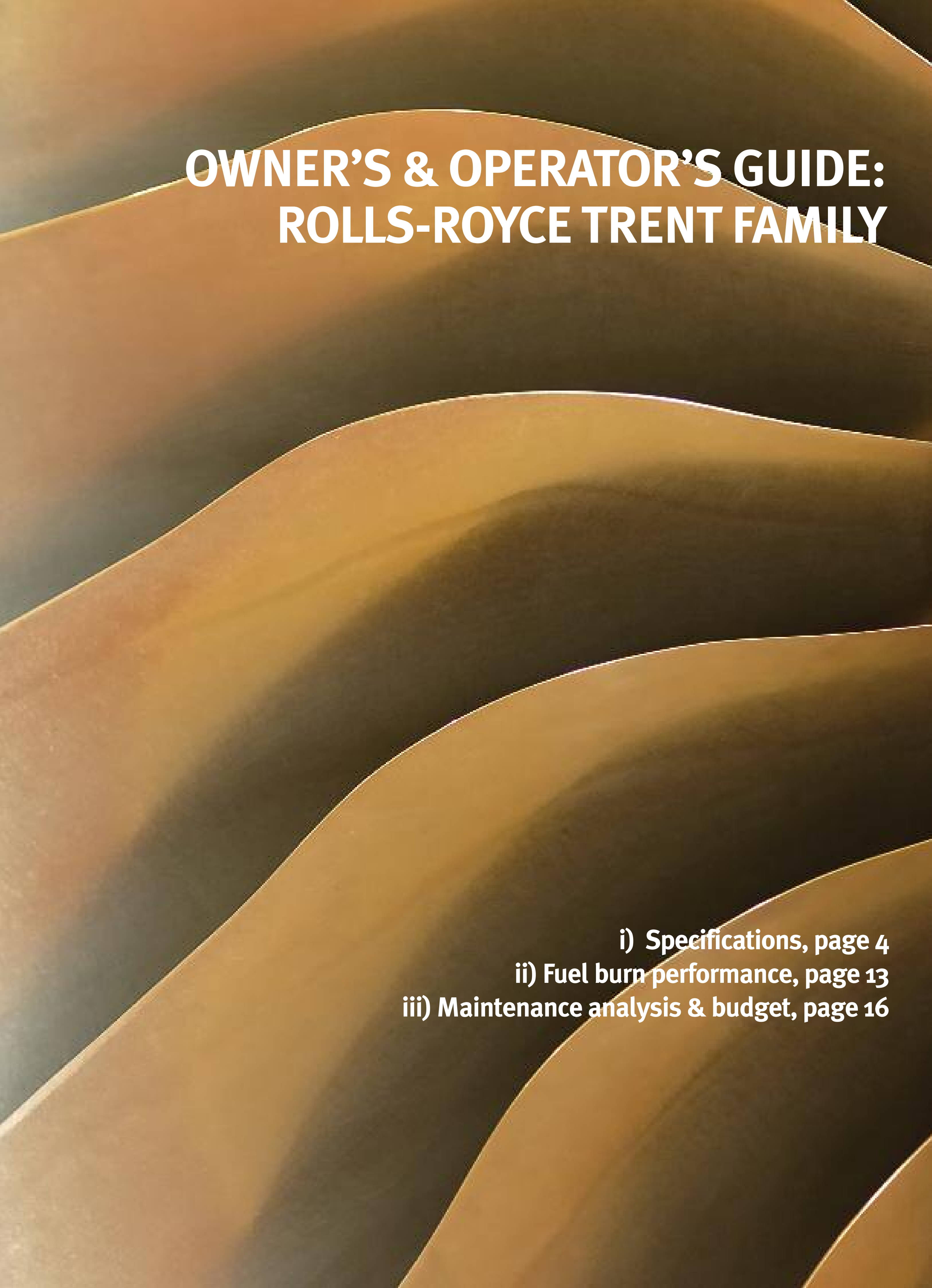

OWNER'S & OPERATOR'S GUIDE: ROLLS-ROYCE TRENT FAMILY

Rolls-Royce Trent family specifications

The Rolls-Royce Trent engine family includes six main types. Their development, configuration, thrust ratings, bypass ratios, specific fuel consumption, and emissions standards are examined.

The Rolls-Royce (RR) Trent engine family was based on the manufacturer's three-shaft RB211 widebody engine, which was developed in the 1970s and 80s. The Trent family has six main models that have thrust ratings from 53,000lbs to 97,000lbs for widebody aircraft *(see tables, pages 5 & 11)*.

Architecture

The Trent shares the same basic architecture as the RB211, although each main model has different intake fan and core engine rotor and stator disk (stages) diameters. The three-shaft or three-spool architecture is unique among turbofan designs, and is credited with giving the RB211 and Trent families greater thrust growth capacity than competing two-shaft designs.

The Trent's three-shaft configuration provides six main modules of rotating and static stages: the fan; intermediate pressure compressor (IPC); high pressure compressor (HPC); high pressure turbine (HPT); intermediate pressure turbine (IPT); and low pressure turbine (LPT).

All turbofan manufacturers have tried to increase their engines' fan diameters to achieve higher bypass ratios. That is, the ratio of the volume of air bypassing around the core engine to the volume of air passing through the core engine. A higher bypass ratio is therefore achieved with a wider intake fan; which also increases the air volume and mass. With an unchanged size of core engine, a wider fan diameter will increase the volume and mass of air bypassing around the core.

A higher volume and mass of bypassed air has multiple benefits. The prime one is that the air's exit velocity can be reduced, which improves propulsive efficiency and specific fuel consumption (sfc). A higher volume of bypassed air and slower exit speed also reduces exhaust temperature and noise emissions.

There are limitations to increasing fan diameter, however. The first is the need to limit the fan-blade tip speed. Fan tip speed has to be at a level that optimises the engine in terms of trades between fuel burn, weight, and other design parameters. As fan diameter increases, blade-tip speed increases for the same number of revolutions per minute (RPMs), because of the longer fan blades. Engine performance is optimised generally by RPMs being reduced as fan diameter is increased. Wider diameter fans therefore have to turn at slower RPMs than smaller diameter fans. Slower RPMs result in lower compression of air, however, resulting in lower efficiency.

The second limitation of wider-diameter fans is that they weigh more, and so require more power to turn them. This requires a larger turbine, with more stages and airfoils. Another issue is that because the RPMs also have to be reduced, more turbine stages are required to extract enough energy from the exhaust gases to turn the fan.

For a given core engine, the fan diameter cannot be increased beyond a certain point without incurring performance and cost penalties. First, this is because the higher weight of a larger fan and additional turbine stages outweighs the benefits of a higher bypass ratio. Second, not only will the additional weight cancel some of the fuel burn savings, but the additional number of turbine airfoils and disks will also increase the engine's maintenance costs.

Three-shaft design

A main feature of the RB211/Trent is that the fan and the first module of the core engine compressor, the IPC, rotate on separate shafts. Although each shaft requires its own turbine to turn it, the IPC rotates at higher RPMs than the fan.

This compares to two-shaft engines, where the fan and first module of the core engine compressor rotate on the same shaft. The first core engine compressor is the low pressure compressor (LPC), which turns at the same RPMs as the fan. The first compressor module is referred to as the LPC because it turns at slower RPMs than the IPC in a RB211/Trent engine.

The IPC on a Trent variant rated at 95,000lbs thrust, for example, rotates at more than 7,500 RPM. This compares to fan, and LPT, speeds of 2,000-3,000 RPMs on the same Trent engine; and other large two-shaft turbofan engines of similar thrust ratings and fan diameters.

This difference in RPMs of at least 4,000 RPMs means IPC stages in a three-shaft engine achieve a higher compression than the LPC in a two-shaft engine. Because the Trent's IPC stages are able to rotate at higher RPMs than two-shaft engines, the Trent requires fewer stages to achieve the same air compression. The engine can also achieve a higher overall pressure ratio. Moreover, the air exiting the IPC, and entering the HPC, is at a higher pressure than air exiting the LPC in a two-shaft engine. The HPC module downstream of the IPC requires fewer stages than the HPC in a two-shaft engine to achieve the same compression. The HPC and HPT can rotate at rates of up to 13,500 RPM.

The Trent's two core engine compressor modules therefore have a higher capacity to achieve the same compression with the same volume of air compared to the same-sized compressor modules of a two-shaft engine. This has several inherent advantages, which are key to RR's design philosophy on the RB211 and Trent.

The first is that the Trent can use fewer IPC and HPC stages than a two-shaft engine to achieve the same compression. The compressor stages can run closer to optimum speeds than in a two-shaft engine, thereby enhancing efficiency and increasing pressure ratio.

The Trent 700, for example, powering the A330 family has 14 stages: eight IPC and six HPC. This compares with the CF6-80E1's four LPC and 14 HPC stages; 18 in total. This has a further advantage of making the three-shaft engine shorter.

The second is that in some cases the compressor modules in a three-shaft engine can be of a smaller diameter compared to the compressor modules in a two-shaft engine to turn a fan of equal diameter. Compressor modules of a smaller diameter allow the three-shaft engine to achieve a higher bypass ratio than a two-shaft engine for the same fan size.

A third is that the three-shaft engine has more potential to be developed to a wider range of thrust ratings; which the Trent family has achieved.

Nevertheless, the three-shaft configuration has some disadvantages.

The first is that the fan, IPC and HPC turning on three shafts each require a turbine; resulting in three turbine modules: the LPT for the fan; IPT for the IPC; and HPT for the HPC. This increases engine weight and complexity of construction.

This complexity of construction has particular relevance to maintenance, since the HPC/HPT typically has shorter intervals for maintenance than the fan/LPT and IPC/IPT. The engine will require full disassembly, however, to allow the HPC/HPT, the high pressure spool, to be removed and disassembled.

Despite these disadvantages, the Trent's three-shaft configuration generally means it requires fewer turbine stages than two-shaft engines with similar fan diameters and thrust ratings. Five of the six Trent models have single-stage HPTs and IPTs; which turn the HPC and LPC. Many competing two-shaft engines have dual-stage HPTs; although they of course do not require an IPT. Trent models generally have LPTs with fewer stages than competing two-shaft engines.

The Trent has been developed to use additional technologies to improve efficiencies of successive family members.

A main objective with the Trent family has been to increase overall pressure ratio. This increases thermal efficiency, and the sfc. A higher pressure ratio can only be achieved through improvements in 3D aerodynamics, component efficiencies, and material capabilities.

Later variants of the Trent, starting with the 900 and 500, used wider chord swept fan blades. These gave the fan higher aerodynamic efficiency through reduced drag and higher massflow.

A higher thermal efficiency also has the added advantage of lower CO2 emissions. It also, however, increases NOx emissions. This increase has to be offset by improved combustor design.

The Trent family has been in development since the late 1980s, and the most recent models are due to enter service with the A350XWB family in 2013-2017. In contrast to the RB211-524 models that powered variants of the 747 and had limited sales success, the Trent family has won larger shares of firm orders for the aircraft they power.

The first Trent model in development was the Trent 600; originally intended for the MD-11. This variant was dropped following order cancellations from its only two customers.

