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Costs of mitigating CO_2 emissions from passenger aircraft

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In response to strong growth in air transportation CO_2 emissions, governments and industry began to explore and implement mitigation measures and targets in the early 2000s. However, in the absence of rigorous analyses assessing the costs for mitigating CO_2 emissions, these policies could be economically wasteful. Here we identify the cost-effectiveness of CO_2 emission reductions from narrow-body aircraft, the workhorse of passenger air transportation. We find that in the US, a combination of fuel burn reduction strategies could reduce the 2012 level of life cycle CO_2 emissions per passenger kilometre by around 2% per year to mid-century. These intensity reductions would occur at zero marginal costs for oil prices between US$50–100 per barrel. Even larger reductions are possible, but could impose extra costs and require the adoption of biomass-based synthetic fuels. The extent to which these intensity reductions will translate into absolute emissions reductions will depend on fleet growth.

Air transportation releases around 2.5% of global fuel combustion-related CO_2 emissions[1,2]. In addition, since 1980, this sector's emissions have increased at 3.6% per year, that is, twice the world total growth rate[2]. Non-CO_2 effects from aviation, which partly scale with CO_2 emissions, can also contribute to climate change[3]. In response to this growth trend, the European Commission, two US Government agencies, the International Civil Aviation Organization, and the International Air Transport Association began to explore or implement CO_2 mitigation measures and targets (see Supplementary Information: Government and Industry Action.) For these interventions to have an economic rationale, they need to rely on a solid understanding of the potential for and costs of mitigating CO_2 emissions. Yet, this need contrasts sharply with the current body of studies in this area.

Existing studies consist of consultancy reports with a global focus[4–6] and a UK perspective[7], two studies of the UK air transportation system[8,9], and one detailed techno-economic study of three retrofit technologies[10]. These analyses are valuable first steps towards a better understanding of the economic benefits and costs of CO_2 mitigation but possess limitations. For example, refs 5,6 do not report the underlying assumptions, methods and data employed, which yields non-reproducible results; refs 8,9 do not consider the age composition of the aircraft fleet, which is a critical omission as fuel efficiency differs by age cohort thus affecting mitigation potentials and costs; ref. 7 omits important cost elements of key mitigation options; refs 7,10 consider only a narrow range of mitigation strategies, thus limiting our understanding of the overall mitigation potential. The shortage of carefully conducted studies may help explain the lack of comprehensive economic assessments of aviation emission reduction opportunities in the transport chapter of all Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, and the perception that reducing aircraft CO_2 emissions may be more difficult and more expensive compared with other sectors[11].

Here we present a techno-economic analysis of 21 CO_2 emission mitigation options for the domestic US aviation sector, the world's single largest air transportation system. We focus on narrow-body aircraft with 100–189 seats, which generate 80% of revenue passenger kilometres (RPKs), that is, those passenger kilometres that generate airline revenue, burn nearly 75% of commercial passenger aircraft consumed jet fuels, and hence also release nearly 75% of CO_2 emissions (Supplementary Table 1). Our analysis is based on an aircraft fleet composition and CO_2 emissions model that allows: a realistic simulation of the introduction of improvements to existing aircraft (retrofits) and of new aircraft generations; a robust assessment of the CO_2 emissions mitigation potential and cost of all mitigation options related to the aircraft age cohort (those aircraft of a given vintage) that would be affected; and simulation of the scheduling of aircraft retrofits in line with major maintenance checks to minimize the opportunity costs of non-available aircraft (see Methods). In addition, we account for all relevant cost elements affecting airline operating costs, using the most recent data available.

Fleet CO_2 intensity

Figure 1 depicts the historical decline in life cycle CO_2 intensity (life cycle CO_2 emissions per RPK) of the US commercial passenger aircraft fleet and of the narrow-body passenger fleet[12,13]. Also shown is the estimated historical development of the CO_2 intensity of new narrow-body aircraft, which, after around 15 years, translates into that of the aircraft fleet.

The decline in fleet CO_2 intensity was particularly strong (at a rate of nearly 5% per year) between 1970 and 1980, mainly owing to increases in the efficiency of aircraft engines. Thereafter, CO_2 intensity continued to decline at a lower rate of 2% per year owing to mainly continuous improvements in engine efficiency, aerodynamics and utilization of aircraft capacity[12]. As commercial air transportation nearly exclusively burns petroleum-derived jet fuel, the historical decline was entirely a result of fuel efficiency improvements. Despite the past achievements, there continue to exist opportunities for further strong reductions, as shown by the projected future developments in Fig. 1 and discussed below.

