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Keywords: Air Transport, Technological Innovation, Energy Efficiency, Carbon Intensity, Macro-Level Methodology.

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March 22, 2012

Abstract

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1 Introduction

Over the past thirty years, air traffic has been steadily increasing with growth rates dramatically superior to world's Gross Domestic Product (GDP) growth rates. It is clearly established that the air transport sector has encountered during the second half of the 20^{th} century a growth strictly superior to most sectors in the economy. This development may appear problematic during the 21^{st} century (IPCC, 1999, 2007a, 2007b; RCEP, 2002; ECI, 2006; SEG, 2007; IEA, 2009a, 2009b, 2009c).

Be it because the fossil fuel resources are becoming scarce, or because of climate change, the evolution of air transport and its environmental consequences are now clearly taken into account by public policies. The classical example is the decision by the European Commission to include the aviation sector in the European Union Emissions Trading Scheme (EU ETS) during Phase III[1].

Policy makers distinguish between two kinds of measures to limit the environmental impact of the growth of air transport. The first one consists in improving the energy efficiency of aircrafts (and thus to lower their carbon intensity) by promoting technological innovation. The second one consists in binding measures dealing with the demand for air transport. These two types of measures are not antinomic and may be pursued simultaneously. For instance, the European Commission actively promotes innovation efforts by air companies through research and development programs[2], while also taking binding actions with the fight against climate change. However, these public policies do not follow the same logic. Indeed, the latter kind of measure deals directly with the causes of greenhouse gases emissions linked to the growth of the air transport sector, while the former kind of measure only attempts at diminishing its negative consequences.

There is a sharp debate today on the best measures to adopt in order to reduce significantly, and within a reasonable time horizon, greenhouse gases emissions from the air transport sector. Shall we solely aim at reducing the carbon intensity of the air transport sector through innovation? Or shall we admit that technological innovation only does not

[1] As of 2012, air companies traveling in the EU must limit their CO_2 emissions to 97% of the annual mean registered between 2004 and 2006. The airplanes taking off and landing in the EU 27, as well as coming from other countries, will fall under this regulation.

[2] Two main projects are devoted currently to alternative fuels (other than jet fuel) for aviation. The program Alfa-Bird, which was created in 2008 for a period of four years and coordinated by Airbus, aims at better identifying the needs in terms of research and investments. The Swafea program, led since January 2009 by the French Aerospace Lab, aims at elaborating a roadmap for deploying alternative fuels in the mid-term. Many industrial actors (Airbus, Avio, Dassault, EADS, Rolls-Royce, Safran, Sasoil, Shell, Snecma, etc.) are participating to these programs, along with public research centers.

allow to achieve the objectives of stabilization and reduction of greenhouse gases that were set? In both cases, shall we limit the development of the air transport sector?

This article aims at addressing these various questions by focusing on both estimating air traffic energy efficiency and energy gains. Arguably, energy efficiency gains due to technological progress and the enhancement of the Air Traffic Management (ATM) have largely limited the impact of the growth of the air transport sector on the growth of its greenhouse gases emissions. Indeed, the growth of jet fuel demand following the growth of air traffic may be mitigated by energy efficiency gains[3]. Thus, an increase by 5% per year of air traffic does not necessarily imply an increase by the same magnitude of jet fuel demand, and thus corresponding CO_2 emissions. It depends, among others, on air traffic energy efficiency improvements. Estimating air traffic energy efficiency and energy gains then appears to be a central issue when addressing the debate on air traffic environmental impacts. In this article, this task is performed based on the specific 'Traffic Efficiency method' developed by the UK DTI (Department of Trade and Industry) for the special Intergovernmental Panel on Climate Change (IPCC) report on air traffic (IPCC, 1999).

Energy Efficiency is a measure for the technological performance of an individual aircraft or an aircraft fleet. It is obtained thanks to enhancements of (i) ATM, (ii) existing aircrafts (changes in engines for example) and (iii) the production of more efficient aircrafts (which is linked to the rate of change of aircrafts)[4]. Currently, no Energy Efficiency metric standard has been clearly established in the literature[5]. In this article, it has been chosen to express Energy Efficiency in terms of mass of jet fuel per Available Tonne-Kilometres (ATK)[6]:

$$EE_{i,t} = \frac{Tjet_{i,t}}{ATK_{i,t}} \tag{1}$$

[3]For instance, over the last twenty years, the strong increase of air traffic has been accompanied by important progresses in the energy efficiency of aircrafts and aviation tasks (Greene, 1992, 2004). Consequently, if jet fuel demand has increased over the period, its growth rate has been largely lower than the air traffic one.

[4]See among others on this topic Greene (1992, 1996, 2004), IPCC (1999), Lee et al. (2001, 2004, 2009), Eyers et al. (2004), Lee (2010).

[5]According to Peeters et al. (2005), Lee et al. (2001) first introduced the term Energy Intensity (expressed in Mjoule/ASK) as a measure for the technological performance of an individual aircraft. Following Peeters et al. (2005), we prefer to use the term 'Energy Efficiency' rather than 'Energy Intensity'. Indeed, 'Energy Intensity' more refers to individual aircraft performances, whereas this study deals with estimating the actual efficiency of the collective fleet, *i.e.* on a global basis rather than at the aircraft level.

[6]See Owen (2008) for other EE metric definitions used in the literature.

with $EE_{i,t}$ the abbreviation for Energy Efficiency (EE) coefficient in zone i at time t[7]. Thus defined, EE may be interpreted as the quantity of jet fuel (expressed in tonne of jet fuel) required to power the transportation of one tonne over one kilometre (ATK)[8].

Thus, one of the major tasks of this article consists in examining the expected rates, expressed per year, of EE coefficients corresponding to the evolution of air traffic energy gains. According to previous literature[9], traffic efficiency improvements depend on: (i) load factors improvements (aircraft are using more of their capacity); (ii) energy efficiency improvements. In the former case, no technological progress is achieved: airlines diminish their jet fuel consumption by filling more their aircrafts. In the latter case, there may be some opportunities for technological progress to happen. Energy efficiency improvements depend on a wide variety of factors, some of which are not linked to technological progress (such as Air Traffic Management), while others do. In the latter category, which is most likely predominant in the evolution of energy efficiency, the factors concern first the upgrade of existing aircrafts, and second changes in aircraft and airframe/engine design which are conditioned to the fleet renewal rate.

To estimate air traffic energy efficiency and energy gains, previous literature uses a specific methodology called 'bottom-up' in the remainder of the article. Nevertheless, this method has several limits that we will develop later. We propose to enhance this methodology with original and complementary ideas. The major contribution of this article consists in proposing a new methodology to obtain EE coefficients based on modeling at the macro-level. This new approach constitutes an important contribution, since it allows estimating the energy efficiency of aircraft fleets without assumptions on the actual composition of the fleet.

Our 'macro level' methodology allows obtaining 'aggregated' energy efficiency (EE) coefficients and their growth rates from 1983 to 2006. We notice that each of the regions considered have registered traffic efficiency improvements during the whole period at the aggregated (domestic + international) level. At the world level, energy efficiency improvements have been equal to 2.88% per year during the whole period. There are significant differences between regions. At the world level, domestic energy efficiency appears to be lower than the international one. This comment applies in all regions. This result confirms the intuition that domestic air travels are more energy intensive than international travels. One of the main reasons found in previous literature is that domestic flights are more energy intensive due to

[7]Available Tonne-Kilometres (ATK) is a measure of an airline's total capacity (both passenger and cargo). It is the capacity in tonnes multiplied by the number of kilometres flown. .

[8]Jet fuel consumption is obtained from the IEA, while ATK are given by the ICAO. See Section 3 for more details.

[9]References are given in section 2.

more frequent take-off and landing. These remarks lead to the following stylized fact: even if both international and domestic air travels have encountered energy efficiency improvements form 1983 to 2006, international air travels appear to be less energy intensive than domestic air travels.

The remainder of the article is structured as follows. Section 2 summarizes previous 'bottom-up' methodologies. Section 3 introduces the new macro-level methodology. Section 4 contains the results from the new methodology. Section 5 compares the results of both approaches, by estimating the carbon intensity of several aircrafts and of the air transport sector as a whole. Section 6 concludes.

2 Methodologies used in previous literature: the 'Bottom-up' approaches

Previous literature features two ways of modeling air transport mobility. First, modeling by routes (gravity models), and second modeling without routes (simple time-series analysis). In the former modeling, air traffic is estimated for various routes. At a more aggregated level, it allows to forecast traffic flows between two regions, for instance between Europe and Asia. On the contrary, the latter modeling does not allow to forecast traffic flows, but the expansion of various regions. In other words, the latter methodology provides spheres instead of routes.

