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A320 NEO vs. CEO comparison study

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Abstract

New engine technology was introduced in commercial operation for single-aisle aircraft in 2016. Two of the world's largest engine manufacturers, CFM International (CFMI) and Pratt & Whitney (P&W), launched solutions to re-engine the A320 aircraft model. The A320 is the only in production western-built single-aisle that offers engine choice. The Airbus group designated the current engine option as A320CEO and the new variant, the new engine option, as A320NEO. The evolution from CEO to NEO is part of a larger industry advancement that seeks to improve aircraft efficiency, decrease fuel consumption and lower environmental foot print.

The first A320NEO entered commercial service in January 2016 with a PW1100G-JM engine (PW1127G-JM variant) and shortly after, in July 2016, the first CFMI powered A320NEO entered service with a LEAP-1A engine (LEAP-1A26 variant). PW1100G-JM belongs to the PW1000G family of P&W and LEAP-1A belongs to the LEAP-X family of CFM International.

The aim of this paper is to investigate the consequences of equipping the A320 with new engines and draw a comparison between A320CEO and A320NEO variants from a technical and commercial point of view, with emphasis on the changes and cost differentials introduced by the new engine types.

1. A320 developments

The new engine models are the main difference between A320NEOs and A320CEOs. Advancements such as new options for cabin and rear galley configuration, ambiance lighting, the possibility to increase the seats capacity, are all part of the continuous product improvement efforts by Airbus in the last few years. These recent improvements developed for the NEOs can also be applied to the latest CEO vintages. Aerodynamic revisions such as Sharklet wingtips, or increased capacity from using new cabin configuration, are available for both NEO and CEO aircraft.

The major upgrades relative to the CEOs are the replacement of the IAE V2500 and CFM56-5B models with the PW1100G-JM and LEAP-1A series engines, respectively. The new engine solutions proposed by CFMI and P&W are very different. P&W developed an innovative geared turbofan engine, while CFMI refined a more traditional engine configuration.

1.1. PW1100G-JM and LEAP-1A engines on the A320NEO

One major similarity between the LEAP-1A and PW1100G-JM series engines is their significantly larger fan diameter engines than their predecessors. This enables a higher bypass ratio, which in turn increases the jet propulsion efficiency and reduces the fuel consumption.

The PW1100G-JM engines are manufactured by Pratt & Whitney. P&W has the largest ownership stake in the International Aero Engines (IAE) joint venture, which manufactures the V2500 series engines installed on the A320CEO aircraft. The most novel feature of the PW1100G-JM is the gearbox between the fan and the low-pressure system. This enables the fan to rotate at closer to its optimum speed, which is one third of the speed of the low-pressure turbine. In turn, this doubles the bypass ratio to 12:1 relative to the 6:1 ratio of the equivalent V2500 engine. The separation of the fan and the LPT rotation makes the LPT more efficient, which in turn allows the LPT to have less stages than an engine with a more conventional architecture. The principal differentiator of this engine is its gear box which improves the propulsive efficiency.

The LEAP engines are manufactured by CFM International, the long standing 50:50 joint venture between GE and Safran Aircraft Engines. Compared to the CFM56-5B, its predecessor on the A320 aircraft, the LEAP-1A has an extra stage in the high-pressure turbine (HPT) section, operates at a higher temperature, and has more advanced materials such as ceramic matrix composites (CMC) in the HPT and titanium aluminide (Ti-Al) blades in the LPT. The advanced materials allow an increase in the turbine temperature, which improves the thermal efficiency.

1.2. Wingtip devices

Sharklets are large wingtip devices with a height of 2.4m and weight of 200kg that contribute to the efficiency of an aircraft by improving the lift-to-drag ratio. Sharklets increase the lift of the wingtip while simultaneously decreasing the drag along the wing caused by wingtip vortexes, thus allowing for fuel savings and longer ranges. The benefits are comparable to increasing the span of the wings, but without doing so. Sharklets contribute to a reduction of up to 4% in fuel consumption on routes longer than 2500nm and circa 2% for routes of 500nm, when compared to wingtip fences. The longer the route, the higher the fuel saving.