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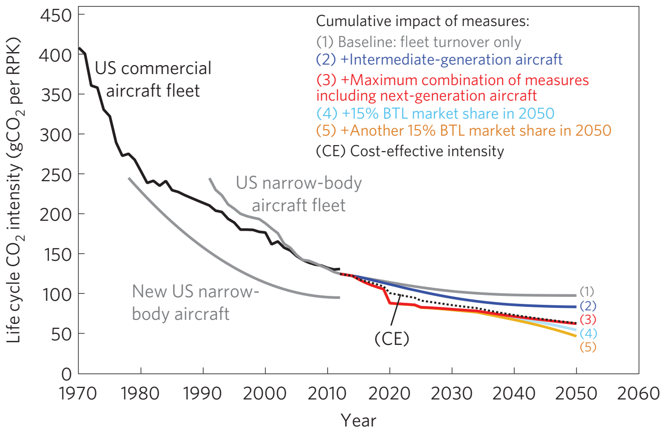

Figure 1 | Life cycle CO_2 emissions intensity of the US commercial passenger aircraft fleet operating in domestic service (black) and of the narrow-body fleet (grey), historical development (1970–2012) and projections (2013–2050). Owing to increases in aircraft fuel efficiency improvements, the CO_2 intensity of the US aircraft fleet declined by nearly 5% per year between 1970 and 1980, and by 2% per year thereafter. Despite the past achievements, there continue to exist opportunities for further strong reductions at least to 2050. Data sources for historical trends: refs 12,13.

Opportunities for mitigation

The opportunities for reducing aircraft CO_2 intensity can be illustrated by the Breguet range equation, modified such that CO_2 intensity represents the left-hand-side variable (equation (1)). Although this equation applies only to cruise flight, most fuel is burnt in the cruise phase and hence it offers intuition to understand the determinants of CO_2 emissions.

$$\frac{CO_2}{RPK} = CO_2EF\frac{Q \times SFC}{PAX \times V \times L/D}\frac{W_F}{\ln(W_0/(W_0 - W_F))} \qquad (1)$$

In equation (1), CO_2EF is the CO_2 emissions factor (87.6 $gCO_2\,MJ^{-1}$ for Jet A-1 fuel on a life cycle basis, that is, after accounting for upstream emissions with respect to crude oil extraction, transportation, refining, jet fuel distribution and storage, which represent around 21% of the fuel carbon-related CO_2 emissions[14]), Q is the fuel's lower heating value (42.8 $MJ\,kg^{-1}$ for jet fuel), SFC is the engine-specific fuel consumption (fuel burn per unit thrust), PAX is the number of passengers, V is the aircraft speed, L/D is the lift-to-drag ratio, W_F is the fuel weight before takeoff, and W_0 is the aircraft weight at takeoff. Hence, aircraft CO_2 intensity can be reduced through fuels containing less carbon on a life cycle basis, higher engine efficiency, a larger number of passengers, higher aerodynamic efficiency, and a lower structural weight (a smaller W_0–W_F). Note that the variables in equation (1) are interrelated. Thus, changing one variable will lead to changes in others, typically offsetting part of the impact on CO_2/RPK.

Each of the 21 mitigation options examined in this study influences at least one determinant of the CO_2 intensity in equation (1). We derive these options' CO_2 emissions reduction potential and costs from academic studies, industry sources and our own calculations. (Supplementary Information: Measures for Reducing Narrow Body Aircraft CO_2 Emissions.) The measures, which are listed with the main techno-economic characteristics in Tables 1–3, can be grouped into four families.

Technology options (Table 1) represent the first family of measures and comprise five retrofit options, one intermediate-generation aircraft type and two next-generation aircraft types aiming to reduce SFC, structural weight, and/or increase L/D. The second family includes cellulosic biomass-based synthetic fuels (biomass-to-liquids (BTL)) aiming to reduce CO_2EF (Table 1). Air traffic management measures (Table 2) correspond to the third family and contain five strategies that consist of bundles of measures, aiming to reduce SFC and the excess distance an aircraft flies. The last family of measures encompasses airline operational strategies (Table 3). Theses include nine measures aiming to increase the number of PAX and L/D, or to reduce SFC along with the fuel weight.