ROLLS-ROYCE TRENT 500, 700, 800 & 900 SPECIFICATIONS TABLE

Engine Model				Trent 768	Trent 772	Trent 772B
Thrust rating-lbs				67,500	71,100	71,100
Fan diameter (inches)				97.4	97.4	97.4
Fan blades				26	26	26
Bypass ratio				5.1	5.0	5.0
Overall pressure ratio				33.7:1	34.5:1	35.5:1
SFC: lb/lbf/hr				0.56	0.56	0.56
Flat rate temp.				30	30	38
Application				A330-300	A330-200/-300	A330-200/-300
Engine configuration						
Fan stages				1	1	1
IPC stages				8	8	8
HPC stages				6	6	6
HPT stages				1	1	1
IPT stages				1	1	1
LPT stages				4	4	4

Engine Model	Trent 875	Trent 877	Trent 884	Trent 892	Trent 892B	Trent 895
Thrust rating-lbs	74,600	77,200	84,950	91,600	91,600	95,000
Fan diameter (inches)	110	110	110	110	110	110
Fan blades	26	26	26	26	26	26
Bypass ratio	6.2	6.1	5.9	5.8	5.8	5.8
Overall pressure ratio	42:1	42:1	42:1	42:1	42:1	42:1
SFC: lb/lbf/hr	0.56	0.56	0.56	0.56	0.56	0.56
Flat rate temp.	30	30	30	30	30	25
Application	777-200	777-200	777-200ER	777-200ER	777-200ER	777-200ER
Engine configuration						
Fan stages	1	1	1	1	1	1
IPC stages	8	8	8	8	8	8
HPC stages	6	6	6	6	6	6
HPT stages	1	1	1	1	1	1
IPT stages	1	1	1	1	1	1
LPT stages	5	5	5	5	5	5

Engine Model	Trent 970	Trent 972	Trent 977		Trent 553	Trent 556
Thrust rating-lbs	70,000	72,000	76,500		53,000	56,000
Fan diameter (inches)	116	116	116		97.4	97.4
Fan blades	24	24	24		26	26
Bypass ratio	8.7	8.6	8.5		7.7	7.6
Overall pressure ratio	37-39:1	37-39:1	37-39:1		36.3:1	36.3:1
SFC: lb/lbf/hr	0.518	0.518	0.518		0.54	0.54
Flat rate temp.	30	30	30		30	30
Application	A380-800	A380-800	A380F		A340-500	A340-600
Engine configuration						
Fan stages	1	1	1		1	1
IPC stages	8	8	8		8	8
HPC stages	6	6	6		6	6
HPT stages	1	1	1		1	1
IPT stages	1	1	1		1	1
LPT stages	5	5	5		5	5

Trent 700

The Trent 700 was the first Trent model developed, and it followed the RB211-524G/H that powered the 747-400 and 767-300ER. This was rated at 58,000-60,600lbs thrust, had a 86.3-inch diameter fan, and a bypass ratio of between 4.1 and 4.3:1.

The Trent 700 was initially developed to provide 67,500lbs of thrust at sea level for the initial, low maximum take-off weight (MTOW) versions of the A330-300 that entered service in 1994; referred to as the Trent 768. The Trent 700 has a 97.4-inch diameter fan and bypass ratio of 5.1:1.

The Trent 700 has an eight-stage IPC, six-stage HPC, single-stage HPT, single-stage IPT, and four-stage LPT *(see table, this page)*. The core engine has one more IPC stage and two more LPT stages than

The Trent 700 series was the first Trent family member in service. This has a sfc of 0.565lbs of fuel per lb of thrust. All Trent family members developed since have a lower sfc.

the RB211-524G/H.

All Trent family members utilise wide-chord, hollow and snubberless fan blades. These were first developed for the RB211-535E4 engines in the 1980s. Hollow blades reduce weight, while the wide chord design means fewer fan blades are required than when using older generation clappered blades, which incur more drag.

Lower drag on the fan assembly means it requires less power from the turbine to rotate it. The fan also increases airflow and so overall efficiency. The Trent 700 family has 26 fan blades.

The Trent 700's additional IPC and LPT stages allow its core to turn a larger fan and achieve a higher bypass ratio than the RB211-524G/H with similar-sized core engines.

The Trent 768's configuration allows it to generate an overall pressure ratio of 33.7:1.

The Trent 772, which has a sea level thrust rating of 71,100lbs thrust, was developed for higher MTOW variants of the A330-300, as well as the A330-200 with the shorter fuselage. While the Trent 772 has the same basic configuration as the Trent 768, the 772 achieves a marginally lower bypass ratio of 5.0:1 and has a higher overall pressure ratio of 34.5:1 *(see table, page 5)*.

The Trent 768 and 772 are both flat rated at 30 degrees centigrade, so they provide a constant static take-off thrust rating up to an outside temperature of 30 degrees. Thrust has to be reduced for outside temperatures higher than 30 degrees to prevent the exhaust gas temperature (EGT) exceeding the engine's certified red line limit. 30 degrees centigrade is the standard flat rating temperature for all Trent family and RB211 family engines.

The Trent 772B was developed for hot and high operations. Rated at 71,100lbs thrust at sea level, it differs from the Trent 772 in that the 772B is flat rated to 38 degrees centigrade *(see table, page 5)*. The 772B also produces higher thrust at airport elevations of up to 8,000 feet, so that the engine can maintain its maximum thrust rating to a higher outside temperature of 38 degrees. This makes it suitable for 'hot and high' operations.

The Trent 700 has a cruise sfc of 0.565lbs of fuel per lb of thrust. This compares to the RB211-524H's 0.603lbs of fuel per lb of thrust.

The Trent 700 has to comply with CAEP IV NOX emissions standards. The recent Trent 772 Improved variant has a CAEP IV margin of 16.9 grams per kN (g/kN) of thrust.

The engine has a Stage 4 cumulative noise emissions margin of 9.1 equivalent perceived noise decibels (EPNdB).

The most recent variant is the 772C, also with a sea level rating of 71,100lbs thrust. It can provide higher thrusts than other variants up to airport elevations of 8,000 feet.

In 2009, RR introduced an upgraded version of the 700, called the Trent 700EP; the EP suffix designating enhanced performance. This included a package of technological and design improvements used in the development of later family members in the interim: elliptical leading edges on compressor airfoils; and optimised fan and HPT blade tip clearances. These improvements reduced fuel consumption by 1.2% compared to the original Trent 700. Some of these improvements can be made to existing engines during shop visits.

Trent 800

The Trent 800 was developed at a similar time to the Trent 700. The Trent 800 has six variants with sea level ratings of 74,600lbs to 95,000lbs thrust, and powers the 777-200/-300 family.

The 777 family has MTOWs of 506,000lbs to 766,000lbs for the shorter -200 series, and 660,000lbs to 766,000lbs for the longer -300 series. When the first 777 variants were developed and entered service it was not clear how high the fuel capacity and MTOW of the two main variants would go. The required engine thrust ratings for later aircraft variants were therefore not certain either.

The Trent 800 was one of three engine choices for 777-200s with MTOWs of up to 656,000lbs, and for 777-300s with MTOWs of up to 660,000lbs.

The Trent 800 configuration has the same number of core engine stages as the Trent 700 family. The Trent 800's core has a wider diameter, however, and so has a higher mass flow than the 700's core.

The Trent 800 consequently has a 110-inch fan diameter, and higher bypass ratio of 5.8:1 to 6.2:1 for its six thrust ratings *(see table, page 5)*. The family generates an overall pressure ratio of 42:1.

The first variant was the Trent 875, which has a sea level rating of 74,600lbs thrust *(see table, page 5)*. The Trent 877 has a slightly higher rating of 77,200lbs thrust. These two variants power lower MTOW models of the 777-200 up to 545,000lbs.

The Trent 884 (rated at 84,950lbs thrust), the Trent 892 (rated at 91,600lbs thrust), and the Trent 895 (rated at 95,000lbs thrust) power the 777-200ER models which have MTOWs of 580,000-656,000lbs. These aircraft also have higher fuel capacities than the lighter -200 models. The Trent 892B is rated at 91,600lbs, and powers the 777-300, which has a MTOW of 660,000lbs.

The first five of the six Trent 800 variants are flat rated at 30 degrees centigrade. The highest-rated Trent 895 is flat rated only up to 25 degrees, however.

The Trent 800 has a cruise sfc of 0.56lbs of fuel per lb of thrust. It has to comply with CAEP NOx emissions standards, and has a margin of 12.7 g/kN.

The Trent 800 series, which powers the 777-200/-200ER and 777-300, has the highest rated variant of all Trent engines. The Trent 800 is one of the Trent series that is no longer winning further orders.

Its noise emissions give it a Stage 4 compliance margin of 6.5EPNdB.

Boeing later developed ultra-long-range versions of the 777-200 and -300. These aircraft, designated the -200LR and -300ER, have MTOWs of 766,000lbs and 775,000lbs and an additional 2,500 US Gallons of fuel capacity over their lighter weight counterparts. These aircraft were expected to require engines rated at more than 100,000lbs thrust. Higher rated variants of the Trent were developed from the Trent 800.

The first development engine was designated the Trent 8104, and was later scaled up to the Trent 8115; the two suffixes indicating their thrust ratings. These two engines were proposals for powering the 777-200LR and -300ER.

The Trent 8104 had the same-sized core and fan as the Trent 800, but the 8104 featured several improvements to the core and had swept fan blades.

Swept fan blades not only reduce drag, and so improve the overall efficiency of the engine, but also meant fewer fan blades were required because the swept blades had a wider chord than those used on the Trent 800. Swept blades also meant that the same fan generated more air flow for the same fan size. The fan diameter therefore did not have to change.

Several changes were incorporated to the core, which improved its efficiency. The engine was tested with three-dimensional IPC stators, and HPC rotors and stators. New blade coatings and single-crystal alloys were also tested in the IPT. Aerodynamically improved LPT blades were also added, which would add to the LPT's turning power. The LPT would therefore not have to be larger, despite the engine's higher thrust rating. The Trent 8104 reached a rating of 110,000lbs during testing.

The Trent 8115 was to have an enlarged fan of up to 120 inches in diameter; 10 inches wider than the Trent 800. The Trent 8115's core was also to be scaled up by 2.5% compared to the 8104's core. The Trent 8115 was never built, since General Electric became the exclusive engine supplier for the 777-200LR and -300ER. The Trent 8104 and 8115 nevertheless had technologies developed for them which were used in later variants.

Trent 900

The Trent 900 was one of two new family members developed in parallel; the other being the Trent 500. These two variants used technologies from the Trent 8104 development.

The Trent 900 and 500 were developed for the four-engined A380 and A340-500/-600. The Trent 700 and 800 were developed for twin-engined aircraft.

The Trent 900 and 500 share the same core engine, although the 500's core is scaled down. The Trent 900's core is scaled down by about 10% compared to the 800. The core engines have the same number of stages as the Trent 800. The Trent 900 and 500 have higher bypass ratios than the 700 and 800.

Net thrust at cruise speed is lower for engines with a high bypass ratio than for one with a narrower fan and lower bypass ratio. This is because a wider fan will experience greater intake momentum drag at the same speed as an engine with a lower bypass ratio. Engine bypass ratio can thus be higher for a four-engined aircraft than a twin, since a lower net thrust does not compromise aircraft operation in the event that power is lost from one engine.