To convert air transport traffic into jet fuel demand, researchers generally use a 'bottom-up' approach to (i) obtain EE coefficients, and (ii) deduce an evolution rule for EE coefficients (see for instance Greene (1992, 1996, 2004), IPCC (1999) and Eyers et al. (2004)). This 'bottom-up' approach is mostly used for modeling by routes. In his econometric estimation of demand for air travel in the USA, Bhadra (2003) defines 'top-down' and 'bottom-up' approaches. When demand is determined econometrically by GDP, among other things, the estimated relationship is then allocated from the top down to the terminal areas, taking into consideration the historical shares of the airport, master plans, and expert opinion, to derive traffic forecasts. By contrast, when econometric relationships are estimated at a lower level (i.e., between origin and destination travel), they may be called a bottom-up approach. While traffic forecasts are primarily designed to serve as a terminal area planning tool, the latter approach focuses on market routes and flows (i.e. passengers and aircraft) within. Thus, 'bottom-up' approaches appear especially useful for network flow aspects. Several studies may be cited in this literature. Bhadra and Kee (2008) analyze the structure and dynamics of the origin and destination of core air travel market demand using 1995-2006 US quarterly time-series data. They show that passenger flows between origin and destination travel markets have exhibited strong growth in recent years. Macintosh and Wallace (2009) document international aviation emissions until 2025. They remark that the fuel efficiency gains associated with the latest generation of aircraft are unlikely to be sufficient to offset the increases in international demand, and conclude that the slow rate of turnover in the fleet will hinder progress on curbing emissions growth. Mazraati and Faquih (2008) model aviation fuel demand in the case of the USA and China. By estimating jet fuel demand in these two extremes of a mature sector versus a quickly developing one, they confirm that mature sectors tend to be more sensitive to fluctuations in fuel prices and economic growth, as opposed to the quickly growing regions where the price effect is less pronounced[10].

The so-called 'bottom-up' approach starts with the observation of aircrafts' energy efficiency (expressed in Mtoe/ASK, liter/ASK or Mjoule/ASK)[11]. Aircrafts' energy efficiencies are published by manufacturers. By replacing aircrafts' models by their vintage year, one can obtain (i) approximations of the values of jet fuel consumption for a typical aircraft, and (ii) an idea of the evolution rule of EE coefficients overtime (Greene, 1992, 1996, 2004; IPCC, 1999; Eyers et al., 2004).

Such a representation is given in Figure 1. The first point represents the average jet fuel consumption of the Comet 4 aircraft model issued in 1958. The last point represents the average jet fuel consumption of the A350-900 aircraft model issued in 2011. In Figure 1, notice that due to technological innovations aircrafts' energy efficiency has been improving with a factor equal to 3.50 between 1958 and 2007.

Having detailed the 'bottom-up' methodology, one understands why it is usually used in the literature due to its intuitive appeal. However, this approach encounters several important empirical limits.

First, it relies on a few assumptions which may be seen as too restrictive. Indeed, once the 'bottom' step has been performed (as illustrated by Figure 1), some assumptions need to be made in order to obtain EE coefficients at the aggregated level. These assumptions include basically: (i) the composition of the aircrafts' fleet, and (ii) an evolution rule for this fleet concerning the renewal/upgrade policy of existing aircrafts. This underlying information about fleet characteristics and their evolution appears hard to investigate in practice, since researchers lack the access to detailed and reliable databases on this topic. The need for

[10]Besides, they show that the Chinese aviation sector and jet fuel consumption will continue to outpace that of the United States, but growth in both regions will reach a steady state as the Chinese economy cools down and approaches maturity.

[11]Available Seat-Kilometres (ASK) measures an airline's passenger carrying capacity. It is: seats available $\times$ distance flown.

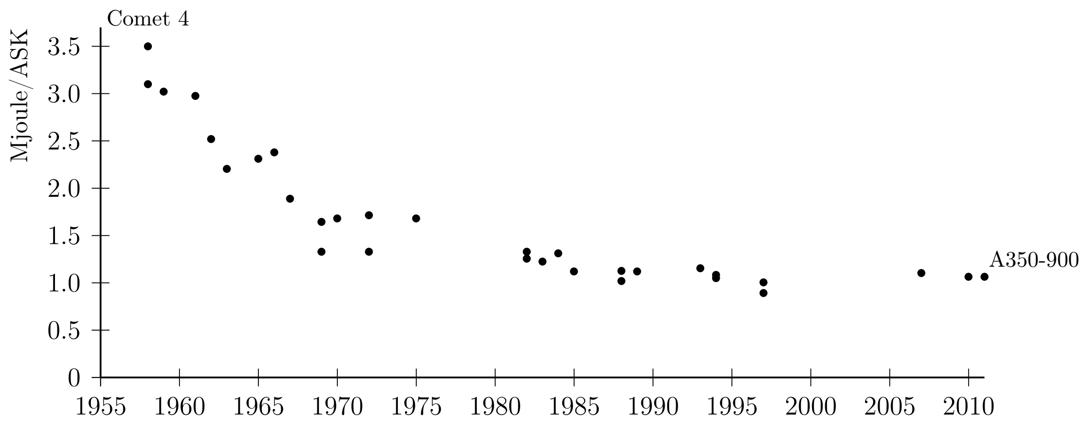


Figure 1: Evolution of the average jet fuel consumption by aircraft vintage expressed in Mjoule per ASK (1955-2010). Source: Authors, based on manufacturers' data.

such data is all the more complicated that it is required by routes. Based on these restrictive assumptions, average aircrafts' jet fuel consumption are used to obtain aggregated EE coefficients and their evolution rule.

Second, besides relying on restrictive assumptions, this approach is very time-consuming in terms of data management. Modeling by routes adds another layer of complexity, since this approach necessitates to obtain aggregated EE coefficients for each route.

Third, recall that there exist two main factors to increase traffic efficiency: load factors improvements on the one hand, and energy efficiency improvements on the other hand. The latter factor contains three possible sources of improvements: air traffic management (ATM), aircrafts' upgrades, and fleet renewal. Regarding energy efficiency improvements, the 'bottom-up' approach relies only on the last two sources. No improvements stemming from ATM can thus be accounted for when using this methodology.

Fourth, the last drawback concerns data availability. Recall that (i) $EE_{i,t} = Tjet_{i,t}/ATK_{i,t}$, and (ii) 'bottom-up' approaches are mostly used with modeling by routes. The International Civil Aviation Organization (ICAO) provides air traffic by routes only for international scheduled air traffic (not for domestic air traffic)[12]. The International Energy Agency (IEA) does not provide jet fuel consumption by routes, but by countries. Whereas the 'bottom-up' approach leads to obtain jet fuel consumption by routes, results cannot be confronted to actual data. Even if the 'bottom-up' approach is not used for modeling by route, it supposes to infer

[12]When forecasting jet fuel demand at the worldwide level, this data limitation generates some incoherence in the methodology used: international air traffic may be modelled by route, while domestic air transport cannot. This limitation involves to use another type of dataset.

jet fuel consumption data which is then adjusted to match historical data, as provided by the IEA.

Given these various limitations, an alternative methodology to compute directly aggregated EE coefficients is presented in the next section based on deductions from empirical data.

3 Our Macro-level approach

This section proposes another approach to reconstruct EE coefficients values and their evolution rule. It departs from the previous methodology by (i) providing directly aggregated EE coefficients; and (ii) deducing them directly from empirical data.

As defined in eq(1):

$$EE_{i,t} = \frac{Tjet_{i,t}}{ATK_{i,t}}$$

where EE coefficients for the i-th region and date t correspond to the ratio of jet fuel consumption ($Tjet_{i,t}$) over air traffic ($ATK_{i,t}$).

The methodology proposed to obtain EE coefficients is to directly compare the jet fuel consumption and the evolution of air traffic. As straightforward as it may look like, to our best knowledge, this methodology has not been implemented in such details before due to both data availability and time-consuming problems when re-aggregating the jet fuel consumption and air traffic series at regional levels[13].

Again, jet fuel consumption is obtained from the IEA, while air traffic is given by the ICAO for the 1980–2006 period. Air traffic data have been obtained from the ICAO. This specialized agency of the United Nations provides the most complete air traffic database[14]: international and domestic, passenger and freight traffic (both for scheduled and non-scheduled flights). The ICAO database used in this Working Paper is the 'Commercial Air Carriers - Traffic' database. As detailed on the ICAO website[15] it contains, on annual basis, operational, traffic and capacity statistics of both international and domestic scheduled airlines as well as non-scheduled operators. Where applicable, the data are for all services (passenger, freight and

[13] Peeters et al. (2005) and Owen (2008) already had the same intuition, but they did not apply the methodology at such a detailed level compared to what we do here.

[14] Note the International Air Transport Association (IATA), which represents about 230 airlines comprising 93% of scheduled international air traffic, also provides Air Traffic data, but this source is less detailed to our best knowledge.

[15] *http://www.icaodata.com*

mail) with separate figures for domestic and international services, for scheduled and non-scheduled services, and for all-freight services[16]. One of the interest of this database consists in providing data by country, and not by pre-aggregated regions. Thus, it allows to recompose any kind of regions. Within the database by country, statistics are provided for airlines registered in a given country on a yearly basis[17].

Jet-Fuel consumption (expressed in ktoe) is drawn from the 'World Energy Statistics and Balances' database of the IEA. Both databases provide these data by country. It is thus readily possible to re-aggregate these time-series at a regional level by adding countries' series which constitute a same region. However, the IEA data are based on the amount of fuel sold on its soil whereas the data series published by ICAO are based on the traffic operated by the airlines registered in one country. Thus, there exists one limit with the use of such data for when computing EE coefficients. When re-aggregating the data by regions, one considers that the airline which declared the flights as 'international air traffic' has not registered international flights outside the country within which it is registered, and thus outside of the region within which it has been re-aggregated[18].

For our analysis, we choose the following geographical decomposition: Central and North America, Latin America, Europe, Russia and CIS (Commonwealth of Independent States), Africa, the Middle East, China[19], Asian countries and Oceania. Worldwide basis corresponds to the computation of these eight distinct regions.