Other studies (for example, ref. 8) evaluated also the CO_2 mitigation characteristics of engine upgrade kits and auxiliary power units. We deliberately exclude these and other options from our analysis, as they seem too speculative in the absence of reliable data. We also exclude secondary mitigation opportunities that arise from some of the above options, such as increased seat density due to lighter and thinner aircraft seats and subsequent cabin re-optimization, as their degree of exploitation is uncertain.

Mitigation potentials and costs

To estimate the CO_2 abatement potentials and costs for the US narrow-body aircraft fleet, we introduce the mitigation options summarized above and described in Tables 1–3 into our fleet composition and CO_2 emissions model. (Our model and choice of parameters are designed to minimize possible interactions of mitigation measures.) As a reference condition we use the average operational characteristics of the US narrow-body aircraft fleet (Supplementary Table 1). We assume that aircraft utilization remains unchanged relative to the 2012 level, that is, an average of 268 million RPK per narrow-body aircraft per year.

The baseline development, which incorporates only the introduction of 2012 technology through natural fleet turnover, would lead to a 22% decline in the life cycle CO_2 intensity of the narrow-body fleet from 125 gCO_2 per RPK in 2012 to 98 gCO_2 per RPK in 2050, as depicted by curve (1) in Fig. 1. If also taking into account the planned adoption of more fuel-efficient intermediate-generation aircraft starting in 2016, the 2050 fleet CO_2 intensity would be 15% below the baseline development or 34% below the 2012 intensity as shown by curve (2) in Fig. 1. The related annual average decline corresponds to 1% per year.

We now explore the implications of introducing the maximum feasible combination of retrofit options, air traffic management measures and airline operational strategies that already exist or are under development. In addition, we simulate the introduction of a next-generation aircraft starting in 2035, which could offer a roughly 30% fuel burn and CO_2 emissions reduction over the intermediate-generation aircraft. This pronounced decline is enabled by mainly open rotor engines, an all-carbon fibre airframe, and the structural advantage resulting from non-swept wings, which are made possible by a slight reduction of cruise speed[15,16]. As a result of introducing this portfolio of mitigation strategies, the 2050 fleet CO_2 intensity could decline by an additional 25% relative to the baseline development plus intermediate-generation aircraft technology, as shown by curve (3) in Fig. 1. Further reductions could be realized through cellulosic biomass-based synthetic fuels. A 15% (or 30%) BTL share of jet fuels consumed in 2050 could lead to a further 13% (or 26%) decline in the 2050 CO_2 intensity of the narrow-body fleet, as depicted by curves (4) and (5) in Fig. 1. Thereby, the 30% BTL share would lead to an average decline in CO_2 intensity by 2.6% per year. If taking into account only the CO_2 emission reduction options with negative or zero marginal costs identified in Fig. 2 below, the projected 2050 fleet CO_2 emissions intensity would decline by 50% compared with the 2012 level; see dotted curve (CE) in Fig. 1. The associated annual decline by nearly 2% of the cost-effective intensity trajectory essentially continues the more recent (1980–2012) development.

Table 1 | Techno-economic characteristics of CO_2 mitigation technologies and synthetic fuels at a fuel price of US$3.1 per gallon (crude oil price of US$100 per bbl).

	Year of introduction	Application potential* (% of fleet)	Life cycle CO_2 emissions reduction (% per aircraft)	Payback period† (yr)	Mitigation costs† (US$ per tonne of CO_2)
Retrofits					
Blended winglets	2015	25	3.0 (2–4)	3.3	−80
Carbon brakes	2015	13	0.35 (>0)	1.0	−10
Re-engining	2016	70	12.5 (1–12)	15	830
Cabin weight reduction					
Mild	2015	0	1.2	2.9	−110
Aggressive	2015	50	2.1 (0.6–1.6)	5.3	70
Electric taxiing	2018	50	2.8 (1.5–4)	2.1	−170
Intermediate-generation aircraft					
A320NEO/B737MAX/CSeries	2016	100	15‡	2.9	−250
Next-generation aircraft					
Evolutionary	2035	0	30‡	6.2	−160
Open rotor	2035	100	40‡	9.7	−70
Synthetic fuels					
Biomass-to-liquids (BTL)	2020	15-30§	13-26‖	0-∞¶	−10-70