As well as a smaller core than the Trent 800, the Trent 900 has a 116-inch fan diameter; six inches wider than the Trent 800's. This allows the 900 to achieve a higher bypass ratio than the 800.

The Trent 900 has three thrust ratings from 70,000lbs to 76,500lbs *(see table, page 5)*. The engine is capable, however, of thrust ratings up to 84,000lbs for growth variants of the A380. The corresponding bypass ratios of these three ratings are 8.7:1 to 8.5:1 *(see table, page 5)*. This compares to the 800's bypass ratios of 5.8:1 to 6.2:1.

The same three Trent 900 variants have overall pressure ratios of 37:1 to 39:1; slightly lower than the Trent 800.

The Trent 900 used several new technologies, including the swept fan blades developed for the Trent 8104. These reduce the number of blades to 24, compared to the 26 used by the 700 and 800. The 900's fewer fan blades increase air mass flow and thrust for a given RPM.

As with the 8104, the Trent 900 uses 3-D aerodynamic airfoils in its compressor and turbine sections.

RR also developed a tiled combustion chamber to achieve lower NOx emissions. An element of improved sfc and fuel efficiency is higher combustion temperatures; a higher temperature improves the efficiency of combustion and so lowers the sfc. It also has the benefit of reducing CO_2 emissions.

A higher combustion temperature has several drawbacks. One is that it results in higher NOx emissions, so design technologies are required to offset this. Another issue is the need for improved cooling of the combustors, since the temperature exceeds the melting point of the combustor material. The Trent 900's combustor introduced tiling on the inner walls. Perforated tiles result in a film of cooling air forming on the inner wall of the combustor.

Another feature introduced in the Trent 900 was the contra-rotating turbine. In earlier Trent and RB211 models, the stages of all three turbine sections turned in the same direction. This caused a problem because air leaving the nozzle guide vane (NGV) of the HPT

ROLLS-ROYCE TRENT 1000 & XWB SPECIFICATIONS TABLE

Engine Model	Trent 1000-A	Trent 1000-C	Trent 1000-D Hot/High	Trent 1000-E	Trent 1000-G	Trent 1000-H	Trent 1000-J	Trent 1000-K Hot/High
Thrust rating-lbs	63,800	69,800	69,800	53,200	67,000	58,000	73,800	73,900
Fan diameter (inches)	112	112	112	112	112	112	112	112
Fan blades	20 swept	20 swept	20 swept	20 swept	20 swept	20 swept	20 swept	20 swept
Bypass ratio	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
Overall pressure ratio	52:1	52:1	52:1	52:1	52:1	52:1	52:1	52:1
SFC: lb/lbf/hr	0.506	0.506	0.506	0.506	0.506	0.506	0.506	0.506
Flat rate temp.	30	30	35	30	30	30	30	33
Application	787-8	787-8/-9	787-8/-9	787-8	787-8/-9	787-8	787-9	787-9
Engine configuration								
Fan stages	1	1	1	1	1	1	1	1
IPC stages	8	8	8	8	8	8	8	8
HPC stages	6	6	6	6	6	6	6	6
HPT stages	1	1	1	1	1	1	1	1
IPT stages	1	1	1	1	1	1	1	1
LPT stages	6	6	6	6	6	6	6	6

Engine Model	Trent XWB-75	Trent XWB-79	Trent XWB-79B Hot/High	Trent XWB-84	Trent XWB-97
Thrust rating-lbs	75,000	79,000	79,000	84,000	97,000
Fan diameter (inches)	118	118	118	118	118
Fan blades	22 swept	22 swept	22 swept	22 swept	22 swept
Bypass ratio	9.3	9.3	9.3	9.3	9.3
Overall pressure ratio	52:1	52:1	52:1	52:1	52:1
SFC: lb/lbf/hr					
Flat rate temp.	30	30		30	30
Application	A350-800	A350-800	A350-800	A350-900	A350-1000
Engine configuration					
Fan stages	1	1	1	1	1
IPC stages	8	8	8	8	8
HPC stages	6	6	6	6	6
HPT stages	1	1	1	1	1
IPT stages	2	2	2	2	2
LPT stages	6	6	6	6	6

was forced to turn through 90 degrees before entering the first stage of the IPT, so that it could turn in the same direction. This requires large NGV airfoils.

The use of a contra-rotating turbine means that air leaving the HPT's NGV only has to turn through 40 degrees. The LPT then turns in the same direction as the IPT. This system allows for smaller NGVs and makes the turbine overall aerodynamically more efficient.

The Trent 900 has a cruise sfc of 0.518lbs of fuel per lb of thrust. This illustrates how the engine's configuration and use of technological developments have reduced fuel burn compared to earlier Trent and RB211 variants.

The Trent 900 has to comply with CAEP VI NOx emissions, and has a margin of 31.1 g/kN.

Noise emissions are among the lowest of all Trent family members, and give the engine a cumulative margin of 18 EPNdB over Stage 4 compliance.

The 900's high bypass ratio provides the A380 with a 11.8EPNdB margin over allowed stage 4 noise emissions for its MTOW.

In the past few years RR has introduced technical packages that result in sfc reductions. Many of the improvements can be retrofitted to engines while going through a shop visit.

The first package of improvements includes the introduction of elliptical leading edges in compressor airfoils, and improved LPT blade tip clearance. This package reduces sfc by 1%.

The second package gives optimised fan-blade tip clearance, and improved turbine case cooling, LPT seals, and elliptical leading edges of stators. This package reduces sfc by another 0.8%.

Trent 500

The Trent 500 was developed at the same time as the Trent 900. The Trent 500 has a core engine with the same configuration as the Trent 800 and 900, but is scaled down. The Trent 500 uses the same 26-blade and 97.4-inch diameter fan as the Trent 700. It therefore achieves a bypass ratio of 7.6:1 to 7.7:1 for its two thrust rated variants.

The two variants are the 553 rated at 53,000lbs for the A340-500, and the 556 rated at 56,000lbs for the A340-600 *(see table, page 5)*. The overall pressure ratio is 36.3:1.

The Trent 500 uses many of the same technological developments used in the Trent 900.

The Trent 500's design has resulted in a lower cruise sfc than other family variants of 0.54lbs fuel per lb of thrust.

It also has a CAEP VI NOx emissions compliance margin of 16.4 g/kN, and a Stage 4 noise compliance margin of 13.3EPNdB.

Trent 1000

The Trent 1000 is one of two engine choices for the 787 family. To meet Boeing's objectives for fuel burn, RR developed the Trent 1000 with the objective of a 15% lower sfc than the first Trent family member; the Trent 700. The Trent 1000 uses a wide fan diameter for similar thrust ratings than previous generation engines. The 787 has up to eight variants with sea level thrust ratings of 63,800-73,900lbs *(see table, this page)*. These overlap the Trent 700's thrust ratings.

The Trent 1000 has a 112-inch diameter fan. This is the second largest of the Trent family and just two inches wider than the 800's fan. This is turned

The Trent 500 series is one of two series that utilises technologies developed for the Trent 8104 and 8115. This includes the use of wider chord swept fan blades and three-dimensional airfoils.

by a scaled down core engine with the same configuration as the 800, 900 and 500 models; only the 1000 has a six-stage LPT, needed to turn the larger intake fan.

This fan and core configuration achieve a high bypass ratio of 10:1 to 11.0:1 for the eight variants, and an overall pressure ratio of 52:1 *(see table, page 11)*. These two factors are important in achieving Boeing's improved target fuel burn performance.

Six of the eight variants are flat rated up to 30 degrees centigrade. The Trent 1000-D is flat rated up to 35 degrees, and the Trent 1000-K is flat rated up to 33 degrees. These two variants also have high sea level thrust ratings, and so are configured for hot-and-high operations.

The Trent 1000 uses several technological features to achieve the fuel burn and emissions performance required of the 787. The first of these is wide-chord, low hub-tip ratio swept fan blades. This is possible through the use of a smaller diameter fan hub. This means a larger fan intake area is possible for the same fan diameter. This allows air to pass through more efficiently.

Like the Trent 900, the use of swept blades generates a higher mass flow, and so increases engine efficiency. The Trent 1000 fan has 20 of these blades *(see table, page 11)*, compared to the 900's 22 blades, and other members' 26.

The Trent 1000 also uses several technologies in the core engine, including many of the features used in the Trent 900. The Trent 1000 will also have 15% fewer airfoils than the Trent 700. This will contribute to lower maintenance costs.

Compared to other engines, the Trent 1000 powers an electric aircraft. Instead of using air bleed from the engines, the 787 uses the power of the engine to generate electrical power. The Trent 1000 has two high power generators in its IP shaft.

The Trent 1000 also uses soluble core technology. This provides better external and internal cooling of HPT blades. This raises temperature capability, and allows higher combustion temperature which improves sfc and lowers CO2 emissions. The HPT blades use a thermal barrier and anti-corrosion coatings to prevent oxidisation, corrosion and thermal degradation.

The configuration and technologies used in the Trent 1000 give it a cruise sfc of 0.506 lbs of fuel per lb of thrust. This is about 10% less than the Trent 700's sfc. When this is combined with aerodynamic advances in the 787's airframe and utilisation of lower weight materials, the aircraft should reach its target of about 15% lower fuel burn per seat over previous generation aircraft such as the 767 and A330-200.

The 1000's high bypass ratio gives it a margin over Stage 4 noise emission standards of 20EPNdB. The engine also has NOx emissions that are 35-40% within CAEP VI standards.

In July 2012 RR announced a package of modifications and improvements to reduce sfc of standard Trent 1000s by 3%. This package is termed Trent 1000-TEN (TEN stands for Thrust, Efficiency and New technology).

The TEN package incorporates advances in the HPC and HPT, and blisk technology. The Trent 1000-TEN will be certified at 76,000lbs thrust, and will enter service in 2016. It will be used for the existing 787-8 and -9 variants, as well as the stretched 787-10X, if launched.

Trent XWB

The Trent XWB engine model exclusively powers the A350WXB family. The XWB has the highest thrust ratings in the Trent range of engines; with the A350-1000 requiring an engine rated at 97,000lbs thrust. The first XWB is due to enter service in late 2013, while the highest rated engine for the A350 is scheduled to enter service in 2017.

The lowest-rated variant is the XWB-75 with a sea level rating of 75,000lbs thrust, powering the A350-800. The XWB-79 and XWB-79B are rated at 79,000lbs, and also power the A350-800 *(see table, page 11)*. The XWB-79B has a higher flat rating temperature than the standard 30 degrees for hot-and-high operations.

The XWB-84 is rated at 84,000lbs for the A350-900, and the XWB-97 is rated at 97,000lbs for the A350-1000.

Like the Trent 1000, the Trent XWB has been configured to generate a high overall pressure ratio and a high bypass ratio to provide 16% lower sfc than the first generation Trent engines. This would be about 0.48lbs of fuel per lb of thrust.

The Trent XWB has a fan diameter of 118 inches, and uses the same fan blade design as the 1000 model. The XWB has 22 fan blades; two more than the Trent 1000.

