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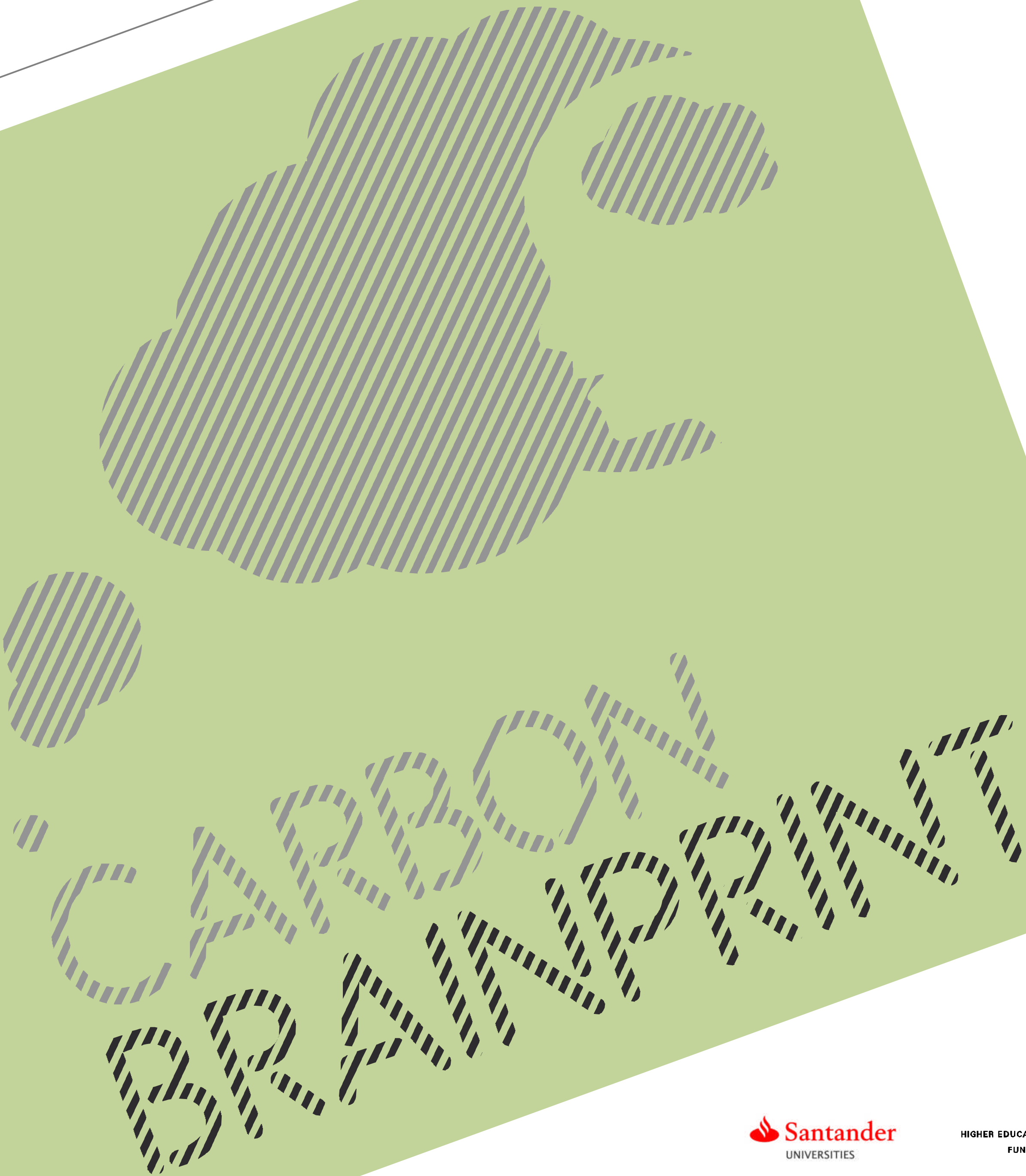
Carbon brainprint case study

Ceramic coatings for jet engine turbine blades



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Carbon Brainprint Case Study

Ceramic coatings for jet engine turbine blades

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Summary

Ceramic thermal barrier coatings (TBCs) are applied to jet turbine blades to protect them from the high temperature gases leaving the combustion chamber and to increase the efficiency of the engine. Professor John Nicholls of the Surface Science and Engineering Group, Cranfield University has been working with Rolls-Royce plc for about 17 years to improve the insulating performance of TBCs. As a result, the TBCs used in the current generation of aircraft turbofan jet engines achieve a temperature drop about 80 ^{o}C greater than at the start of the work, with an estimated fuel saving of about 1%.

This case study considered two engine types: Trent 700, used on about half the Airbus A330 aircraft currently in service, and Trent 500, used on all Airbus A340-500 and A360-600 aircraft. The greenhouse gas emissions considered were, in order of magnitude, carbon dioxide from combustion of the fuel, emissions during extraction and refining of the fuel, and emissions of other greenhouse gases during combustion. Emissions associated with transport of the fuel were found to be negligible compared with these, and all emissions not related to fuel consumption, for example manufacture of the coating, were also assumed to be insignificant or excluded from the assessment because they were unaffected by the change in the TBC.