All monetary units are in 2010 US dollars. *Numbers underlying our analysis represent upper limit as retrofits are implemented only if investments are fully recuperated by the time the respective age cohort reaches the mean aircraft lifetime of 29 years. †At year of introduction; economic lifetime: 20 years for new aircraft, 5 years for retrofits; discount rate 5%. ‡Reference point: average new narrow body aircraft introduced in 2012. §In 2050. ‖For BTL share of 15–30%. ¶The projected lower end fuel price of US$3.0 per gallon results in immediate benefits, whereas the projected higher end fuel price of US$3.6 per gallon will never result in cost-effectiveness at identical fuel burn at a jet fuel price of US$3.1 per gallon. For details see Supplementary Information. References for estimates and/or literature ranges (in parenthesis): Winglets, refs 4,7,8,20–22; Carbon brakes, refs 23,24; Re-engining, refs 4,8,10,25; Cabin weight reduction, refs 8,26,27; Electric taxiing, refs 28–31; Synthetic fuels, refs 32–34.

Table 2 | Techno-economic characteristics of air traffic management measures at a fuel price of US$3.1 per gallon (crude oil price of US$100 per bbl).

	Full deployment (yr)	Application potential (%)	Life cycle CO_2 emissions reduction* (% per aircraft)	Payback period† (yr)	Mitigation costs† (US$ per tonne of CO_2)
Surface congestion management	2020	100	0.8	0.5	−310
Single-engine taxi	2015	50	2.0	0.1	−320
Optimized departures procedures	2020	75	1.6	3.3	−240
Lateral/vertical/speed inefficiency reduction during cruise	2020	75	4.6	0.2	−320
Optimized approach procedures	2020	75	1.6	3.3	−240

All monetary units are in 2010 US dollars. *Assuming gate-to-gate (block) fuel burn is divided into taxi, departure, cruise and arrival on a 5%, 8%, 83% and 4% basis according to BTS Form 41 block hour analysis. †At year of introduction. For details see Supplementary Information. References for estimates: Surface congestion management: benefits, ref. 35; Single-engine taxiing: benefits, ref. 36; Optimized departures procedures: benefits, ref. 37; costs, refs 38,39; Lateral/vertical/speed inefficiency reduction during cruise: benefits, lateral, ref. 40; vertical, ref. 41; speed, ref. 42; Optimized approach procedures: benefits, Area navigation/Required navigation performance (RNAV/RNP), ref. 37; Continuous descent approaches (CDAs), ref. 43; Delayed deceleration approaches (DDAs), ref. 44; costs, refs 38,39.

A detailed account of the cost-effectiveness of the various mitigation options is shown in Fig. 2 for a jet fuel price of US$3.1 per gallon, which corresponds to an oil price of about US$100 per barrel. In addition, the shape of the curve for an oil price of US$50 per barrel is shown as a thin dashed line. Underlying this figure is a 1.5% annual growth rate of the narrow-body fleet. This rate is slightly lower than industry projections over the shorter 2014–2033 period[17,18], to account for the continuous maturation of the domestic US market. Combining the growth in the narrow-body fleet with the baseline CO_2 intensity described above leads to cumulative (2012–2050) life cycle CO_2 emissions of 4.0 billion tonnes. As can be seen from the horizontal axis of Fig. 2, these projected cumulative emissions could be reduced by about 1 billion tonnes for a 15% adoption of synthetic fuels from biomass in 2050 (or by 1.1 billion tonnes for a BTL share of 30% in 2050, which is not shown here).

Clearly, a combination of strategies would be required for a meaningful mitigation impact. Yet, the mitigation potential is distributed unevenly across the measures. Overall, one-third of the 21 measures could exploit around 80% of the cumulative mitigation potential. Aircraft technology options provide around half of the entire cumulative CO_2 emissions mitigation potential. The second largest potential is offered by air traffic management measures and airline operational strategies with around 20% each. Synthetic fuels from cellulosic biomass would then account for the remaining roughly 10% under the assumed penetration rates.

Table 3 | Techno-economic characteristics of airline operational strategies at a fuel price of US$3.1 per gallon (crude oil price of US$100 per bbl).