This macro-level methodology allows then to obtain the 'aggregated' EE coefficients – as opposed to 'bottom-up' EE coefficients – and their growth rates from 1980 to 2006. This idea is summarized for a typical region in Figure 2. On the left panel, the solid black line represents air traffic (expressed in ATK) and the dotted black line represents jet fuel consumption (expressed in ktoe) for a given region. As defined in eq(1), EE coefficients for each year may be obtained by dividing ktoe/ATK (right panel).

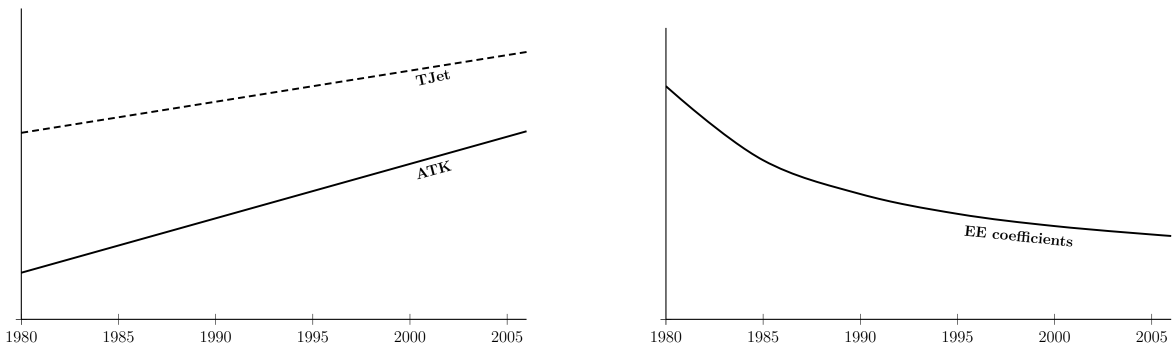
Thus defined, EE corresponds to the quantity of jet fuel required to power the transporta-

[16]These data are not provided on air routes basis.

[17]With such statistics, air traffic data of a given airline cannot be provided in two different tables. Thus, it avoids the problem of double-counting.

[18]For some particular regions, such as Africa or the Middle East, the combination of ICAO an IEA data series could not be relevant to measure regional EE ratios. Indeed, a region that would be predominantly dependent on traffic operated by foreign airlines would then display a very bad EE ratio since it would sell important amounts of fuel that would be reported in the corresponding IEA data series while the ICAO traffic data series could only account for the portion of traffic operated by the minority domestic airlines. EE coefficients estimates provided thereafter for these particular regions should then been used with caution.

[19]We chose to focus on that specific region due to its solid economic growth.



Left panel: Jet fuel consumption (expressed in Mtoe) and air traffic (expressed in ATK).

Right panel: EE coefficients computed as the ratio of the former over the latter.

Figure 2: Illustration of the Macro-level methodology used to compute 'aggregated' EE coefficients and their yearly growth rates.

tion of one tonne over one kilometre. For a given region $EE_{t+1} < EE_t$ means that quantities of jet fuel required to power the transportation of one ton over one kilometre have decreased. Thus, a negative growth rate of EE coefficients, as it is expected, indicates the realization of energy efficiency improvements in air traffic for the region under consideration. As it may be deduced from the illustrative Figure 2, EE coefficients negative growth rates arise when, in a given year, jet fuel consumption growth rates are slower than air traffic ones.

By following this methodology, first for each zone the value of the EE coefficients until 2006 is obtained. Second, an evolution rule for these EE coefficients in the future may be derived for each zone by observing the evolution of their growth rates between 1980 and 2006. Actually, both datasets are available at an even more disaggregated level for each zone, *i.e.* domestic *vs.* international. Following the same methodology for each region, it becomes thus possible to obtain not only the 'aggregated' EE coefficients, but also EE coefficients corresponding to both international and domestic air travels.

This methodology allows to investigate three issues. First, by comparing the evolution of EE coefficients overtime, one may observe the occurrence (or not) of energy efficiency improvements over the last 30 years. Second, by comparing the values found for aggregated EE coefficients, one may deduce which zone is more energy efficient compared to others. Third, by comparing 'domestic' and 'international' EE coefficients within each zone, one may observe if domestic air travel is effectively less efficient than international air travel[20]. These questions are investigated in-depth in Section 4.

[20]As highlighted in the literature (Gately, 1988; Vedantham and Oppenheimer, 1998), domestic air traffic is supposed to be more energy intensive than international air traffic due to more frequent take-off and landing of aircrafts, the most energy-intensive components of a flight.

The new methodology proposed seems promising. However, it is also characterized by some limitations.

First, EE coefficients obtained cannot be used in a modeling by routes. This restriction supposes a modeling without routes, as done in this article. This corresponds to an output loss compared to the 'bottom-up' approach, which does not prevent from using either of the two modeling types of air transport mobility.

Second, even if all potential sources of energy efficiency improvements are covered by the macro-level methodology, it is not possible to disentangle the effects from which improvements in energy efficiency are obtained. Recall that it could come from ATM, aircrafts' upgrades, aircraft and airframe/engine design (which is linked to fleet renewal rates). However, this drawback is relatively less important than the corresponding limitations of the 'bottom-up' approach, which cannot account for the ATM source of possible energy efficiency improvements.

4 Results of the Macro-level methodology

Databases are first re-aggregated by region. Then, EE coefficients are computed for each region. Countries do not necessarily start declaring their data simultaneously. For instance, China has started to declare its air traffic data to the ICAO since 1993. As a consequence, exogenous shocks in the evolution of EE coefficients values may be wrongly interpreted, as they only reflect a bias corresponding to the entrance of a new data source. This potential bias may be a downward or an upward bias, depending whether a country starts declaring either its jet fuel consumption or its air traffic data[21]. Thus, to smooth these potential biases in the data, EE coefficients are presented in Tables 1–3 in mean values during two sub-periods: 1983-1996 and 1996-2006, besides the whole period.

The USSR started to declare its air traffic data in 1983 only. Besides the USSR, other countries did not declare either air traffic data or jet fuel consumption during the first years of the 1980s. Thus, it has been chosen to start the first sub-period in 1983, in particular to allow comparisons of the Russia and CIS region with other regions.

EE mean values during the first sub-period are not provided for two regions: China, and Russia and CIS. Again, China starts declaring its air traffic data in 1993. Russia and CIS presents some inconsistencies in the data during 1991-1992, since this region had to be re-aggregated.

[21]In Figure 4, the huge variations of curves, especially those corresponding to the right panel regions, illustrate this bias.

This section presents results from the macro-level methodology. A three-step analysis is conducted here.

First, EE coefficients values for each zone and the world and their respective growth rates are presented and analyzed. By comparing the evolution of EE coefficients overtime, one may address both research questions, *i.e.* what is the value of the EE coefficients for each zone, and what is their respective evolution rule. These coefficients are given for international and domestic travels, and at the aggregated (domestic + international) level.

Second, EE coefficients values are compared in order to assess which region is more energy efficient compared to the world's average.

Third, within each zone, domestic EE coefficients are compared with international EE coefficients. This is done to test if domestic air travel is less energy efficient than international air travel, as underlined in the literature.

It is worthy to remark that, to our best knowledge, this article provides for the first time EE coefficients at such a detailed level: (i) by region; and (ii) by type of travel (domestic *vs.* international).

4.1 How do EE coefficients evolve over time? An analysis for each zone and worldwide

EE coefficients mean values, their yearly mean growth rates for sub-periods and the whole period, and the rate of change during the whole period are provided in Table 1. These coefficients are presented for domestic travel, international travel, and aggregated (domestic + international) travel, and for each region and the world[22]. However, the comparison of these coefficients between and within regions yields significant economic insights. These comments are presented in the two next subsections (respectively in Tables 2 and 3)[23].

In what follows, only yearly mean growth rates are commented upon. EE coefficients indicate the quantities of jet fuel required to power the transportation of one tonne over one kilometre (recall eq(1)). Hence computed, a decrease in EE coefficients indicates that less jet fuel is needed to power the same unit of air transport. Thus, negative growth rates of EE coefficients shall be interpreted as energy efficiency improvements.

All regions have registered energy efficiency improvements during the whole period at the

[22] Comments are not provided for the mean value of each zone, as the actual figures obtained are not meaningful.

[23] As explained in the introduction, some authors rather express energy efficiency coefficients as the ratio of jet fuel consumption over air traffic ($EE'_{i,t} = \frac{Tjet_{i,t}}{ATK_{i,t}}$). In this case, one generally prefers to use the term 'Traffic Efficiency' (see Owen (2008) for more details). Traffic efficiency is then the reciprocal of fuel efficiency.