The baseline fuel consumption during each flight phase (landing and take-off cycle and cruise) was estimated from publicly available data. Airline activity data for A330 and A340 models from European operators was taken to represent typical patterns of use, enabling annual emissions per aircraft to be calculated. Data on current operating aircraft and orders were then used to estimate the total current and projected future emissions. From these, the higher emissions that would have occurred in the past if the improved TBCs had not been used, and the corresponding future emissions, were estimated.

The best estimates of the current emissions (the retrospective brainprint) for individual aircraft were 1016, 1574 and 1646 t CO_2e/year for A330, A340-500 and A340-600 respectively, giving 568 kt CO_2e/year for the total fleet. Including all the aircraft on order, the prospective emissions reduction was 833 kt CO_2e/year. Assuming a service life of 20 years, the total brainprint was approximately 17 Mt CO_2e.

An uncertainty analysis was performed with assumed uncertainties for aircraft activity, fuel consumption and the efficiency change. The 95% confidence interval for the current annual emissions reduction was 429–721 kt CO_2e/year excluding the efficiency change uncertainty, and 258–1105 if it was included. The relative changes in the other output measures were similar. Assuming that older engines do not and will not benefit from the improvement, reduced the total brainprint to 14 Mt CO_2e. The assessment did not include an adjustment for the effect of emissions at high altitude, which would increase all the outputs by a factor of 1.9.

General description

This study concerned the high pressure turbine blades located immediately behind the combustion chamber of a jet engine (Figure 1), where the temperature exceeds the melting point of the alloy used in the blades. The temperature in the combustion chamber is about 2000 C and, after mixing with cooling air, the temperature of the gases reaching the turbine is 1400–1500 C, whereas the nickel super alloy used in the blades melts at 1300 C (Rolls-Royce, 2007). Although we will consider only aircraft jet engines, the same technology is used in other gas turbines, such as static engines in power stations.

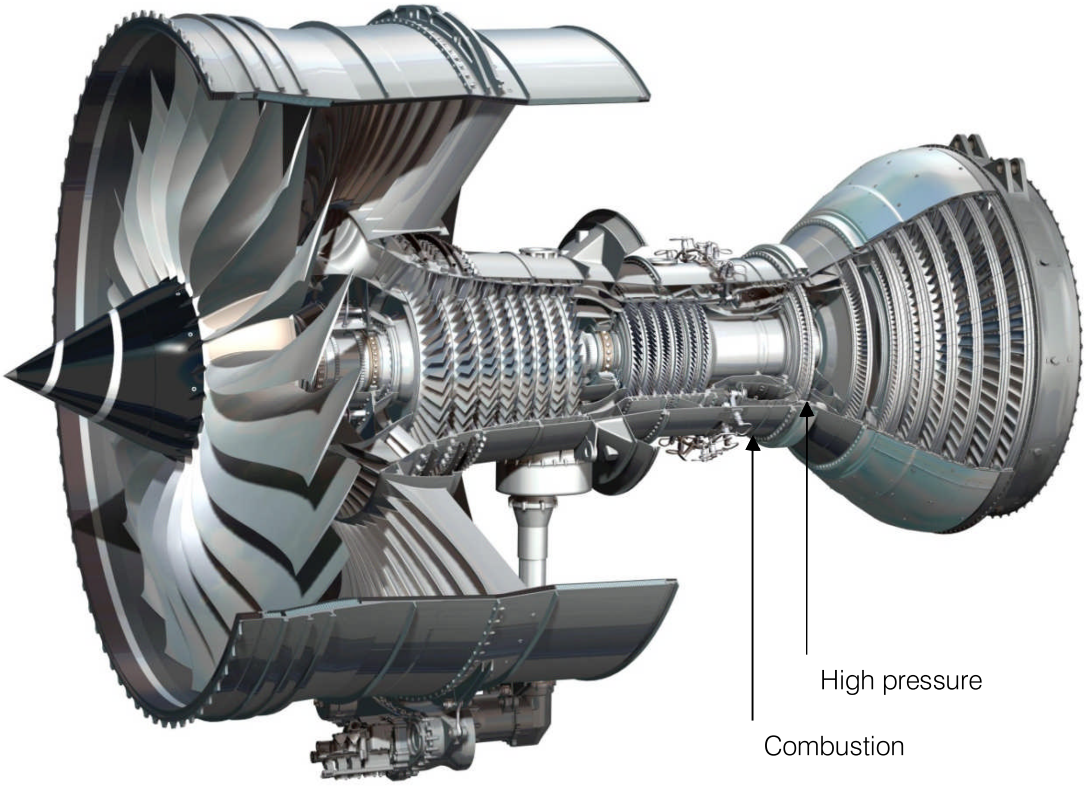

Figure 1. Cutaway view of Rolls-Royce Trent XWB jet turbine
This photograph is reproduced with the permission of Rolls-Royce plc, copyright © Rolls-Royce plc 2010

Two methods are used to protect the blades: internal passages through which air from the compressor is forced from the blade root allowing it to form a layer over the blade surface, and ceramic thermal barrier coatings (TBCs) to insulate and protect them (Figure 2). The benefits of TBCs can be realised in different ways. Less cooling air is required to operate at the same blade temperature, so less power is used by cooling, increasing the efficiency to deliver the same power from less fuel, or deliver more power from the same fuel. Alternatively, the same volume of air can be used, reducing the temperature and increasing the life of the blades.