The Trent XWB has the same core engine configuration as the 1000, except that the XWB uses a two-stage IPT. This makes it the first RB211 or Trent model to do so. The core will need a higher flow rate of air to moderate HPT inlet temperature. This will not be achieved through higher overall pressure ratio, since this is already high, and will increase turbine inlet temperature, but by using a larger core.

The core engine has high efficiency compressors which have been developed from the Vision3 programme, and the latest generation tip-clearance control.

The Trent XWB will have 10% fewer IP and HP airfoils than the Trent 700, contributing to lower maintenance costs.

The Trent XWB is expected to have similar noise and NOx emissions margins over Stage 4 and CAEP VI standards as the Trent 1000. AC

Rolls-Royce Trent family fuel burn performance

The Rolls-Royce Trent family has several applications. The fuel burn performance of several common types is analysed here.

The Rolls-Royce (RR) Trent engine family is used by five aircraft families and 10 types. These include the: A330-200/-300, A340-500/-600, A380, 777-200/-300, and 787-8/-9. The Trent XWB will be used on the A350XWB *(see Rolls-Royce Trent family specifications, page 4)*.

The A340-500/-600 use variants of the RR Trent 500, the A330-200/-300 utilises the Trent 700, the 777 family (except the 777-200LR and 777-300ER) utilises variants of the Trent 800 engine, the A380 uses the RR Trent 900 engine, while the 787-8 uses the Trent 1000.

The fuel burn performance of some RR Trent 500, 700, 800 and 900 engines on examples of the aircraft they power is examined here on sample routes of increasing distance. The Trent 1000 has only recently entered service, so it is too early to analyse this engine type.

Aircraft analysed

There are several weight and fuel capacity variants of each aircraft type. The aircraft specifications of the aircraft analysed here are summarised *(see table, page 14)*. An international tri-class seat configuration has been used for each aircraft due to the long-haul nature of the routes used, together with the average number of seats used by airlines' configurations.

The A340-500 analysed here uses Trent 553 engines, with a maximum take-off weight (MTOW) of 804,700lbs. It has a maximum structural payload of 113,900lbs, and a fuel capacity of 56,750 US gallons (USG), and 238 seats on-board *(see table, page 14)*.

The A340-600 is a further stretched variant of the A340, and is powered by the Trent 556. The A340-600 has the same MTOW as the A340-500 of 804,700lbs. Maximum payload is higher, however, at 139,100lbs, with a lower fuel capacity of 51,480USG. The average airline three-class layout of the A340-600 is 300 seats *(see table, page 14)*.

The A330 family uses Trent 700 engines. The A330 variants analysed here are the A330-200 and -300, both powered by Trent 772B engines. Both aircraft have an MTOW of 513,765lbs.

The A330-200 has a higher fuel capacity, however, of 36,744USG, compared to a fuel capacity of 25,858USG for the A330-300 *(see table, page 14)*.

The A330-300 has a maximum payload of 108,282lbs, compared with 107,819lbs for the A330-200. The three-class average number of seats for the A330-200 is 231, compared with 257 for the A330-300 *(see table, page 14)*.

Two variants of the Trent 800 are analysed here, powering 777-200ER aircraft. The Trent 884 powers a lower gross weight version of the 777-200ER with an MTOW of 580,000lbs.

Also examined here is the Trent 892 engine, powering a higher gross weight 777-200ER with an MTOW of 656,000lbs. Both aircraft have a fuel capacity of 31,000USG, with 285 seats on-board *(see table, page 14)*.

The Trent 970 powering the A380-800 is also included. The MTOW of the aircraft is 1,235,000lbs, carrying a payload of 200,000lbs, including 486 seats in a three-class layout. Fuel capacity is 84,600USG *(see table, page 14)*.

Routes analysed

Routes chosen for analysis are a variety of common long-haul routes, of increasing distance. These will show the fuel burn performance of the aircraft on an absolute basis in USG, as well as at a rate of USG per seat-mile, when distance increases on the different aircraft types.

Three long-haul routes from Frankfurt (FRA) have been chosen. These are to: New York JFK (JFK), Chicago O'Hare (ORD) and Los Angeles (LAX). A route between Singapore (SIN) and London Heathrow (LHR) has also been included as the longest distance route.

All routes are analysed in a westerly direction, where headwinds increase the effective distance of the route.

It is important to note here that aircraft cover a longer tracked distance than the great circle distance between two points. This is due to Air Traffic Control (ATC), following airways and transatlantic tracks, and extended-range twin-engine operations (ETOPs) requirements. It is also due to the effects of departure and arrival routeings.

The distance an aircraft actually flies is the tracked distance. The tracked distance is affected by en-route winds.

The Trent 892- & 895-powered 777-200ER has the lowest fuel burn per seat mile compared to the Trent-powered A330-200, A330-300, A340-500 and A380.

FUEL BURN PERFORMANCE OF THE ROLLS-ROYCE TRENT SERIES

Route	Aircraft type	Engine model	MTOW (lbs)	Fuel capacity (USG)	Passenger payload (seats)	Tracked distance (nm)	ESAD (nm)	Wind (kts)	Block time (hr:min)	Block fuel (USG)	Fuel burn USG per seat-mile
FRA-JFK	A340-500	RR Trent 553	804,700	56,750	238	3,501	3,714	-27	08:24	21,187	0.0240
	A340-600	RR Trent 556	804,700	51,480	300	3,501	3,723	-28	08:25	22,906	0.0205
	A330-200	RR Trent 772B	513,765	37,644	231	3,501	3,725	-28	08:31	16,270	0.0189
	A330-300	RR Trent 772B	513,765	25,858	257	3,501	3,726	-28	08:32	16,893	0.0176
	777-200ER	RR Trent 884	580,000	31,000	285	3,501	3,727	-29	08:18	19,099	0.0180
	777-200ER	RR Trent 892	656,000	31,000	285	3,501	3,728	-29	08:20	19,342	0.0182
	A380-800	RR Trent 970	1,235,000	84,600	486	3,501	3,717	-28	08:13	35,319	0.0196
FRA-ORD	A340-500	RR Trent 553	804,700	56,750	238	3,964	4,121	-18	09:13	23,718	0.0242
	A340-600	RR Trent 556	804,700	51,480	300	3,964	4,130	-19	09:14	25,620	0.0207
	A330-200	RR Trent 772B	513,765	37,644	231	3,964	4,132	-19	09:20	18,217	0.0191
	A330-300	RR Trent 772B	513,765	25,858	257	3,964	4,132	-19	09:21	18,416	0.0173
	777-200ER	RR Trent 884	580,000	31,000	285	3,964	4,118	-18	09:04	19,321	0.0165
	777-200ER	RR Trent 892	656,000	31,000	285	3,964	4,128	-19	09:07	21,541	0.0183
	A380-800	RR Trent 970	1,235,000	84,600	486	3,964	4,117	-18	09:00	39,321	0.0197
FRA-LAX	A340-500	RR Trent 553	804,700	56,750	238	5,279	5,476	-17	12:05	32,914	0.0253
	A340-600	RR Trent 556	804,700	51,480	300	5,279	5,475	-17	12:02	35,409	0.0216
	A330-200	RR Trent 772B	513,765	37,644	223	5,279	5,479	-17	12:17	22,045	0.0180
	A330-300	RR Trent 772B	513,765	25,858	190	5,279	5,479	-17	12:18	22,489	0.0216
	777-200ER	RR Trent 884	580,000	31,000	250	5,279	5,473	-17	11:56	26,188	0.0191
	777-200ER	RR Trent 892	656,000	31,000	285	5,279	5,463	-16	12:02	28,759	0.0185
	A380-800	RR Trent 970	1,235,000	84,600	486	5,279	5,471	-17	11:49	54,112	0.0204
SIN-LHR	A340-500	RR Trent 553	804,700	56,750	238	6,037	6,153	-9	13:21	37,705	0.0257
	A340-600	RR Trent 556	804,700	51,480	300	6,037	6,153	-9	13:20	39,553	0.0214
	A330-200	RR Trent 772B	513,765	37,644	49	6,037	6,143	-8	13:44	22,533	0.0753
	A330-300	RR Trent 772B	513,765	25,858	16	6,037	6,143	-8	13:46	22,972	0.2400
	777-200ER	RR Trent 884	580,000	31,000	47	6,037	6,140	-8	13:16	26,808	0.0923
	777-200ER	RR Trent 892	656,000	31,000	225	6,037	6,152	-9	13:08	29,443	0.0213
	A380-800	RR Trent 970	1,235,000	84,600	486	6,037	6,151	-9	13:06	58,075	0.0194

Source: Navtech

The tracked distance is represented by the equivalent still air distance (ESAD). Against a headwind, the ESAD will be longer than the tracked distance, whereas with a tailwind, the ESAD will be shorter than the tracked distance.

Assumptions in these flight plans include average temperatures from June being used, with 85% reliability winds. International Flight Rules are used, and include standard assumptions on fuel reserves, diversion fuel, and contingency fuel.

Optimum routes and flight levels have been used where possible. Long-range cruise (LRC) speed is used for each aircraft on each route. Although this may mean less than optimal block time, LRC enables the aircraft to achieve the optimum fuel burn rate per nautical mile. A total taxi time of 30 minutes has been assumed, with this added to the actual fuel burn figures for the flight to give total fuel burn.

The shortest route analysed here is between FRA and JFK, with a great circle distance of 3,350nm, and a tracked distance of 3,501nm. Due to headwinds of 27–29 knots (kts), the ESAD for this route ranges from 3,714nm to 3,728nm. Block times range from 8 hours, 13 minutes (08:13) to 08:32 *(see table, this page)*. Block times vary between aircraft due to differences in climb, cruise and descent speeds.

FRA-ORD is the second route analysed, with a longer great circle distance of 3,774nm. Tracked distance is 3,964nm, with headwinds of 18/19kts contributing to an ESAD of 4,117nm to 4,132nm. This gives block times a range of 09:00 to 09:21 *(see table, this page)*.

Increasing distance still further is FRA–LAX. Great circle distance is 5,045nm, with a tracked distance of 5,279nm. Headwinds of 16/17kts increase the ESAD to 5,463–5,479nm. Block times are about 12 hours, ranging from 11:49 to 12:18 *(see table, this page)*.

The longest route examined here is between SIN and LHR. Great circle distance is just short of 6,000nm at 5,951nm. Tracked distance is 6,037nm, with a small headwind of 8-9kts increasing the ESAD to between 6,140nm and 6,153nm. The shortest block time for this route is 13:06, with the longest being 13:46 *(see table, this page)*.

Fuel burn performance

Total fuel burn (block fuel), as well as fuel burn per seat-mile are shown for each aircraft and engine type, for each route *(see table, this page)*. Block fuel used is related both to aircraft weights and route distance, with block fuel increasing for each aircraft type when route distance increases.

To make a fair comparison between aircraft and engine types, therefore, the fuel burn per seat-mile can be used.

The twin-engined A330 and 777 aircraft, powered by Trent 700 and 800 models respectively, show slightly lower fuel burn in most cases than their four-engined counterparts, the A340 and A380, powered by Trent 500 and 900 respectively.

The A330-300 was the best performer on the FRA–JFK route, burning 0.0176USG per seat-mile, compared with 0.0189USG per seat-mile on the A330-200 *(see table, this page)*. This is despite the A330-300 burning about 600USG more in total block fuel. The difference in seat-mile fuel burn is because the A330-300 is carrying 26 more passengers than the A330-200.

