Efficiency Trends for New Commercial Jet Aircraft

1960 to 2008

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

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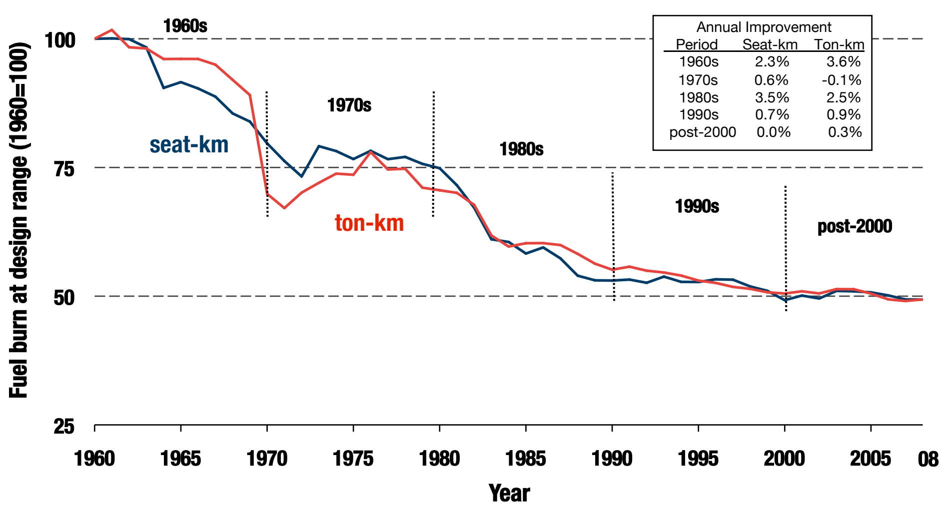
ABSTRACT

Concerns about aviation's growing climate impact have revived interest in CO_2 emission standards for new aircraft. To date, commercial aviation has been perceived to produce continuous improvements in efficiency by quickly adopting fuel-efficient technologies and designs as a natural response to fuel prices. This paper describes an historical analysis of sales- and activity-weighted fuel efficiency for new jet aircraft from 1960 to 2008 that suggests that fuel costs alone have not produced consistent improvements in aircraft efficiency. Key findings include:

- The average fuel efficiency of new passenger aircraft has approximately doubled on both a seat-km (passengers only) and ton-km (passengers + freight) basis since 1960, less than previous estimates.
- New aircraft efficiency has improved substantially in only two of the last five decades, and stagnated in recent years. On average, fuel efficiency has remained flat on a seat-km basis and improved only 0.29% annually on a ton-km basis since 2000.
- Diminished efficiency gains are correlated with historically low fuel prices between 1987 and 2004 and a tripling in the average age of aircraft and engine manufacturer production lines since 1989.

We conclude that fuel costs alone have not been sufficient to stimulate increased aircraft efficiency, and that improvements in fuel efficiency due to the introduction of new aircraft have decreased over time. These findings suggest that a CO_2 standard that applies to newly built aircraft from current production lines, not just to new designs, is most likely to reduce emissions.



ABSTRACT 1. AVERAGE FUEL BURN FOR NEW AIRCRAFT, 1960-2008

1. INTRODUCTION

The need to constrain the rapid growth of aviation's impact on the global climate is becoming increasingly clear. Since 1997, when Article 2.2 of the Kyoto Protocol requested that developed countries pursue the limitation and reduction of greenhouse gas emissions from aircraft through the International Civil Aviation Organization (ICAO), aviation's contribution to global carbon dioxide (CO_2) emissions has continued to grow. Global CO_2 emissions from aircraft grew an estimated 45% between 1992 and 2005. After accounting for their significant non-CO_2 climate impacts, aircraft were responsible for an estimated 3.5% of historical anthropogenic radiative forcing (RF) in 2005 and 4.9% of total RF counting the probable effects of aircraft through aviation-induced cloudiness (Lee et al. 2009). Moreover, ICAO recently forecast that global CO_2 emissions from aviation will increase an additional 150% above 2006 levels by 2036 (ICAO 2009a), a pace that would quadruple emissions by 2050. Given the lack of a global agreement on reducing international aviation emissions, studies suggest that aviation emissions threaten to erase the gains of developed countries that succeed in reducing emissions from other sectors (Bows et al. 2005).

These facts have renewed calls for fuel efficiency or CO_2 standards[1] for new aircraft from a variety of stakeholders. In 2001, ICAO's Committee on Aviation Environmental Protection (CAEP) concluded that a CO_2 standard was unnecessary and potentially even counter-productive because fuel costs provided sufficient incentive for manufacturers and airlines to reduce actual CO_2 emissions in operation (ICAO 2001). Since that time, the UK Department for Transport (DfT 2009) and US EPA (Federal Register 2008), among others, have expressed interest in an aviation emission standard. Boeing has also indicated its support for a CO_2 standard for new aircraft designs (Carson 2009). ICAO has since reversed course and will present its plans for a CO_2 standard for new aircraft types at the Copenhagen meeting of COP-15, where a post-Kyoto climate agreement will be discussed (ICAO 2009b).

While a variety of technical issues need to be addressed in order to set a meaningful CO_2 standard[2], one key input into any standard will be to understand the natural historical rate of fuel efficiency improvement for aircraft. The aviation industry argues that the high cost of fuel motivates it to quickly adopt fuel-efficient technologies and practices. References to aviation, supported by industry analysis, typically allude to a "continual improvement" in fuel efficiency demonstrated by new equipment. A Rolls-Royce analysis cited first in Albritten et al. (1997) and later in an influential IPCC report (Penner et al. 1999) estimated that the fuel burn[3] of new jet aircraft had been reduced by 70% between 1960 and 1997. Other studies, including Lee et al. (2001) and Peeters et al. (2005), have estimated relatively smaller reductions (approximately 64% and 55%, respectively) over similar timescales for new equipment.