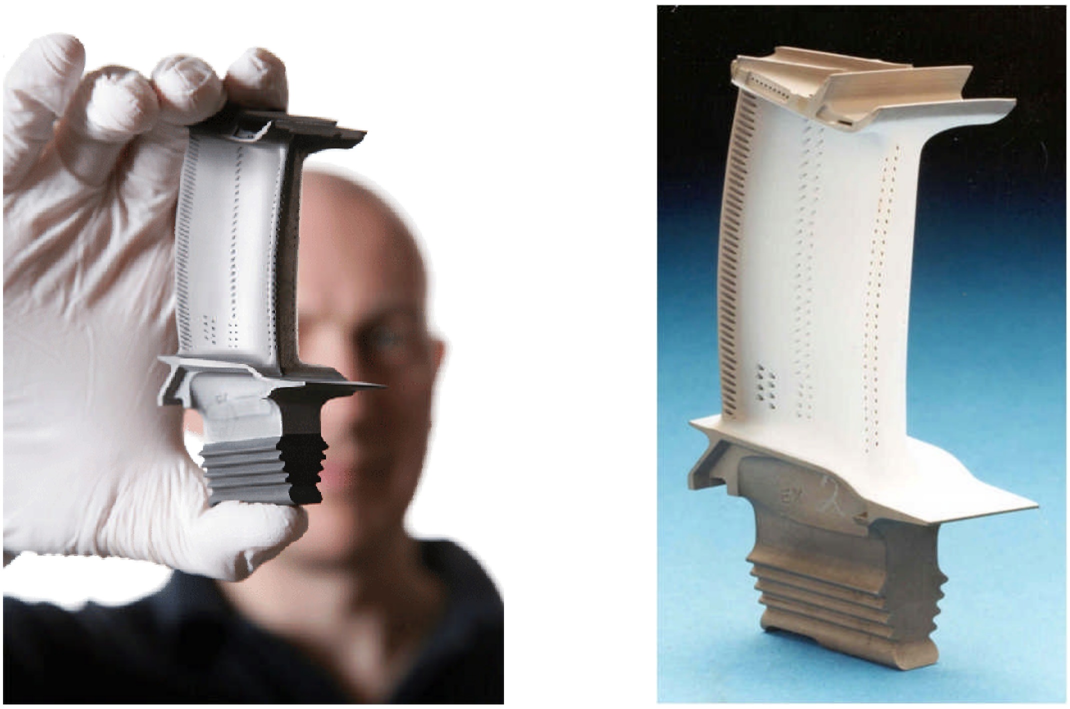

Figure 2. Rolls-Royce jet turbine blade with (a) ceramic coating (white) and (b) outlets for cooling air.
Figure 2a is reproduced with the permission of Rolls-Royce plc, copyright © Rolls-Royce plc 2010

The involvement of Cranfield began about 17 years with an approach to Professor Nicholls from Rolls Royce, who held the patents on the coatings then in use. They have since been developed through a series of contracts, with the first paper published in 1998. Other manufacturers and universities have also been developing TBCs. Before Cranfield started working with Rolls Royce, the temperature drop achieved by the TBC was about 70 C; now it is over 150 C from a 200 μm coating. Coatings of this type are used in all Rolls-Royce Trent series large aircraft engines, found in several Airbus and Boeing models. It has been estimated that these could save a carrier the size of British Airways £25M/year in fuel costs (Rolls-Royce plc, personal communication via J. Nicholls). Professor Nicholls' aim is to increase the temperature drop to 200 C, equivalent to a further £35M/year saving, by improving the insulation and near infra-red reflectance.

Because all modern Trent engines have adopted the new coatings, it was necessary to adopt an inverted baseline approach for this study. The baseline was current engines and aircraft with the current generation of TBCs. Emissions estimates were made for these aircraft using data on fuel consumption and annual use. This was compared with a counterfactual in which the engines delivered the same power without the improved TBCs and therefore had higher fuel consumption. This enabled assessment of the past change in emissions, which were projected forward to estimate the continued change in emissions from this generation of aircraft engines.

This study considered two models of engine: the Trent 700, first introduced in 1995 and used in all models of the Airbus A330, and the Trent 500, introduced in 2002 and used on the A340-500 and A340-600 (Table 1, Table 2).

