharan Africa
BLT	Lithuania, Estonia and Letonia	EGY	Egypt
POL	Poland	NOAN	North Africa Non-producers
SVK	Slovak Republic	NOAP	North Africa Producers
TUR	Turkey	GOLF	Gulf States
BGR	Bulgaria	MEME	Mediterranean Middle East
ROU	Rumania		
RCEU	Rest of Central Europe		
ROWE	Rest of Western Europe		

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[3] The number of members increases up to 330 during the whole period covered by the available statistics, due to changes in membership and existing airlines.

Table 2 shows the structure of the data provided by IATA. For each reporting member airline, the information is split into scheduled (including all-cargo flights) and charter services, and into international, domestic and system-wide traffic.

Table 2: items in World Air Transport Statistics

	IATA CODE	Description	Units
Scheduled Services	SAKMT	Kilometres flown	thousands km
	SDEPT	Aircraft departures	number dep
	SHRST	Hours flown	number hour
	SPAXT	Passengers carried	number pax
	SFRTT	Freight tonnes carried	number ton
	SRPKT	Passenger-kilometres flown	thousands pkm
	SASKT	Available seat-kilometres	thousands pkm
	SPLFT	Passenger load factor	%
	STKPT	Tonne-kilometres performed (passenger, including baggage)	thousands tkm
	STKFT	Tonne-kilometres performed (freight, including express)	thousands tkm
	STKMT	Tonne-kilometres performed (mail)	thousands tkm
	SATKT	Available tonne-kilometres	thousands tkm
	SWLFT	Weight load factor	%
	NTWRK	Length of scheduled route network	number km
All-cargo scheduled flights (included above)	SAKMC	Kilometres flown	thousands km
	SDEPC	Aircraft departures	number dep
	SHRSC	Hours flown	number hour
	SFRTC	Freight tonnes carried	number ton
	STKFC	Tonne-kilometres performed (freight, including express)	thousands tkm
	STKMC	Tonne-kilometres performed (mail)	thousands tkm
	SRTKC	Total tonne-kilometres performed in all-cargo flights	thousands tkm
	SATKC	Available Tonne-Kilometres	thousands tkm
	SWLFC	Weight load factor	%
Charter Services	CAKMT	Kilometres flown	thousands km
	CDEPT	Aircraft departures	number dep
	CHRST	Hours flown	number hour
	CAPXT	Passengers carried	number pax
	CFRTT	Freight tonnes carried	number ton
	CRPKT	Passenger-kilometres flown	thousands pkm
	CASKT	Available seat-kilometres	thousands pkm
	CPLFT	Passenger load factor	%
	CTKPT	Tonne-kilometres performed (passenger, including baggage)	thousands tkm
	CTKFT	Tonne-kilometres performed (freight, including express)	thousands tkm
	CTKMT	Tonne-kilometres performed (mail)	thousands tkm
	CRTKT	Total tonne-kilometres performed in charter flights	thousands tkm
	CATKT	Available tonne-kilometres	thousands tkm
	CWLFT	Weight load factor	%
Fleet and Utilization	Fleet	All aircraft in service and available for operation on 31 December, including equipment leased in from other organizations but excluding aircraft leased out to other operators on that date.	number aircraft
	Utilization	Average block time flown (including taxi time on runways)	number hour/aircraft/day

IATA provides detailed fleet and utilization data for each member airline. Disregarding the model variants, there are 135 different aircraft models currently in use. These models have been classified into ten groups of airplanes according to purpose, propulsion and size criteria.

According to their use, airplanes can be split into passenger (able to carry passengers and cargo) or freighters aircrafts (only suitable for cargo). With respect to propulsion, aircrafts can be equipped with engine jets (either supersonic or subsonic) or turbo propellers.

Regarding size or carrying capacity, aircrafts can be grouped into jumbo jets (with more than 400 seats), wide-body jets (two aisle, between 240 and 400 seats), narrow-body jets (single aisle, between 90 and 240 seats), regional jets (below 90 seats), supersonic jets (narrow-body like), regional turboprops (between 20 and 90 seats), and small propellers (up to 20 seats).

Passenger jets are split into five size categories (supersonic, jumbo, wide body, narrow body, and regional jets), while turboprops are divided into two classes (regional and small). Freighter jets are divided into three size categories (jumbo, wide body and narrow body jets).

Table 3 shows the groups (and their corresponding acronyms) used in the following.

Table 3: aircraft models and groups

Passenger jets		Freighter jets		Passenger turboprops	
Group	Model	Group	Model	Group	Model
Jumbo (PJJ)	B747 100	Jumbo (FJJ)	An 124 F	Regional (TP)	An 24
	B747 400		B747 100 F		An 26
Narrow-body (PJN)	A319		B747 400 F		An 32
	A320	Narrow-body (FJN)	B707 F		An 74
	A320 200		B727 200 F		ATR 42
	A321		B737 200 F		ATR 72
	B707		B737 300 F		BAe ATP
	B727		B757 F		BAe Avro RJ100
	B727 200		DC 8 F		BAe Avro RJ70
	B737 200		IL 76 F		BAe Avro RJ85
	B737 300	Wide-body (FJW)	A300 F		BAe HS 748
	B737 400		B767 F		BAe Jetstream 31
	B737 500		DC 10 F		BAe Jetstream 41
	B737 600		MD 11 F		CASA 212
	B737 700				CASA 235
	B737 800				DHC 8 100
	B737 900				DHC 8 300
	B757				EMB 120
	DC 8				Fokker 27
	IL 62				Fokker 50
	MD 80				IL 18
	MD 90				L 100
	Tu 154				L 188
	Tu 204				L Jet Star
Wide-body (PJW)	A300				Saab 2000
	A300 600				Saab SF 340
	A300 B4				Saab SF 340B
	A310 200			Small (TS)	An 12
	A310 300				Beechcraft 1900
	A330				Beechcraft 58
	A330 300				Beechcraft 99
	A340 200				Beechcraft A 36
	A340 300				BN 2
	B767				Cessna
	B777				Convair 580
	B777 300				DC 3
	DC 10				DC 4
	IL 86				DHC 1
	IL 96				DHC 2
	L 1011				DHC 3
	MD 11				DHC 5
Regional (RJ)	BAe 146				DHC 6 Twin Otter
	BAe 146 300				Dornier 228
	BAe BAC 1 11				EMB 110
	BAe Gulfstream 2				EMB 200
	BAe Gulfstream 3				Eurocopter
	BAe Gulfstream 4				Harvard
	Canadair CL 65				JU 52

	Canadair CL600				LET 410
	CRJ				Metro II
	DC 9				Metro III
	EMB 145				Mi 8
	Falcon 900				MU 2
	Fokker 100				PA 31 350
	Fokker 28				Shorts SC 7
	Fokker 70				Shorts SD 18
	IL 40				Shorts SD 360
	Tu 134				Sikorsky 76
	Yak 40				Vickers
	Yak 42				
Supersonic (SJ)	Concorde				

IATA members' fleet by the end of 2002 was made up of 11338 aircraft, of which 10455 were jets. Airbus (2003) reported a global fleet consisting of 10789 aircraft with at least 100 seats by the end of 2002. According to Boeing (2003a), world fleet was comprised of 15600 airplanes (i.e. 30% higher than IATA) of which 11800 were jets.

When possible, most aircraft technical specifications (Table 4) have been obtained directly from manufacturers. Energy use and emission indexes have been obtained from publicly available sources (Kalidova et al. (1997), and Sutkus et al. (2001), and (2003)). In some cases, for Russian aircrafts and old aircraft models, specifications are taken from similar aircrafts.

Table 4: aircraft specifications included in the database

Manufacturer	
Model	
Aircraft type	
Average flight distance (km)	
Average age (year)	
Date of first flight	
Maximum take-off weight (ton)	
Engine model	
Number of engines	
Average speed (km/h)	
Seats	
Cargo capacity (ton)	
Fuel consumption (l/h)	
Emission index 1-9 km altitude band	NO_X (g/kg fuel)
	CO (g/kg fuel)
	HC (g/kg fuel)
Emission index 9-13 km altitude band	NO_X (g/kg fuel)
	CO (g/kg fuel)
	HC (g/kg fuel)

1.3 Model equations

1.3.1 Transport demand

1.3.1.1 Market demand

The world has been split into a number of regions with the aim of describing appropriately the most significant traffic flows between and within those regions. To this purpose, the regional markets used in the model are defined as all the possible pairs of macro-regions listed in Table 5, disregarding the direction of the traffic[4]. Thus, the model considers 78 regional markets (combinations of two macro-regions such as NOANOA or NOAEUR), of which 12 are intraregional.

Table 5: Macro-regions

Macro-region	POLES Countries
North America (NOA)	CAN, USA
Central America (CEA)	MEX, RCAM
South America (SOA)	BRA, RSAM
Europe (EUR)	Europe (first column in Table 1)
Commonwealth of Independent States (CIS)	RUS, UKR, and RFSU
Africa (AFR)	NOAN, NOAP, SSAF
Middle East (MEA)	EGY, MEME, GOLF
China (CHI)	CHN
North East Asia (NEA)	COR, JPN
South East Asia (SEA)	RSEA
Oceania (OCE)	RJAN
South West Asia (SWA)	NDE, RSAS,

The functional form assumed to represent air transport demand is based on the gravity modelling approach explained by Verleger (1972). Under this hypothesis, transport demand in year t, D_t, is expressed as the product of a series of factors that may influence the demand (α, β…), modified by a set of elasticities (a, b…), and a constant K representing other unaccounted factors:

(1)
$$D_t = K \cdot \alpha_t^a \cdot \beta_t^b \ldots \cdot \omega_t^z$$

In this model air transport demand is assumed to be driven by the market price and the GDP. The corresponding elasticities have been taken from Eurocontrol (2005), historical demand time series from Boeing (2003b), and Schafer et al. (2000), and GDP and population figures from the POLES database.

1.3.1.2 National share in a market

An important variable used in the following sections is the share of a given country in each of the passenger transport markets. This is defined from the country's share in total global demand, which is defined as the ratio of the total national transport supplies to each market, to the market size.