There are significant limitations to the studies described above. Each of these studies drew conclusions about historical trends using a relatively small number of aircraft, predominately or completely models flown on long-haul routes. Those studies also did not weigh the relative efficiency of individual aircraft models by sales or activity, a technique commonly used to minimize outliers and to assure that the importance of the most commercially successful vehicle designs are accurately captured. As a result, the studies may not be representative of the broad historical trend for all new aircraft, particularly given the substantial contribution of narrowbody aircraft and regional jets to global fuel burn today.

To inform current discussions of a CO_2 standard for new aircraft, this paper presents an analysis of sales- and activity-weighted historical trends in new aircraft efficiency from 1960 to 2008. It aims to answer two simple questions: first, has the average efficiency of new aircraft improved continuously over time in response to fuel prices? Second, if progress has not been continuous, what factors other than fuel price seem to influence the rate of improvement? The following section describes our method of analysis. Section 3 describes the study's key findings, while Section 4 briefly explores its policy implications.

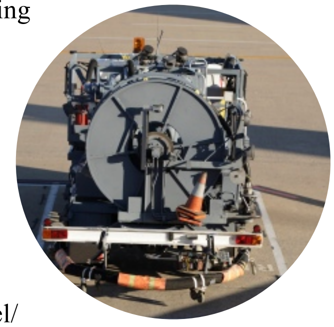
2. METHODS

This analysis was conducted in three basic steps. First, representative aircraft were identified to cover the more than 27,000 new commercial jet aircraft sold worldwide since 1952. Second, the fuel burn of those aircraft over characteristic missions was modelled using Piano-X[4], an aircraft performance and emissions database. The Piano software suite has been used in ICAO policymaking and for the construction of several prominent aviation emissions models.[5] Third, the fuel burn of representative aircraft was weighted by actual aircraft sales and estimated activity to create industry average efficiency trends for new aircraft. A detailed description of the methodology follows: readers new to this subject are encouraged to refer to the glossary in Appendix A as necessary.

For this analysis, a data set of aircraft deliveries[6] (month and year) by manufacturer, aircraft model/series, and engine model/series was purchased from Jet Information Services, publisher of the World Jet Inventory. The data set included 27,370 individual aircraft delivered between 1952 and 2008 seating 31 passengers or more. From this data set, 26,331 aircraft (96% of total) delivered by the ten largest commercial jet aircraft manufacturers (Boeing, Airbus, Douglas, Embraer, Bombardier, Fokker, BAE Systems, British Aircraft Corp, Aerospatiale, and Lockheed) between 1958 and 2008 were isolated.

From this data set 704 distinct airframe/engine combinations were extracted and matched to 96 representative aircraft in the Piano-X database, current to November 2009. Representative Piano-X models were identified by matching aircraft model/series and engine model/series information provided by the developer of the Piano suite to the delivery dataset. Where multiple Piano-X aircraft models existed for a given aircraft/engine combination, representative models were assigned by using the most updated and highest maximum take off weight (MTOW) variants within Piano-X in order to assure that the most productive aircraft were being used. Since Piano-X was created to analyze current in-service aircraft, two Douglas DC-8 models (-53 and -55) were created by its developer to improve coverage of early deliveries in the dataset; additionally, the B737-200 was modified by the developer to make it more representative of early deliveries.[7] Dedicated new freighters and military aircraft were removed, as were airframe/engine combinations for which no clear representative aircraft could be identified within the Piano-X database (a total of 36 combinations, representing 698 deliveries). Table 1 summarizes the Piano-X aircraft models used, which covered in total 25,354 deliveries, or 93% of the initial delivery dataset.

Block fuel burn (fuel/available seat kilometer, or ASK, and fuel/available ton kilometer, or ATK) of aircraft delivered in each year was compared using Piano-X. Model default values were adopted for design weights, nominal seat counts, thrust, drag, and fuel flow. Aircraft were "flown" at full loads (all seats filled or maximum mass payload) over design range routes, including landing and take off, at available flight levels of 310 and 350 and at cruise speeds enabling 99% specific air range. Fuel reserves and allowances were set at 370 km diversion distance, 30 minutes holding time, and 5% mission contingency fuel for all aircraft. Fuel burn per ATK was estimated through fuel burn with maximum payload (maximum zero fuel weight minus operating empty weight) at maximum range, while fuel burn per ASK was estimated at design range using Piano-X default values for the passenger to mass conversion. No additional allowance was made for belly freight for the ASK fuel burn estimation.



The average fuel burn for new equipment (g fuel/ASK and g fuel/ATK by year of delivery) by year was estimated by weighting the fuel burn of the 96 representative aircraft by their sales and contribution to a year of fuel burn for aircraft delivered that year, normalized to 1960 for easy comparison to previous studies (1960 FB = 100). Deliveries were classified as either widebody or narrowbody aircraft within the original Jet Information Services dataset: for further segmentation, narrowbody aircraft seating fewer than 100