Sharklets are an element of the continuous A320 family jetliner development. They can be fitted on both CEOs and NEOs. Sharklets have been available as an option on production A320CEO aircraft since 2013 and for retrofit for earlier production aircraft. They are standard fit on all A320NEO aircraft.

1.3. Passenger capacity

The fuselage dimensions have remained the same with the transition from the CEO to NEO. However, in recent years, Airbus has redesigned aspects of the interior of the A320 aircraft to enable increased passenger capacity. The available galley capacity in the aft of the aircraft has been reduced, while the two aft lavatories have been redesigned and relocated to fit into the freed-up galley space. The extra space allows the installation of at least one additional row of seats. This has increased the maximum capacity from 180 passengers to a typical upper limit of 186 passengers. The increased seating capacity is available on current production aircraft for both the A320NEO and A320CEO.

1.4. Elements of operating costs

Fuel represents one of the largest elements of operating costs of an aircraft and, industrywide, this percentage is estimated to be around 20% in the current context of moderately low fuel prices scenario. Other categories of operating costs may affect the overall share composition of fuel costs as a percentage. Other significant operational costs include crew (ca. 40%) and maintenance costs (ca. 15%), with the remainder accounted for by navigation, ground support and landing fees. Of these categories, operation of the NEO should result in savings in fuel and landing fees, in addition to different maintenance costs, in comparison with the CEO. Overall, the impact of the NEO over the CEO could be seen on around 40% of the operating cost of the aircraft (the cumulative share of fuel, maintenance and landing fees). In a higher fuel price environment, this cumulative percentage could be as high as 50% if, for example, the fuel price was to rise to over 3 US dollars per Gallon. Of these different operational cost elements (fuel, maintenance and landing fees), the potential fuel cost savings are the most significant at over 10%.

This paper reviews and analyses the NEO cost differentials by three parameters: fuel price, maintenance cost and landing fees.

2. Fuel costs

2.1. Pratt & Whitney PW1127G-JM

According to Airbus, A320NEOs with PW1127G-JM engines being delivered as of now, have a 15% fuel burn improvement compared to an A320CEO delivered in 2010 with V2527-A5 engines installed, with a further 3% improvement due to sharklets, at typical utilisation patterns. For this study, we assume both the CEO and NEO to be sharklet equipped. Considering the efficiency improvement between 2010 and 2018 on the V2500-A5 engine, it is assumed that a 2018 A320NEO has an improved fuel burn attributable to the engine of around 14%, compared to a 2018 delivered A320CEO. However, this is somewhat offset by a penalty due to an increase in engine weight and an increase in induced drag due to the larger diameter engine. This reduces the fuel burn improvement by 3%. Therefore, in our view, the fuel burn improvement between a 2018 build NEO and a 2018 build CEO, with sharklets, is close to 11%.

Moreover, P&W had promised improvements to these engines which they stated would mean a further 2% fuel burn improvement for deliveries from 2019. This additional improvement will not be available for retrofit on existing PW1100G-JM. Given P&W's current engineering focus on addressing in-service issues, there is some doubt over the timing of the introduction of this improvement, and it may well be delayed beyond 2021.

Figure 1 illustrates how the fuel burn improvement translates into cost savings for an PW1127G-JM powered A320 NEO. The baseline comparison is done for an average utilization of nine flight hours per day, of two-hour sector length or, equivalently, 3,300 FH/ 1,650 FC per year. Two additional scenarios are considered to show the outer range of annual saving by the aircraft utilization; Scenario 2 and 3 assume low utilization at 4 flight hours per day and high utilization at 12 flight hours per day, respectively. Obviously, the higher the utilization the higher the savings, especially in an environment with increased jet fuel prices.

Our baseline comparison is close to the global average A320 family annual utilization of 3,250 FH / 1,750 FC.