The initial values of country's share in total global demand have been obtained combining the information provided by IATA (2004) and Schafer et al. (2000). The demand of a given country in each market is obtained by multiplying the market size by the national share in the market. These national demands are used later to compute the average fuel costs within each market. The equivalent variables for freight traffic are obtained in a similar way.

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[4] I.e. the market North-America/Europe includes all the traffic from North-America to Europe and vice versa.

1.3.2 Transport capacity

1.3.2.1 Capacity by market, country, and aircraft class

Total transport capacities available in each country are given by the combination of the carrying capacity (the number of seats per aircraft and the number of tons that can be carried in the holds), the average aircraft range (expressed in km per flight or departure) and the use, represented by the number of departures carried out in one year.

The number of departures gives a notion of the airport and air traffic management capacity. It is assumed that departures in a given country grow as the demand in the markets where this country operates, using the national shares in each market demand, and therefore traffic congestion is not considered in the model.

Air transport capacities are allocated to the markets according to the national shares in each market demand.

1.3.2.2 Average daily use

The average daily use of each type of aircraft (expressed in day/day) is required for the purpose of computing the energy use and the energy-related transport costs.

Daily use is defined as the ratio between the total amount of hours flown by all the aircrafts of a given class in one year and the fleet of each aircraft type present in each region. For each aircraft category, the number of hours flown during the whole year is obtained by dividing the kilometres flown into the average speed. The kilometres flown in one year by each aircraft class are obtained from the ratio of transport supplies to the carrying capacities, taking into account the load factors.

Daily average use ranges from a lower bound (since little use is not profitable for airlines) to an upper bound (due to organisational and safety reasons). This model assumes that the daily average use is limited by the minimum use during the past five years and 80% of the day.

1.3.3 Transport supply

National transport supply curves in each of the markets, by aircraft type, are assumed to be shaped as the integral of normal distributions. According to this specification, individual supply curves indicate the “willingness to offer” of an economic agent operating in a given market. The average of each normal (i.e. the inflection point of the supply curve) corresponds to the average operating expenses (which include the remuneration of all production factors, defined in section 1.3.4), while the standard deviations have been calibrated to fit the market price data. Each supply curve is rescaled by the transport capacity in the market (the asymptote of the curve). It is assumed that only the countries belonging to a given market can supply to it (thus NOANOA market is supplied only by USA and CAN).

The transport supply curve in a given market is calculated by the aggregation of individual supply curves by country and aircraft. The intersection of the market supply curve and the market demand determines the market price. Transport supplies in the equilibrium are calculated by the intersection of the market price with the individual supply curves.

National transport supplies are obtained by the aggregation of the supplies by country and aircraft in each market. National supplies are used later to calculate the expected supply, required for capacity planning (see section 1.3.5). An analogue calculation is used to compute freight transport demand.

The procedure explained above guarantees that the demand is satisfied at the minimum possible cost and fulfils the restrictions on capacity. In order to carry out the procedure explained above, the model uses a set of functions contained in an external library specifically programmed to this purpose. Supply curves are determined by using the approximation of the cumulative normal distribution defined by Abramowitz et al. (1970). Market prices are calculated following the standard *regula falsi* method.

Figure 2 illustrates the calculation procedure explained above in the case of a market made up of four suppliers. The market demand in each period is prescribed by the demand function. The individual supply curves grow from zero up to an asymptotic value that represents the maximum capacity that can be provided by the supplier from a given price upwards. The cheaper the supplier, the faster the supplier capacity is saturated. Thus, if there is unsatisfied demand after using up all the capacity of the cheapest supplier (yellow curve), the other suppliers (the cheaper first) use up their capacity until the market demand is met. The most expensive suppliers only meet a small share of the demand. The aggregated market supply is obtained by addition of the individual supply curves. The market price (represented by the vertical red line) is obtained by the intersection between the market demand and the market supply curve. The intersection of this line with each supply curve determines the supplies provided in the equilibrium.

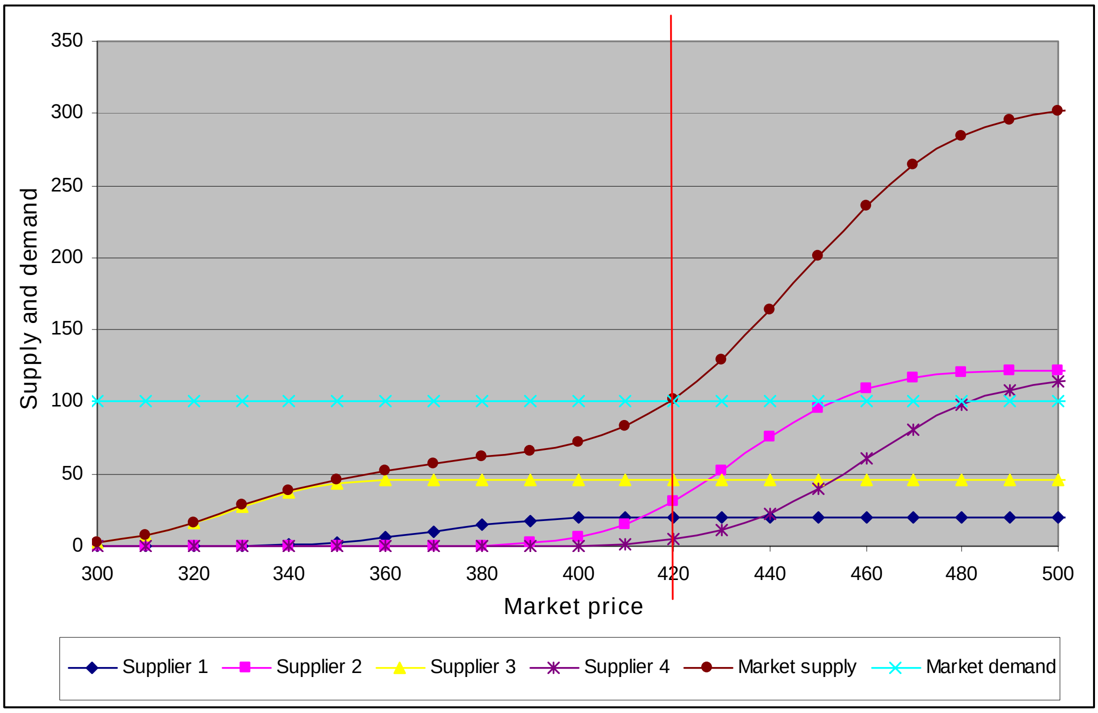

Figure 2: transport supply

1.3.4 Transport costs

According to IATA (2004), operating expenses are made up of the items shown in Table 6. Fuel accounts for around 30% of direct operating expenses (16% of total operating expenses).

Table 6: airline operating expenses (total international operations)

Operating Expenses	2001			2002		
	USc/ATK	Share over DOE/IOE	Share over TOE	USc/ATK	Share over DOE/IOE	Share over TOE
Flight Deck Crew	2.5	12.08	6.79	2.5	11.79	6.67
Fuel and Oil	6.1	29.47	16.58	5.9	27.83	15.73
Flight Equipment Insurance	0.1	0.48	0.27	0.2	0.94	0.53
Maintenance & Overhaul	4	19.32	10.87	4.1	19.34	10.93
Flight Equipment Depreciation	2.7	13.04	7.34	2.9	13.68	7.73
Rentals	2.3	11.11	6.25	2	9.43	5.33
Airport Charges	1.5	7.25	4.08	1.8	8.49	4.80
Air Navigation Charges	1.5	7.25	4.08	1.8	8.49	4.80
Direct Operating Expenses (DOE)	20.7	100	56.25	21.2	100	56.53
Station and Ground	3.8	23.60	10.33	3.3	20.25	8.80
Cabin Attendants	2.6	16.15	7.07	2.6	15.95	6.93
Passenger Service	2.2	13.66	5.98	2.7	16.56	7.20
Ticketing, Sales & Promotion	5.5	34.16	14.95	4.9	30.06	13.07
General & Administrative	1.8	11.18	4.89	2.5	15.34	6.67
Load Insurance	0.2	1.24	0.54	0.3	1.84	0.80
Indirect Operating Expenses (IOE)	16.1	100	43.75	16.3	100	43.47
Total Operating Expenses (TOE)	36.8		100	37.5		100

It is assumed that all aircraft types use a homogenous jet fuel. Basic jet fuel price may be incremented by a surcharge depending on the carbon content of the jet fuel when a CO_2 emission tax or an emission allowance market is implemented.

Since aircrafts from a given country can refuel anywhere, it is necessary to calculate the average jet fuel price in each market. To this purpose, the average jet fuel price in a market is calculated by multiplying the price in each country within the market by the national demand in that market, and the result is added by country and divided into the market demand.

In order to represent properly the technical characteristics of the fleet at any time, as well as the fleet ageing and renewal processes, it has been adopted a vintage model. The average specific fuel consumption per km of each type of aircraft is calculated as the weighted sum of the fuel consumption of the different aircraft vintages.

The energy-related utilisation costs of each aircraft class are obtained from the specific fuel consumption, the national shares and the average jet fuel price in each market, the carrying capacity, and the load factors. The total operating expenses are estimated by adding the non energy-related variable costs, calibrated to fit the market price data.

1.3.5 Fleet planning

The current fleet in year *t*, is computed by adding all the aircrafts *i* years old still in service in year *t*, which are a fraction of the aircrafts that were added during the previous years *t-i* (from an initial point in the past t_0, onwards).

Remaining aircrafts are given by the product of the new additions in *t-i*, and the survival rate of aircrafts *i* years old. The survival rate is the complement of the scrappage rate, which is represented by a Gompertz function. Figure 3 shows the survival rate resulting for passenger narrow-body jets.