TABLE 1. PIANO-X REPRESENTATIVE MODELS USED

B707-320C	B747-400 (875)	Airbus A310-300	Douglas DC 8-53
B717-200 (v00)	B747-400ER (910)	Airbus A318-100 59t	Douglas DC 8-55
B727-200A	B747-SP (degrad)	Airbus A318-100 68t	Douglas DC 9-14
B737-200	B757-200 (220) p	Airbus A319 basic	Douglas DC 9-34
B737-300 (basic)	B757-200 (255) p	Airbus A319-100 64t	Douglas DC 10-10
B737-400 (basic)	B757-200 (220)r	Airbus A319-100 75t	Douglas DC 10-30
B737-500 (basic)	B757-200 (255)r	Airbus A320-200 77t	Embraer 170 LR (v07)
B737-600 (NG basic)	B757-300 (273)p	Airbus 321-100	Embraer 190 LR (v07)
B737-600 (145) rev	B757-300 (273)r	Airbus A320-200 73t	Embraer 190 AR (v07)
B737-700 (133) wglt	B767-200 basic	Airbus 321-200 89t	Embraer 190 STD (v07)
B737-700 (NG basic)	B767-200ER	Airbus 321-200 93t	Embraer EMB-135
B737-700 (154) wglt	B767-300	Airbus A330-200 233t	Embraer EMB-145
B737-BBJ1	B767-300ER	Airbus A330-300 230t	Canadair RJ 100
B737-700ER (158) wglt	B767-400ER basic	Airbus 340-200 275t	Canadair CRJ 200ER
B737-800 (155) wglt	B777-200 ER (IGW)	Airbus 340-300E 276t	Canadair CRJ 701
B737-800 (NG basic)	B777-200 ER (max)	Airbus A340-500 (v09)	Canadair CRJ 900
B737-800 (174) wglt	B777-200 LR (v04)	Airbus 340-600 (v09)	Fokker-F28 Mk4000
B737-BBJ2	B777-200 LR (max)	Airbus A380-800 (v08h)	Fokker F70 basic
B737-900 (NG option)	B777-300 (660)	Douglas MD-11 basic	Fokker F100 basic
B737-900ER (187a) wglt	B777-300 ER (v04)	Douglas MD-81	Avro RJ-70
B747-100 (degrad)	Airbus A300 600 light	Douglas MD 82-88	Avro RJ 85 basic
B747-200B (833)	Airbus A300 600R	Douglas MD-83 auxCap	Avro RJ-100
B747-300 (833)	Airbus A300 B2-200	Douglas MD-87	Lockheed L-1011-200
B747-400-stretch (v91)	Airbus A310-200	Douglas MD-90-30	Lockheed L-1011-500

EQUATION 1. METHOD OF FUEL BURN WEIGHTING

$$FB(y) = \left[\frac{\sum_{i=1}^{96} n_i(y) \times f_i \times [h_i / t_i]}{\sum_{i=1}^{96} n_i(y) \times s_i \times r_i \times [h_i / t_i]} \right]$$

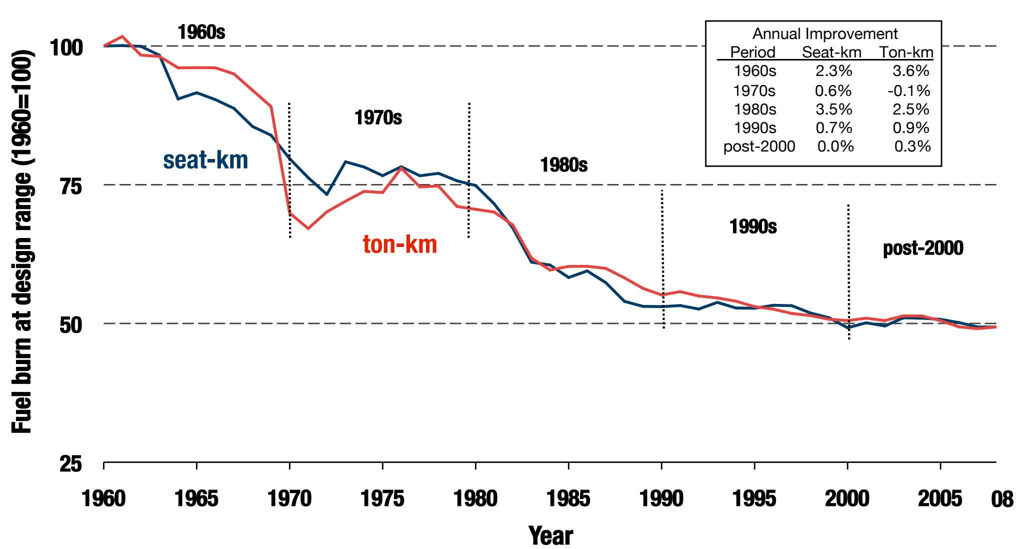
Where:
$FB(y)$ = fuel burn in year y (g fuel/ASK)
i = Piano-X representative aircraft
$n_i(y)$ = number of aircraft delivered in year y and represented by i
f_i = fuel burnt by aircraft i in design mission
h_i = annual block hours for aircraft i
t_i = block time of design mission for aircraft i
s_i = seats in aircraft i
r_i = design range of aircraft i

passengers were classified as regional jets unless obvious derivatives of larger aircraft (e.g. 737-BBJs). Block hours flown were set at 2700, 2900, and 4200 hours per year for regional jets, narrowbodies, and widebodies, respectively, to reflect differences in the utilization across aircraft classes. As an example, fuel burn per ASK for aircraft delivered in a given year (y) was estimated via Equation 1.

The results of this analysis are summarized in Section 3. Simple sensitivity analyses of two key assumptions – the use of design range to estimate fuel burn performance, and the assumption of no incremental improvement within an aircraft-engine combination over its production lifetime – are presented in Appendix B.

3. RESULTS AND DISCUSSION

The results of this analysis are summarized in Figure 1. The 51% reduction of fuel burn shown in that figure on both a seat-km (passengers only) and ton-km (passengers + cargo) basis translates to a more than doubling of the average efficiency of new aircraft between 1960 and 2008[8], an annual improvement of 1.5%. In contrast to conventional wisdom, efficiency has not improved continuously over time. Improvements were particularly rapid during the 1960s, peaking when widebody aircraft such as the 747 family came into wide



Annual Improvement		
Period	Seat-km	Ton-km
1960s	2.3%	3.6%
1970s	0.6%	-0.1%
1980s	3.5%	2.5%
1990s	0.7%	0.9%
post-2000	0.0%	0.3%

FIGURE 1. AVERAGE FUEL BURN FOR NEW AIRCRAFT, 1960-2008

production in 1970, and in the early to mid-1980s, when mid-range aircraft like Boeing's 757 and 767 families powered by new high bypass ratio turbofans began to dominate production lines. At other times, such as during the 1970s and after 1990, efficiency has improved slowly or stagnated. The average fuel burn per ton-km for new deliveries actually increased during the 1970s due to greater sales of narrowbody aircraft, which are designed to carry little belly freight and are therefore less efficient on a ton-km basis.