Table 1. Airbus A330 and 340 models (derived from Airbus web site)

Model	A330-200	A330-300	A340-200	A340-300	A340-500	A340-600
Max range, km	12,500	10,500	14,800	13,700	16,700	14,600
Passengers, typical	253	295	240	295	313	380
MTOW*, t	230	230	275	277	372	368
Fuel capacity, l	139,100	97,170	155,040	147,850	214,810	195,881
Engines, number	2	2	4	4	4	4
Engines, models	Trent 700 CF6-80E1 PW4000	Trent 700 CF6-80E1 PW4000	CFM56-5C4	CFM56-5C4P	Trent 500	Trent 500

* MTOW = Maximum take-off weight

Table 2. A330 and A340 aircraft and Rolls-Royce engine variants (First flight data from Airfleets, 2011)

Airbus model	Engine model	First flight
A330-243	RR Trent 772B-60	1998
A330-243F	RR Trent 772B-60	2009
A330-244	RR Trent 775-60	
A330-341	RR Trent 768-60	1996
A330-342	RR Trent 772-60	1994
A330-343	RR Trent 772B-60/C-60	2004
A340-541	RR Trent 553-61	2002
A340-642	RR Trent 556-61	2001

System boundaries

The impact of TBCs on manufacturing and servicing is confined to the turbine blades themselves, so the rest of the engine and the aircraft were excluded from the assessment. We found no evidence to suggest that coatings with improved thermal performance would reduce the lifetime of the blades, or that the coatings themselves had shorter lifetimes, so no change in the blade lifecycle was included in the assessment. The equipment to manufacture and coat the blades is capital, so it could be excluded from the assessment (Parsons & Chatterton, 2011a).

This left only the change in the composition of the coating and the deposition process as possible sources of non-operational changes in emissions. A typical turbine blade life is 10,000 hours, based on historical data (J. Nicholls, personal communication). Indeed, prior to their introduction it had been shown that the early TBCs could potentially survive in the engine environment for 16,000 hours (Toriz *et al.*, 1989). This is several orders of magnitude longer than the coating process, and the engine is an intensive energy user, sustaining combustion chamber temperatures up to 2000 C, so it is reasonable to assume that the total energy consumed during the life of a blade will vastly exceed that used in the production and deposition of the coating (with a mass of the order of 10 g per blade). Furthermore, for the brainprint only the change in emissions between the new coatings is relevant, so any effect was assumed to be negligible relative to operation of the engine.

The emissions of greenhouse gases from combustion of jet fuel were be included, plus the emissions from extraction, refining and transport of the fuel. A 1% environmental relevance cut off was applied (Parsons & Chatterton, 2011a).

Data

Fuel consumption

Three methods are used to calculate the emissions from aircraft for national inventories (EMEP/EEA, 2009). Tier 1 and Tier 2 are fuel based. Tier 1 uses total fuel sales divided into domestic and international flights, with total numbers of landings and take-offs (LTO) assuming an average fleet mix and average emission factors for LTO and cruise. Tier 2 refines the data by aircraft types. Tier 3 uses aircraft type and distance data for each flight with specific aircraft type emission data provided by EMEP/EEA. As this study related to specific engine, and hence aircraft, models, and fuel use data are not publicly available at this level of detail, a simplified version of the Tier 3 method was used. A more detailed method has been produced for Defra (Watterson *et al.*, 2010), but this is based on movement data for specific airports by aircraft type, which would have been to detailed for this study.

EMEP/EEA (2009) calculated the fuel use for LTO from the data in standard LTO cycle tests for engines specified by the International Civil Aviation Organization (ICAO, 1995), carried out in the UK by the Civil Aviation Authority (CAA, 2010). These included four relevant engine models (Table 3). These LTO tests are the best freely available data, although they have several limitations: they are conducted with the engine static and only represent performance below 3000 feet; they use fixed durations and thrust settings, although these depend on flight conditions in practice; and they measure engine performance not aircraft performance. EMEP/EEA (2009) state that

> 'uncertainties lie in emission factors for the engines. ICAO (1995) estimates that the uncertainties of the different LTO factors are approximately 5–10%.'

Table 3. Fuel consumption in the LTO cycle by four Rolls-Royce engines

			Fuel consumed, kg			
	Power, % full	Duration, min:sec	Trent 768	Trent 772	Trent 553	Trent 556
Take-off	100	26:00	123	132	89	94
Climb out	85	00:42	319	341	228	242
Approach	30	02:12	192	202	144	149
Idle	7	04:00	406	421	359	359
Total			1040	1096	820	844
Per aircraft			2080	2192	3280	3376

EMEP/EEA (2009) used a detailed model for the cruise phase and the results for different models and flight ranges are available as a spreadsheet. However, it did not differentiate between the three available engine manufacturers for the A330 or between the A340 models, although the A340-500 and A340-600, which have Rolls-Royce engines, are over 30% heavier than the A340-200 and A340-300.