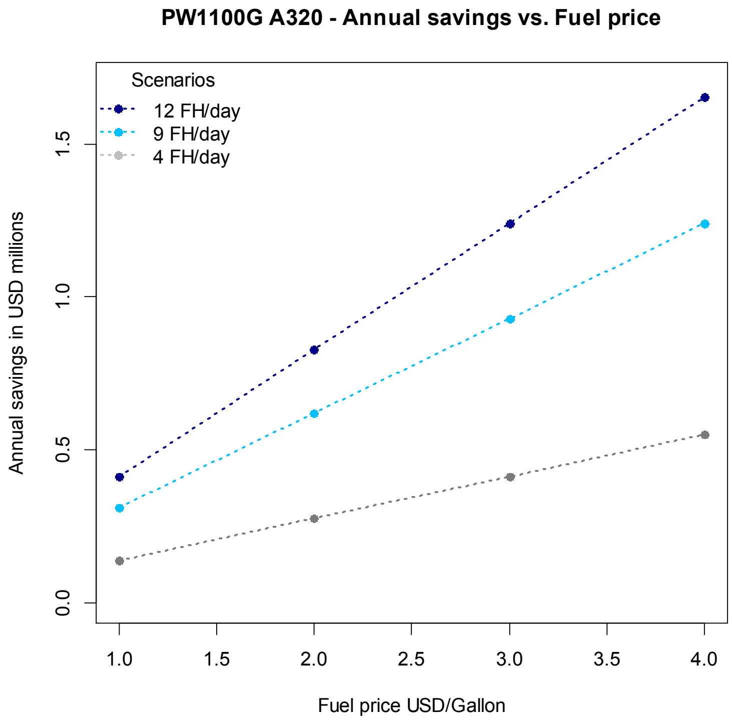

Figure 1: Annual savings per aircraft by fuel price assuming two-hour flight lengths. The comparison is made between a 2018 build A320NEO and a 2018 build A320CEO, both with sharklets. The A320NEO is powered by PW1127G-JM engines and the A320CEO is powered by V2527-A5 IAE engines.

2.2. CFMI LEAP-1A26

According to Airbus, one should expect a fuel burn improvement of approximately 15% for CFM LEAP-1A powered aircraft compared to its predecessor. Further 3% fuel saving is expected due to sharklets. For this study, we assume both the CEO and NEO to be sharklet equipped. There have been fuel efficiency improvements in the build standard that are available on the A320NEO as well as A320CEO.

As with the case of the PW1127G-JM engine, the CFMI LEAP-1A26 fuel burn improvement should be penalized for the increase in engine weight and induced drag caused by the larger diameter engine. This reduces the fuel burn improvement by 3%. Hence, our opinion is that the fuel burn improvement between a 2018 build NEO powered with a LEAP-1A26 engine and a 2018 build CEO powered by CFM56-5B4/3 engine, with sharklets, is close to 12%.

Figure 2 illustrates the cost savings due to fuel burn and three utilization scenarios. As mentioned before, the annual cost saving grows with the increase in fuel prices and utilization.