The flattening slope of the fuel burn curves in Figure 1 suggests a notable decrease in the rate of fuel efficiency improvement over time, with an apparent inflection point around 1990 on a seat-km basis and 2000 on a ton-km basis. Through 1990, we estimate that the efficiency of new aircraft improved 2.1% and 2.0% annually on a seat-km and ton-km basis, respectively. The annual improvement fell to only 0.75% (seat-km) and 0.88% (ton-km) during the 1990s. Since 2000, the average efficiency of newly delivered aircraft has been flat on a seat-km basis and improved only 0.29% annually on a ton-km basis. Appendix C compares the results of this analysis with previous assessments of historical aircraft efficiency improvements, of which all save one (Thomas et al. 2008) show a similar fall-off in efficiency improvement over time.

Further work is needed to understand these trends; however, some initial observations can be offered about likely drivers. In historical terms jet fuel was relatively cheap from 1987 until 2004, as measured in terms of its share of overall operating costs for major US airlines (Figure 2, left axis). This correlates well to the period of modest efficiency improvement shown in the shadowed brown line (ASK line from Figure 1, shown on the right axis of Figure 2) if one considers the amount of time needed to design, test, certify, and manufacture a modern jet aircraft. Since aircraft manufacturers compete not only on fuel efficiency but also on cost, performance, reliability, etc. (a point we return to below), it is perhaps not surprising that during periods of cheap fuel the efficiency of new

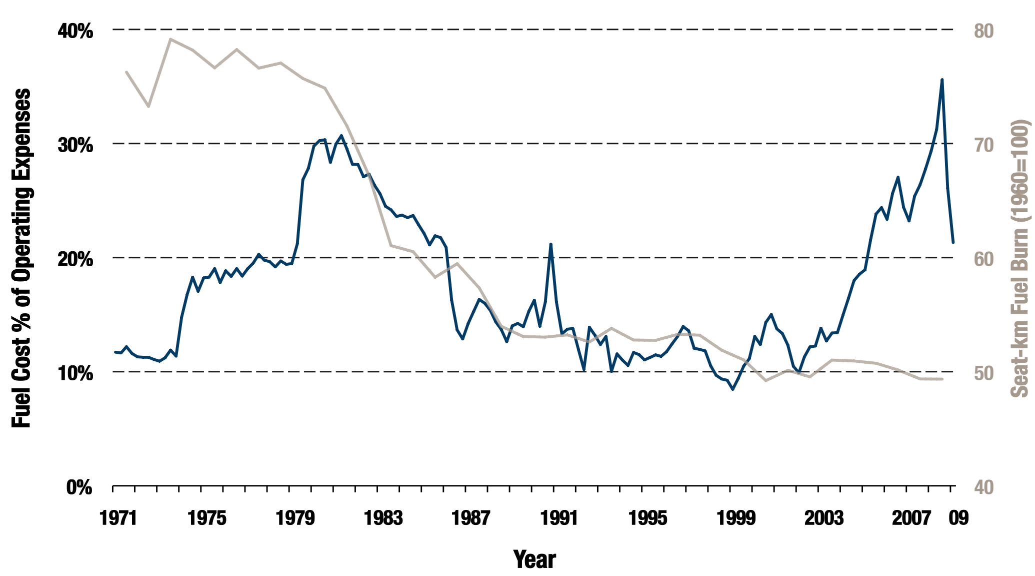


FIGURE 2. FUEL COSTS AS A SHARE OF TOTAL OPERATING EXPENSES FOR US AIRLINES

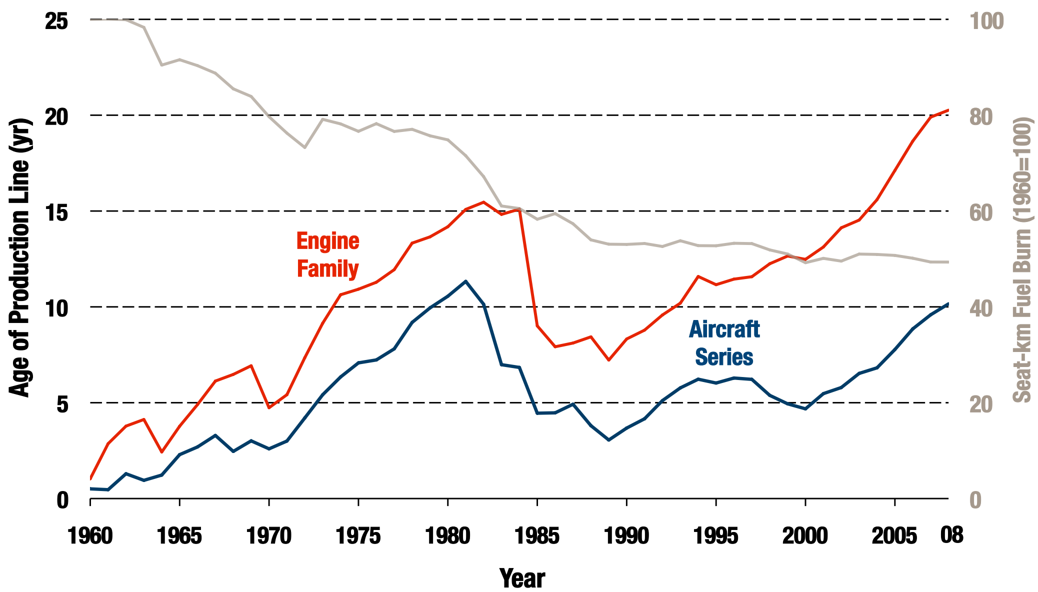


FIGURE 3. ESTIMATED AGE OF PRODUCTION LINE, 1960-2008

aircraft stagnates. Figure 2 also shows the dramatic run-up in fuel prices after 2004, including the post-2007 spike and subsequent crash, the policy implications of which we will return to in Section 4.