		Mean values			Yearly average growth rates (EE gains)			Rate of change
		Sub-periods		Whole period	Sub-periods		Whole period	
		1983-1996	**1996-2006**	**1983-2006**	**1983-1996**	**1996-2006**	**1983-2006**	**1983-2006**
Central and North America	**Aggregated**	3.93E-07	2.90E-07	3.49E-07	-1.78%	-3.18%	-2.39%	-42.65%
	Domestic	4.58E-07	3.62E-07	4.16E-07	-1.71%	-1.86%	-1.78%	-33.80%
	International	2.60E-07	1.80E-07	2.25E-07	-1.04%	-5.27%	-2.91%	-49.25%
Europe	**Aggregated**	3.52E-07	2.71E-07	3.18E-07	-2.97%	-1.20%	-2.20%	-40.10%
	Domestic	8.75E-07	7.31E-07	8.17E-07	-3.99%	1.40%	-1.68%	-32.35%
	International	3.02E-07	2.35E-07	2.74E-07	-2.58%	-1.25%	-2.00%	-37.22%
Latin America	**Aggregated**	4.22E-07	4.35E-07	4.31E-07	-3.73%	1.18%	-1.63%	-31.42%
	Domestic	7.21E-07	6.24E-07	6.81E-07	-4.05%	-3.81%	-3.95%	-60.41%
	International	2.85E-07	3.31E-07	3.08E-07	-3.46%	5.03%	0.14%	3.34%
Russia and CIS	**Aggregated**	n.a.	1.00E-06	n.a.	n.a.	-5.79%	n.a.	-44.92% *
	Domestic	n.a.	2.09E-06	n.a.	n.a.	-5.37%	n.a.	-42.39% *
	International	n.a.	6.89E-07	n.a.	n.a.	-5.86%	n.a.	-45.33% *
Africa	**Aggregated**	7.81E-07	9.18E-07	8.30E-07	4.45%	-7.22%	-0.80%	-16.79%
	Domestic	1.80E-06	3.94E-06	2.69E-06	12.51%	-7.14%	3.50%	120.60%
	International	6.60E-07	6.78E-07	6.62E-07	2.65%	-7.63%	-1.95%	-36.43%
The Middle East	**Aggregated**	6.75E-07	5.07E-07	6.02E-07	0.02%	-8.68%	-3.86%	-59.56%
	Domestic	5.53E-07	1.00E-06	7.36E-07	8.40%	-11.23%	-0.62%	-13.29%
	International	7.08E-07	4.87E-07	6.14E-07	-0.79%	-8.46%	-4.20%	-62.75%
Asian countries and Oceania	**Aggregated**	3.17E-07	2.44E-07	2.85E-07	-2.88%	-1.54%	-2.30%	-41.46%
	Domestic	5.87E-07	4.03E-07	5.08E-07	-6.31%	-2.80%	-4.80%	-67.73%
	International	2.69E-07	2.10E-07	2.44E-07	-2.35%	-0.79%	-1.67%	-32.18%
China	**Aggregated**	n.a.	2.22E-07	n.a.	n.a.	-1.65%	n.a.	-15.37% *
	Domestic	n.a.	3.53E-07	n.a.	n.a.	-2.37%	n.a.	-21.32% *
	International	n.a.	1.56E-07	n.a.	n.a.	-2.45%	n.a.	-21.94% *
World	**Aggregated**	4.17E-07	2.98E-07	3.66E-07	-3.09%	-2.61%	-2.88%	-48.95%
	Domestic	4.52E-07	4.17E-07	4.36E-07	-0.20%	-1.95%	-0.96%	-19.94%
	International	3.96E-07	2.35E-07	3.28E-07	-5.23%	-2.56%	-4.08%	-61.62%

Note: $*$ means that rates of change are not computed for the whole period, but for the second sub-period.

Table 1: EE coefficients (ktoe/ATK) for each zone and worldwide. Means values and growth rates during 1983-2006. Source: Authors, from ICAO and IEA data.

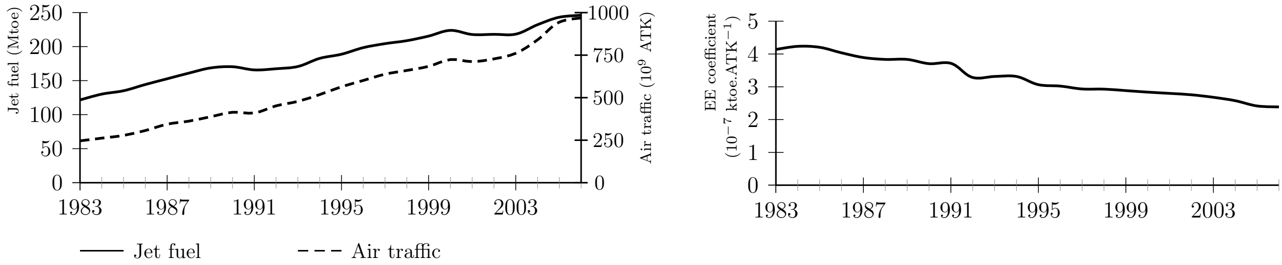


Figure 3: Jet fuel consumption (Mtoe), ATK (billions) and EE coefficient at the world level. Source: Authors, from ICAO and IEA data.

aggregated (domestic + international) level. As shown in Table 1, all yearly mean growth rates are negative, ranging from -0.80% (Africa) to -3.86% (the Middle East)[24]. At the world level, energy efficiency improvements have been equal to 2.88%/yr during the whole period. As illustrated by Figure 3, still at the world level, energy efficiency improvements have been more important during 1983-1996 (3.09%/yr) than during 1996-2006 (2.61%/yr).

The macro-level methodology proposed here leads us to recover, and quantify, previous results highlighted in the literature. Energy efficiency improvements have been effectively accomplished in the air transport sector. According to our methodology, these energy efficiency improvements have been rather important during the last 30 years (about 3%/yr at the world level).

These results depart however from previous literature. First, energy efficiency improvement values drawn from the macro-level approach are relatively higher than those obtained with the 'Bottom-up' method. Indeed, the most often cited energy efficiency gains estimates are generally comprised between 1.5%/yr (Lee et al., 2004) and 2.2%/yr (Airbus, 2007)[25]. Second, applied to the eight different regions, the macro-level methodology indicates that energy efficiency improvements have been very heterogeneous between regions during the last 30 years.

4.2 Which region is more energy efficient?

To compare EE coefficients between regions, three kinds of ratios between EE coefficients are computed. Results are presented in Table 2.

[24] Note the presence of two outliers at the domestic *vs.* international level: Africa registers a yearly mean growth rate of +3.50% at the domestic level during the whole period (this region records however negative yearly mean growth rates during the second sub-period), and Latin America registers a positive growth rate of +0.14% at the international level during the whole period.

[25] See Eyers et al. (2004) and Mayor and Tol (2010) for a more comprehensive literature review.

		Mean values			Yearly average growth rates			Rate of change
		Sub-periods		Whole period	Sub-periods		Whole period	
		1983-1996	**1996-2006**	**1983-2006**	**1983-1996**	**1996-2006**	**1983-2006**	**1983-2006**
Central and North America	**Zone's aggregated EE / World's aggregated EE**	0.95	0.97	0.96	1.36%	-0.59%	0.51%	12.34%
	Zone's domestic EE / World's domestic EE	1.01	0.87	0.95	-1.52%	0.09%	-0.82%	-17.31%
	Zone's international EE / World's international EE	0.69	0.76	0.71	4.41%	-2.78%	1.22%	32.24%
Europe	**Zone's aggregated EE / World's aggregated EE**	0.85	0.91	0.88	0.13%	1.44%	0.70%	17.33%
	Zone's domestic EE / World's domestic EE	1.94	1.76	1.87	-3.80%	3.41%	-0.73%	-15.50%
	Zone's international EE / World's international EE	0.79	1.00	0.88	2.79%	1.35%	2.16%	63.58%
Latin America	**Zone's aggregated EE / World's aggregated EE**	1.00	1.49	1.22	-0.66%	3.88%	1.29%	34.33%
	Zone's domestic EE / World's domestic EE	1.59	1.50	1.56	-3.86%	-1.90%	-3.02%	-50.55%
	Zone's international EE / World's international EE	0.74	1.45	1.05	1.86%	7.79%	4.40%	169.25%
Russia and CIS	**Zone's aggregated EE / World's aggregated EE**	n.a.	3.34	n.a.	n.a.	-3.27%	n.a.	-28.26% *
	Zone's domestic EE / World's domestic EE	n.a.	4.95	n.a.	n.a.	-3.49%	n.a.	-29.87% *
	Zone's international EE / World's international EE	n.a.	2.91	n.a.	n.a.	-3.38%	n.a.	-29.12% *
Africa	**Zone's aggregated EE / World's aggregated EE**	1.95	3.03	2.39	7.78%	-4.74%	2.15%	62.99%
	Zone's domestic EE / World's domestic EE	4.00	9.27	6.22	12.73%	-5.30%	4.51%	175.54%
	Zone's international EE / World's international EE	1.80	2.83	2.21	8.31%	-5.20%	2.22%	65.63%
The Middle East	**Zone's aggregated EE / World's aggregated EE**	1.66	1.67	1.66	3.21%	-6.24%	-1.01%	-20.78%
	Zone's domestic EE / World's domestic EE	1.23	2.37	1.71	8.61%	-9.46%	0.35%	8.31%
	Zone's international EE / World's international EE	1.90	2.04	1.95	4.68%	-6.06%	-0.13%	-2.95%
Asian countries and Oceania	**Zone's aggregated EE / World's aggregated EE**	0.76	0.82	0.79	0.21%	1.10%	0.60%	14.66%
	Zone's domestic EE / World's domestic EE	1.29	0.96	1.15	-6.12%	-0.87%	-3.87%	-59.70%
	Zone's international EE / World's international EE	0.70	0.90	0.79	3.04%	1.82%	2.51%	76.71%
China	**Zone's aggregated EE / World's aggregated EE**	n.a.	0.75	n.a.	n.a.	0.98%	n.a.	10.22% *
	Zone's domestic EE / World's domestic EE	n.a.	0.81	n.a.	n.a.	-0.43%	n.a.	-4.22% *
	Zone's international EE / World's international EE	n.a.	0.67	n.a.	n.a.	0.12%	n.a.	1.19% *

Note: a ratio >(<) 1 means that the region's energy efficiency is inferior (superior) to the world's energy efficiency. These ratios are provided for the aggregated (domestic + international), domestic, and international travels.
$*$ means that rates of change are not computed for the whole period, but for the second sub-period.