Using the Trent 772 LTO data gave fuel consumption values that were 98% of those used by EMEP/EEA, the less powerful Trent 768 gave 93% and other manufacturers gave 84–87%. We therefore concluded that the data were representative of the Trent engines and it was reasonable to use the EMEP/EEA cruise emissions. For the A340, the LTO fuel consumption given by EMEP/EEA matched the CFM International CFM56-5C4 used on the smaller A340-200 and A340-300, whereas the Trent 533-61 and 556-61 were 62% and 67% higher respectively. We therefore scaled the cruise consumption by the average of the consumption ratios for climb and approach (because cruise thrust is between the two), which was 1.50 for A340-500 and 1.57 for A340-600.

To permit the use of cruise distances between those tabulated by EMEP/EEA, linear regressions for consumption against distance were fitted to the data for flights over 1000 km. This range was used because the relationship was nonlinear for short ranges, and these are long-haul aircraft. These gave for the A330

$$f_c = 6.57\ (x - 75.28), \qquad 1$$

for the A340

$$f_c = 6.99\ (x - 107.45), \qquad 2$$

adjusted by the factors above for A340-500 and A340-600. EPEM/EEA state 'For cruise, the uncertainties are assumed to be 15–40%.' The errors in the regression were less than 5%.

Combustion and life cycle emissions from jet fuel

Combustion

The standard emission factor for combustion of jet fuel is 3.155 kg CO_2/kg fuel (UNFCC, 1996). There are two main areas of debate over emissions from aircraft engines: emissions other than carbon-dioxide and the effect of altitude:

> The emission factors refer to aviation's direct carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions only. There is currently uncertainty over the other non-CO_2 climate change effects of aviation (including water vapour, contrails, NOx etc) which may indicatively be accounted for by applying a multiplier. The appropriate factor to apply is subject to uncertainty but was estimated by the IPCC in 1999 to be in the range 2-4, with current best scientific evidence suggesting a factor of 1.9. (AEA, 2010)

PAS2050 (BSI, 2008) says:

> No multiplier or other correction shall be applied to the GWP of emissions arising from aircraft transport. *Note The application of a multiplier for aircraft emissions will be given further consideration in future revisions of this PAS, once there is scientific consensus regarding the approach to be taken*.

This study followed this approach, so probably underestimated the impact of improved efficiency.

The LTO cycle tests record total hydrocarbons (HC), oxides of nitrogen (NOx) and carbon monoxide (CO) emissions. Methane is usually assumed to be 10% of total hydrocarbons during LTO and nitrous oxide is 0.5–1.25% of total NOx during LTO (EMEP/EEA, 2009); for this study it was assumed to be 1%. Using these factors, the non-carbon dioxide greenhouse gas emissions were derived from the LTO data (Table 4), converted to global warming potential using standard global warming factors (IPCC, 2007), then combined with carbon-dioxide emissions to give a net emission factor of 3.22 kg CO_2e/kg fuel for all four engine models.

Table 4. Greenhouse gas emissions during LTO

Engine	768	772	553	556
Fuel consumed, kg	1040	1096	820	844
HC emitted, g	752	735	60	57
NOx emitted, g	18672	21462	14444	16167
CO emitted, g	4496	4175	3979	3762
CH_4 emitted, g	75	74	6	6
N_2O emitted, g	187	215	144	162
Total non-CO_2, as kg CO_2e	66	74	51	55
CO_2 emitted, kg	3281	3458	2587	2663
Total emission factor, kg CO_2e/kg fuel	3.22	3.22	3.22	3.22

It is usually assumed that there are no methane emissions during cruise, and a constant emission factor of 0.1 g/kg fuel is used for nitrous oxide (EMEP/EEA, 2009), giving 29.8 g CO_2e/kg fuel, which is less than 1% of the carbon dioxide emissions, so it was omitted from the assessment.

For flights over 1000 km the emission factors from EMEP/EAA for carbon monoxide during climb, cruise and descent are 1.32–1.71 g/kg for A330 and 0.91–2.82 g/kg for A340. As the EMEP/EAA data appear to be based on the smaller A340 models with CFM engines, and the LTO data show that Trent 500 engines have approximately half the carbon monoxide emissions of these climb and descent, it is likely that the emissions during cruise are similarly reduced. The GWP100 of carbon monoxide is 1.9, so these emissions are well below 1% of carbon dioxide were also omitted from the assessment.

The standard emission factor of 3.155 kg CO2/kg fuel was therefore used for cruise.

Extraction and refining

In addition to the direct emissions, there are indirect emissions from extracting and refining fuel. These are not included in the standard emission factor, because they appear elsewhere in the national inventory. We calculated the greenhouse gas emissions to air from the data for extraction and refining of kerosene in the European Life Cycle Database (ELCD, 2010) using IPCC global warming potentials (IPCC, 2007), giving a total of 0.344 kg CO_2e/kg (Table 5). Using CCaLC-tool (Azapagic, 2011) with the built-in ELCD database gave a similar value (0.343 kg CO_2e/kg). However, with the EcoInvent database (EcoInvent Centre, 2011) it gave 0.482 kg CO_2e/kg for the ‘European average, at refinery’ case. The Defra/DECC guidelines (AEA, 2010) give a value of 0.563 kg CO_2e/kg for Scope 3 emissions from kerosene, which include production and transport. We were unable to determine the reason for the differences between these sources, so the most conservative estimate based on the ELCD was used in the assessment.