Second, the falling rate of efficiency improvement for new aircraft is also correlated with a two-decade dearth of new aircraft and engine designs, which translates to a noticeable increase in the production line age for today's major commercial aircraft manufacturers (Figure 3). As estimated by that graph, the average age of the production lines of today's four major commercial jet manufacturers (Airbus, Boeing, Bombardier, and Embraer) has tripled since 1989. Since over the long-term most of the aggregate efficiency improvements for new equipment are expected to come from the commercialization of new, more efficient aircraft and engines, this trend helps explain the falling rate of improvement over time. Note as well the sharp reduction of average production line age during the early 1980s – a period of unusually fierce competition between manufacturers – and the corresponding period of rapid efficiency improvement shown on the right-hand axis.

The final likely driver – introduced only briefly here and to be the subject of a future ICCT report – are notable improvements in the non-fuel burn related performance of new passenger aircraft, as measured by their design range, cruise speed, customer amenities offered, and cargo capacity. These improvements impose a fuel efficiency penalty, particularly on a seat-km basis, on passenger aircraft by boosting empty aircraft weight and drag during cruise.[9] These trends suggest that aircraft manufacturers reacted to low fuel prices by devoting an increasing share of component efficiency improvements to boosting the performance of passenger aircraft instead of reducing fuel burn and emissions.[10] Such a development would be consistent with Peeter et al.'s (2005) finding that other performance attributes, notably speed and range, were prioritized over fuel efficiency during the transition from piston-driven to jet aircraft during the late 1950s and early 1960s.

4. POLICY IMPLICATIONS

Returning to the questions posed in Section 1, this analysis suggests that, contrary to conventional wisdom, on average the efficiency of new commercial jet aircraft does not improve continuously: while efficient technologies and designs *may* be developed more or less continuously, their deployment is likely to be much more "clustered" and subject to market forces. When fuel prices remain low for an extended period of time, the incentive to market new aircraft and engine designs may weaken, and manufacturers may sacrifice fuel efficiency to increase other aircraft performance attributes. Since over the long-term the bulk of efficiency improvements from new equipment comes from new aircraft and engine designs rather than incremental improvements within a particular design's production lifecycle, a lack of new designs directly contributes to stagnating new aircraft efficiency.

This analysis shows that fuel price alone has failed to continuously promote new aircraft efficiency since 1960; furthermore, the rate of improvement has flattened since 1990. The latter finding is likely due to historically low fuel prices between 1987 and 2004, although limits on the efficiency of current "tube and wing" airframe designs and interdependencies between fuel consumption, local air pollution, and noise may mean that the efficiency of new equipment is less influenced by fuel price now than it has been in the past (Royal Aeronautical Society 2005; Lee et al. 2009). It seems reasonable to assume that high fuel prices after 2004, should they continue, will impact the efficiency of not yet designed aircraft. Given that it now takes a decade or more for a new aircraft design to be brought to market, accurately predicting how large of an impact today's fuel prices may have on new aircraft in the 2015 time frame will be important to setting a CO_2 standard for new aircraft that provides real, additional emission reductions.

Worryingly, the slow pace of improvement since 1990 suggests that short-to-medium term efficiency gains from the introduction of new equipment may be quite limited. As a first approximation, fleetwide efficiency tracks the efficiency of new equipment with a 20-year delay. By this rule, the falling rate of fuel burn improvement identified in this report means that new equipment delivered in 2008 will burn 9% less fuel on average than the in-service fleet per seat-km of activity, compared to a 33% reduction from new aircraft delivered ten years ago relative to the 1998 in-service fleet. Absent dramatic, unforeseen improvements in the efficiency of new delivered aircraft over the next decade, the benefits of introducing new equipment will fall even further.[11]

A well-designed CO_2 standard for new aircraft, adopted either through ICAO or by member countries, may help alleviate this trend provided that it sufficiently incentivizes the deployment of efficient technologies and designs. A CO_2 standard that promotes both new aircraft and engine offerings and incremental improvements from in-production designs would have the greatest impact on emissions. In particular, ICAO's stated high-level preference for a CO_2 standard for "new aircraft types" (ICAO 2009b), which in essence would grandfather in existing production lines and possibly derivative products as well, could prolong the current period of limited efficiency improvements by *delaying* the introduction of new aircraft designs by manufacturers wishing to avoid triggering the standard. A broader standard affecting all in-production designs would promote the timely deployment of efficiency innovations and would likely be more effective as a result.

Given the outlook for continued growth, market-based measures to constrain demand growth and accelerated improvements in operational efficiency will also be needed to meet the climate protection goals being discussed today (Lee et al. 2009).