The two 777-200 models analysed had the second and third lowest fuel burn per seat-mile respectively in this analysis, and had similar fuel burn figures. The Trent-884-powered model burned 0.0180USG per seat-mile, while the Trent-892-powered model burned

The Trent 900 has a lower sfc than the earlier-generation Trent 700 and 800. Despite this, the A380 has a higher fuel burn per seat-mile than the smaller, twin-engined A330-200/-300 and 777-200ER.

0.0182USG per seat-mile *(see table, page 14)*. This higher fuel burn represents the higher gross weight variant of the 777-200 that the Trent 892 is powering.

The A380 was the best performing quad jet on the FRA–JFK route, burning 0.0196 USG per seat-mile, compared to 0.0205 USG per seat-mile for the A340-600 and 0.0240 USG per seat-mile for the A340-500 *(see table, page 14)*. These aircraft burn slightly more fuel than their twin-engined counterparts due to the extra weight of carrying four engines across similar numbers of seats. The A380 makes up for this through larger seat numbers.

A similar pattern can be seen on the FRA–ORD route, where fuel burn per seat-mile across the aircraft types and engine variants remained consistent.

Again the twin-engined A330s and 777s had slightly lower fuel burn per seat-mile than the quads.

The lower weight 777 had the lowest fuel burn per seat-mile of 0.0165USG, with the A330-300 burning slightly more per seat-mile at 0.0173USG *(see table, page 14)*. The higher weight 777 burns 0.0183USG per seat-mile, while the A330-200 burns 0.0191USG per seat-mile.

The four-engined A340 and A380 showed similar fuel burn rates on FRA–ORD as on FRA–JFK. The A380 burned 0.0197USG per seat-mile, compared with 0.0207USG per seat-mile for the A340-600 and 0.0242USG per seat-mile for the A340-500 *(see table, page 14)*.

The twin-engined aircraft have a 17.25% lower burn per seat-mile than the quads.

When route length further increases, however, on the FRA–LAX route, the lower gross weight 777-200ER (with Trent 884) and A330-200/-300 get closer to the edge of their payload-range envelopes.

This means that they must suffer payload restrictions in terms of passenger numbers to complete the route non-stop.

The A330-300 suffered the largest restriction on this route, being able to carry only 190 passengers out of a possible 257. This increases fuel burn per seat-mile for the A330-300 to 0.0216USG per seat-mile, which is comparable to the four-engined aircraft on the route, such as the A340-600, which also burns 0.0216USG per seat-mile *(see table, page 14)*, yet carried a full complement of 300 passengers. Airlines are unlikely to actually use the A330-300 on a route of this length.

The lower gross weight 777-200ER (with Trent 884) had its passenger load reduced to 250 (out of a possible 285) on the route, and as a consequence fuel burn per seat-mile increased to 0.0191USG per seat-mile, which is higher than the shorter routes *(see table, page 14)*.

The higher gross weight 777-200ER (with Trent 892 engines) could still carry a full passenger load on this route, and burns 0.0185USG per seat-mile *(see table, page 14)*.

The fuel burn per seat-mile of the four-engined aircraft remained consistent with previous routes.

On the longest route analysed here, SIN–LHR, fuel burn figures are skewed for the twin-engined aircraft, since they are close to the edge of their payload-range envelopes, and therefore suffer further restrictions in the number of passengers they carry. In practical airline operations the twin-engined aircraft would not be used on this route because of its length. The 777-200ER is, however, used on a large number of Europe-Asia Pacific routes.

The route length significantly increases fuel burn per seat-mile on this route. For example, the A330-300 burns 0.240USG per seat-mile, with the A330-200 burning 0.0753USG per seat-mile *(see table, page 14)*.

The lower gross weight 777-200ER also has a higher fuel burn on this route of 0.0923USG per seat-mile *(see table, page 14)*.

The four-engined aircraft, however, operate the route without restrictions and again show consistent fuel burn.

The A380 is the best performer on the SIN–LHR route, burning 0.0194USG per seat-mile on the route *(see table, page 14)*.

The higher gross weight 777-200ER (with Trent 892), with a seat number restriction of 60, shows almost identical fuel burn to the A340-600 on this route, at 0.0213 and 0.0214USG per seat-mile respectively. The A340-500 burns 0.0257USG per seat-mile *(see table, page 14)*, which is consistent with other routes in this analysis.

Overall, however, fuel burn across the RR Trent variants was similar on all routes where passenger numbers were not restricted. The rates of fuel burn per seat-miles between all aircraft and engine types on unrestricted routes from FRA were similar at 29%.

On FRA–JFK, the highest fuel burn per seat-mile was 0.0240 for the A340-500, whereas the lowest was 0.0176 for the A330-300 *(see table, page 14)*. This is a difference of 0.0063 USG for all engine variants analysed.

For FRA–ORD, this difference is 0.0077USG; and for FRA–LAX the difference was 0.0072USG.

The four-engined A340 and A380 are equipped with Trent 500 and 900 engines that have lower specific fuel consumption (sfc) rates than the Trent 700 and 800 engines powering the older-generation A330s and 777s. The lower sfc rates of the Trent 500 and 900 are offset, however, by the four-engined design of the aircraft they power. The Trent 500 and 900 have at least kept the fuel burn performance of the A340 and A380 at a competitive level. AC

Rolls-Royce Trent family maintenance costs

Removal intervals,shop visit workscopes, shop visit costs, and LLP lives and list prices give an indication of maintenance reserves for the Trent 700, 800, 900 & 500 series.

Reserves for maintenance costs are affected by several variables. The most important are interval to shop visit, shop visit workscope and cost, life-limited part (LLP) lives and utilisation, and LLP costs. These elements can be examined to get a reserve per engine flight hour (EFH) and per engine flight cycle (EFC) for the two main elements of engine maintenance.

Total care packages

Most Rolls-Royce (RR) engines are maintained under total care packages (TCP). Engine shop visits are performed through facilities that are either owned by RR, or are a joint venture between RR and a major maintenance provider. These include TAESL in Texas, SAESL in Singapore, HAESL in Hong Kong, and N3 in Germany. RR therefore maintains control of most RB11 and Trent engines in operation.

In addition to the shop-visit maintenance of engines and the replacement of LLPs, the TCP packages offered by RR provide a wide variety of services related to the management of engines, and which airline engineering and maintenance departments have traditionally organised themselves.

The services provided under TCP can be selected by airlines from a menu, and paid for on a cost per EFH basis. The aim is to provide airlines with a predictable and stable cost, and remove the need to arrange and perform the function.

A key element of RR's TCP packages is comprehensive engine health monitoring (EHM). This is provided by RR's subsidiary optimised systems and solutions (Osys). This service analyses engine health and performance data sent from the aircraft in real-time. It is part of the engine management traditionally carried out by airlines, but needs specialist equipment and trained staff.

In hand with health monitoring, RR provides TotalCare workscope, which defines the appropriate shop-visit workscope to allow the engine to achieve the optimum time on-wing to the subsequent removal and shop visit.

RR also offers a reliability improvement service through selection of appropriate modifications to improve on-wing reliability. RR can also offer specialist line maintenance for aircraft-on-ground (AOG) situations. These occur randomly, and can be expensive, especially when aircraft are grounded for long periods and replacement engines have to be sent long distances.

Another element of line maintenance is managing and provisioning engine line replaceable units (LRUs) and accessories. Since these components fail, and require replacement, at random this requires a logistics service and organisation. RR provides this as an element of TCP on a flat-rate cost basis. As part of this, RR also monitors the component configuration of engines as an engineering management service for airlines.

Technical records of all maintenance performed also have to be kept. RR provides a technical records service by capturing, storing and retrieving records as required. This can also be added for creating work documents and continuing airworthiness management.

RR also provides spare engines, on a long- or short-term basis, through its subsidiary Rolls-Royce Partners Finance Ltd. RRPF has a portfolio of 290 engines, including the Trent family, available to airlines and lessors globally. RR also offers a lease return conditions management service. This ensures that leased engines are returned in the right maintenance condition and LLP life status.

Shop-visit maintenance

With shop-visit removal intervals, workscopes, shop-visit costs, and LLP replacement timings and costs it is possible to get approximate reserves for engines on a $ per EFH or per EFC basis.

LLPs in Trent engines are sub-divided between Group A parts, the disks and shafts; and Group B parts, the fan blades and annulus fillers that are placed between the fan blades. The list price of a shipset of Group A parts for the Trent 700 is $4.1 million, and the list price of Group B parts is about $2.0 million.

For the Trent 800, the list price of Group A parts is $4.9 million, and Group B parts have a list price of $2.7 million.

The Trent 500 has list prices of $4.6 million and $2.0 million for Group A and B parts. The Trent 900 has list prices of $4.9 million and $1.9 million for Group A and B parts.

The life limits of LLPs are an important factor in engine management. Each Trent family member has a target life for LLPs, and actual certified lives. Target lives are either 10,000EFC or 15,000EFC, depending on engine variant and thrust rating.

Actual certified lives are the lives of different part numbers for LLPs installed in the engine. These can be as low as 1,000EFC or as high as 15,000EFC at service entry. Certified lives can be extended for a part number while in service, as a result of testing by RR. When these parts are removed at a shop visit, they can be replaced with part numbers that have a higher certified life. The certified lives of replacement parts can be target lives, or just a longer life compared to the life of the original part.

RR's stated intention is for certified lives to be gradually extended to target lives. The lives to which parts get extended ultimately depends on the amount of testing done by RR.

The short or 'stub' certified life limits of individual parts can force early engine removals, or compromise removal intervals. LLP reserves account for a large portion of total maintenance costs. If the cost of a replacement part were amortised over the short certified life of the original part, then LLP reserves would be excessively high. It may be possible for operators to be compensated for short lives of individual parts through various mechanisms. One possible mechanism is for the operator to not pay full price for the replacement LLP, but pay a pro-rated price in proportion with its certified life. For example, a cost of $100,000 may only be charged for a part with a list price of $300,000 and a target life of 15,000EFC, but which had a certified life of 5,000EFC. This way LLP reserves per EFC would be kept to a level that is equivalent to list prices amortised over an interval equal to target lives.

The Trent 700 has a target life of 15,000EFC for all Group A LLPs. This is different to an earlier target life of 10,000EFC in its high pressure (HP) modules, and 15,000EFC for the

Fan blades and annulus fillers are life-limited parts in Trent engines. These are termed Group B LLPs, and their life limits are at the target lives of Group A parts, the disks and shafts. Fan blades and annulus fillers are removed relatively easily.

intermediate pressure (IP) and low pressure (LP) modules.

The lives of Group B parts are 20,000EFC, but Group A parts have varying certified lives of 4,200-15,000EFC.

Trent 800 engines fall into two groups. The Trent 875, 877, 890 and 892 engines all have LLP target lives of 15,000EFC. The Group B fan blades and annulus fillers have lives of 15,000EFC, while Group A parts have varying lives of between 4,500EFC and 15,000EFC.

The highest-rated Trent 895 has a target life of 10,000EFC. This is the limit of Group A parts, while Group B parts again have varied lives.