Table 5. Emissions to air from extracting and refining kerosene (Source: European Life Cycle Database)

Chemical	Resulting amount, kg/kg kerosene	GWP, kg CO_2e/kg	Emission factor, kg CO_2e/kg kerosene
carbon dioxide	0.2593	1.0	0.259
carbon monoxide	0.0004	1.9	0.001
CFC-11	2.46E-09	4750.0	0.000
CFC-114	2.52E-09	10000.0	0.000
CFC-12	5.30E-10	10090.0	0.000
CFC-13	3.33E-10	14400.0	0.000
HCFC-22	5.79E-10	1810.0	0.000
methane	0.0033	25.0	0.083
nitrous oxide	5.93E-06	298.0	0.002
sulphur hexafluoride	1.46E-12	22800.0	0.000
Total			0.344

Transport

Most major airports are supplied with jet fuel by pipelines from the refineries via distribution centres. This is usually the lowest cost method and avoids congestion. The second choice is usually rail, with road haulage the most expensive, and the worst case for greenhouse gas emissions.

To estimate the emissions from road transport we assumed a 34,000 l tanker, with a total weight of 44 t made up of 27 t payload (density about 0.8 kg/l) and 17 t tare for tractor unit and tanker. The total direct and indirect emissions (excluding construction) from an articulated large goods vehicle are 0.845 kg CO_2e/km unladen and 1.4 kg CO_2e/km fully laden (AEA, 2010). Expressing all distances in terms of the outward journey and assuming an unladen return trip, the emissions were 2.245 kg CO_2e/km, or 0.0166 kg CO_2e/kg load, assuming a full 27 t payload and a representative 200 km outward journey. This agreed well with an estimate of 0.0144 kg CO_2e/kg made using CCaLC-tool (Azapagic, 2011) based on the EcoInvent database (EcoInvent Centre, 2011). GHG emissions for rail freight and barge tankers estimated by CaLC-tool/EcoInvent were similar to or lower than road. EcoInvent does not include data for pipeline transport of refined oils, but GHG emissions derived through CCaLC-tool for crude oil and natural gas were also smaller than road transport for all pipeline types.

The emissions for all forms of transport were thus less than 1% of the emissions from combustion, so transport was not included in the assessment.

Aircraft movements

Data from the Association of European Airlines (AEA) were analysed to give the number of landings and the average stage distance by operator for A330 and A340 fleets (C. Miyoshi, personal communication). There were five operators with 27 aircraft for the A330 and 11 operators with 106 aircraft for the A340. This was a small proportion of the total sales of the A330, but a substantial proportion of the A340. Most of the data did not distinguish between the models; where they did, they all referred to the A340-300, not the larger A340-500 and A340-600, the majority of operators of which are in the Middle and Far East. It was therefore necessary to assume that usage patterns for the different models and operators were similar. As shown above (Table 1) the A340-500 has approximately 20% longer range than the other models, but not all of the stages will exploit this, so the difference in average stage length is likely to be smaller. Examining the data showed that two A330 operators, with a total of five aircraft, were atypical with average stage lengths less than 3500 km, compared with over

5500 km for the remainder. Similarly, one A340 operator with four aircraft had an average stage length of 4614 km, compared with over 6000 km for the others. These operators had correspondingly high numbers of landings per aircraft. These two atypical operators were excluded, because A330 and A340 are long-haul aircraft and these data would bias the fuel consumption upward, possibly exaggerating the brainprint.

For the remaining operators, the A330 averaged 692 landings/aircraft and 6059 km/stage, and the A340 635 landings/aircraft and 6629 km/stage.

Aircraft numbers

Data on the number of aircraft ordered and delivered broken down by model (Table 6) were available from a spreadsheet on the Airbus web site (Airbus, 2010). Greater detail on aircraft in service was available from the Airfleets web site (Airfleets, 2011) which gave the full model numbers, the first flight date and the status (active, stored, written off, ordered). The number ordered was many fewer than shown in the Airbus data, but the total of the other categories agreed with the deliveries. The fifth digit of the model number denotes the engine manufacturer: 4 is Rolls-Royce, for example A330-243. From these data, the total number of active A330s with Rolls-Royce engines was 356. The airbus data showed that a further 354 A330s had been ordered, and Rolls-Royce say that 70% of these have Trent engines (Rolls-Royce, 2011), so the potential fleet in future was 610, including those currently stored.