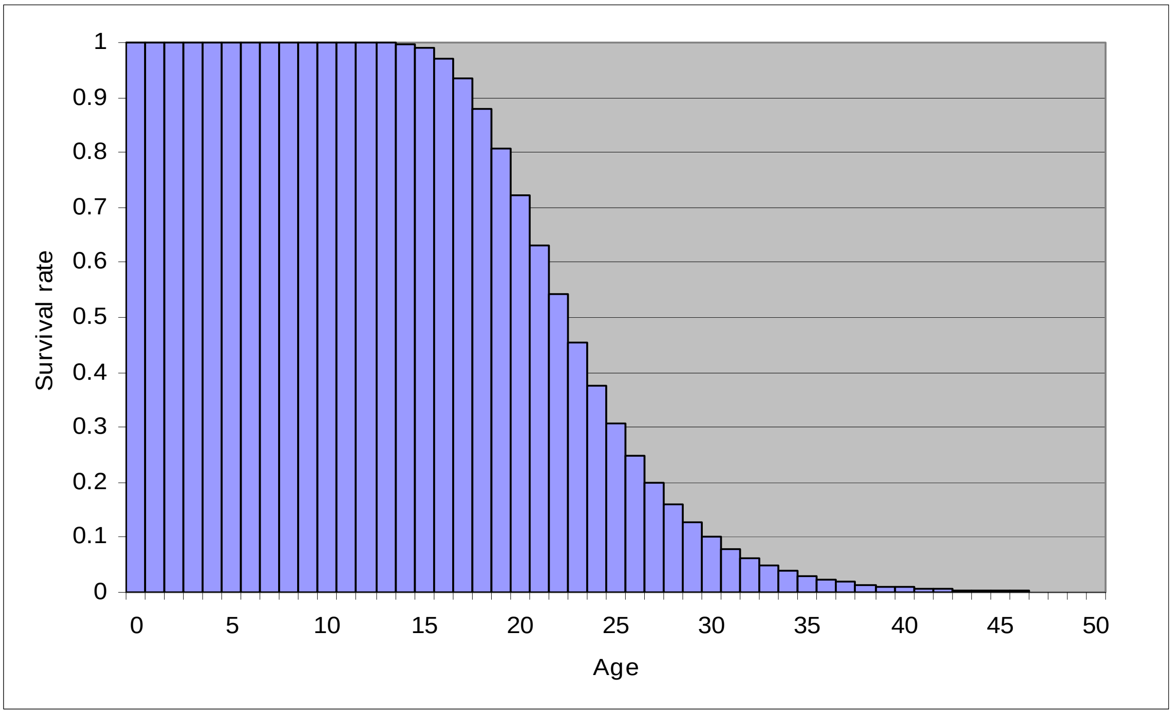

Figure 3: survival rate for narrow-body aircrafts

Figure 4 shows the capacity planning procedure. In any year *t*, the fleet existing in *t*-1, minus the fleet retired in *t*, equals the fleet in *t* minus the new fleet planned in *t*-1 (to be added in *t*). In *t* also, the existing fleet minus the fleet to be retired in *t*+1 equals the expected[5] fleet in *t*+1 minus the new fleet planned in *t* (note that all the "expected" values are calculated in *t*).

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[5] The word "expected" is used here meaning that this fleet represents the amount of aircrafts required to produce the expected supply in *t*+1, calculated later in this section.

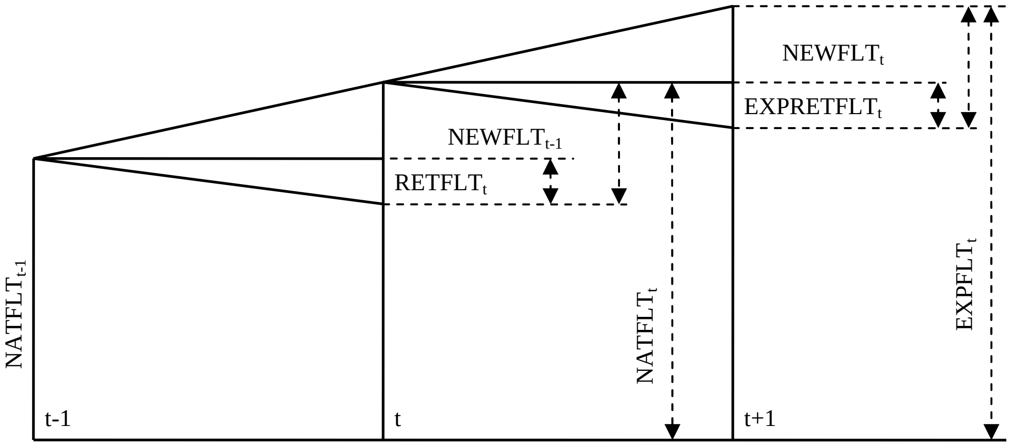

Figure 4: capacity planning

New aircraft planned to be added in *t*+1 are calculated from the existing fleet in *t*, the expected fleet in *t*+1, and the fleet to be retired in *t*+1, which is a function of the past additions to the fleet and the corresponding survival rates.

The expected fleet in year *t*+1 depends on the expected passenger and freighter fleets. The fleets expected in *t*+1 are calculated assuming that the ratio between fleet and kilometres flown is proportional to a given constant (calibrated to fit the available data).

The expected kilometres flown depend on the expected transport supplies, which are given by the ratio of the expected supplies to the corresponding carrying capacities. The expected passenger supplies in *t*+1 are estimated by linear regression using the transport supplies during the past five years.

1.3.6 Energy use and emissions

The pollutants considered in the model are CO_2, H_2O, SO_2, NO_X, CO and HC. Pollutant emissions of CO_2, H_2O and SO_2 are proportional to fuel consumption, while emissions of NO_X, CO and HC also depend on flight altitude and other operation conditions. For these substances two different emission indexes are considered, according to the available sources (Sutkus et al. (2001), and (2003)), each one corresponding to a specific altitude band (climb and descent phases, which takes place between ground level and 9 km during 10% of the flight time, and cruise phase, between 9 km and 13 km of altitude). The corresponding emissions of each pollutant are obtained by multiplying the emission indexes by the jet fuel consumption. Jet fuel consumption is the aggregation of the products of each vintage fleet by its corresponding fuel consumption and the average use.

2 Simulation results

2.1 Population and economic assumptions

For clarity purposes, the simulation results presented in this section have been organised taking into account the regional split defined in Table 5. All the scenarios described in the following are based on the same demographic and economic assumptions, taken from the current POLES reference.

Population and GDP are expected to grow in most of the regions (see Figure 5). At world level, population would change from 6000 millions inhabitants in 2000 to 8900 millions by 2050. Developing regions experiment the higher increments according to this projection, especially in Africa (130%) and Middle East (113%). Demographic growth would be more moderated in the other regions. European population would stagnate, while population would decrease only in the former Soviet Union (-16%) and North East Asia (-10%). Between 2000 and 2050 more than half of the world population is concentrated in Asia, and Africa's share in total population changes from 12% to 19%, whereas the share of developed regions (North America, Europe and Oceania) declines from 20% to 14%.

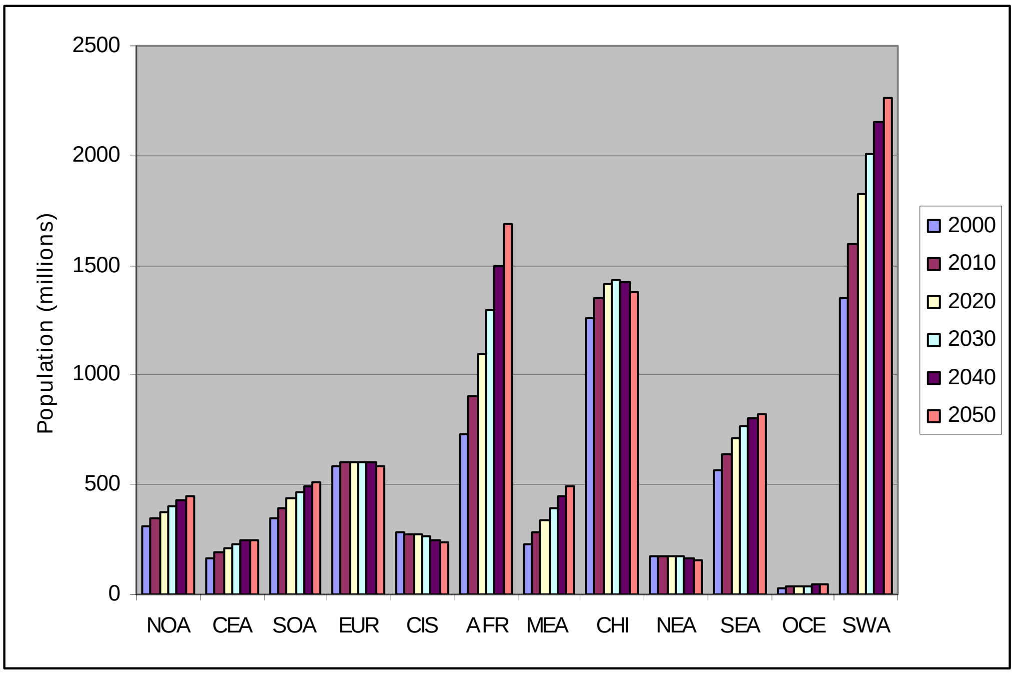

Figure 5: population

With respect to GDP, world output would rise from 41 T€ to 154 T€. This GDP (see Figure 6) would be generated mostly in Asia (32% to 46% of the global GDP during the simulation period), Europe (25% to 16% of the global GDP), and North America (24% to 16% of the global GDP). By 2050 China would produce 18% of the global GDP, and South West Asia 15%. Although GDP would boost in developing regions (for instance, the increment expected in South West Asia between 2000 and 2050 is 654%) North America, Oceania, and Europe are expected to have the highest GDP per capita.