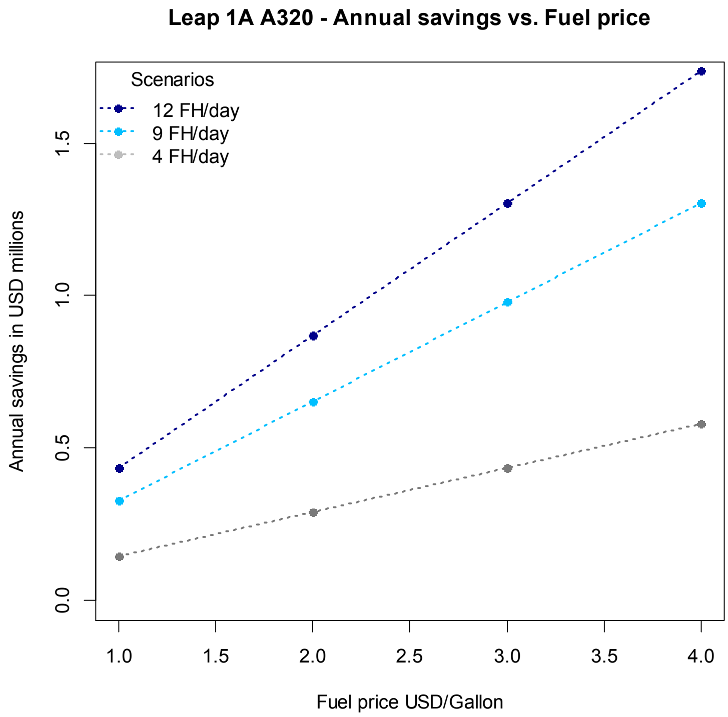

Figure 2: Annual savings per aircraft by fuel price assuming two-hour flight lengths. The comparison is made between a 2018 build A320NEO and a 2018 build A320CEO with sharklets. The A320NEO is powered by LEAP-1A26 engines and the A320CEO is powered by CFM56-5B4/3 engines.

The two factors, fuel price and utilization, have a compound effect on savings, with the utilisation variable having a higher impact on saving than fuel, when stressed in a realistic range. This can be inferenced in Figure 3, from the cost saving 3D representation by fuel (prices from $1 to $4 per USG) on the x-axis and utilization (1 to 12 flight hours per day) on the y-axis. The ranges are chosen to coincide with historical ones for the price of jet fuel, as depicted in Figure 4, and a realistic number of flights per day on utilization, while wide enough to cover some extreme utilization scenarios as well. On a short route of 800 nm, even with a very short 30-minute turn time at the gate, it is unlikely to have more than 12 flight hours per day. Similarly, on longer routes of 1600 nm, the most plausible airborne time is of maximum 12 flight hours per day. In both scenarios, the cost saving improves more with the increase in utilisation than with fuel prices. This is particularly meaningful, as part of the discourse on the new technology focuses on fuel prices alone, to the detriment of factors such as aircraft utilisation. For comparison, we illustrate the fuel reduction between NEOs and CEOs on both shorter routes (ca. 800nm) and longer routes (ca. 1600nm). The annualized cost of fuel saving on longer routes is higher than on shorter routes, although not significantly higher. The similarity comes from the limitation of flying the longer routes as frequent as the shorter routes per day.

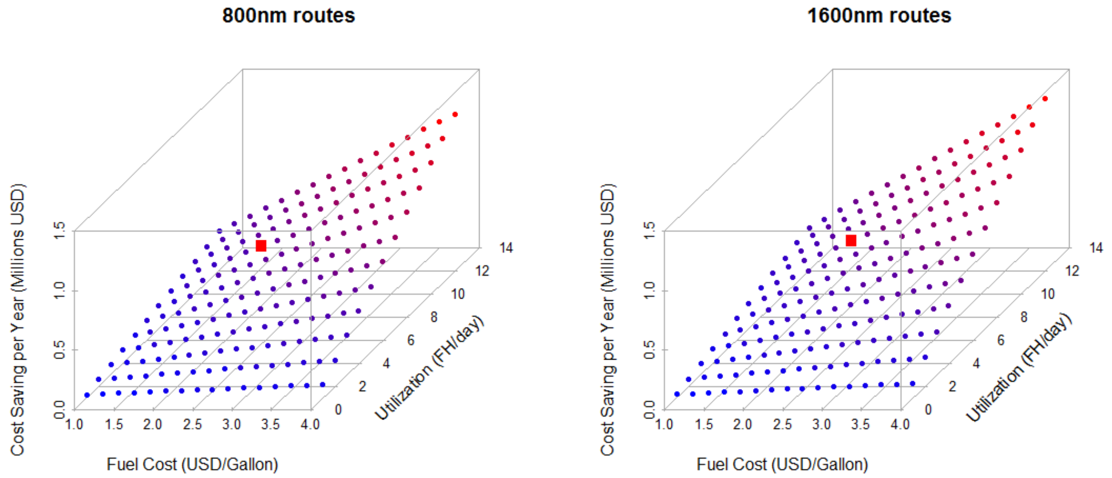

Figure 3: The hyper-plane of annual savings (vertical *z*-axis) by fuel cost (horizontal *x*-axis) and utilisation (horizontal *y*-axis). The surface has a steeper profile on the utilisation side. Cost saving at today's fuel price of 2 USD/Gallon and an average utilization of 9 FH/day is highlighted by the red square in each plot at approximately USD 0.50 million for the shorter routes and USD 0.54 million for the longer routes.