APPENDIX A: GLOSSARY

Term	Explanation
Aircraft model	An aircraft production family, e.g. B757, B767 etc.
Aircraft series	A variant within an aircraft model, e.g. 767-200, 767-300, etc.
Activity	A measure of use. Here, block hrs per year.
Available flight level	The flight altitudes allowed to an aircraft. Multiplying flight level by 100 feet gives nominal ("pressure") altitude.
Available seat-km (ASK)	A measure of capacity (passengers only) on commercial aircraft.
Available ton-km (ATK)	An aggregate measure of aircraft capacity for passengers plus cargo on commercial aircraft.
Aviation-induced cloudiness	Impact of aviation emissions on cloud formation, including contrails and secondary cirrus formation.
Belly freight	Non-luggage cargo carried on passenger aircraft.
Block hours	Gate to gate hours in operation, including taxi, takeoff, and landing.
Block fuel burn	Gate to gate fuel burn
Delivery	When a new aircraft is provided to an airline. Used for weighting instead of sales due to large time lag between signing a purchasing contract and actual delivery.
Design range	A design parameter denoting the maximum range an aircraft can fly at full load, either all seats filled (passengers only) or at maximum payload (passengers plus cargo).
Engine model	An engine production family, e.g. TRENT, JT9D, etc.
Engine series	A variant within an engine model, e.g. TRENT 772, 900, etc.
Fuel burn	A fuel consumption term for an entire aircraft. Typical units are grams of fuel/ASK or fuel/ATK.
High bypass ratio turbofans	Large, efficient modern jet engines with low fuel consumption and relatively high NOx emissions.
Maximum takeoff weight (MTOW)	A regulatory maximum weight of a loaded aircraft at takeoff.
Maximum zero fuel weight (MZFW)	The maximum weight of an aircraft minus fuel.
Narrowbody aircraft	Single isle aircraft used to serve short-haul and regional routes.
New aircraft types	A regulatory term denoting new aircraft designs.
Operating empty weight (OEW)	The weight of an aircraft without payload or fuel.
Specific air range	Air distance traveled per unit of fuel burn (km/kg).
Radiative forcing (RF)	A measure of a change in the balance of energy entering and exiting the Earth's atmosphere. Used to predict climate impacts such as temperature, drought and precipitation changes.
Regional jets	Small, single-aisle jet aircraft used on regional routes.
Revenue seat kilometers (RSK)	A measure of passengers moved, calculated as ASK times a load factor.
Widebody aircraft	Dual aisle aircraft typically used to serve high-capacity medium and long-haul routes.

APPENDIX B: SENSITIVITY ANALYSIS

Two simple sensitivity analyses – one on mission length, and the other on the potential for year on year improvements within an aircraft-engine combination – were conducted on the results summarized in Section 3.

DESIGN RANGE VERSUS OPERATIONAL RANGE

This report aims to estimate the efficiency of new aircraft *as designed*. Consistent with that aim, the seat-km and ton-km fuel burn of representative aircraft models were estimated at design ranges, either maximum range with a design payload (seat-km), or maximum range at maximum payload (ton-km).

Modern commercial aircraft are typically designed for extreme rather than representative missions, allowing airlines to reduce capital and some operational costs by flying a single aircraft model on a large variety of missions. Aircraft are most often operated on flight lengths considerably shorter than their designed range.

While the practice of flying aircraft on missions well below their design range reduces system wide efficiency[12], aircraft do burn more fuel at design lengths than shorter ranges due to the need to "burn fuel to carry fuel." It is therefore useful to consider whether this paper's primary findings are sensitive to assumption of stage length. Table B-1 summarizes the results of a sensitivity test with respect to mission length, using flight lengths of 900 km for narrowbody aircraft and regional jets and 5400 km for widebody aircraft in place of design ranges. Where either range exceeds maximum range at maximum payload for the ATK metrics, maximum range at maximum payload was used instead.

As Table B-1 indicates, with the exception of seat-km improvements from 1990 to 2008, our results are broadly insensitive to assumptions about range. The flattening of improvement after 1990 is in fact more pronounced using simulated operational ranges in place of design ranges. The most significant difference, the annual rate of post-1990 improvement on a seat-km basis, appears to be attributable to a slower rate of improvement post-1990 for narrowbody aircraft and regional jets operating inefficiently at very short stage lengths.

INCREMENTAL IMPROVEMENTS WITHIN AN AIRCRAFT TYPE

The second major way in which this study's findings may be sensitive to assumptions relates to the potential for hypothetical year-on-year improvements within an aircraft type. Since this analysis uses static representative Piano models to estimate fuel burn, it is not clear how possible year-on-year improvements (e.g. engine modifications, minor aerodynamic improvements such as reshaping pylons, etc.) within a given aircraft and/or engine series are handled. Industry sources typically assume some level of improvement within an aircraft design through incremental improvements over its production life.

Where improvements over time within an aircraft model are linked to a change in series (-100 to -200) or a new aircraft/engine combination within a given series, in many cases this leads to a change in representative Piano models and a subsequent change in estimated fuel burn. Relative reductions in fuel burn by delivery year are observed within most major in-production narrow and widebody aircraft families (Table B-2, negative values imply an increase in fuel burn). Incremental changes that do not translate to a new aircraft series name or aircraft/engine combination are a more

TABLE B-1. SENSITIVITY ANALYSIS ON MISSION RANGE

Metric	Case	Annual improvement 1960-1990	Annual improvement 1990-2008	Cumulative Improvement
Seat-km	Baseline	2.1%	0.40%	103%
	Operational Range	2.1%	0.22%	92%
	Variation	**-4%**	**-44%**	**-11%**
Ton-km	Baseline	2.0%	0.62%	103%
	Operational Range	2.0%	0.52%	98%
	Variation	**-1%**	**-16%**	**-4%**

TABLE B-2. ESTIMATED ANNUAL EFFICIENCY IMPROVEMENTS BY AIRCRAFT FAMILY

Family	Year of Delivery First	Year of Delivery Last[1]	# of Piano-X models	Implied annual eff. change ASK	Implied annual eff. change ATK
B737	1967	2008	17	1.0%	0.8%
B747	1969	2005	7	1.0%	0.8%
B757	1982	2005	6	0.2%	0.3%
B767	1982	2008	5	0.2%	0%
B777	1995	2008	6	0.3%	0.2%
A320	1988	2008	10	0%	0%
DC-8	1959	1972	2	0.1%	0.9%
DC-9	1965	1982	2	0.3%	0.4%
DC-10	1971	1989	2	-1.4%	0.2%
MD-80	1980	2000	5	-0.2%	0.2%