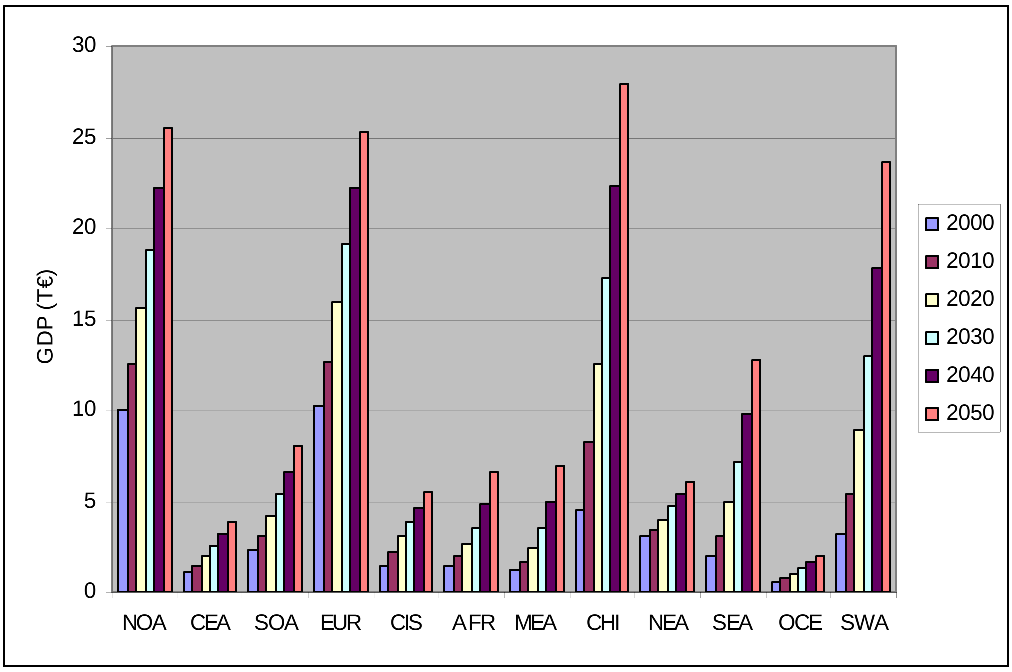

Figure 6: GDP

2.2 Reference scenario

2.2.1 Transport demand

Global passenger transport demand[6] is expected to grow significantly from 3000 Gpkm in 2000 to 16500 Gpkm in 2050, i.e. 448%. By 2000, traffic originated in North America represented 36% of the global demand, followed by traffic originated Europe (23%), and Asia (21.5%, of which 7.5% originated in North East Asia, 6.74% in South East Asia, and 5.3% in China). In 2050, traffic originated in North America would have the largest share. Traffic from Europe to other destinations would keep a similar level with respect to the global total (20%). Traffic from China and South East Asia would increase significantly, both reaching 11% of the world share respectively. Figure 7 shows the mentioned evolution.

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[6] According to Airbus and Boeing, global air passenger transport demand amounted to approximately 3394 Gpkm in 2000; whereas freight demand was 132 Gtkm. The projections described in this document are based on IATA statistics and therefore our figures for 2000 are lower.

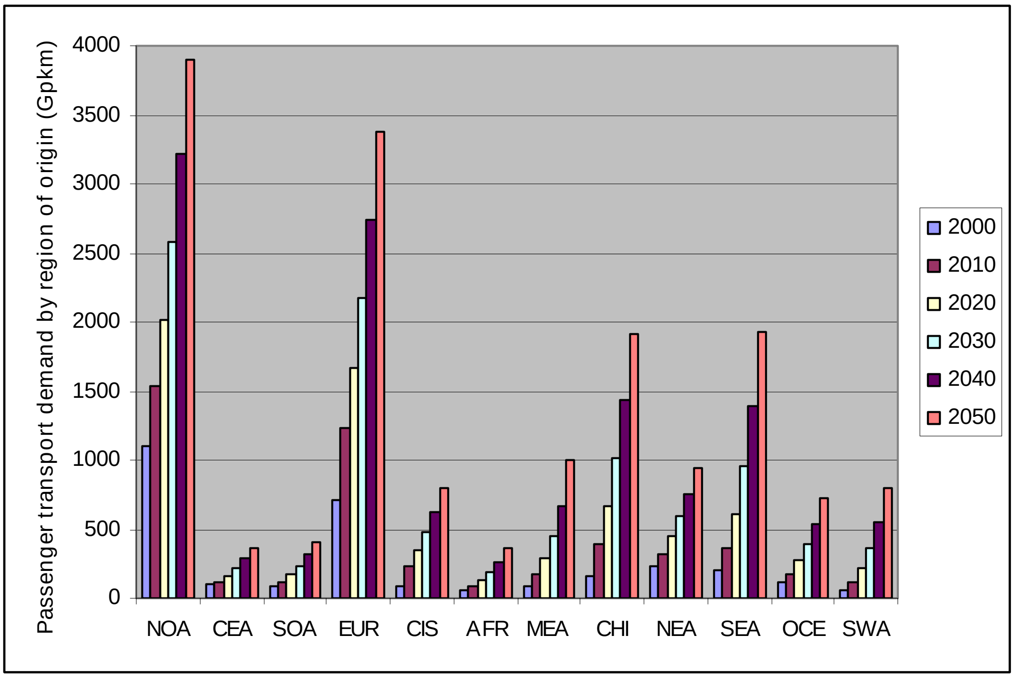

Figure 7: passenger transport demand

Global freight transport demand multiplies by seven, changing from 124 Gtkm in 2000 to 835 Gtkm by 2050. Around 80% of the global traffic in 2000 would be originated in North America (35%), Europe (24%) and Asia (22%, of which 7.5 from North East Asia, 7% from South East Asia, and 5.5% from China). By 2050 traffic from North America and Europe would shrink to 21% and 19% of the global figure respectively, while traffic from Asia would expand reaching 38% of the global total (China and South East Asia accounting for 14% each). Figure 8 illustrates the evolution of the air freight sector in this period.

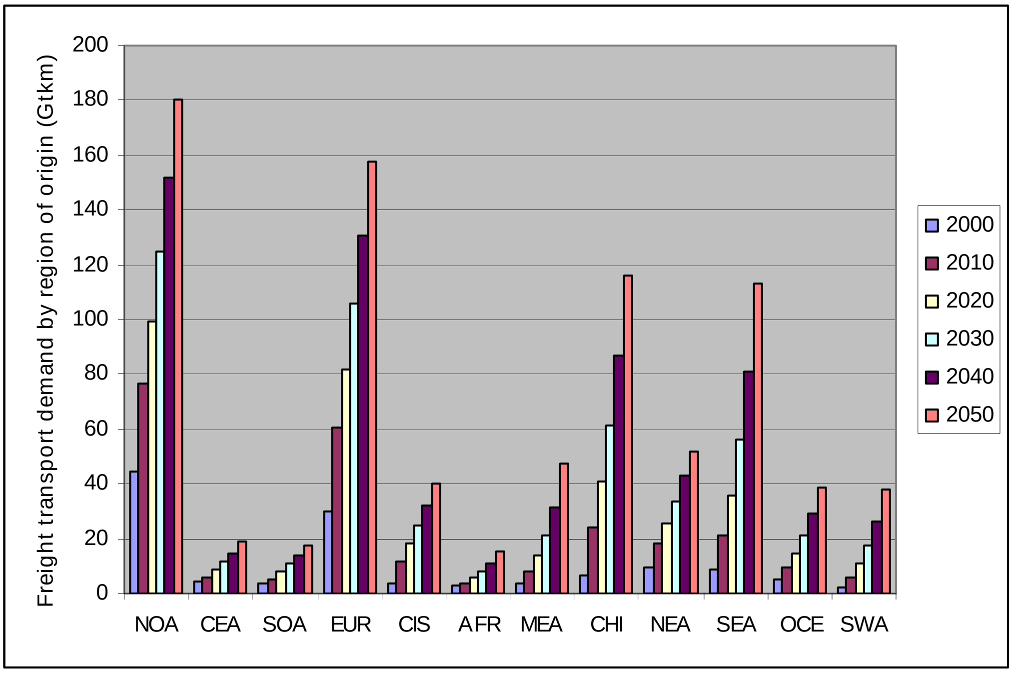

Figure 8: freight transport demand

2.2.2 Fleet

The model described in the previous sections projects a sustained and strong growth of the world aircraft fleet (Figure 9), from 11609 units in 2000 up to 71659 in 2050, i.e. 517%. Air freight is expected to become widely used, and the freighter fleet would increase fivefold, from 764 units in 2000 to almost 3600 units by 2050. Passenger fleet would experiment also a remarkable increment, from 10845 to 68000 units in the same period.

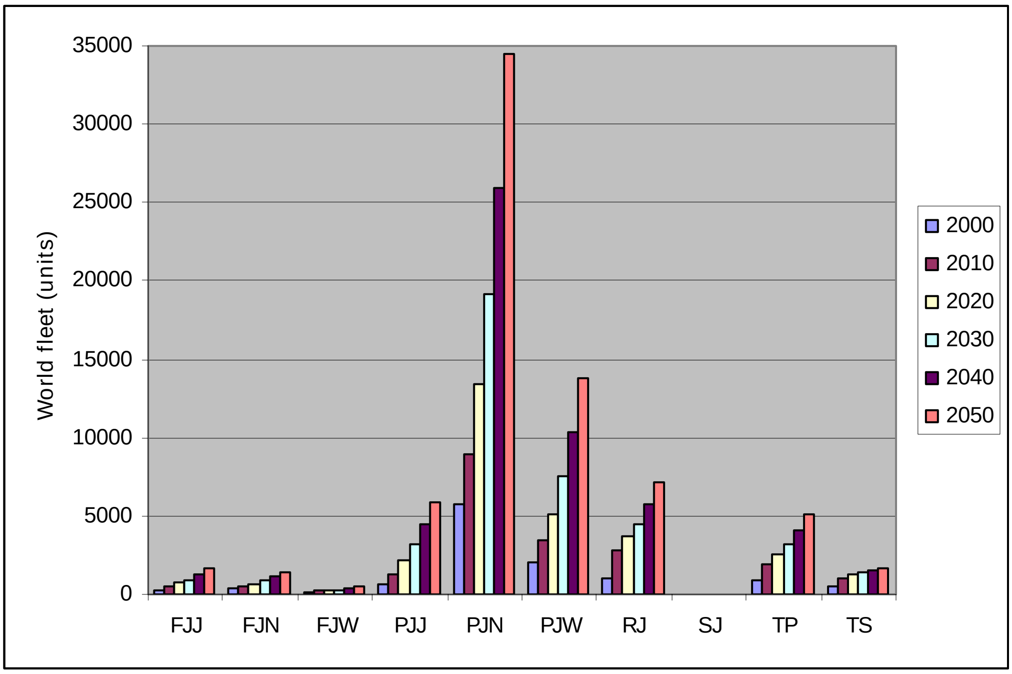

Figure 9: world fleet projection

By aircraft size, the jumbo jets are expected to grow by 822% between 2000 and 2050, while the other categories would increase by more than 480%. The amount of supersonic jets remains negligible. Jets and turboprops will grow in a similar proportion according to this projection.