	Application potential (% of fleet)	Life cycle CO_2 emissions reduction		Payback period (yr)	Mitigation costs (US$ per tonne of CO_2)
		(% per aircraft)	(% of fleet)		
Reducing contingency fuel by 300 kg	100	0.38 (0.38)	0.38	0	−330
Early replacements by intermediate-generation aircraft					
≥25 years of age, in 2016	10*	55	8.7	11	100
≥30 years of age, in 2016	1*	65	1.0	7	−50
≥25 years of age, in 2020	11*	52	8.7	12	160
≥30 years of age, in 2020	4*	57 (5–20)†	3.9	10	80
Increased PAX load factor through:					
2% reduction of flight frequency	100	−0.3	3.1‡	0.5	−200
Enhanced use of regional jets	0.4§	33	0.3	23	7,500
Enhanced use of turboprops	0.3§	57	0.3	96	32,000
Reduced fuel tankering	15	0.26	0.04 (0.2)	>1	4,100
Additional engine wash	50	0.25 (0.5–1.2)	0.13	0.4	−190
Surface polish and reduced decorative paint	10	0.1 (0.1–1.5)	0.01	>1	4,500

All monetary units are in 2010 US dollars. *Based on 1.5% fleet growth per year. †Replacing 5–20-year-old aircraft: refs 4,8. ‡A large part is related to the retirement of the oldest 2% of the aircraft in the fleet, which are not required anymore. §%RPK. For details see Supplementary Information. Key references for estimates and/or literature ranges (in parenthesis): Reducing contingency fuel, ref. 8; Early aircraft replacements, refs 4,8; Reduced fuel tankering, refs 4,8,9; Additional engine wash, refs 8,45; Surface polish, refs 4,8,46.

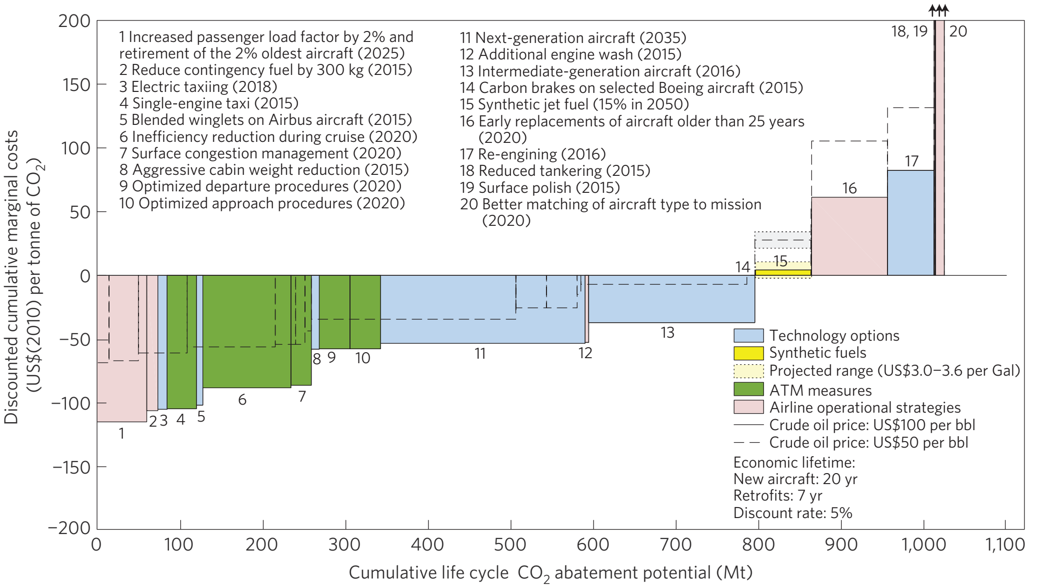

Figure 2 | Discounted marginal abatement costs for cumulative (2012–2050) life cycle CO_2 emissions from narrow-body aircraft in US domestic passenger service. Mitigation options are ranked in sequence of declining cost-effectiveness. Around one-quarter of the cumulative CO_2 emissions of 4.0 billion tonnes that are based on fleet turnover and growth (1.5% per year) could be mitigated if employing all options. At least 75% of that potential could be reduced at zero marginal costs.