[1] Passenger aircraft only. Dedicated freighter deliveries may be continuing.

difficult issue, although we note that those reductions might also be expected to be smaller than the annual improvements values summarized in Table B-2.[13]

To test the sensitivity of our results to year-on-year improvements within a given aircraft type, we here assume that a given aircraft engine combination continues to improve in efficiency by 0.25% annually after their introduction. For example, a 777-200 with a TRENT 892 engine delivered in 2007 is assumed to have only 97.5% ($1/1.0025^{10}$) the fuel burn of one delivered in 1997. This value is consistent with previous industry projections of future aircraft efficiency improvements, and due to the manner in which Piano models are calibrated is likely to overestimate the magnitude of year-on-year improvements within an aircraft design.[14] The results of this sensitivity analysis are shown in Table B-3.

As with mission range, our results are largely insensitive to assumptions about year-on-year improvements within an aircraft series, with aggregate and annual fuel burn reductions assuming incremental improvements within a given aircraft design being about 1 to 3% larger over the long run and prior to 1990 than without. Consistent with the understanding that the average age of aircraft production lines has increased significantly after 1990, the assumption of incremental improvements increases the annual modelled fuel burn reduction by 14% and 9% for ASK and ATK, respectively, over baseline conditions. This does not change the primary findings regarding the falling pace of efficiency improvements since 1990.

APPENDIX C: COMPARISON WITH PREVIOUS WORK

As noted in Section 1, industry, academic, and research organizations have in the past made efforts similar to that summarized in this paper to estimate long-term improvements in new aircraft fuel burn. While all of these studies save Thomas et al. (2008) have found

TABLE B-3. SENSITIVITY ANALYSIS ON INCREMENTAL EFFICIENCY IMPROVEMENTS

Metric	Case	Annual improvements 1960-1990	Annual improvements 1990-2008	Cumulative Improvement
Seat-km	Baseline	2.1%	0.40%	103%
	YoY improvement	2.2%	0.46%	106%
	Variation	**1%**	**14%**	**3%**
Ton-km	Baseline	2.0%	0.62%	103%
	YoY improvement	2.0%	0.67%	106%
	Variation	**1%**	**9%**	**3%**

TABLE C-1. COMPARISON OF RESULTS TO NOTABLE PREVIOUS WORK

Source	Metric	Period	Reduction (%)
Rolls-Royce, cited in Albritten et al. (1997)	fuel/ASK	1960-1997	70%
Lee et al. (2001)	fuel/ASK	1960-1995	64%[1]
Peeters et al. (2005)	fuel/ASK	1960-2000	55%
Thomas et al. (2008)	fuel/RSK[2]	1960-2010	82%
This study	fuel/ASK fuel/ATK	1960-2008	51% 51%

[1] 1960-2000, as estimated from power curve relationship by Peeters et al. (2005).
[2] Implied – see discussion below.

a falling rate of new aircraft fuel efficiency improvement over time, the relative magnitude of total fuel burn reductions varies. This appendix compares study results and, where possible, offers tentative suggestions for the differences in results.

Table C-1 summarizes the previous studies considered in this paper.

As shown in Table C-1, this analysis has generated the smallest estimated fuel burn reduction of the studies to date. While a lack of transparency in methodology and assumptions for many of these analysis, particularly Thomas et al. (2008) make comparison difficult, these differences are likely attributable primarily to the following:

1. This report's use of sales-weighting, which minimizes the influence of commercially unimportant models and reflects the fact that older, less-efficient aircraft models often continue to be produced for years after a more efficient model or configuration has been introduced.
2. The inclusion of short-haul aircraft (narrowbody and regional jets), which tend to be less efficient than widebodies on certain missions, particularly on a ton-km basis.

A more detailed comparison with each of the studies summarized in Table C-1 is provided below.

ROLLS-ROYCE, CITED IN ALBRITTEN ET AL. "GLOBAL ATMOSPHERIC EFFECTS OF AVIATION." (1997)

While not discussed in the original Albritten report, upon request Rolls-Royce provided general information about methods and assumptions underlying its analysis, including seat counts (three class seating for all aircraft), load factor (70%), range (1850 km), and payload (passenger to mass conversion factor of 100 kg used). While a detailed sensitivity analysis could not be conducted due to time constraints, we offer the following possible reasons for the higher fuel burn reduction estimated in that graph:

- The analysis is not sales-weighted. As a result, the Rolls-Royce trend line should act as a leading indicator for efficiency in that it overweights new designs relative to their prevalence in a given year's delivery mix.
- The report started its trend line with the unusually inefficient Hawker Siddeley Comet-4 (76 deliveries between 1958 and 1967 in all configurations), rather than the more efficient and more commercially successful Douglas DC-8 family (319 deliveries over the same period) or the Boeing 707 family (504 deliveries). This generated a high baseline and therefore a larger reduction.

- As noted above, the analysis excludes short-haul narrowbodies and regional jets, which might be assumed to adopt fuel efficiency technologies more slowly than long-haul aircraft.
- Assumption of three class seating (first, business, and economy class) for early long-haul jets likely leads to lower seat counts and therefore higher fuel burn on a seat-km basis relative to Piano for 1960's and 70's era aircraft. Since airlines began using business class around 1980, those seat counts may be representative of older aircraft in-service since that time rather than as delivered in the 1960's and 70's, the focus of this report.