Fleets would grow significantly in all regions (see Figure 10), but especially in South Asia and the Middle East. During the simulation period 80% of the fleet would be concentrated in North America, Europe and Asia. In 2000 these region would represent 40%, 28% and 12% of the global fleet respectively. By 2050 the distribution is expected be 28%, 28% and 24%.

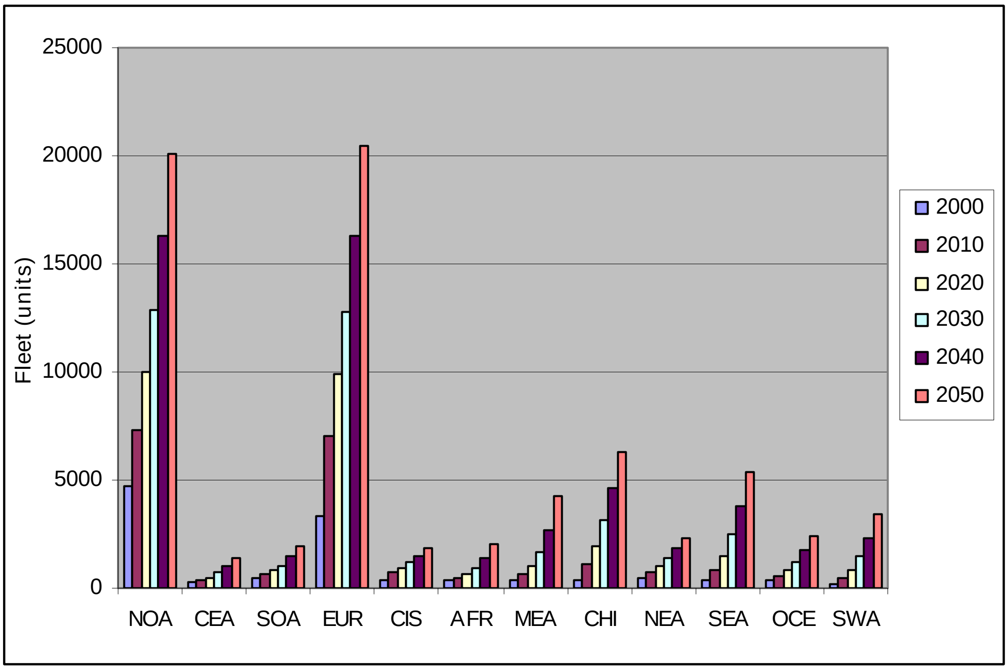

Figure 10: fleet projection by region

2.2.3 Energy demand

Global energy demand from civil aviation would increase by 294%, from 228 Mtoe in year 2000 (221 Mt of jet fuel) to 899 Mtoe in 2050 (871 Mt of jet fuel). Growth in energy use will be almost proportional to the fleet growth according to this simulation (see Figure 11).

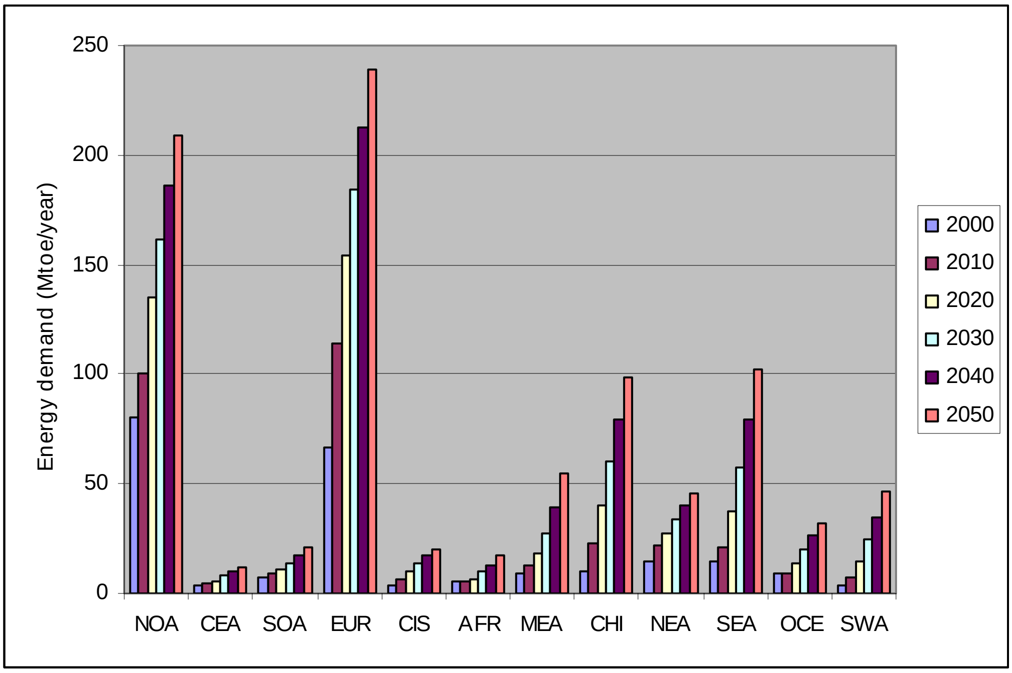

Figure 11: energy demand

2.2.4 Emissions

CO_2 emissions are directly linked to energy use. At world level, CO_2 emissions are expected to grow from 542 $MtCO_2$ in 2000 to 2748 $MtCO_2$ in 2050.

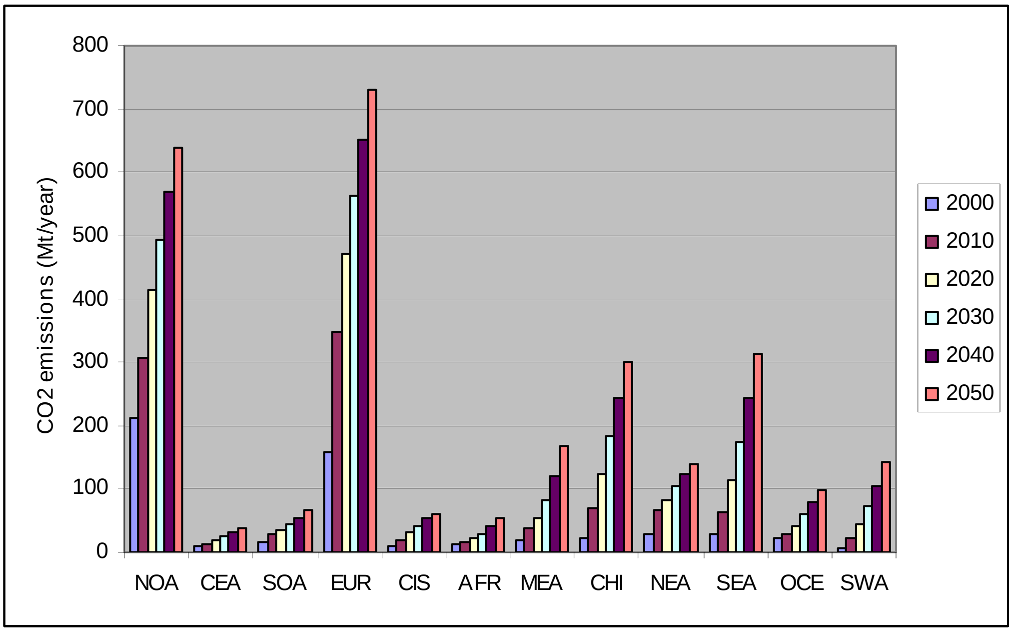

Figure 12: CO_2 emissions

Air transport produces other non-CO_2 emissions that have been summarized in Table 7 at world level.

Table 7: emissions from air transport (Mt/year)

	2000	2010	2020	2030	2040	2050
CO_2-eq	912.42	1725.58	2434.80	3145.90	3872.33	4609.25
CO_2	542.52	1022.88	1451.65	1877.71	2309.88	2747.28
CO	0.69	1.31	1.92	2.46	3.01	3.57
NO_X	2.12	4.04	5.63	7.26	8.94	10.66
H_2O	212.71	401.05	569.16	736.21	905.65	1077.14
HC	0.20	0.40	0.58	0.74	0.91	1.07
SO_2	0.14	0.26	0.37	0.48	0.59	0.70

Taking into account the emission of other pollutants and expressing them in terms of CO_2 equivalent, global emissions would change from 912 $MtCO_2$ in 2000 to 4609 $MtCO_2$ in 2050, of which one third would be on account of NO_X emissions, and around 7% on account of H_2O emissions. Since non-CO_2 emission figures are based on energy use, emissions by region would evolve as the regional energy demand.

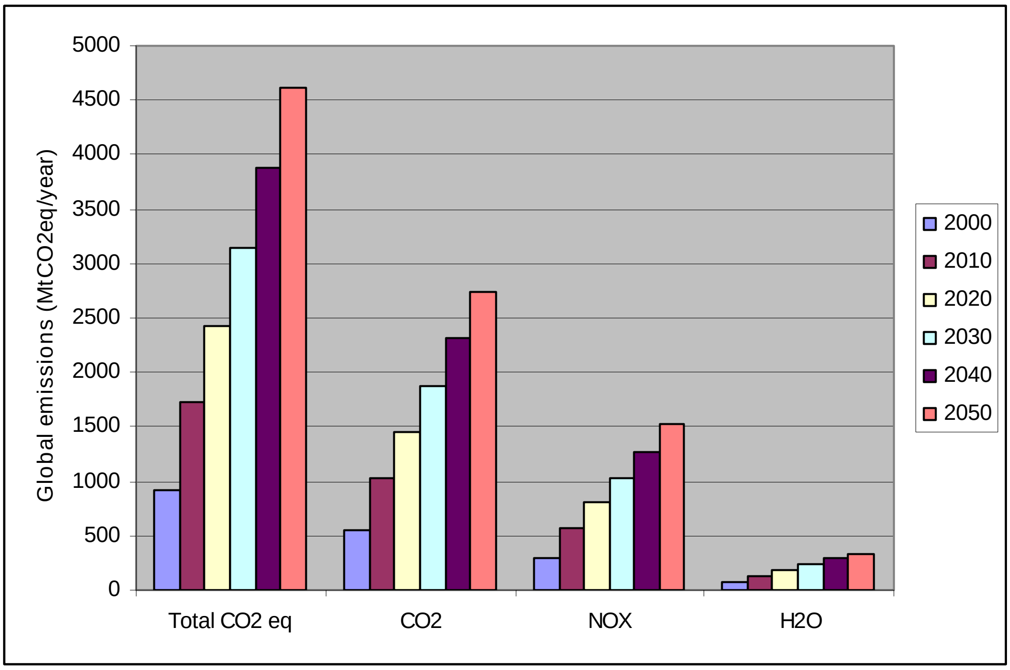

Figure 13: global CO_2 equivalent emissions

2.2.5 Comparison with other analyses

Table 8 compares the projected global demand figures and other results of the reference scenario with the values expected by other analyses in 2020.