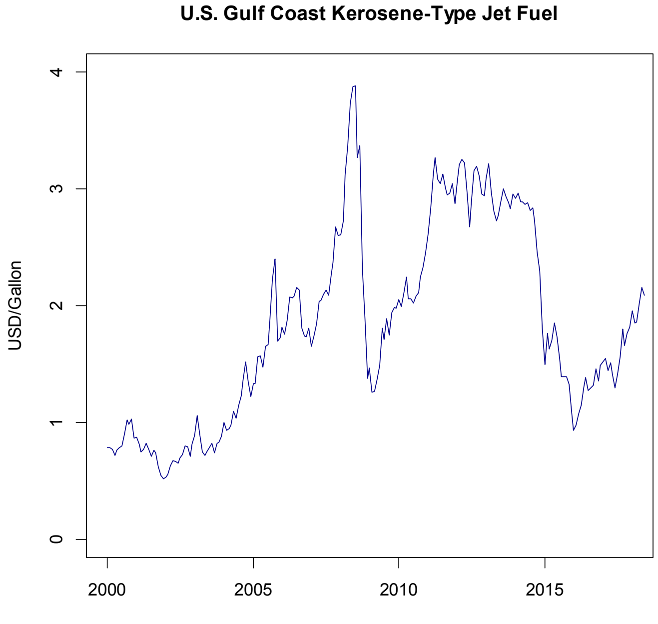

Figure 4: Monthly spot prices of jet fuel per gallon as of July 2018. Source: US Energy Information Agency.

3. Maintenance costs

From a lessor or investor's point of view, there are two main elements to bear in mind when assessing the cost of maintaining engines. Firstly, the cost of restoring the engine during a shop visit by a workscope, often referred to as an overhaul or a performance restoration, which on single aisle aircraft typically occurs every five to eight years. The second significant element is the cost of replacement of the life limited parts (LLPs). The frequency of replacement is dependent on the sector length and utilisation of the aircraft, but normally individual LLPs would not require replacement more frequently than once every ten years. Here, we examine these different maintenance costs for the engines on the NEO and compare them to their predecessor engines on the CEO.

3.1. PW1100G-JM maintenance costs

3.1.1. PW1100G-JM overhaul

P&W state that the PW1100G-JM series engines will have broadly similar or lower maintenance costs compared to the engines they are replacing. At this stage of the PW1100G-JM engine programme, there is no empirical data available on actual shop visit costs or intervals of engine overhauls. However, by comparing the architecture of the PW1100G-JM to the V2500-A5 engine, it is possible to have a general assessment of the reasonableness of P&W statements. A comparison of this nature just provides an indication of relative maintenance costs. It could be superseded by the real-life engine maintenance costs being unexpectedly higher, or indeed lower.

The PW1100G-JM has a gearbox between the fan and low-pressure shaft, unlike conventional engines such as the V2500. This enables the fan, the low-pressure compressor (LPC) and LPT to rotate at speeds closer to their most efficient speed. Hence, on the PW1100G-JM there is a need for less stages in the LPC (1 less) and LPT (2 less), compared to the V2500. As the high-pressure compressor (HPC) on the PW1100G-JM engine operates at higher speed, it can have 2 less stages than the HPC on the V2500. The PW1100G-JM has a total number of 16 stages: 3 (LPC), 8 (HPC), 2 (HPT) and 3 (LPT).