The target life for Trent 500 LLPs is 10,000EFC, and is the life limit of Group B parts. Group A disk and shaft parts have varying lives from 2,600EFC to 10,000EFC.

The Trent 900 has an LLP target life of 15,000EFC . Group A parts vary between 1,000EFC and 4,000EFC in the HP modules, and 3,200-12,500EFC in the IP and LP modules.

The uniform target lives for LLPs are intended to make managing engine shop-visit intervals and workscopes relatively easy. This is especially the case with engines operated on long-haul operations where EFH:EFC ratios are 6-7EFH per EFC. Engines therefore operate at utilisations of up to 750EFC per year.

In this case LLPs are only likely to be replaced either after 9,000EFC and 12-30 years of operation; or after 13,500-14,000EFC and 18 or more years of operation. Engines would therefore only likely have their LLPs replaced once in their operating life. Engines operated on medium-haul operations may only need to have their LLPs replaced twice.

LLP reserves, theoretically, not need be paid for the remainder of the engine's operational life after the LLPs have been replaced for the first or second time.

Based on current LLP list prices, and no allowances for annual price increases, LLP reserves for parts amortised over their target lives would be $454-507 per EFC for parts with a uniform life of 15,000EFC. They would be up to $660-760 per EFC for parts with uniform lives of 10,000EFC.

The actual lives of LLPs initially installed in the Trent 500, 700, 800 and 900 were not uniform for the earlier-built engines. These were staggered, with some parts having limits as low as 1,000EFC.

Staggered LLP lives complicate shop-visit management and raise LLP reserves. Parts with short lives force early removals for shop visits, which can increase the reserves per EFH for shop visits.

The replacement of these stub life or limited LLPs at the first shop visit then may either be with a part that has the same or a different restriction on its life limit, or may be a part with a full target life limit of 15,000EFC. In either scenario, the engine has a shipset of LLPs in the engine with staggered lives following the shop visit. This means subsequent removal intervals may be compromised, and some LLPs will have to be replaced early. This could raise both shop visit reserves. Engine removals need to be managed around LLP lives.

LLPs with uniform lives of 15,000EFC became available with later-build engines. These LLPs can be used to replace the earlier parts with restricted lives as they come due. Shop-visit intervals will not be so compromised, and engine management and LLP replacement will be made simpler.

Another main issue is shop-visit intervals. Besides being influenced by LLPs with restricted lives, they can be affected by the erosion of the turbine gas temperature (TGT) margin. Most Trent models and variants have a steady rate of mature TGT margin erosion, and few engines tend to be removed for TGT margin loss. The notable exception to this is the Trent 895; the highest-rated variant of the Trent family.

With the exception of some Trent 700s and 800s that operate on short- and medium-haul operations, all Trent models operate at EFC times of at least 6.0EFH. Some operate on EFC times as long as 11.0EFH. TGT margin erosion is not a major cause of engine removals for engines operated on long-haul services. Engines are more often removed due to hardware deterioration after long intervals of accumulated EFH.

Trent 700

The Trent 700 was the first Trent family member into service in 1994. It operates on the A330-300 on a mixture of medium- and long-haul operations, while the A330-200 is confined mainly to long-haul services.

Medium-haul operations have EFC times of 2.5-3.5EFH, while long-haul operations have EFC times of 6-7EFH.

The LLPs in the earlier-built Trent 700s had lives of 4,200EFC to

15,000EFC. The three parts with the shortest lives are the high pressure turbine (HPT) shaft at 4,200EFC, the high pressure compressor (HPC) rotor at 6,000EFC, and the HPT disk at 9,000EFC. These parts forced early removals in the earlier-built Trent 700s.

The target lives of Group A parts in the high pressure (HP) module were 10,000EFC, but were later increased to 15,000EFC. All Group A parts now have target lives of 15,000EFC. The fan disk and intermediate pressure compressor (IPC) drum had initial lives of 13,000EFC and 12,600EFC. These also compromised removal intervals.

The Trent 700 has a reputation for good TGT margin, and operators report that earlier-built engines get removed for their first shop visit because of the HPT shaft life limit of 4,200EFC.

Even engines operated at 2.5-3.5EFH per EFC have enough TGT margin retention to remain on-wing for up to 5,000EFC. The Trent 700 is generally capable of achieving longer removal intervals than the other A330 engine choices: the PW4000-100 and CF6-80E1.

The range of first removal intervals is 2,500-4,200EFC, the higher interval being imposed by the LLP limit. British Midland, for example, operated the A330-200 at 7.1 flight hours (FH) per flight cycle (FC). The Trent 700 in this case remained on-wing up to its first LLP limit of 4,200EFC.

Air Canada, which operates the 772B on its A330-300 fleet at 6-7EFH per EFC, says the cause of the engine's first removals were HPT disk and HPC drum life limit restrictions.

The HPC drum's or rotor's life limit of 6,000EFC could reduce the second removal to just 1,800EFC if not removed and replaced at the first shop visit.

Since the Trent 700 has sufficient TGT margin to remain on-wing for a longer first interval, the engine can be expected to stay on-wing for up to 4,200EFC for EFC times of 2.5-7.0EFH. This would be equal to 10,500EFH to 29,400EFH *(see table, page 20).*

The first shop visit would at least include full disassembly of the HP rotor, as well as disassembly of the intermediate pressure (IP) rotor. A level 3 workscope involves the full disassembly of the HP system and combustor. A level 4 workscope also includes a full disassembly of the IP system and the low pressure (LP) system. The need to disassemble both the HP and IP systems means the workscope will be larger than a level 3 shop visit.

The second interval could be up to a maximum of 4,800EFC, given the 9,000EFC limit of its HPT disk. Second run intervals are about 80% of first run intervals. Leaving the HPT disk in place at the first shop visit should therefore not compromise the second interval.

Second removal intervals would be: 3,400EFC for those operated at 2.5EFH per EFC; 3,300EFC for those at 3.5EFH; 2,800EFC for those at 6.0EFH; and 2,500EFC for those at 7.0EFH. This is equal to 8,500EFH, 11,500EFH, 16,800EFH and 17,500EFH.

The workscope at this interval could include a full engine disassembly that includes the fan or low pressure compressor (LPC), low pressure turbine (LPT) and gearboxes. The HPT disk would also have to be replaced. This would be a level 4 workscope.

The third removal interval would likely be reduced to a mature level closer to 3,000-3,400EFC for engines operated on medium-haul operations, and to 2,400-2,600EFC for those operated at 6-7EFH per EFC.

LLPs with lives restricted at up to 12,000EFC, which include the fan disk and IPC drum, would have to be replaced at this third shop visit. The engine would therefore undergo a high level of disassembly - a level 4 workscope.

Mature intervals mean the remaining LLPs with lives of 15,000EFC would have to be replaced at the fourth shop visit in engines operated on medium-haul operations, and more likely at the fifth shop visit for engines operated on long-haul services. Replacing remaining LLPs would mean a third level 4 workscope in

TRENT 700 MAINTENANCE RESERVES

	Engines with old LLPs				Engines with full-life LLPs			
EFH:EFC	**2.5**	**3.5**	**6.0**	**7.0**	**2.5**	**3.5**	**6.0**	**7.0**
1st interval								
EFC	4,200	4,200	4,200	4,200	4,800	4,600	4,400	4,300
EFH	10,500	14,700	25,200	29,400	12,000	16,100	26,400	30,100
LLP replacement:	HPT shaft & HPC rotor				None	None	None	None
LLP reserve-$/EFC	374	374	374	374	436	448	395	411
S-V workscope level	3	3	3	3	3	3	3	3
1st S-V -$	4.25m	4.4m	4.6m	4.7m	4.3m	4.45m	4.65m	4.75m
S-V reserve -$/EFH	405	299	183	160	358	276	176	158
Total reserve-$/EFH	**554**	**406**	**245**	**213**	**533**	**404**	**242**	**217**
2nd interval								
EFC	3,400	3,300	2,800	2,500	3,800	3,700	3,500	3,300
EFH	8,500	11,550	16,800	17,500	9,500	12,950	21,000	23,100
LLP replacement:	HPT disk @ 9,000EFC				None	None	None	None
LLP reserve-$/EFC	374	374	374	374	436	448	395	411
S-V workscope level	4	4	4	4	3/4	3/4	4	4
2nd S-V -$	5.0m	5.2m	5.4m	5.5m	4.7m	4.7m	5.5m	5.6m
S-V reserve -$/EFH	588	450	321	314	495	363	262	242
Total reserve-$/EFH	**738**	**557**	**384**	**368**	**669**	**491**	**328**	**301**
3rd interval								
EFC	3,300	3,100	2,600	2,400	3,600	3,500	3,300	3,200
EFH	8,250	10,850	15,600	16,800	9,000	12,250	19,800	22,400
LLP replacement:	Parts with lives of 12,000EFC				All Gp A	All Gp A	None	None
LLP reserve-$/EFC	374	374	374	374	436	448	395	411
S-V workscope level	4	4	4	4	4	4	3	3
3rd S-V -$	5.0m	5.2m	5.4m	5.5m	5.1m	5.3m	4.6m	4.7m
S-V reserve -$/EFH	606	479	346	327	567	433	232	210
Total reserve-$/EFH	**756**	**586**	**408**	**381**	**741**	**561**	**298**	**269**
4th interval								
EFC	3,300	3,100	2,600	2,400	3,600	3,500	3,300	3,200
EFH	8,250	10,850	15,600	16,800	9,000	12,250	19,800	22,400
LLP replacement:	All remaining original parts		None	None	None	None	All Gp A	All Gp A
LLP reserve-$/EFC	374	374	374	374	393	395	395	411
S-V workscope level	4	4	3	3	3	3	4	4
4th S-V -$	5.0m	5.2m	5.4m	5.5m	4.5m	4.5m	5.5m	5.6m
S-V reserve -$/EFH	606	479	346	327	500	367	278	250
Total reserve-$/EFH	**756**	**586**	**408**	**381**	**657**	**480**	**344**	**309**

succession could be required.

The replacement of Group A life-restricted LLPs at the first, second and third shop visits means the engine would have LLPs with staggered lives.

Mature shop visit intervals of 3,000-3,400EFC for medium-haul engines mean Group A LLPs would be replaced every fourth or fifth shop visit after 13,000-15,000EFC if managed well. Engines operating at 6-7EFH may have LLPs replaced every five or six shop visits.

Group B parts, with lives of 20,000EFC, would likely be replaced at the fifth or sixth shop visit.

Reserves for Group A parts would be $274 per EFC, on the basis that the list price is amortised over the full target life, 15,000EFC. Reserves for Group B parts, fan blades and annulus fillers, would be $100 per EFC, taking total LLP reserves to $374 per EFC *(see table, this page)*. This reserve is based on the assumption that the cost of new LLPs have their list prices pro-rated to compensate for the stub life of parts they are replacing.

Costs for the first workscope after the first removal would be $4.25-4.5 million for engines operated at 2.5-3.5EFH, and marginally higher at $4.6-4.8 million for engines at 6-7EFH. This cost excludes the replacement of LLPs. The shop visit costs result in reserves of $405 per EFH for engines operated at 2.5EFH; $299 per EFH for those operated at 3.5EFH; $183 per EFH for those at 6EFH; and $160 per EFH for those at 7EFH *(see table, this page)*.