The evolution of the civil aviation industry foreseen with this model is in line with other available studies, even though the database used based on IATA statistics underestimates the regional demands and fleets (IATA member airlines met 86% of global demand in 2002, see 1.2).

Table 8: comparison with other analyses for 2020

	Units	IPTS	Airbus (2002), and (2003)	Boeing (2003a), and (2003b)	Eyers et al. (2004)	Olsthoorn (2001)	Schafer et al. (2000)	Sutkus et al. (2003)	Vedantham et al. (1998)
Population	Millions	7496					IPCC/IS92a-e		IPCC/IS92a-f
GDP growth	%	3.25	3.2	3.2		1.6-3.1	IPCC/IS92a-e	3	IPCC/IS92a-f
Passenger demand	Gpkm	7004	8300	8800			7539	8390	6500-15200
Freight demand	Gtkm	362	383	380-570					
Total fleet	Aircrafts	29863						32954	
Passenger fleet	Aircrafts	28195	19700[7]	30498					
Freight fleet	Aircrafts	1668	3338	3501					
Energy demand	Mt	474.93			289			347	390-951
CO_2	Mt	1451.65			912	438-503		1094	1228-3006
CO	Mt	1.92			1.01			1.44	
NO_X	Mt	5.63			3.04			4.89	3.06-7.93
H_2O	Mt	569.16			358				
HC	Mt	0.58			0.13			0.23	
SO_2	Mt	0.37							

2.3 Aviation and the EU emission trading system

2.3.1 Emission trading hypotheses

This section compares the reference scenario explained above to four alternative scenarios in which aviation is included in the EU emission trading system from 2012 onwards. Eight set of results, assuming the same economic and demographic hypotheses used previously, are presented below for the period 2013-2020. The results are obtained combining two exogenous emission allowance prices and CO_2 reduction targets for the European air transport sector, with four options covering emissions from different types of flights. In addition, in all the cases, all the allowances up to the emission targets would be auctioned each year. The hypotheses are summarized in Table 9.

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[7] With more than 100 seats.

Table 9: emission trading scenarios

	Allowance price and reduction target	
	Emission allowance price: 10 €/tCO_2 Emission reduction target: stabilization at 2013 emission levels by 2020	Emission allowance price: 30 €/tCO_2 Emission reduction target: stabilization at 2008 emission levels by 2020
Emission coverage	Scenario 1: all CO_2 emissions from intra-EU flights.	
	Scenario 2: all CO_2 emissions from intra-EU flights and all flights departing from EU.	
	Scenario 3: all CO_2 emissions from intra-EU flights and all flights arriving and departing to signatories to the Kyoto Protocol.	
	Scenario 4: all CO_2 emissions from intra-EU flights and all arriving and departing flights in the EU.	

The first emission reduction target is defined as “stabilizing CO_2 emissions from the European air transport sector by 2020 at 2013 emission levels”, which amounts to reducing the CO_2 emissions calculated in the reference scenario for 2020 by 17%. The second target would be “stabilizing CO_2 emissions at 2008 emission levels by 2020”, which would imply to reduce the reference emissions for 2020 by 33%. It is arbitrarily assumed that both emission reduction targets would be reached progressively from 2013. Thus, the CO_2 emission reduction targets for each year with respect to the reference emissions would grow linearly from a 3% emission reduction target up to 17% and 33% respectively.

In order to calculate the potential costs and environmental outcomes of the proposed CO_2 emission trading schemes, the marginal abatement cost curves (MAC) for the European air transport sector have been calculated by introducing into the model carbon values varying in the range from 0 to 200 €/tCO_2, for each year during the period 2013-2020. The introduction of a carbon value would reduce air transport demand. As the carbon value increases jet fuel price rises according to its carbon content. Such a change would translate into different increments in aircraft operating costs, depending on the characteristics of aircrafts and markets. Penetration of more energy efficient, and less polluting, aircraft would be encouraged.

The total costs of emission trading would be the result of adding up the costs of reducing CO_2 emissions by undertaking internal measures, the costs of purchasing to other sectors additional permits needed to meet the emission reduction target, and the costs incurred in the auction of all permits up to the allowed emission level. These costs can be calculated by integrating the corresponding areas shown in Figure 14. The emission reduction costs of the internal abatement measures are represented by the area below the MAC and the emission reduction achieved at the equilibrium price. If the emission reduction target is higher than the reduction achieved at the equilibrium price, the European air transport sector would have to buy additional permits to other sectors covered by the trading regime, and those additional costs are given by the product of the market equilibrium price multiplied by the difference between the target and the reduction at the market price. At the end of the year each sector included in the trading scheme would be requested to surrender an allowance for each ton of CO_2 emitted. If the allowances are not grandfathered the air transport sector would need to bid for them and buy all the rights up to the allowed emission level. Note that if the sector is requested to meet an emission reduction target without emission trading the abatement costs would be given by all the area limited by the MAC and the reduction target.

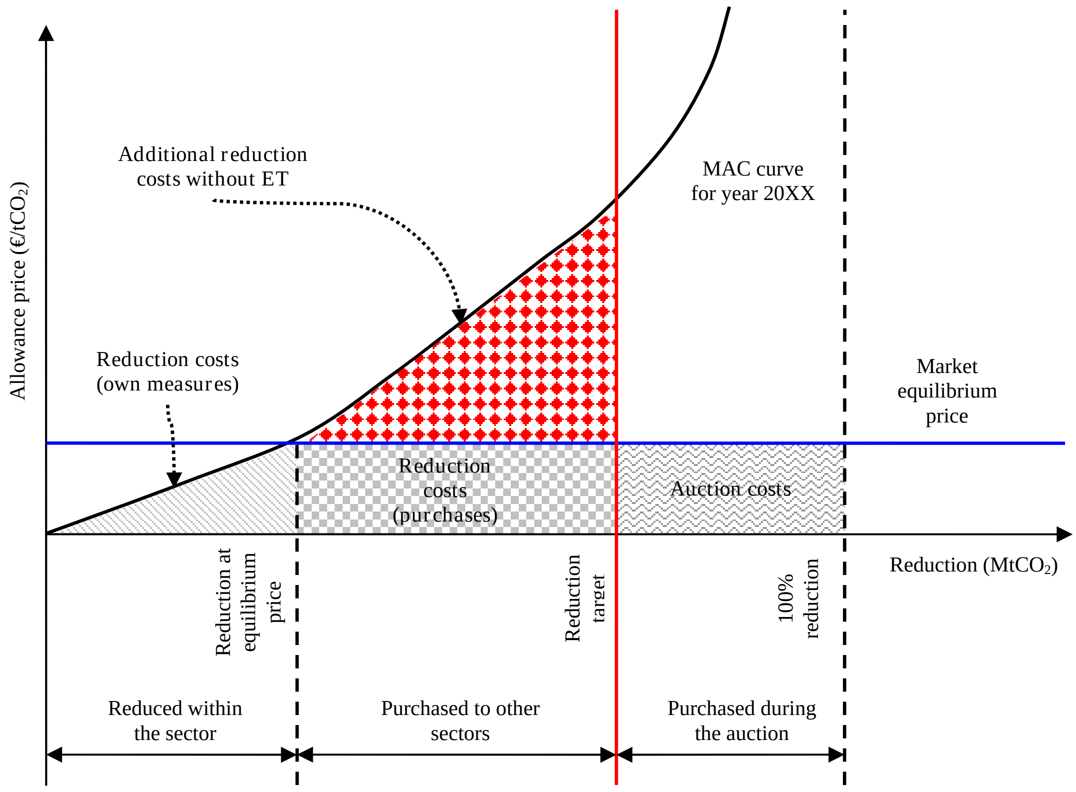

Figure 14: emission trading costs

2.3.2 Costs and environmental impacts of emission trading

Using the procedure explained above, the model produces the results summarized in Table 10 (detailed results are available at the end of the document, Table 11). In the least stringent case the European air transport sector would be requested to reduce its emissions from 11.72 MtCO$_2$ in 2013 to 80.11 MtCO$_2$ in 2020. Total costs of the emission trading system (made up of reductions within the sector, purchases to other sectors, and auctioning costs) would range between 3903 M€ in 2013 and 4703 M€ in 2020, depending on the flight coverage. The cheapest option would be to include all CO$_2$ emissions from intra-EU flights and all arriving and departing flights in the EU (scenario 4 in Table 9). In that case total costs of emission trading would change from 3903 M€/year in 2013 to 4693 M€/year in 2020.

The air transport sector is not flexible enough to abate emissions internally, i.e. its MAC has a very steep slope. Thus, the target would be achieved mainly either buying permits (up to 3.88 MtCO$_2$ in 2020 in the best case) to other sectors or reducing the demand. In any case the results show that emission trading would be a cost-effective method to address the environmental impact of CO$_2$ emissions from aviation.

If the European air transport sector is requested to meet the emission reduction targets without trading, either by means of a tax on CO$_2$ or by using a very restricted emission trading system with no interaction with other sectors, the costs to be faced could rise up to 19414 M€/year in 2020. The yearly costs of emission trading would represent between 2.52% and 2.34% of the European airlines' revenues (these figures are a linear extrapolation of the available time-series published in "Airline Business").