Table 2: Comparison of EE coefficients (ktoe/ATK) between zones using world's EE coefficients as benchmark (1983-2006). Source: Authors, from ICAO and IEA data.

In Table 2, aggregated (domestic + international), domestic and international EE coefficients mean values of each region are compared to the world mean values for the whole and the corresponding sub-periods. The ratios presented in the first (respectively second and third) line of the i-th region correspond to, for the period under consideration, the aggregated (respectively domestic and international) EE coefficient mean value of the i-th region over the aggregated (respectively domestic and international) EE coefficient mean value of the world. In other words, these ratios are computed as follows:

$$\frac{EE_{i,t,k}}{EE_{w,t,k}} \tag{2}$$

where $EE_{i,t,k}$ represents the EE coefficient mean value of region i, at time t=*{1983-1996;1996-2006;1983-2006}*, and for the type of travel k=*{aggregated; domestic; international}*. $EE_{w,t,k}$ represents the EE coefficient mean value of the world, at time t=*{1983-1996;1996-2006;1983-2006}*, and for the type of travel k=*{aggregated; domestic; international}*.

For instance, the value in the first line of the first column (0.95) represents the relative energy efficiency mean value of the Central and North American region during 1983-1996, when compared to the world's energy efficiency. It corresponds to the ratio of $3.93E-0.7/4.17E-0.7$, where 3.93E-0.7 is equal to the Central and North American region EE coefficient value during 1983-1996, and $4.17E-0.7$ is equal to the World's EE coefficient value during 1983-1996 (Table 1).

A ratio superior to one means that one needs more quantity of jet fuel to transport one tonne-kilometre in a given region compared to the world's average. Thus constructed, a ratio $>(<)$ 1 means that the region's energy efficiency is inferior (superior) to the world's energy efficiency.

During the whole period[26], aggregated (domestic + international) EE ratios are less than one for four regions (Central and North America, Europe, China, Asia and Oceania), and greater than one for the four others (Latin America, Africa, Russia and CIS, the Middle East) (Table 2). This result means that, for aggregated (domestic + international) travel, the former regions are in average more energy efficient during the whole period than the world's benchmark. On the contrary, the four latter regions are less energy efficient than the world's average during 1983-2006. According to previous literature (Greene, 1992, 1996, 2004; IPCC, 1999; Eyers et al., 2004), these results appear quite intuitive except for the Middle East region. Indeed, the Middle East seems to be 1.66 more energy-intensive than the world's benchmark

[26]Comments apply only for the second sub-period for Russia and CIS, and China. See above in Section 4 for more details.

(Table 2). This particular case is further investigated below by a visual inspection of the data. Comments are not further developed at the domestic *vs.* international level, since they follow the same trends as observed at the aggregated (domestic + international) level.

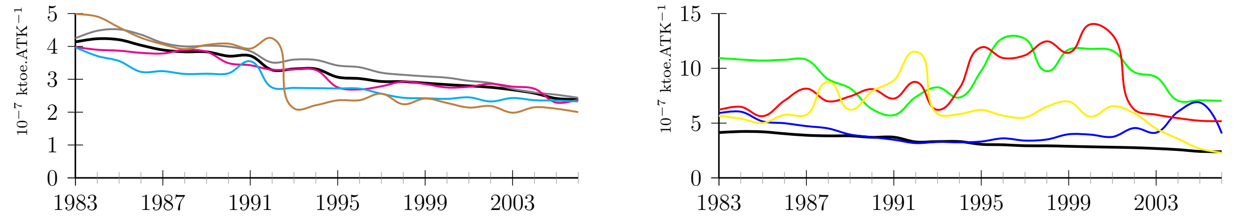
Figure 4(a) provides a visual representation of the evolution of EE coefficients. It compares each region's aggregated EE coefficients against the world's benchmark. To understand the evolution of EE coefficients, one needs to know the evolution of these two time-series (Figure 4(b-c)). By looking at Figure 4, one may observe the results commented in Table 2. EE coefficients of Central and North America, Europe, Asia and Oceania and China (Figure 4(a), left panel) are globally below the EE world's benchmark. One retrieves indeed the result that these regions are the least energy-intensive in the world. Similarly, the same patterns as in Table 2 are observable for the four more energy-intensive regions. Figure 4 provides an additional information compared to Table 2: all EE trends are decreasing globally. These trends confirm that each region has achieved energy efficiency improvements.

Figure 4 allows to understand the evolution of EE coefficients by representing the evolution of its constituent aggregates: jet fuel consumption (expressed in Mtoe, Figure 4(b)) and air traffic (expressed in ATK, Figure 4(c)). This representation is convenient, since it may explain the *a priori* counter-intuitive results observed in the Middle East. Indeed, Table 2 indicated that this region is less energy efficient than the world's benchmark. It is common knowledge that airline companies in the Middle East are currently purchasing new aircrafts. Thus, they have a higher fleet renewal rate than other airlines. One may deduce that in this region the performance in terms of energy efficiency should be relatively better than the world's benchmark. By looking at the right panel of Figure 4, EE coefficients are effectively always above the world's benchmark during the period, but they have dramatically decreased since 2001 to be below this benchmark in 2006. When looking at the right panel of Figure 4, a strong increase of the traffic registered in this region may be noted since 2001. However, one cannot notice an equivalent increase in the consumption of jet fuel during the same period, which means that energy efficiency improvements must have occurred through the use of newer aircrafts.

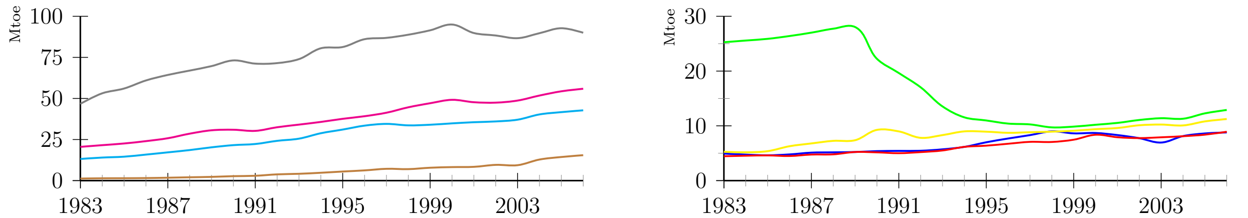
4.3 Are domestic air travels less energy efficient than international ones?

To reply to this question, one proposes to compare EE coefficients within regions. To do so, three kinds of ratios between EE coefficients are computed. Results are presented in Table 3.

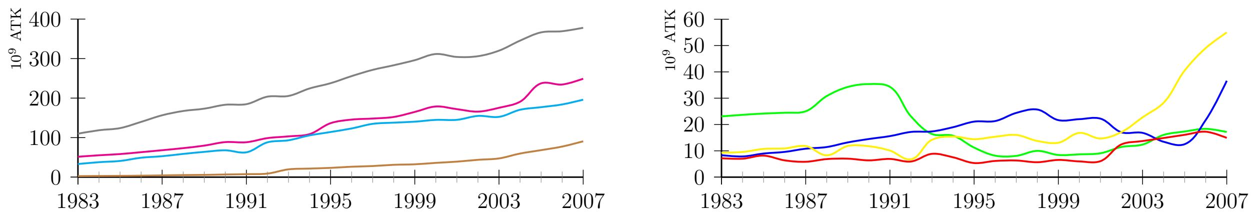
In Table 3, within each zone, domestic and international EE coefficients mean values are



(a) Aggregated (domestic + international) EE coefficients by region against the world



(b) Jet fuel consumption (expressed in Mtoe) by region



(c) Air traffic (expressed in ATK (billions)) by region

World
China
Europe
Asian countries and Oceania
North and Central America

World
The Middle East
Africa
Latin America
Russia and CIS

Note: China starts declaring some of its air traffic data in 1993. Russia and CIS presents some inconsistency in the data until 1991. Thus, some statistics must be interpreted with great care.

Figure 4: Aggregated (domestic + international) EE coefficients by region against the world; evolution of jet fuel consumption (expressed in Mtoe) and air traffic (expressed in ATK (billions)) by region. Source: Authors, from ICAO and IEA data.