Table 6. Airbus A330 and A340 sales to 31 December 2010
(Source: Airbus, 2010)

	A330-200	A330-200F	A330-300	Total	A330-500	A330-600	Total
Ordered	556	66	482	1104	36	97	133
Delivered	404	5	341	750	32	97	129
Write off	4		1	5		2	2
Active	400	5	340	745	32	95	127

Table 7. Airbus A330 with Rolls-Royce engines
(Source: Airfleets, 2011)

	A330-200	A330-200F	A330-300	Total
Active	171	4	181	356
Write off	2			2
Stored	3		3	6

Brainprint

Baseline emissions

For one aircraft the baseline annual emissions are

$$E_a = n_s(f_l e_l + f_c(x) e_c) \qquad 3$$

where n_s is the number of stages flown, f_l is the fuel consumption for one LTO cycle, e_l is the emission factor for LTO, x is the mean stage length, f_c is the fuel consumption during cruise (from equation 1 or 2 corrected for engine type) and e_c is the emission factor for cruise. Both emission factors include indirect emissions. The resulting total emissions were 101 kt for A330, 156 kt for A340-500 and 163 kt for A340-600.

Table 8. Baseline emission calculations for single aircraft

	A330	A340-500	A340-600
n_s	692	635	635
x, km	6059	6629	6629
f_l, t	2.192	3.280	3.376
f_c, t	39.313	68.378	71.569
e_l, kg CO_2e/kg fuel	3.564	3.564	3.564
e_c, kg CO_2e/kg fuel	3.499	3.417	3.417
E_a, t CO_2e/year	100,595	155,790	162,931

Retrospective brainprint

There are no published data on the effect of the improved TBCs on fuel consumption, but the best estimate we were able to obtain through discussions and from indirect evidence in non-scientific literature was a 1% reduction. Using this value for the reduction from the unmodified counterfactual, the reductions in emissions per aircraft were 1016, 1574 and 1646 t CO_2e/year for A330, A340-500 and A340-600 respectively. Combining this with the data on aircraft numbers above gave a total emissions reduction of 568 kt CO_2e/year.

Table 9. Emissions reduction calculation for existing fleet

	A330	A340-500	A340-600	Total
E_a, t CO_2e/year	100,595	155,790	162,931	
Emissions reduction for one plane, t CO_2e/year	1016	1574	1646	
Number active	356	32	95	
Emissions reduction for fleet, kt CO_2e/year	362	50	156	568

Prospective brainprint

As shown in Table 6, there were 354 outstanding orders for A330, of which 70% (248) had Rolls-Royce engines, and 4 for A340-500. Including these, the annual emissions reduction was 833 kt CO_2e/year (Table 10). The service life of an aircraft depends on the number of LTO cycles and operating hours, with 20 years being a conservative target. The total brainprint was approximately 17 Mt CO_2e.

Table 10. Emissions reduction calculation for future fleet

	A330	A340-500	A340-600	Total
E_a, t CO_2e/year	100,595	155,790	162,931	
Emissions reduction for one plane, t CO_2e/year	1,016	1,574	1,646	
Number of aircraft	610	36	95	
Emissions reduction for fleet, kt CO_2e/year	620	57	156	833
Lifetime (20 year) emissions reduction, Mt CO_2e	12.4	1.1	3.1	16.7

Uncertainties

There is some uncertainty about the number of engines using the improved coatings, given that the first Trent 700s were manufactured around the time that the research began. The Trent 500 is comparatively recent, so it is reasonable to assume that all those in service in A340 aircraft use the new coatings. Turbine blades have a typical service life of about 10,000 hours, or less than 3 years given the operating hours for these aircraft. It is therefore possible that the new blades have been fitted to existing Trent 700 engines, but this would not in itself save fuel, unless the operation of the engine was adjusted to take advantage of it. However, there is a clear financial incentive to do so. The total number active is thus the best estimate, but a conservative lower bound would be those A330-x4x aircraft that entered service from 2005 onwards. The Airfleets data show that there are 229 active and 3 stored, making a potential future fleet of 480 using the same estimate of future deliveries as above. Using these estimates reduced the total emissions reductions to 439 and 701 kt CO_2e/year for the current and potential fleets respectively and the total prospective brainprint to 14 Mt CO_2e.

If the emissions factor discussed above for emissions at high altitude were included, all the results would be increased by a factor of 1.9, or slightly less if it were applied to cruise only.

The main remaining sources of uncertainty – fuel consumption, aircraft use and performance effects of the TBCs – were included in an uncertainty analysis by Monte-Carlo simulation.

According to EMEP/EEA (2009)

> Uncertainties lie in emission factors for the engines. ICAO (1995) estimates that the uncertainties of the different LTO factors are approximately 5–10%. For cruise, the uncertainties are assumed to be 15–40%.

We were unable to find the first statement in ICAO (1995), to find a justification for the second, or to find an explanation of how to interpret a range of uncertainties. The limitations of using the LTO test data for predicting performance in service noted in the Fuel Consumption section add an additional uncertainty to the LTO consumption. The uncertainty analysis used 20% for LTO, to allow for other sources of uncertainty, and 30% for cruise. In the absence of other information, a normal distribution was assumed and the range was interpreted as representing two standard deviations, following the IPCC good practice guide (IPCC, 2000), which says that there should be a 95% confidence that the value of a variable is within the limits given.