As a mitigation cost metric, we employ the cumulative (2012–2050) marginal abatement costs, discounted to 2012 at a rate of 5%. This metric captures all mitigation opportunities over time, as otherwise especially the retrofit options would emerge and vanish owing to the evolving age structure of the fleet. The cumulative nature of the mitigation costs also accounts for fuel burn reductions beyond the period of economic accounting (20 years for new aircraft and 5 years for retrofits according to industry practice), provided they are introduced sufficiently long before 2050. (Partly as a consequence, the mitigation costs in Fig. 2 are lower than those in Tables 1–3.) In addition, our specification of mitigation costs accounts for the stock properties of CO_2 that result from its long atmospheric lifetime. As the exact mitigation potential and costs depend on the year of introduction of each measure (as different age cohorts with different fuel burn characteristics would be affected) and the extent to which each measure is introduced, the figure legend specifies the introduction characteristics in more detail. As can be seen, at least 75% of the CO_2 emissions mitigation potential comes at negative or zero marginal costs. In particular, some airline operational strategies, nearly all technology options, and the entire

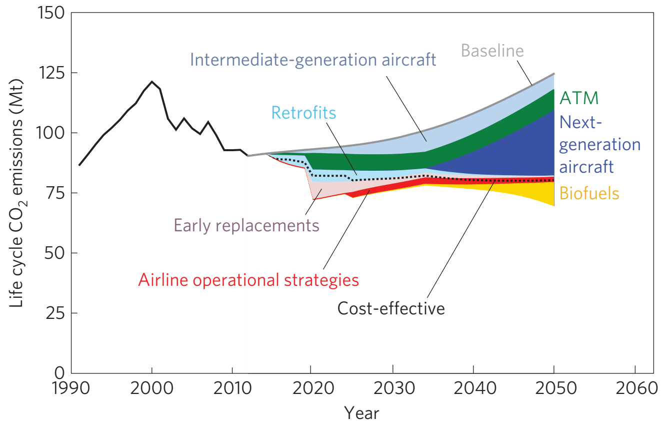

Figure 3 | Life cycle CO_2 emissions, historical trend (1991–2012) and future projections (2013–2050) of the mitigation potential by category of measures. In light of the anticipated fleet growth rate of 1.5% per year, life cycle CO_2 emissions from the US narrow-body aircraft fleet could be reduced by about 10% between 2012 and 2050, even without the introduction of synthetic fuels from cellulosic biomass.

range of air traffic management measures turn out to be cost-effective. If the lower end of the projected range of BTL supply costs of US$3.0–3.6 per gallon can be realized, synthetic fuels could just become cost-effective at a jet fuel price of US$3.1 per gallon.

The identified negative and zero marginal cost measures represent the economically attractive mitigation opportunities from an industry viewpoint (at the chosen discount rate and economic lifetime). Even larger reductions could be justified from a societal perspective, as long as the mitigation costs do not exceed the marginal damages of CO_2. Estimates of the social cost of carbon are highly uncertain, but likely to be above the upper end of the projected cost range of up to US$34 per tonne of CO_2 (oil price of US$50 per barrel) for BTL (ref. 19).

Figure 3 shows the associated wedge diagram of annual CO_2 emissions, where some of the families of measures are further broken down and ranked broadly according to their cost-effectiveness. The introduction of new, highly fuel-efficient aircraft technologies in 2035 is of paramount importance to outpace the anticipated growth in air transportation demand. Additional significant emission reductions could be achieved from synthetic cellulosic biomass-based fuels. The same figure also shows the emission mitigation benefit of retrofits and early aircraft replacements is only short-term; by 2050, their effect over time has virtually evaporated, as by then nearly all of the retrofitted and the early replaced aircraft would have been substituted. Yet, owing to the long atmospheric lifetime of CO_2, the cumulative emission reductions remain beneficial. If only introducing cost-effective options at a fuel price of US$2.0–3.1 per gallon from Fig. 2, the 2050 narrow-body aircraft CO_2 emissions could decline to a level of 77 million tonnes, a roughly 10% decline relative to the 2012 level (dotted line).

Future developments

Natural fleet turnover, the scheduled introduction of intermediate-generation aircraft, the eventual adoption of next-generation aircraft, improvements in air traffic management and slightly more efficient airline operations could reduce the average CO_2 intensity of the US narrow-body fleet by about 2% per year at zero marginal costs for oil prices between US$50–100 per barrel. Further reductions could be achieved through cellulosic biomass-based synthetic fuels.