		Mean values			Yearly average growth rates			Rate of change
		Sub-periods		Whole period	Sub-periods		Whole period	
		1983-1996	1996-2006	1983-2006	1983-1996	1996-2006	1983-2006	1983-2006
Central and North America	**Zone's domestic EE / Zone's aggregated EE**	1.16	1.25	1.20	0.06%	1.36%	0.63%	15.44%
	Zone's international EE / Zone's aggregated EE	0.66	0.62	0.64	0.74%	-2.16%	-0.53%	-11.50%
	Zone's domestic EE / Zone's international EE	1.77	2.06	1.85	-0.68%	3.60%	1.16%	30.44%
Europe	**Zone's domestic EE / Zone's aggregated EE**	2.46	2.71	2.57	-1.05%	2.63%	0.53%	12.94%
	Zone's international EE / Zone's aggregated EE	0.86	0.87	0.86	0.40%	-0.05%	0.20%	4.81%
	Zone's domestic EE / Zone's international EE	2.87	3.13	2.99	-1.45%	2.68%	0.33%	7.76%
Latin America	**Zone's domestic EE / Zone's aggregated EE**	1.69	1.44	1.57	-0.34%	-4.93%	-2.36%	-42.27%
	Zone's international EE / Zone's aggregated EE	0.68	0.75	0.72	0.28%	3.81%	1.80%	50.69%
	Zone's domestic EE / Zone's international EE	2.53	1.89	2.21	-0.61%	-8.42%	-4.09%	-61.69%
Russia and CIS	**Zone's domestic EE / Zone's aggregated EE**	n.a.	2.04	n.a.	n.a.	0.45%	n.a.	4.59% *
	Zone's international EE / Zone's aggregated EE	n.a.	0.69	n.a.	n.a.	-0.07%	n.a.	-0.75% *
	Zone's domestic EE / Zone's international EE	n.a.	2.99	n.a.	n.a.	0.53%	n.a.	5.38% *
Africa	**Zone's domestic EE / Zone's aggregated EE**	2.30	4.29	3.24	7.71%	0.09%	4.33%	165.11%
	Zone's international EE / Zone's aggregated EE	0.86	0.74	0.81	-1.72%	-0.43%	-1.16%	-23.60%
	Zone's domestic EE / Zone's international EE	2.72	5.81	4.06	9.60%	0.53%	5.56%	247.03%
The Middle East	**Zone's domestic EE / Zone's aggregated EE**	0.82	1.93	1.28	8.37%	-2.79%	3.37%	114.41%
	Zone's international EE / Zone's aggregated EE	1.05	0.96	1.01	-0.81%	0.24%	-0.36%	-7.91%
	Zone's domestic EE / Zone's international EE	0.80	2.02	1.21	9.26%	-3.02%	3.74%	132.81%
Asian countries and Oceania	**Zone's domestic EE / Zone's aggregated EE**	1.81	1.65	1.74	-3.52%	-1.28%	-2.56%	-44.88%
	Zone's international EE / Zone's aggregated EE	0.85	0.87	0.86	0.55%	0.76%	0.64%	15.86%
	Zone's domestic EE / Zone's international EE	2.15	1.91	2.05	-4.05%	-2.03%	-3.18%	-52.43%
China	**Zone's domestic EE / Zone's aggregated EE**	n.a.	1.58	n.a.	n.a.	-0.73%	n.a.	-7.03% *
	Zone's international EE / Zone's aggregated EE	n.a.	0.70	n.a.	n.a.	-0.81%	n.a.	-7.77% *
	Zone's domestic EE / Zone's international EE	n.a.	2.27	n.a.	n.a.	0.08%	n.a.	0.80% *
World	**Zone's domestic EE / Zone's aggregated EE**	1.10	1.41	1.23	2.99%	0.68%	1.98%	56.83%
	Zone's international EE / Zone's aggregated EE	0.94	0.79	0.88	-2.21%	0.05%	-1.23%	-24.82%
	Zone's domestic EE / Zone's international EE	1.14	1.78	1.33	5.31%	0.63%	3.25%	108.60%

Note: a ratio >(<) 1 means that the energy efficiency of the kind of travel in numerator is inferior (superior) to the kind of travel in denominator. These ratios aim at comparing. within each region, (i) the domestic vs. aggregated (domestic + international) EE coefficients mean values, (ii) the international vs. aggregated (domestic + international) EE coefficients mean values, and (iii) the domestic *vs.* international EE coefficients mean values.

$*$ means that rates of change are not computed for the whole period, but for the second sub-period.

Table 3: Comparison of domestic and international EE coefficients (ktoe/ATK) within each zone (1983-2006). Source: Authors, from ICAO data.

compared to respectively aggregated (domestic + international) and international mean values for the whole and the corresponding sub-periods. Ratios presented in the first (respectively second and third) line of the i-th region correspond to, for the period under consideration, the domestic (respectively international and domestic) EE coefficient mean value of the i-th region over the aggregated (respectively aggregated and international) EE coefficient mean value of the same region. In other words, these ratios are computed as follows:

$$First\ Ratio = \frac{EE_{i,t,dom}}{EE_{i,t,agg}} \quad ; \quad Second\ Ratio = \frac{EE_{i,t,int}}{EE_{i,t,agg}} \quad ; \quad Third\ Ratio = \frac{EE_{i,t,dom}}{EE_{i,t,int}} \quad (3)$$

where:

$EE_{i,t,dom}$ represents the EE coefficient mean value of region i, at time t=*{1983-1996;1996-2006;1983-2006}* for domestic air travel;

$EE_{i,t,agg}$ represents the EE coefficient mean value of region i, at time t=*{1983-1996;1996-2006;1983-2006}* for aggregated (domestic + international) air travel;

$EE_{i,t,int}$ represents the EE coefficient mean value of region i, at time t=*{1983-1996;1996-2006;1983-2006}* for international air travel.

Thus constructed, a ratio $>(<)$ 1 means that the energy efficiency of the kind of travel in numerator is inferior (superior) to the kind of travel in denominator. These ratios aim at comparing, within each region, (i) the domestic vs. aggregated (domestic + international) EE coefficients mean values, (ii) the international vs. aggregated (domestic + international) EE coefficients mean values, and (iii) the domestic *vs.* international EE coefficients mean values.

At the world level, domestic energy efficiency appears to be lower than at the international level. There is a ratio of 1.33 to one between world's international and domestic energy efficiencies for the whole period (Table 3). This comment applies in all regions: domestic energy efficiency appears to be inferior to international energy efficiency whatever the region considered (third line for each zone). This result confirms the intuition that domestic air travels are more energy intensive than international air traffic. One of the main reasons found in previous literature is that domestic flights are more energy intensive due to more frequent take-off and landing.

Figure 5 clearly illustrates this stylized fact. At the world level, international air travels (black dashed line) are more energy efficient than domestic air travels (gray dashed line), over the last twenty years. Indeed, the curve of domestic EE coefficients is above the curve for international EE coefficients[27]. Thus, this figure illustrates previous results presented in

[27] As a consequence the curve of aggregated (domestic + international) EE coefficients (solid black line) is

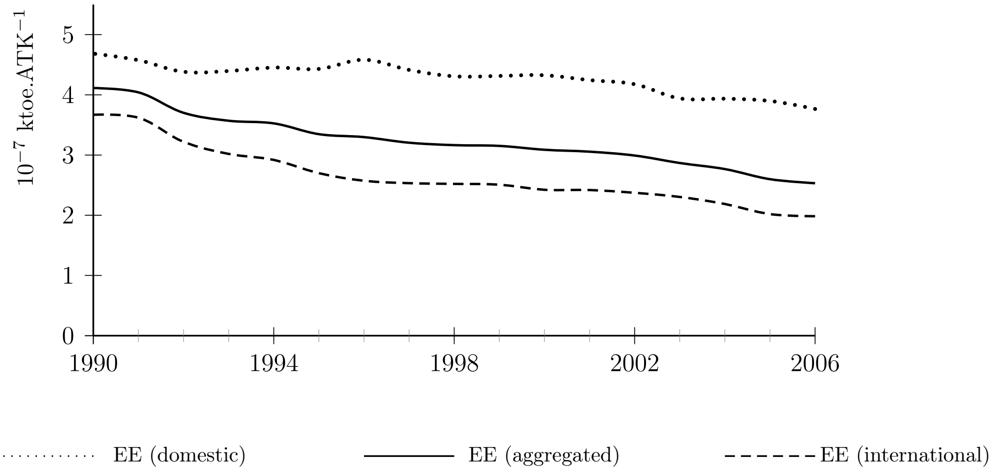


Figure 5: Comparison of the evolution of (i) aggregated (domestic + international), (ii) domestic and (iii) international EE coefficients at the world level from 1990 to 2006. Source: Authors, from ICAO and IEA data.

Table 3. Moreover, the decreasing trend of the three curves illustrates the results presented in Table 1: both international and domestic air travels – and as a consequence aggregated (domestic + international) air travel too – have encountered energy efficiency improvements during 1983-2006 at the world level. The same kind of figures may be obtained at the regional level[28].

The two precedent remarks lead to the following stylized fact: even if both international and domestic air travels have encountered energy efficiency improvements from 1983 to 2006, international air travels appear to be less energy intensive than domestic air travels. The macro-level approach proposed in this article conducts to the same conclusions as in previous literature, but obtained with 'bottom-up' approaches. Applied to air traffic at the world level, the macro-level approach allows to quantify this stylized fact: air traffic efficiency gains have been equal to +4.08%/yr and +1.00%/yr during the whole period, respectively for international and domestic air travels (Table 1).

This macro-level methodology has been initially developed to deduce air transport energy efficiency improvements scenarios in order to forecast jet fuel consumptions and CO_2 emissions from aviation. As already explained, the first interest of the macro-level methodology is to obtain precisely quantified results regarding air transport energy efficiency improvements

between the two other ones.

[28]These figures are not provided here as they would exhibit exactly the same kind of pattern and stylized fact. They may be obtained upon request to the authors.

both at the world level and at a more disaggregated level (the eight regions). Beyond this primary important output, the interest of this macro-level methodology is reinforced by the opportunity to make use of these results in many different ways.

5 Comparison of estimates provided by 'bottom-up' and 'macro' methodologies

These two methodologies are designed to investigate whether air transport has experienced (or not) an improvement in energy efficiency during last decades. They aim (i) at estimating the absolute levels of energy consumption of air transport, and (ii) at quantifying the potential improvement. The next two subsections compare the estimates provided by these two methodologies. These comparisons allow us to highlight the complementarities and limitations of both methods.