Table 10: costs and environmental impacts of the new emission trading scheme including the European air transport sector

	Scenario 1				Scenario 2				Scenario 3				Scenario 4			
	Stabilization at 2013 level 10 €/tCO2		Stabilization at 2008 level 30 €/tCO2		Stabilization at 2013 level 10 €/tCO2		Stabilization at 2008 level 30 €/tCO2		Stabilization at 2013 level 10 €/tCO2		Stabilization at 2008 level 30 €/tCO2		Stabilization at 2013 level 10 €/tCO2		Stabilization at 2008 level 30 €/tCO2	
	2013	2020	2013	2020	2013	2020	2013	2020	2013	2020	2013	2020	2013	2020	2013	2020
European airlines' revenues (M€)	154880	200580	154880	200580	154880	200580	154880	200580	154880	200580	154880	200580	154880	200580	154880	200580
Air transport emissions (MtCO_2)	390.55	471.26	390.55	471.26	390.55	471.26	390.55	471.26	390.55	471.26	390.55	471.26	390.55	471.26	390.55	471.26
Emission reduction target (%)	3	17	3	33	3	17	3	33	3	17	3	33	3	17	3	33
Emission reduction target (MtCO_2)	11.72	80.11	11.72	155.52	11.72	80.11	11.72	155.52	11.72	80.11	11.72	155.52	11.72	80.11	11.72	155.52
Reduction within the sector (MtCO_2)	0.19	1.88	0.55	5.49	0.29	2.89	0.81	8.26	0.22	2.17	0.63	6.3	0.39	3.88	1.06	10.94
Reduction costs (M€) with ET	116.22	791.68	343.04	4581.84	115.72	786.58	338.89	4538.65	116.07	790.21	341.82	4569.2	115.22	781.54	334.91	4496.8
Average reduction costs (€/tCO_2) with ET	9.92	9.88	29.28	29.46	9.88	9.82	28.92	29.18	9.91	9.86	29.17	29.38	9.83	9.76	28.58	28.92
Auctioning costs (M€)	3788	3911	11364	9472	3788	3911	11364	9472	3788	3911	11364	9472	3788	3911	11364	9472
Total ET costs (M€)	3904	4703	11707	14054	3904	4698	11703	14011	3904	4701	11706	14041	3903	4693	11699	13969
Average ET costs (€/tCO_2)	10	9.98	29.98	29.82	10	9.97	29.97	29.73	10	9.98	29.98	29.8	10	9.96	29.96	29.64
Reduction costs (M€) without ET	4438	19414	4438	73155	3226	13525	3226	50964	3922	17055	3922	64269	2521	10774	2521	40599
Average reduction costs (€/tCO_2) without ET	378.81	242.33	378.81	470.41	275.36	168.82	275.36	327.71	334.76	212.9	334.76	413.27	215.18	134.49	215.18	261.06
Ratio total ET costs to airline revenues	2.52%	2.34%	7.56%	7.01%	2.52%	2.34%	7.56%	6.99%	2.52%	2.34%	7.56%	7.00%	2.52%	2.34%	7.55%	6.96%
Ratio reduction costs (NO ET) to airline revenues	2.87%	9.68%	2.87%	36.47%	2.08%	6.74%	2.08%	25.41%	2.53%	8.50%	2.53%	32.04%	1.63%	5.37%	1.63%	20.24%

As expected, the costs of meeting the most stringent target would be higher. In this case the air transport sector in Europe would need to reduce between 11.72 $MtCO_2$ in 2013 and 155.52 $MtCO_2$ in 2020. The cheapest option would be again the one covering more emissions, i.e. to include all CO_2 emissions from intra-EU flights and all arriving and departing flights in the EU, and total costs of emission trading would change from 11699 M€ in 2013 to 13969 M€ in 2020. Most of the reduction would be actually achieved by other sectors, which could sell up to 150 $MtCO_2$ emission allowances to the European air transport sector. In this case emission trading costs would range between 7.55% and 6.96% of the European airlines' revenues, i.e. three times higher than the cost in the previous case.

Due to the steepness of the MAC curves, the average reduction costs of emission trading would be virtually equal to the market price corresponding to each emission reduction target.

The impact on air transport demand is expected to be negligible in all cases, as depicted in Figure 15. Assuming an allowance market price of 30 €/CO_2, the aircraft operating costs would increase at most by 0.008 €/pkm in 2020. The use of the least stringent target would diminish the passenger transport demand originated in Europe by 9.35 Gpkm per year on average between 2013 and 2020, i.e. 0.62% of the amount foreseen in the reference scenario. The most stringent target would lead to a yearly average reduction of 25.96 Gpkm during the same period, 1.73% of the traffic originated in Europe. According to these results, the market position of the European vs. non-European airlines would not be altered after including aviation in the EU emission trading regime. Virtually the same considerations would apply to the freight transport sector.

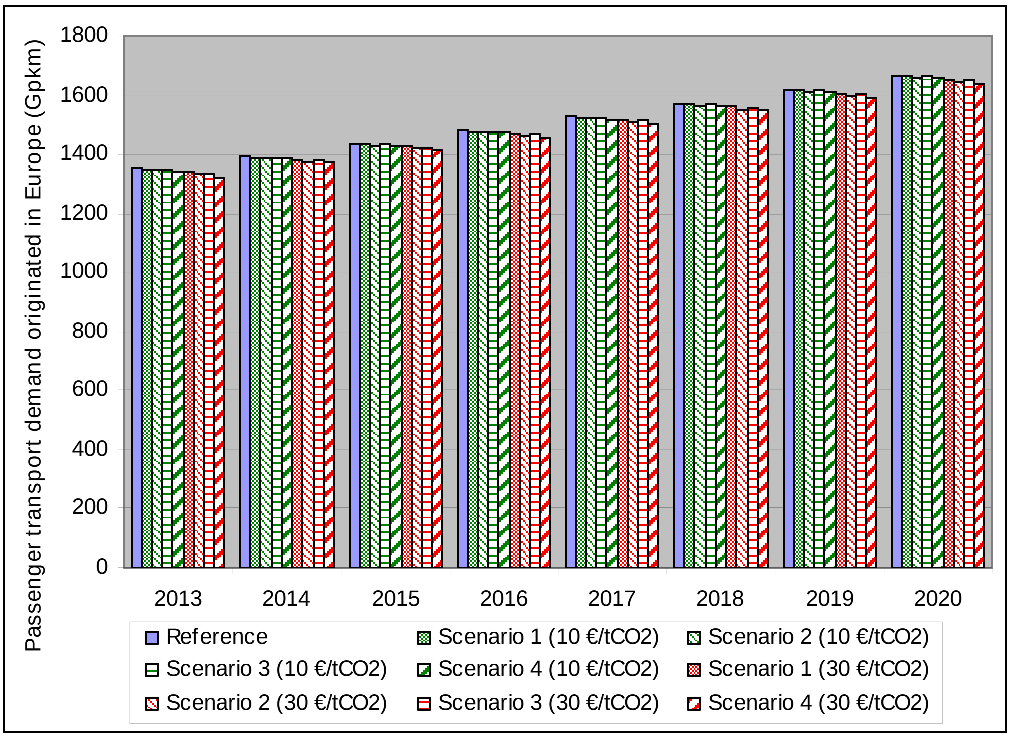

Figure 15: impacts on passenger air transport demand

Since the air transport demand is not expected to shrink noticeably, the fleet composition and size in Europe would be practically the same as in the reference simulation during the period 2013-2020. The same consideration applies to the jet fuel demand.

To our knowledge, the only available study analysing the potential consequences of applying an economic instrument with the aim of reducing the environmental impact of the air transport sector is reported in Olsthoorn (2001). It consists of the application of a tax on CO_2 emissions. According to Olsthoorn (2001) surcharges on jet fuel price would have to be high in order to produce a certain impact on air transport demand growth rates, but is unlikely that a high tax would be implemented instantaneously. It would be more feasible to introduce a relatively low tax that increases with time. Olsthoorn (2001) proposes to impose a tax on kerosene that is introduced in the year 2000, and which grows between 20 and 30 US$ per ton of fuel annually during the period 2000-2050. The results from Olsthoorn (2001) suggest that this tax could only make a very minor contribution to reaching CO_2 emission abatement targets (emissions would be limited to current levels if the tax is set to US$

1500 per ton of fuel). The conclusions of this study reinforce the use of emission trading scheme as the most cost-effective instrument that can be used in the framework of environmental policies.

Notice that assuming 100% grandfathering up to the emission targets there would not be any auctioning costs and total costs of emission trading would be equal to the reduction costs up to the target.

3 Conclusions

The IPTS Air Transport Model is the most recent quantitative tool able to project the detailed evolution of the air transport sector at the global and regional scales, taking into account all the technical and economic characteristics that determine its behaviour under very different conditions.

The results of the reference simulation foresee a very strong and sustained growth of global air transport demand till year 2050, a conclusion in line with those from other projections available in the literature. Traffic originated in Europe is expected to account for 20% of the global air transport demand during the period 2000-2050. In Europe as well, jet fuel demand would be multiplied by a factor four in this period, and CO_2 emissions from aviation would rise from 157 $MtCO_2$ in 2000 to 730 $MtCO_2$ in 2050.

Currently air transport accounts for some 3% of all global anthropogenic CO_2 emissions. If the EU sector grows as projected, its emissions will increase accordingly, neutralizing by 2012 a significant share of the emission reduction target assigned to the EU by the Kyoto Protocol. At present the environmental costs of air transport are far from being reflected in the prices paid by the consumers. Moreover, although there is some uncertainty yet, it is widely accepted by the scientific community that CO_2 emissions from aircraft only explain around half of the aviation-related impacts on environment.

Bearing in mind all these reasons, it is clear that sooner or later the negative environmental impacts of the air transport sector will be addressed by means of economic instruments, at least in the EU. Using the model explained in this document it is possible to obtain some insight into the potential consequences of including the air transport sector in the EU emission trading system beyond 2012. The outcome of the model shows that even considering a very demanding regime requiring stabilization of CO_2 emissions in 2020 at 2008 levels, and without any grandfathering, the emission trading costs would not be disproportionately expensive. Emission trading performs as the most cost-effective measure that can be used to reduce the externalities of aviation.