The limitations of the aircraft movement data were noted earlier. There were no data for the freight variant (A330-200F), so the same pattern was assumed; with only 5 in service this would have little effect on the retrospective results, but could have more influence on the prospective brainprint. The number of landings and the mean stage distance are negatively correlated, so it was not appropriate to vary these independently. The number of landings and mean stage length for each operator in the data set were used to calculate their emissions, giving a distribution of emissions from which the coefficient of variation was calculated to be 7.4% for the A330 and 7.9% for the A340. These excluded the within-operator variability, so 10% was used for A330 and 20% for A340, because the activity data were not for the models under investigation. Again, a normal distribution was assumed.

Given the absence of published data on the effect of the improved TBCs, a large uncertainty was assumed: a factor of 2 in each direction, that is from 0.5% to 2.0%. As the uncertainty was defined multiplicatively, a lognormal distribution was used, with mean 1.0 and standard deviation 0.35, to give 95% confidence that its value was between the bounds chosen.

The analysis was performed using the @RISK (Palisade Corporation, 2007) package for Microsoft Excel™. The target variable was the reduction in emissions for the whole of the present fleet, which was found above to be 568 kt CO_2e/year before the uncertainty analysis, and the distributions were generated using 10,000 samples. As the effect of the uncertainty in the emissions reduction from the improved TBC was very large, the analysis was performed with and without it. The resulting distribution without this factor was approximately normal, with mean 568 and 95% confidence interval 429–721 (Figure 3). When the uncertainty in emissions reduction was included the distribution had positive skew, with mean 570, mode 531 and 95% confidence interval 258–1105 (Figure 4).

The relationships in the model were generally linear, so the same relative results were obtained for the other results reported above. Thus the lowest estimates of the emissions reduction, assuming only a proportion of the fleet has the improved coatings, were approximately 219 and 350 kt CO_2e/year for the current and potential fleets respectively. The corresponding lower estimate of the total prospective brainprint was 7 Mt CO_2e. The maximum total prospective brainprint including the adjustment for altitude was approximately 61 Mt CO_2e.

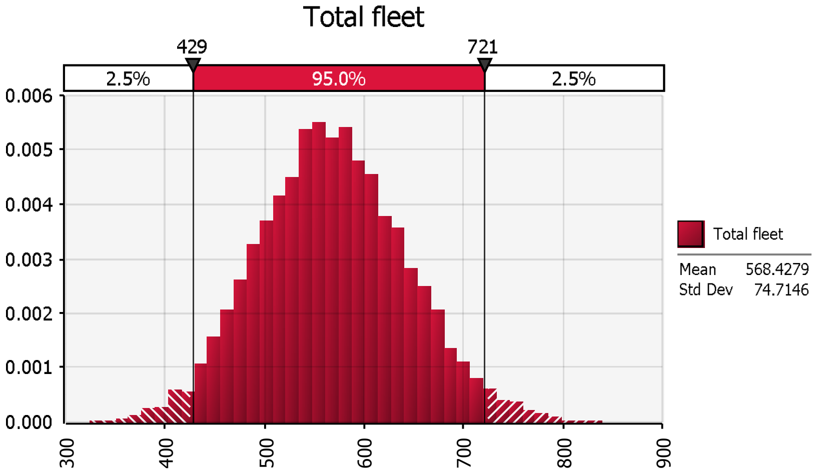

Figure 3. Distribution of total present fleet emissions reductions from uncertainty analysis, excluding uncertainty in the emissions reduction

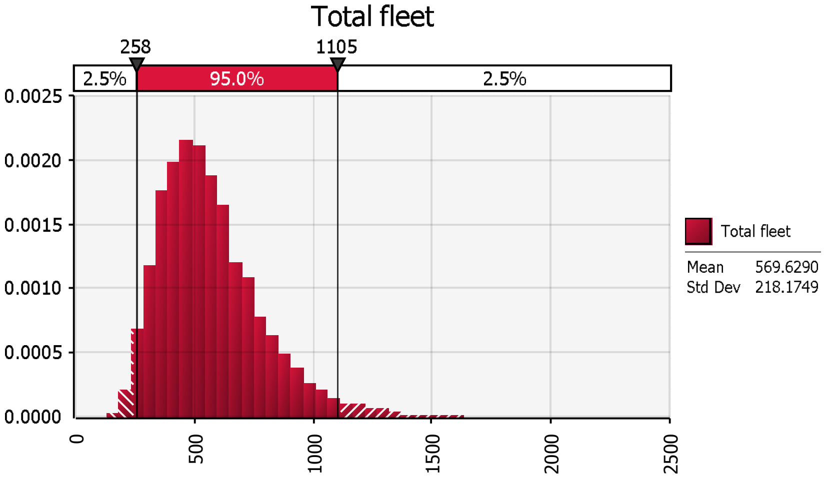

Figure 4. Distribution of total present fleet emissions reductions from uncertainty analysis, including uncertainty in the emissions reduction

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