With LLP reserves converted to rates per EFH, total reserves are: $554 per EFH for engines operated at 2.5EFH; $406 per EFH for those operated at 3.5EFH; $245 per EFH for those at 6EFH; and $213 per EFH for those at 7EFH *(see table, this page)*.

The second shop-visit workscope would either be close to an overhaul or a full overhaul, and cost $5.0-5.5 million, depending on the total number of accumulated EFC and EFH on-wing.

These shop visit inputs will have reserves of $588 per EFH for engines operated at 2.5EFH; $450 per EFH for those operated at 3.5EFH; $321 per EFH for those at 6EFH; and $314 per EFH for those at 7EFH *(see table, this page)*.

With LLP reserves converted to rates per EFH, total reserves are: $738 per EFH for engines operated at 2.5EFH; $557 per EFH for those operated at 3.5EFH; $384 per EFH for those at 6EFH; and $368 per EFH for those at 7EFH *(see table, this page)*.

Engines with LLPs with lives of 15,000EFC would have a simpler shop-visit pattern and be easier to manage.

Removal intervals may be longer, since LLPs with restricted lives would not be a removal cause.

The main difference is that engine shop visit workscopes would follow a more simple pattern. This is because a level 4 workscope would not be required at so many removals because LLPs with stub lives would not have to be replaced. This is especially the case with engines operated on longer EFC times.

For engines operating at 2.5-3.5EFH per EFC, the first, second and third removals would be 4,600-4,800EFC, 3,700-3,800EFC and 3,500-3,600EFC. By the third removal, total accumulated time on-wing would be about 12,000EFC. All Group A LLPs would have to be replaced at this stage. A level 4 workscope would therefore be required. A level 3 workscope may therefore only be required at the second shop visit, although this is not certain.

The LLP reserves for Group A parts up to this third shop visit would be $336-348 per EFC. With reserves for Group B parts added, total LLP reserves to the third shop visit would be $436-448 per EFC *(see table, this page)*.

The first two shop visit inputs would incur similar costs to engines with restricted LLP lives, removal intervals being up to 2,000 EFH longer.

The first shop-visit costs result in reserves of $358 per EFH for engines operated at 2.5EFH; $276 per EFH for those operated at 3.5EFH.

With LLP reserves converted to rates per EFH, total reserves would be: $533 per EFH for engines operated at 2.5EFH,

The stub lives of many LLPs in the HP, IP and LP modules of different Trent family members can force heavy workscopes earlier than would otherwise be required if the LLPs had certified lives equal to their target lives.

and $404 per EFH for those operated at 3.5EFH *(see table, page 20)*.

The second shop-visit cost will depend on whether a level 3 or level 4 workscope is required. An average shop visit cost of $4.7 million will result in reserves of $495 per EFH for engines operated at 2.5EFH, and $363 per EFH for those operated at 3.5EFH.

With LLP reserves converted to rates per EFH, total reserves would be: $669 per EFH for engines operated at 2.5EFH, and $491 per EFH for those operated at 3.5EFH *(see table, page 20)*.

The level 4 workscope required at the third shop visit, and shorter corresponding removal interval, will result in a higher overall reserve of $741 per EFH for engines operated at 2.5EFH, and $561 per EFH for engines operated at 3.5EFH *(see table, page 20)*.

Reserves to the fourth shop visit should be lower; a level 3 workscope will be required at the shop visit.

Engines operating at 6.0EFH and 7.0EFH per EFC, the first, second and third intervals would be 4,300-4,400EFC, 3,300-3,500EFC, and 3,200-3,300EFC. These intervals mean it would be possible to removal Group A LLPs at the fourth shop visit, after a total time of about 14,000EFC *(see table, page 20)*. This would allow the engine to follow an alternating pattern of level 3 and level 4 shop visit workscopes.

The reserves for Group A parts would be $283-293 per EFC. Group B parts would have a reserve of $112-118 per EFC; taking the total LLP reserves to $395-411 per EFC *(see table, page 20)*.

The first and third shop visits would thus have costs of $4.6-4.8 million, and second and fourth shop visits would have costs in the region of $5.5-5.6 million.

With LLP reserves converted to rates per EFH, total reserves would be: $242 per EFH for those at 6EFH; and $217 per EFH for those at 7EFH to the first shop visit *(see table, page 20)*.

These would increase to $328 per EFH for those at 6EFH; and $301 per EFH for those at 7EFH for the second shop visit *(see table, page 20)*.

Reserves for the subsequent third and fourth shop visit inputs would be higher than this due to shorter, mature removal intervals *(see table, page 20)*.

Trent 800

The Trent 800 variants in operation can be divided into three groups. The first of these are the 875 and 877 engines powering the 777-200s; which are operated on medium-haul operations with EFC times of 2.5-4.0EFH.

The second group are the 884, 890 and 892 engines powering the 777-200ERs on long-haul operations with EFC times of 7.0-10.0EFH. The 892 engines also power 777-300s, which are used on a variety of mission types.

A third group is the 895 engines powering 777-200ERs; and which generally operate at the longest EFC times of 8.0-10.0EFH.

Most Trent variants have enough TGT margin, and a slow enough rate of TGT margin erosion, for loss of margin and engine performance not to be a main removal cause for shop visits. The exception to this is the Trent 895, which in some cases has TGT margin loss as a main removal cause.

The initial Trent 800s from the production line had LLPs with varying, certified lives for individual parts.

Parts with the shortest lives are in the HP spool, and include the HPC 1-4 and HPC 5-6 drums, and the HPT disk. These parts had some part numbers with lives as short as 4,500EFC, but the shortest life of most parts is about 5,000EFC.

Other HP and IP parts have lives of 6,000-8,500EFC. Most other LLPs in the 875, 877, 890 and 892 engines have lives of 12,000-15,000EFC.

The highest life limit for Group A parts in the Trent 895 is 10,000EFC.

As described, different Trent models operate on different route networks and mission lengths. Trent 875s and 877s on low-gross-weight 777-200s and 892s on 777-300s mainly operate on medium-haul missions of 2.5-4.0EFH per EFC. Some 777-300s are used by Thai International and Cathay Pacific to operate medium-haul routes in the Asia Pacific. Other -300s are operated by Emirates on longer sectors.

The Trent 884s, 895s and most 892s are all operated on 777-200ERs on long-haul operations. EFC times are 7.0-10.0EFH in most cases. Most engines are 892s, operated by American, Delta, Thai, Singapore Airlines, and Malaysian.

Smaller numbers of 884s are operated by Singapore Airlines, Cathay Pacific and Emirates. Trent 895s are operated British Airways, Air New Zealand and El Al.

Trent 875, 877 & 892

The 875, 877 and 892 engines operated on medium-haul operations, with an average EFC time of 3.5EFH, can operate up to 5,000-5,500EFC before their first removal. This can be limited to a shorter life if the engine has some HP LLPs with shorter life limits. An example is airworthiness directive (AD) 2011-10-04 which limits the HPC stage 1-4 drum part number FK32580 to an SDC life of 5,580-7,780EFC.

An interval of 5,000-5,500EFC is equal to 17,500-19,250EFH. The first shop visit will require the replacement of LLPs with the shortest lives.

The second removal interval can be up to about 4,500EFC, so total accumulated engine life will be up to 10,000EFC. The second removal interval will depend, however, on which LLPs with restricted lives are left in the engine at the first shop visit. The second removal will be less than 4,500EFC if some of the

IP spool parts with lives of 8,000-9,000EFC are not replaced at the first shop visit.

Given that the third removal interval could be up to 4,250EFC and a total accumulated time of 14,000-14,500EFC, most LLPs with restricted lives will have to be removed and replaced at the first shop visit. Only those with lives of 9,000-10,000EFC can be left in until the second shop visit to prevent compromising the second removal interval.

All parts with lives of up to 14,000EFC should be removed and replaced at the second shop visit to prevent limiting the third interval.

All other original Group A LLPs will have to be removed and replaced at the third shop visit.

A full shipset of LLPs with no life restrictions has a current list price of $7.6 million. The reserve for the cost of the shipset amortised over the accumulated time of about 14,500EFC at the third shop visit results in a reserve of about $524 per EFC *(see table, this page)*.

The first shop visit will therefore have to be higher than a level 3 workscope. This will be full disassembly to piece-part level of the HP modules and combustor section, as well as a full disassembly on the IP modules. The need to fully disassemble the IP modules to allow LLP replacement means the cost of this shop visit will be high. A level 3 shop visit on the Trent 800 can cost $4.7-5.5 million;, but adding of the IP spool means the cost is likely to be higher *(see table, this page)*.

The second shop visit could be with a level 3 workscope again if the LP modules are in good condition, but the engine worked at short cycles. A level 4 workscope, which involves a full disassembly of all modules, will cost $6.5-7.0 million *(see table, this page)*.

The third shop visit will have to be a level 4 workscope so that all remaining LLPs, including all parts in the LP modules, will be replaced. A full workscope costs about $7.0 million.

The reserves for these shop visit costs are about $300 per EFH up to the first workscope, $395 per EFH up to the second, and $471 per EFH up to the third *(see table, this page)*. Total reserves that include LLPs will, therefore, be $446 per EFH up to the first removal, $545 per EFH up to the second, and $620 per EFH up to the third *(see table, this page)*.

TRENT 800 & 500 MAINTENANCE RESERVES

	Trent 800			Trent 500	
Engine Variant	**875/877**	**884/890/892**	**895**	**556**	**553**
EFH:EFC	**3.5**	**7.0**	**9.0**	**8.5**	**10.75**
1st interval					
EFC	5,300	3,500	2,500	2,600	2,600
EFH	18,550	24,500	22,500	22,100	28,000
LLP replacement:	HP parts, IPC	HPTD	HPTD	HPT Disk, Plate	HPT Disk, Plate
LLP reserve-$/EFC	524	596	844	710	710
S-V Workscope level					
1st S-V -$	5.5m	5.1m	5.6m	5.4m	5.7m
S-V reserve -$/EFH	296	208	249	244	204
Total reserve-$/EFH	**446**	**293**	**343**	**328**	**270**
2nd interval					
EFC	4,700	2,500	2,300	2,300	2,300
EFH	16,450	17,500	20,700	19,550	24,725
LLP replacement:	None	Other HP/IP	Other HP/IP	HPC1-4, IPT Disk	HPC1-4, IPT Disk
LLP reserve-$/EFC	524	596	844	710	710
S-V Workscope level					
2nd S-V -$	6.5m	6.75m	7.0m	6.0m	6.4m
S-V reserve -$/EFH	395	386	338	307	259
Total reserve-$/EFH	**545**	**471**	**432**	**390**	**325**
3rd interval					
EFC	4,250	2,250	2,150	2,200	2,200
EFH	14,875	15,750	19,350	18,700	23,650
LLP replacement:	Remainder	Remainder	None	None	None
LLP reserve-$/EFC	524	596	844	710	710
S-V Workscope level					
3rd S-V -$	7.0m	7.0m	5.7m	5.4m	5.7m
S-V reserve -$/EFH	471	444	295	289	241
Total reserve-$/EFH	**620**	**530**	**388**	**372**	**307**
4th interval					
EFC			2,150	2,200	2,200
EFH			19,350	18,700	23,650
LLP replacement:			Remainder	Remainder	Remainder
LLP reserve-$/EFC			844	710	710
S-V Workscope level					
3rd S-V -$			7.0m	6.0m	6.4m
S-V reserve -$/EFH			362	321	271
Total reserve-$/EFH			**456**	**404**	**337**

Trent 884 & 892

The 884 and 892 and variants operated on EFC times of 7-10EFH will have to be managed differently. American Airlines, for example, operates the largest fleet of Trent 892s for its 777-200ERs. It has an average EFC time of 9.0EFH. E Al operates 895s on 777-200ERs at an average of 10EFH per EFC.