The model also shows that, due to the technical characteristics of the air transport sector, most of its emission reduction target would be actually achieved by other (ground-based) sectors included in the trading scheme. The alternatives to achieve a significant reduction of aviation-related emissions are rather limited, since radical technology improvements commercially applicable are not expected in the next decades. Only advances in aerodynamics, science materials, avionics… are expected, but no major breakthroughs comparable to the emergence of hybrid or fuel-cell powered cars (see Sehra et al. (2004) for a description of foreseeable advances in aerospace technology). Anyway, the application of environmental policies to this sector would favour the penetration of more fuel efficient aircrafts.

Finally, the model reveals that in all the cases considered in this study the inclusion of the air transport sector in the EU trading scheme is expected to have a negligible impact on air transport demand, which would reach virtually the same level of the reference case. This effect is explained by the structure of the costs faced by the airlines, where fuel cost accounts at most for 15% of the total operating expenses, and by the negligible increments in the operating costs induced by the emission trading. The simulation results suggest that the market position of the European vis-á-vis non-European airlines would not be noticeably altered after including aviation in the EU emission trading regime.

Table 11: costs and environmental impacts of the new emission trading scheme including the European air transport sector (detailed results)

		Stabilization at 2013 emission levels by 2020, 10 €/tCO2								Stabilization at 2008 emission levels by 2020, 30 €/tCO2							
		2013	2014	2015	2016	2017	2018	2019	2020	2013	2014	2015	2016	2017	2018	2019	2020
European airlines' revenues (M€)[8]		154880	161530	167970	174500	181050	187530	194070	200580	154880	161530	167970	174500	181050	187530	194070	200580
Air transport emissions (MtCO$_2$)		390.55	403.72	416.35	428.37	439.84	450.74	461.14	471.26	390.55	403.72	416.35	428.37	439.84	450.74	461.14	471.26
Emission reduction target (%)		3	5	7	9	11	13	15	17	3	7	11	16	20	24	28	33
Emission reduction target (MtCO$_2$)		11.72	20.19	29.14	38.55	48.38	58.60	69.17	80.11	11.72	28.26	45.80	68.54	87.97	108.18	129.12	155.52
Scenario 1	Reduction within the sector (MtCO$_2$)	0.19	0.61	0.88	1.13	1.34	1.57	1.72	1.88	0.55	1.80	2.58	3.33	3.95	4.56	5.05	5.49
	Reduction costs (M€) with ET	116.22	198.83	287.05	379.86	477.09	578.07	683.04	791.68	343.04	820.68	1334.82	2005.68	2579.14	3175.65	3796.81	4581.84
	Average reduction costs (€/tCO$_2$) with ET	9.92	9.85	9.85	9.85	9.87	9.87	9.87	9.88	29.28	29.04	29.15	29.26	29.36	29.36	29.41	29.46
	Auctioning costs (M€)	3788	3835	3872	3898	3914	3921	3919	3911	11364	11263	11116	10794	10556	10276	9960	9472
	Total ET costs (M€)	3904	4034	4159	4278	4391	4499	4602	4703	11707	12084	12451	12800	13135	13452	13757	14054
	Average ET costs (€/tCO$_2$)	10.00	9.99	9.99	9.99	9.98	9.98	9.98	9.98	29.98	29.93	29.91	29.88	29.86	29.85	29.83	29.82
	Reduction costs (M€) without ET	4438	3804	5331	7268	9668	12443	15761	19414	4438	7457	13165	22973	31961	42409	54919	73155
	Average reduction costs (€/tCO$_2$) without ET	378.81	188.48	182.94	188.54	199.83	212.35	227.86	242.33	378.81	263.87	287.48	335.19	363.33	392.03	425.35	470.41
	Ratio total ET costs to airline revenues	2.52%	2.50%	2.48%	2.45%	2.43%	2.40%	2.37%	2.34%	7.56%	7.48%	7.41%	7.34%	7.26%	7.17%	7.09%	7.01%
	Ratio reduction costs (NO ET) to airline revenues	2.87%	2.36%	3.17%	4.17%	5.34%	6.64%	8.12%	9.68%	2.87%	4.62%	7.84%	13.17%	17.65%	22.61%	28.30%	36.47%
Scenario 2	Reduction within the sector (MtCO$_2$)	0.29	0.95	1.37	1.77	2.09	2.44	2.66	2.89	0.81	2.78	3.97	5.10	6.06	6.93	7.62	8.26
	Reduction costs (M€) with ET	115.72	197.10	284.56	376.67	473.33	573.71	678.33	786.58	338.89	805.45	1313.34	1978.18	2546.71	3138.98	3756.50	4538.65
	Average reduction costs (€/tCO$_2$) with ET	9.88	9.76	9.76	9.77	9.79	9.79	9.81	9.82	28.92	28.50	28.68	28.86	29.02	29.02	29.09	29.18
	Auctioning costs (M€)	3788	3835	3872	3898	3914	3921	3919	3911	11364	11263	11116	10794	10556	10276	9960	9472
	Total ET costs (M€)	3904	4032	4156	4274	4387	4495	4597	4698	11703	12069	12429	12773	13102	13415	13717	14011
	Average ET costs (€/tCO$_2$)	10.00	9.99	9.98	9.98	9.98	9.97	9.97	9.97	29.97	29.90	29.85	29.82	29.79	29.76	29.75	29.73

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[8] Extrapolated from values provided in "Airline Business".

	Reduction costs (M€) without ET	3226	2747	3765	5117	6752	8685	10959	13525	3226	5384	9298	16172	22322	29603	38189	50964
	Average reduction costs (€/tCO_2) without ET	275.36	136.09	129.20	132.73	139.56	148.23	158.45	168.82	275.36	190.52	203.03	235.96	253.75	273.65	295.77	327.71
	Ratio total ET costs to airline revenues	2.52%	2.50%	2.47%	2.45%	2.42%	2.40%	2.37%	2.34%	7.56%	7.47%	7.40%	7.32%	7.24%	7.15%	7.07%	6.99%
	Ratio reduction costs (NO ET) to airline revenues	2.08%	1.70%	2.24%	2.93%	3.73%	4.63%	5.65%	6.74%	2.08%	3.33%	5.54%	9.27%	12.33%	15.79%	19.68%	25.41%
Scenario 3	Reduction within the sector (MtCO_2)	0.22	0.70	1.02	1.31	1.56	1.82	1.99	2.17	0.63	2.09	2.98	3.84	4.55	5.23	5.80	6.30
	Reduction costs (M€) with ET	116.07	198.34	286.35	378.95	476.01	576.82	681.68	790.21	341.82	816.31	1328.66	1997.77	2569.83	3165.07	3785.06	4569.20
	Average reduction costs (€/tCO_2) with ET	9.91	9.83	9.83	9.83	9.84	9.84	9.86	9.86	29.17	28.89	29.01	29.15	29.26	29.26	29.31	29.38
	Auctioning costs (M€)	3788	3835	3872	3898	3914	3921	3919	3911	11364	11263	11116	10794	10556	10276	9960	9472
	Total ET costs (M€)	3904	4033	4158	4277	4390	4498	4601	4701	11706	12080	12445	12792	13126	13441	13745	14041
	Average ET costs (€/tCO_2)	10.00	9.99	9.99	9.98	9.98	9.98	9.98	9.98	29.98	29.92	29.89	29.86	29.84	29.82	29.81	29.80
	Reduction costs (M€) without ET	3922	3346	4672	6385	8483	10928	13823	17055	3922	6559	11539	20181	28044	37247	48166	64269
	Average reduction costs (€/tCO_2) without ET	334.76	165.80	160.34	165.63	175.34	186.51	199.85	212.90	334.76	232.12	251.96	294.45	318.80	344.32	373.04	413.27
	Ratio total ET costs to airline revenues	2.52%	2.50%	2.48%	2.45%	2.43%	2.40%	2.37%	2.34%	7.56%	7.48%	7.41%	7.33%	7.25%	7.17%	7.08%	7.00%
	Ratio reduction costs (NO ET) to airline revenues	2.53%	2.07%	2.78%	3.66%	4.69%	5.83%	7.12%	8.50%	2.53%	4.06%	6.87%	11.57%	15.49%	19.86%	24.82%	32.04%
Scenario 4	Reduction within the sector (MtCO_2)	0.39	1.29	1.86	2.39	2.83	3.27	3.58	3.88	1.06	3.72	5.33	6.80	8.13	9.22	10.11	10.94
	Reduction costs (M€) with ET	115.22	195.37	282.09	373.49	469.59	569.40	673.65	781.54	334.91	790.73	1292.39	1951.55	2514.89	3103.18	3717.64	4496.80
	Average reduction costs (€/tCO_2) with ET	9.83	9.68	9.68	9.69	9.72	9.72	9.74	9.76	28.58	27.98	28.22	28.47	28.69	28.69	28.79	28.92
	Auctioning costs (M€)	3788	3835	3872	3898	3914	3921	3919	3911	11364	11263	11116	10794	10556	10276	9960	9472
	Total ET costs (M€)	3903	4030	4154	4271	4384	4490	4593	4693	11699	12054	12408	12746	13071	13380	13678	13969
	Average ET costs (€/tCO_2)	10.00	9.98	9.98	9.97	9.97	9.96	9.96	9.96	29.96	29.86	29.80	29.76	29.72	29.68	29.66	29.64
	Reduction costs (M€) without ET	2521	2330	3142	4206	5500	7020	8769	10774	2521	4568	7760	13294	18184	23928	30557	40599
	Average reduction costs (€/tCO_2) without ET	215.18	115.47	107.83	109.11	113.69	119.82	126.78	134.49	215.18	161.66	169.45	193.97	206.72	221.20	236.66	261.06
	Ratio total ET costs to airline revenues	2.52%	2.50%	2.47%	2.45%	2.42%	2.39%	2.37%	2.34%	7.55%	7.46%	7.39%	7.30%	7.22%	7.13%	7.05%	6.96%
	Ratio reduction costs (NO ET) to airline revenues	1.63%	1.44%	1.87%	2.41%	3.04%	3.74%	4.52%	5.37%	1.63%	2.83%	4.62%	7.62%	10.04%	12.76%	15.75%	20.24%

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