LEE ET AL. "HISTORICAL AND FUTURE TRENDS IN AIRCRAFT PERFORMANCE, COST, AND EMISSIONS." (2001)

While this study aimed to cover in-fleet efficiency improvements broadly, including operational improvements and technology introduction into the in-service fleet, an estimate of new aircraft efficiency improvement (E_u, or aircraft energy usage) was provided. The following general observations may be made:

- 31 representative aircraft were chosen representing prominent widebody and narrowbody designs. Consistent with the focus on the period to 1995, relatively inefficient yet commercially important regional jets do not appear to have been included.
- The contribution of new equipment to in-service fleet efficiency improvements was estimated from the Breguet range equation using aggregate, publicly sourced variables, supplemented and verified by industry sources. Some input variables to the Breguet equation (e.g. SFC, L/D) deviate from their cruise values at takeoff which may influence the estimated share of efficiency improvements contributed by new equipment to block fuel use, the focus of this study.
- Given the reliance upon actual in-service data, it is unclear how the inclusion of belly freight in the analysis impacts the estimated seat-km fuel burn of passenger aircraft (recall that our study intentionally excludes belly freight from its estimation of fuel burn/ASK).

PEETERS ET AL. "FUEL EFFICIENCY OF COMMERCIAL AIRCRAFT: AN OVERVIEW OF HISTORICAL AND FUTURE TRENDS." (2005)

As shown in Table C-1, owing to similarities in methodology the estimate of 55% reduction in fuel burn from 1960 to 2000 on an ASK basis most closely matches this study's estimate. Key reasons for the smaller discrepancy may include:

- The use of the Boeing 707-320, rather than the Comet-4, as the start point for the analysis. Use of the 737-200, an efficient and commercially successful model, should provide results closest to that obtained by sales-weighting.
- The inclusion of one modern narrowbody aircraft, the Boeing B737-800 with winglets. Note that regional jets were not included.

THOMAS ET AL. PLANE SIMPLE TRUTH: CLEARING THE AIR ON AVIATION'S ENVIRONMENTAL IMPACT. 2008.

This analysis, which has been cited prominently by the International Air Transport Association (IATA 2009), estimated unusually large fuel efficiency improvements that crucially do not tail off over time per every other analysis. Since no detail was provided on methods by the authors in their book, nor made available upon request, it is impossible to adequately compare results beyond the following general observations:

- The analysis appears to be an extrapolation of the Rolls-Royce figure (Albritten 1997), with the same methodological differences discussed above holding true here.
- The post-1997 fuel burn reductions for new aircraft do not appear supportable in light of manufacturer claims and independent modeling results. For example, fuel burn reductions attributed to the A380 and B787 (estimated from the figure as approximately 40% and 45% reductions from the aircraft they are meant to replace, respectively), are more than double that advertised by their manufacturers. One possible explanation is that operational improvements, particularly increasing load factor, have been mixed with pure technology improvements, making the applicable metric fuel burn per revenue seat kilometer (RSK).

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ENDNOTES

[1] Since the CO_2 emitted from an aircraft in flight is inversely related to its efficiency, these terms are synonymous.

[2] See ICSA (2009) and Rutherford (2009) for further details regarding critical issues for standard design.

[3] Fuel burn is a common industry measure of the efficiency of an entire aircraft (airframe plus engine combination). These and other terms are defined in the Glossary in Appendix A.

[4] Information available at www.lissys.demon.co.uk/PianoX.html.

[5] Previous versions of Piano have been used in ICAO work on aircraft efficiency, and the model itself was extensively validated during the development of the European Community's AERO2k emissions inventory (Eyers 2004). Piano fuel burn and emissions estimates have also been used as the basis for ICAO's carbon calculator and Manchester Metropolitan University's FAST model.

[6] For most transport modes, fuel efficiency is calculated as a sales-weighted average to ensure that the prevalence of popular models is adequately reflected in industry or corporate averages. For aircraft, the long delay between an order and that aircraft entering into service makes aircraft deliveries the proper basis for calculating a weighted average. For simplicity's sake we refer to this as "sales weighting" throughout this paper.

[7] During external review of this draft analysis, the original 737-200 in Piano-X was found to be representative of significant post entry-into-service improvements, necessitating this change. The updated versions of all representative aircraft are included in the most recent Piano-X database.

[8] Fuel burn is inversely related to fuel efficiency, so a 50% reduction in fuel burn corresponds to a doubling of fuel efficiency. By convention in this paper we refer to a reduction in fuel burn in figures as an increase in aircraft efficiency.

[9] The replacement of efficient turboprop aircraft with less efficient regional jets, which offer speed, noise, and perceived safety advantages to consumers but can consume 20% more fuel than the turboprops they replace, is another recent example of prioritizing performance over fuel burn.

[10] Increased performance may be also linked to a strategy of reducing the optimization of new aircraft designs around specific missions, which reduces costs for manufacturers by allowing them to market fewer aircraft designs. Note, for example, Boeing's decision to discontinue production of mid-range aircraft (the 757 and 767 families) and to replace the 767 family with 787 Dreamliner. The 787-8 is more similar to a long-haul 777 than a 767 model in terms of speed, range, and cargo capacity: as a result, the 787 is expected to offer little if any reduction in seat-km fuel burn when flown on missions previously served by the 767-300 ER. See Figure 7, in Rutherford (2009).

[11] Recent industry presentations to ICAO (ATAG 2009) estimate a maximum efficiency improvement for new aircraft of 1.16% per annum through 2050. Improvements of this magnitude would require a much faster pace of new aircraft and engine introduction than has occurred over the past two decades.

[12] For example, aircraft designed for 4000 km missions are less efficient when flown on 1000 km routes than an equivalent aircraft optimized around that flight length due to excess wing, engine, and fuel tank weight. Operational efficiencies could therefore be improved significantly through greater optimization of aircraft to individual missions, albeit at a cost to airlines.

[13] If not, the introduction of a new aircraft series within a given family would be associated with an increase in fuel burn.

[14] Piano's representative models are calibrated via comparison to available data from actual aircraft at a variety of stages during their production, with some near the start and others near the end of production cycles. As a result, some of the incremental year-to-year improvements may already be captured.

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