American achieved first removal intervals of 3,000-3,500EFCs with its 892s. Removals were not caused by TGT margin loss, but by other issues.

American says it has a planned for a similar second removal interval, given the engine's ability to retain TGT margin and its durability. A shorter interval of about 2,500EFC should be planned for.

A mature or third interval will about 2,250EFC, equal to an accumulated total time of 8,250EFC. To avoid compromising later removal intervals, the HPT disk should be removed and replaced at the first shop visit.

The remaining HP and IP parts with restricted lives should be removed and replaced at the second shop visit.

Similar subsequent intervals will mean LLPs will have to be replaced at the fourth or fifth shop visits, given the lives of up to 15,000EFC life limit of these remaining parts.

The first shop visit can be a level 3 workscope. This will be smaller than the workscope required by the engines operating on shorter cycles. The cost of this will be $5.1 million. Amortised over the interval, it is equal to a reserve of $208 per EFH *(see table, this page)*.

The second shop visit would include the replacement of other HP and IP LLPs with restricted lives. A larger workscope would be required. With a total on-wing

TRENT 900 MAINTENANCE RESERVES

Engine Variant	Trent 900	Trent 900
EFH:EFC	8.5	10.75
1st interval		
EFC	2,700	2,600
EFH	23,000	28,000
LLP replacement:	All HP, some IP & LP rotor shaft	All HP, some IP & LP rotor shaft
LLP reserve-$/EFC	618	618
S-V Workscope level	Level 3, high	Level 3, high
1st S-V -$	$5.0m	$5.25m
S-V reserve -$/EFH	218	188
Total reserve-$/EFH	**291**	**245**
2nd interval		
EFC	2,200	2,300
EFH	19,000	15,000
LLP replacement:	None	None
LLP reserve-$/EFC	618	618
S-V Workscope level	Level 4	Level 4
2nd S-V -$	$6.3m	$6.5m
S-V reserve -$/EFH	334	263
Total reserve-$/EFH	**407**	**320**

time of 42,000EFH it is possible a level 4 workscope might be needed. An average workscope cost will be $6.75 million, with a corresponding reserve of $386 per EFH *(see table, page 23)*.

The third shop visit would replace all remaining LLPs in all modules. A level 4 workscope would therefore be required. This would cost $7 million, so the reserve for this would be $444 per EFH *(see table, page 23)*.

With reserves for LLPs added, total costs per EFH would be $293 per EFH for the first interval, $471 per EFH for the second and $530 per EFH for the third *(see table, page 23)*.

Trent 895

Trent 895 engines, which are generally operated on longer EFCs of 9-10EFH, have a reputation for being one of the few Trent variants that sometimes have to be removed due to loss of performance and TGT margin.

Air New Zealand, for example, operates the engines at a rate of about 8.5EFH per EFC. It states the engine had an initial TGT margin of 30-40 degrees centigrade. Air New Zealand gives the problem of suspect bearings and LPT Stage 1 damper wire as the main cause for the first removals at an interval of about 22,000EFH, equal to about 2,600EFC. Second removal intervals of about 2,300EFC, and mature intervals of 2,000-2,200EFC can be expected.

The 10,000EFC limit of Group A parts means the engine could follow an alternating shop visit pattern of level 3 and level 4 workscopes, and then have parts with the longest lives replaced at the fourth shop visit. This would be at an accumulated total on-wing time of about 9,000EFC *(see table, page 23)*.

On this basis, LLP reserves would be about $844 per EFC *(see table, page 23)*. The alternating level 3 and level 4 workscopes would mean that shop visit reserves for the first two shop visits would be $249 per EFH and $338 per EFH *(see table, page 23)*. With LLP reserves added, total reserves would be $343 per EFH and $432 per EFH for the first two shop visits *(see table, page 23)*.

Shorter mature removal intervals means total reserves would increase to $388 per EFH and $456 per EFH for the third and fourth removal intervals *(see table, page 23)*.

Trent 500

The Trent 500 powering the A340-500 and -600 operate at some of the longest EFC times of all engine types.

The Trent 553 powering the A340-500 operates on the longest cycles, the aircraft having a longer-range capability. Typical EFC times are 10-11EFH. Operators include Emirates, Etihad, SIA and Thai International.

The Trent 556 powering the A340-600 is in more widespread use. These aircraft are operated on typical long-haul routes, as well as some ultra-long-range missions. Operators include Lufthansa, China Eastern, Thai International, Virgin Atlantic, and South African Airways.

EFC times for the Trent 556 vary from 7.0EFH to 9.5EFH for most operators' fleets, and average 8.50EFH.

All LLPs in the fan, IPC and LPT modules have uniform lives of 10,000EFC. The HPC has four parts, three of which have lives of 10,000EFC but a fourth part has a restricted life of 5,000EFC. The IPT disk is also limited to 5,000EFC, while the IP rotor shaft has a life of 10,000EFC. The HPT has the most restricted parts, with the HPT disk at 2,600EFC and the HPT front cover plate at 4,000EFC.

The HPT disk and HPT front cover plate will therefore limit the first shop visit to 2,600EFC, although this will be about 28,000EFH for the 553 engines operating at almost 11EFH, and 22,000EFH for 556 engines operating at shorter cycles of 8.5EFH. Some operators have reported short first removal intervals, however, due to initial in-service problems related to oil leakages.

The removal and replacement of these parts means that a level 3 shop visit workscope will be sufficient. This will leave the IP and LP modules. A level 3 workscope will cost $5.5-5.7 million, equal to a reserve of $204 per EFH for the 553, and $244 per EFH for the 556 *(see table, page 23)*.

Future removals will be limited if the replacement HPT disk part number does not have a longer life limit. Second and subsequent removal intervals are likely to be shorter at 2,000-2,300EFC. HPT disk lives will still not limit intervals, but the LLP reserves will be raised.

The LLPs that will have to be replaced at the second shop visit include the -04 drum and IPT disk.

The remaining LLPs, with full lives of 10,000EFC, could then be removed and replaced at the fourth shop visit after a total time of about 9,300EFC *(see table, page 23)*. The reserve for Group A and Group B parts amortised over this interval will be $710 per EFC. This will be equal to $66 per EFH and $84 per EFH once they have been adjusted for EFC times *(see table, page 23)*.

The need to replace HP and IP system LLPs at the second shop visit will mean that a workscope higher than level 3 will be required. Given that the accumulated time on-wing will be 42,000-53,000EFH, a level 4 workscope will probably be required. This will cost $6.0-6.5 million, depending on degradation of parts due to accumulated EFH.

No LLPs will have to be replaced at the third shop visit, and most parts will have to be replaced at the fourth. It will therefore be prudent to attempt to manage the engine on an alternating pattern of level 3 and level 4 workscopes.

The total reserves up to the first shop visit will thus be $270 per EFH for the 553, and $328 per EFH for the 556. Reserves up to the second removal will be

$325 per EFH for the 553 and $390 per EFH for the 556 *(see table, page 23)*.

Without adjustments for LLP price indexes, reserves per EFH for the third and fourth removals will be higher than those for the first and second removals because of shorter removal intervals.

Trent 900

The Trent 900 has been chosen by 11 A380 customers; only four airlines have selected the GP7200. Another four airlines have yet to make their engine selections. Lufthansa, Qantas and Singapore Airlines (SIA) have the Trent 900-powered A380 in service, and operate at FC times of 9-11FH.

The Trent 900's Group A LLPs total 18 parts: two fan module; two IPC module; three HPC module; two HPT module; three IPT module; and six LPT module parts. The lives of these vary from 1,000EFC to 12,500EFC. These compare to the target lives of 15,000EFC. These have a list price of $4.9 million.

Each module has parts with restricted life limits, except the fan module. The HPT module has parts with the shortest lives. There are four part numbers for the HPT rotor disk, with lives of 1,000EFC to 3,800EFC. The HPT front cover plate has three different part numbers: two with a life of 1,442EFC and one with a life of 3,800EFC.

The module with the next shortest LLP lives is the IPT. The IPT rotor disk has a life of 2,600EFC, while there are two parts numbers for the IPT rear air seal with a life of 3,984EFC.

Operating at similar EFH:EFC ratios as the Trent 500, the Trent 900 should be able to achieve similar removal intervals of 23,000-28,000EFH to its first shop visit, and 19,000-25,000EFH to its second. This is equal to 2,600-2,700EFC and 2,200-2,300EFC. The total accumulated time on-wing by the second shop visit could thus be 4,800-5,000EFC.

Unless the HPT disk installed in the engine is one of the three part numbers with a life limit of 1,000EFC or 1,250EFC, the engine should be able to operate to these removal intervals without being compromised by LLP lives.

The first shop visit would normally be a level 3 workscope. The large number of parts with lives of up to just 4,200EFC in the IPC and LPT also means these modules would have to be disassembled at the first shop visit. The LP rotor shaft would also have to be replaced.

The fan module would be the only module at the first shop visit that would not have to be disassembled.

All LLPs with restricted lives (that is up to 4,357EFC) would have to be replaced with parts with longer lives, or unrestricted lives of 15,000EFC. This would then mean the second and subsequent removal intervals would not be compromised by limited LLP lives.

Mature intervals after the second shop visit could broadly be expected to be 1,900-2,100EFC; equal to 16,500-21,500EFH.

Original LLPs in the fan, IPC, IPT and LPT modules with lives of 11,600-12,500EFC would start to reach their life limits by the fifth shop visit.

Amortising the cost of all LLPs over the accumulated interval to the fifth shop visit generates a LLP reserve of about $618 per EFC.

The first shop visit would be a heavy level 3 workscope, or a level 4 workscope less the cost of the fan module. This could cost $5.0-5.3 million, with reserves of $188-218 per EFH. With LLPs, total reserves are $245 per EFH for engines operated at 10.8EFH per EFC, and $291 per EFH for engines operated at $8.50EFH per EFC *(see table, page 24)*.

The second shop visit could be a level 3 workscope given that all modules had been disassembled at the first shop visit. Given that the engines had a total accumulated time on-wing of 42,000-53,000EFH, a level 4 workscope would, however, probably be required.

The resulting shop visit would have a cost of $6.2-6.5 million, with reserves of $263 per EFH for engines operating at 10.75EFH per EFC, and $334 per EFH for engines operating at 8.50EFH per EFC. With LLPs add, total reserves would be $320 per EFH for engines operating at 10.75EFH per EFC, and $407 per EFH for engines operating at 8.50EFH per EFC *(see table, page 24)*.