In addition to CO_2 intensity, the amount of CO_2 emissions will depend on fleet growth. Whereas a fleet growth rate below 2% per year could result in lower 2050 emissions relative to the 2012 level, growth rates higher than 2.6% per year would outpace the CO_2 emission reduction potential of the entire portfolio of measures and adoption rates examined here.

Consistent with our findings, the air transportation industry has already started to pursue all options we identified as being cost-effective. Some of these measures, such as blended winglets, are already being adopted. Many others are likely to be introduced into existing and future models once they become available, thus assuring a continuous decline in operating costs (all other factors equal) and increase in industrial competitiveness.

The limited number of data points underlying many mitigation options does not allow for an uncertainty analysis to be performed without expert elicitation. Clearly, better understanding the uncertainties underlying this study is an important next step. Nonetheless, because we omitted several mitigation options owing to a lack of data and did not explore the optimized timing of their introduction, our key finding that a 2% CO_2 fleet intensity reduction could be achieved at zero marginal costs is likely to be conservative.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions
A.W.S. led the specification of aircraft technologies and synthetic fuels, the development of the model, the analysis of the results, and the preparation of the manuscript. A.D.E. led the specification of the airline operational strategies, developed elements of the model, and contributed to the analysis of the results and preparation of the manuscript. T.G.R. developed the techno-economic characteristics of air traffic management systems, contributed to those of aircraft technologies and airline operational strategies, and contributed to the analysis of the results and preparation of the manuscript. L.D. developed elements of the model, including underlying fleet databases, and contributed to the analysis of the results and preparation of the manuscript.

Additional information
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Competing financial interests
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Methods

Fleet composition and CO_2 emissions model. The narrow-body aircraft fleet composition model generates the fleet age distribution, energy use, and CO_2 emissions in absolute terms and per revenue passenger kilometre (RPK). It takes as inputs the projected narrow-body aircraft fleet size at any year along with the energy intensity level of new narrow-body aircraft. The number of new narrow-body aircraft introduced in each year then results from the difference between the projected total fleet and those aircraft remaining. The number of aircraft retirements is estimated with a generic retirement curve. The effect of international sales (to and from the US) is included where data are available; however, the impact on the overall totals is small.

We employ a retirement curve from those globally operating narrow-body aircraft that were produced between 1965 and 2007 (ref. 47). During that period, these curves' characteristics were stable across aircraft from different manufacture years and world regions. The mean aircraft age at retirement of the cohorts forming the narrow-body fleet was 28.6 years; that is, after that period, half of the aircraft fleet has been retired. Owing to the characteristics of the data, the retirement curves were estimated with a logistic function. This symmetric S-curve is based on the BACK Aviation Fleet Database, which describes key attributes of the world aircraft fleet, such as the number of aircraft types by country, their entry into the fleet, sales of secondhand aircraft, and the year of their retirement between 1960 and 2007 (ref. 48). More recent (2007–2012) data describing the age composition of the US narrow-body aircraft fleet are derived from Form 41 Schedule B43 data[13]. The Form 41 data implies a mean age of 12.1 years for the 2012 US narrow-body aircraft fleet used for domestic passenger transport.

Another key determinant of fleet energy use and CO_2 emissions is the energy intensity of new aircraft. There is a 10–15-year lag between the energy intensity level of an age cohort and that of the fleet[12]. We estimated a second-order polynomial function describing the decline in new narrow-body energy intensity over time, such that the resulting fleet energy intensity, after applying the aircraft stock model to each age cohort, best approximates the observed narrow-body fleet energy intensity development from 1991 to 2012 (the derived relationship is: $E/\text{RPK(year)} = 0.00147839 \times \text{year}^2 - 5.949046 \times \text{year} + 5985.82037$; R^2 between observed and estimated narrow-body aircraft fleet energy intensity for the 22-year period = 0.95). Other functional forms were also tested, including exponential and hyperbolic, but the polynomial function was found to be most plausible and to correspond best to the ranges in energy intensity from new narrow-body aircraft presented by ref. 12. For all age cohorts forming the 2012 narrow-body fleet, we assume an annual fuel burn deterioration of 0.2% due to wear and tear, compounded over the respective aircraft age[49].

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