5.1 Evolution of energy efficiency of air transport

Regarding the improvement of energy efficiency in air transport, our estimates are higher than those obtained using the 'Bottom-up' methodology. Nevertheless we find the same trend, i.e. energy efficiency in air transport has improved but at a slower pace since the 1980s.

5.1.1 Energy efficiency of air transport has improved in the last decades ...

The studies using the 'Bottom-up' methodology highlight an improvement in energy efficiency of air transport in recent years (Figure 1). Most studies refer to the previous exhaustive research of Greene (1992). Based on this study, the IPCC special report on aviation (IPCC, 1999) estimated that energy efficiency of air transport has improved by about 70% between 1960 and 2000 (i.e. 3%/yr). Nevertheless, some authors (Peeters et al., 2005; Owen, 2008) argued that a methodological bias may have led to an overestimation of improvement of energy efficiency by Greene (1992). Most values are between 1.5%/yr (Lee et al., 2004) and 2.2%/yr (Airbus, 2007). These values are lower than ours (2.6%/yr over the last ten years, see Table 1). An explanation for these differences may be found at the end of the next subsection.

5.1.2 ... but at decreasing pace

Most studies emphasize the fact that energy efficiency of air transport has improved significantly, but that this pace has slowed. Figure 1 shows the average energy consumption (expressed in Mega-Joules (MJ) per ASK) for different types of aircrafts. It reveals the discontinuity in the improvement of aircrafts' energy efficiency. The sharper improvement between 1950-1980 can be explained by the development of turbojet and turbofan engines (Lee et al., 2001, 2004; Owen, 2008). The pace has been slower during the last 30 years (Figure 1 and/or Table 4).

At the world level, as illustrated by Table 1, the energy efficiency of air transport has been improving by 2.9%/yr between 1983 and 2006, but it was stronger during the period 1983-1996 (3.1%/yr) than between the period 1996-2006 (2.6%/yr). At the regional level, we find the same evidence (Table 1). Nevertheless, we cannot compare our regional estimates with the 'Bottom up' methodology, as this methodology only provides estimates of energy efficiency for a representative world fleet.

We need to remain cautious when comparing the estimates obtained between both methods, as they do not necessarily measure the same phenomenon. Contrary to our methodology, the 'Bottom-Up' approachs only estimates the aircraft's energy efficiency. This methodology does not take into account the effect of ATM in the calculation of energy savings. Hence, the deviation estimates observed between the two methodologies may be partly explained by the non-inclusion of the ATM in the 'Bottom-up' methodology. Thus, these differences underline the need to take into account ATM improvements when estimating energy efficiency gains, and their evolution in air transport.

Another limitation of the 'Bottom-up' methodology lies in its implementation. Assumptions about the composition of the fleet necessarily rely on arbitrary choices. The energy efficiency of the fleet is therefore dependent on these choices. Instead, the 'macro-level' methodology computes the energy efficiency of air transport from data about (i) actual jet fuel consumption, and (ii) air traffic actually observed. By doing so, we can estimate the absolute level of energy efficiency of the world fleet without having to detail the composition of the fleet.

Thus, the two approaches appear rather complementary. The next subsection aims at comparing the absolute levels of energy efficiency that these two methodologies provide.

5.2 Carbon intensity of air transport

Fuel consumption and emissions are two major issues when designing an aircraft. Nevertheless, energy efficiency is not the only parameter that matters as shown by its slight improvement since the 1980's. As underlined by Peeters et al. (2005), airlines buying new aircrafts consider several other parameters such as cruising speed (Frederick, 1961), comfort, or the maximum capacity of the unit. The aircraft A-380 illustrates this fact: its energy consumption is not always better than some models developed twenty years earlier (see Figure 1 and Table 4).

We now compare the average carbon intensity of each aircraft with the average carbon intensity of the world civil fleet. These figures are shown in Tables 4 and 5. Table 4 is obtained by using the 'Bottom-up' methodology, while Table 5 is obtained by using the 'macro-level' methodology[29].

As illustrated by Tables 4 and 5, the two methodologies provide complementary information, and their joint analysis may improve the understanding of the energy efficiency in air transport. The 'Bottom-up' methodology provides the carbon intensity for each aircraft, while the 'macro-level' approach provides carbon intensity for flying fleets. There are genuine differences between these estimates. For example, the A-380 is 60% less carbon-intensive than the world fleet (78 g-CO_2/ASK, see Table 4 *vs.* 126 g-CO_2/ASK, see Table 5)[30].

Tables 4 and 5 show jet fuel consumption (liters per 100 ASK or liters per 100 RPK[31]) and carbon intensity (g- CO_2/ASK and g-CO_2/RPK). By expressing measures in such metrics, we aim at making comparisons with previous literature (particularly with papers related to other transport modes). Carbon intensities are shown to differ widely between transport modes. In Europe, for example, the average consumption of a recent car is generally estimated to fall in the range of 5 to 10 liters per 100 km. To express it in liters per 100 ASK, we must divide this value by five (if we consider that five people may sit in a car). What concerns the train, the French train company SNCF estimates that the carbon intensity of the high-speed train TGV is equal to 22.3 g-CO_2/ASK. This low value may be explained by the fact that electricity generation in France releases about 80g/kWh, because it relies heavily on nuclear power. CO_2 emissions are assumed to be equal to 380g/kWh in the european electricity mix. Thus, we may estimate the carbon intensity of a TGV traveling in Europe to be equal to 105 g-CO_2/ASK.

It is generally assumed that air, railway and road are competitive for passengers transport up to 1,500km. For this range of distances, air transport appears as the less efficient transport mode from a strictly environmental viewpoint[32]. These comparisons between different transport modes reveal another interesting result. The carbon intensity of road transport is

[29]The values in Table 1 are expressed not in ktoe per ATK but in gram of CO_2 per ASK and RPK. These mean values were computed during 2004-2006.

[30]Hence, the carbon intensity computed with the 'macro-level' methodology hinges on an aircraft fleet aged between zero and thirty five years. Contrary to the 'Bottom-Up' methodology, we do not know exactly the composition of the aircraft fleet.

[31]Revenue Passenger-Kilometres (RPK) is a measure of the volume of passengers carried by an airline. A revenue passenger-kilometre is flown when a revenue passenger is carried one kilometre.

[32]Unless we consider that short and medium hauls flight are opeated with A-380 models, which is not a realistic assumption.

Aircraft models	Release date	Energy efficiency (MJ/ASK)	ASK: Jet fuel consumption (l/100 ASK)	ASK: Carbon intensity (g CO_2/ASK)	RPK: Jet fuel consumption (l/100 RPK)	RPK: Carbon intensity (g CO_2/RPK)
Comet 4	1958	3.500	10.16	248.66	13.19	322.93
B707-120	1958	3.100	9.00	220.24	11.68	286.03
B707-320	1959	3.020	8.77	214.56	11.38	278.65
DC8-30	1961	2.975	8.63	211.36	11.21	274.49
B707-120B	1962	2.520	7.31	179.03	9.50	232.51
B707-320B	1963	2.205	6.40	156.65	8.31	203.45
DC8-61	1965	2.310	6.70	164.11	8.71	213.14
B737-200	1965	1.540	4.47	109.41	5.80	142.09
SVC10	1966	2.380	6.91	169.09	8.97	219.59
DC8-63	1967	1.890	5.49	134.28	7.12	174.38
B747-100	1969	1.645	4.77	116.87	6.20	151.78
B747-100B	1969	1.330	3.86	94.49	5.01	122.71
B747-200	1970	1.680	4.88	119.36	6.33	155.01
DC10-30	1972	1.715	4.98	121.84	6.46	158.24
B747-200B	1972	1.330	3.86	94.49	5.01	122.71
B747SP	1975	1.680	4.88	119.36	6.33	155.01
A310-200	1982	1.256	3.65	89.25	4.73	115.91
B767-200	1982	1.329	3.86	94.41	5.01	122.62
B747-300	1983	1.225	3.56	87.03	4.62	113.03
A300-600	1984	1.313	3.81	93.25	4.95	121.10
A310-300	1985	1.120	3.25	79.57	4.22	103.34
B737-400	1988	1.127	3.27	80.04	4.25	103.95
A320	1988	1.018	2.96	72.35	3.84	93.96
B747-400	1989	1.120	3.25	79.57	4.22	103.34
A340-300	1993	1.155	3.35	82.06	4.35	106.57
A330-300	1994	1.085	3.15	77.08	4.09	100.11
B777-200	1994	1.050	3.05	74.60	3.96	96.88
B777-300	1997	1.006	2.92	71.49	3.79	92.84
B737-700	1997	0.893	2.59	63.46	3.37	82.41
A380-800	2007	1.104	3.20	78.43	4.16	101.86
B787-8 dreamliner	2010	1.063	3.09	75.53	4.01	98.09
A350-900	2011	1.064	3.09	75.56	4.01	98.13

Note: Aircrafts' energy efficiency (second column) have been obtained from carriers' websites. These data have then been converted into jet fuel consumption (third and fifth columns), as well as in carbon intensity (fourth and sixth columns). The following assumptions have been made:
- PCI of Jet-A1: 44,23 MJ/kg;
- density of Jet-A1: 0,779 kg/l;
- carbon percentage (C) in Jet-A1: 85,7%;
- molecular weights of carbon dioxide (CO_2) and carbon (C): 44 and 12, respectively;
- aircraft's average filling rate to convert ASK into RPK: 77% (world average in 2007).

Table 4: Energy efficiency (expressed in Mega-Joule per ASK), jet fuel consumption (expressed in liters per 100 ASK and 100 RPK) and carbon intensity (expressed in grams of CO_2 per ASK and RPK) of aircrafts. Source: Authors, based on manufacturers' data.

		ASK		RPK	
		Jet fuel consumption (l/100 ASK)	Carbon intensity (g CO_2/ASK)	Jet fuel consumption (l/100 RPK)	Carbon intensity (g CO_2/RPK)
Central and North America	**Aggregated**	5.15	126.19	6.63	162.18
	Domestic	6.00	146.79	7.79	190.59
	International	3.60	88.01	4.58	112.00
Europe	**Aggregated**	4.30	105.33	5.59	136.73
	Domestic	9.86	241.43	14.50	354.95
	International	3.81	93.19	4.89	119.63
Latin America	**Aggregated**	11.02	269.65	15.64	382.95
	Domestic	12.77	312.62	18.91	462.84
	International	10.22	250.14	14.17	346.84
Russia and CIS	**Aggregated**	12.27	300.24	17.45	427.16
	Domestic	17.55	429.59	24.44	598.34
	International	9.80	239.96	14.05	343.87
Africa	**Aggregated**	9.23	225.98	13.64	333.90
	Domestic	25.56	625.67	36.65	897.14
	International	6.85	167.70	10.16	248.75
The Middle East	**Aggregated**	6.16	150.72	8.43	206.29
	Domestic	7.16	175.28	8.90	217.97
	International	6.13	150.04	8.45	206.85
Asian countries and Oceania	**Aggregated**	4.91	120.14	6.78	166.04
	Domestic	5.79	141.80	8.47	207.33
	International	4.74	116.10	6.50	159.10
China	**Aggregated**	4.07	99.72	5.54	135.66
	Domestic	4.21	103.17	5.84	142.91
	International	4.16	101.87	5.56	136.18
World	**Aggregated**	5.14	125.79	6.81	166.68
	Domestic	6.46	158.03	8.64	211.47
	International	4.40	107.69	5.80	142.02

Note: These values were calculated using 'macro' methodology that aims at obtaining energy efficiency coefficients (expressed in ktoe/ASK or ktoe/RPK). These coefficients were then converted to jet fuel consumption and carbon intensity. We used the following assumptions:

- 1 t of Jet-A1 = 1,061 toe of Jet-A1;
- Jet-A1 density: 0.779 kg/l;
- percentage of carbon (C) in Jet-A1: 85.7%;
- molecular weight of carbon dioxide (CO_2) and carbon (C): 44 and 12, respectively.

Table 5: Jet fuel consumption (expressed in liters per 100 ASK and 100 RPK) and carbon intensity (expressed in grams of CO_2 per ASK and RPK) of fleets within each zone, assessed on a global basis. Mean values for the years 2004-2006. Source: Authors, from ICAO and IEA data.

actually - especially for medium distances - lower than for rail. Indeed, the average carbon intensities of cars has decreased in most countries. The carbon intensity of new manufactured cars is comprised between 100 and 140 g-CO_2/ km, which corresponds to 20 and 28 g-CO_2/ASK respectively. It is lower than the carbon intensity of a TGV traveling in Europe (105 g-CO_2/ASK), and close to the carbon intensity of a TGV traveling in France (22.3 g-CO_2/ASK).

As illustrated by Table 5, the 'macro-level' methodology allows to compile the data at different levels of aggregation. Thus, we may estimate the carbon intensity of a representative aviation world's fleet (or aviation regional's fleet), for both domestic and international flights. Figure 6 shows the heterogeneity between carbon intensities at the regional level and depending on the types of flights.

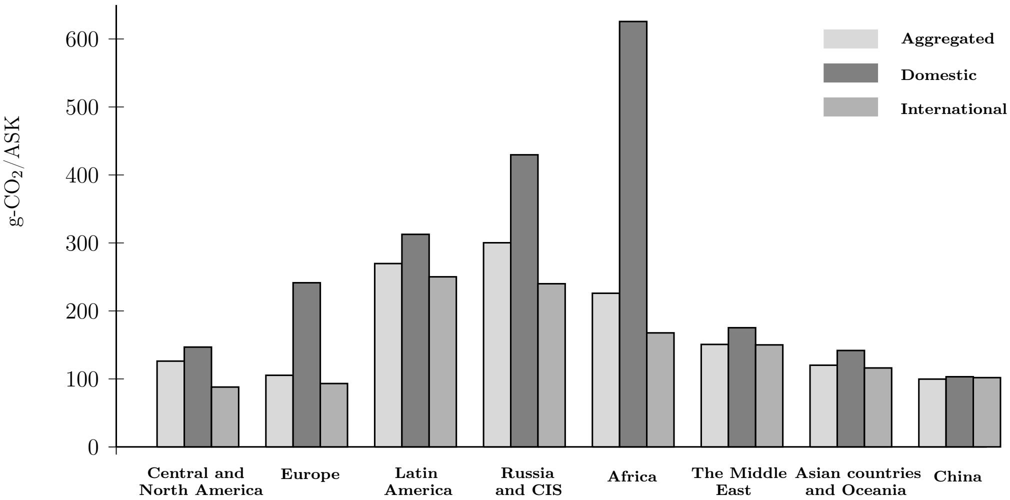


Figure 6: Carbon intensity (expressed in g-CO_2/ASK) of (i) aggregated, (ii) domestic and (iii) international air traffic by region in 2006. Source: Authors, from ICAO and IEA data.

The results shown in Table 5 are comparable with those in Tables 2 and 3. Two insights may be drawn from Table 5. First, the carbon intensity of the aviation fleet used for international flights (107 g-CO_2/ASK, Table 3) is close to the carbon intensity of aircrafts that were recently manufactured (between 75 and 82 g-CO_2/ASK, see Table 3). This result suggests that the fleet used for international flights is composed of relatively recent aircrafts. Second, when comparing the carbon intensities of North American and European regions, it appears that they are similar for international flights (112 g-CO_2/RPK *vs.* 119 g-CO_2/RPK), while they differ significantly for domestic flights (190 g-CO_2/RPK *vs.* 355 g-CO_2/RPK). This difference cannot be explained by a lower energy efficiency of the European companies, but it may be explained by the fact that European flights are shorter than North-American flights.

Hence, the estimated value of the carbon intensity of domestic flights for these two regions does not correspond strictly to the same type of flights.

6 Concluding remarks

The 'Macro-Level' methodology presented in this article has been initially developed to estimate air transport energy efficiency. Compared to the 'Bottom-Up' methodology, the interest of using the 'Macro-Level' methodology lies in the fact that its results are (i) all precisely quantified according to a simply replicable methodology, and (ii) obtained without any (restrictive) assumptions on either the composition of the aircrafts' fleet or the evolution of the renewal/upgrade rate of existing aircrafts. Effectively, our results are obtained just by systematically comparing the evolution of both air traffic and jet fuel consumptions among eight geographical zones during the last 30 years. More precisely, it allows us to obtain 'aggregated' (domestic + international), domestic and international EE coefficients and their growth rates from 1980 to 2006. These coefficients are provided at the world level and for eight geographical zones.

Our results indicate that, first, air travel energy efficiency improvements have been occurring in all regions, but not with the same magnitude (Table 1). At the world level, that is for the world aircraft fleet taken as a whole, energy efficiency improvements have been equal to 2.88% per year during the 1983-2006 period. Still at the world level, energy efficiency improvements have been more important during 1983-1996 (3.09% per year) than during 1996-2006 (2.61% per year). Second, it has been identified that some regions appear effectively more energy efficient than others (Table 2). Central and North America, Europe, China, Asia and Oceania are in average more energy efficient than the world's benchmark. Third, domestic energy efficiency appears to be lower than international energy efficiency. This latter comment applies both at the world level and for all regions (Table 3).

Taken together, these results highlight the necessity to take into account energy efficiency heterogeneity between aircraft fleets when estimating the energy efficiency of air transport. Two kinds of heterogeneities have to be distinguished. First, regional aircraft fleets do not have the same energy efficiency, as fleets are not composed with the same types of aircrafts. Second, domestic air traffic is less energy efficient than international air traffic, *ceteris paribus*. This is due to more frequent take-off and landing, the most energy-intensive components of a flight.

The heterogeneity between regions has important consequences in terms of forecasting CO_2 emissions from air transport. For example, the rapid development of air transport will not

have the same consequences on the overall increase in CO_2 emissions in this sector if it occurs predominantly in relatively energy-efficient regions, *ceteris paribus*.
Similarly, the heterogeneity between different types of flights would encourage policymakers to ensure that the development of air traffic rely more on long-haul flights than on short-medium haul flights. Air transport is indeed the less energy efficient transport mode from an environmental viewpoint when we consider the distances corresponding to the short- and medium-haul flights. Policy-makers should therefore promote other transportation means for distances inferior to 1500 km.

Finally, we highlight that the quest for more energy efficient aircrafts has not been a priority for aircraft and engine manufacturers over the last thirty years. However, in the current economic outlook (i.e., increases in jet fuel prices), greater energy efficiency gains are deemed as desirable. Last but not least, airline companies are now facing tight environmental constraints with the fight against climate change[33]. We may therefore expect further improvement of energy efficiency, and thus of carbon intensity of air transport in the coming years.

[33] As airline companies transiting from and to Europe will fall under the regulation of the European Union Emissions Trading Scheme by 2012.

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