The reduction in number of stages offsets some of the additional weight introduced by the gearbox. Further weight reduction is achieved in the LPT by the adoption of Ti-Al alloys in the last stages of the LPT. Ti-Al alloys were first used in the rotating parts of the LPT blades on the GEnx engine and are currently adopted in the LEAP engines as well. While GE is acknowledged as first to embrace the utilisation of Ti-Al alloys, P&W together with MTU have introduced in engine manufacturing a third generation of Ti-Al alloys that can run hotter and faster (Bewlay, Nag, Suzuki, & Weimer, 2016). Ti-Al alloys are lightweight heat-resistant, and the novel type used in the PW1100G-JM LPT blades, the β-stabilised γ-Ti-Al alloy (TNM), are at the upper strength limit of titanium aluminides (Kartavykh, et al., 2017).

As a result of the fewer stages, the PW1100G-JM has significantly fewer parts than engines currently powering A320CEOs. This should help contain maintenance costs. P&W have extensively tested the gearbox itself, and it has been designed with no significant scheduled maintenance requirements for its life. The gearbox does not contain any LLPs unlike other engine sections. The LPC and HPC feature integrally bladed one-piece disks (blisks) on the PW1100G-JM engine**,** unlike the V2500 which has individual blades installed on each disk. In addition to aerodynamic improvements that reduce leakage flows, one advantage of the blisks is that there is a significant weight saving, compared to conventional bladed disks. However, the disadvantage is that if a blade fails and is not repairable, the entire blisk could require replacement. Blisks have a life expectancy such that they are expected to require replacement every second shop visit.

The LLPs target limits on the PW1127G-JM engine are expected to lead to a two-performance restoration shop visit pattern per LLP stack replacement. This shop visit pattern would be similar to the V2527-A5 engines. However, as the PW1127G-JM LLPs have a greater limit than those on the V2527-A5, this would mean a lower per flight hour cost for the engine performance restorations. Therefore, the architecture of the PW1100G-JM engine compared to its predecessor engine, in combination with the extended LLP limits, could allow for lower maintenance costs on a flight hour basis.

OEM based projections indicate that they expect shop visit costs to remain broadly similar following introduction of the PW1127G-JM compared to the V2527-A5. If this turns out to be the case, it would mean that, in combination with the shop visit pattern introduced by greater LLP limits, it could reduce the shop visit cost on a flight hour basis by around 15% to 20%.

Any firm conclusions being drawn as to projected maintenance cost savings, at this early stage of an engine type's programme, need to be strongly caveated due to the engine manufacturer's control of material costs and power by the hour programmes, as explained in more detail later in this paper.

3.1.2. Introductory issues

There have been a significant number of well publicised issues associated with the introduction into operation of the PW1100G-JM, such as start-up delays, combustion chamber degradation, no. 3 bearing carbon-air seal problems, fan blade defects, and most recently, HPC knife edge seal cracking.

The start-up delays and no. 3 bearing carbon-air seal failures are being addressed by retrofittable design changes. The fan blade delamination issues are being corrected by improved manufacturing processes.

P&W is having to make a number of re-designs to the combustion chamber in an effort to address persistent early degradation of the liner, due to inadequate cooling distribution, which is limiting engine on-wing times. This phenomenon seems to be most prevalent for engines operating in harsh environments. The latest design, block C, is being introduced on production engines in 2018. It is not clear yet if this latest design will correct these problems. Unlike correction of the no. 3 bearing carbon air seal, say, repair of combustion chamber distress requires deep access to the engine's core. This could effectively lead to a shortening of the time between engine overhauls, and a consequent increase in maintenance cost per flight hour beyond P&W's initial expectation.

One of the most recent public issues, the HPC knife edge seal cracking, is the subject of an emergency airworthiness directive issued by European Aviation Safety Agency (EASA), following several in-flight shutdowns and rejected take-offs. P&W had introduced a change to improve the knife edge seal on engines from serial number P770450. However, it turns out this design change introduced excessive loads on the seal, resulting in crack initiation and failure. P&W have now reverted to the original seal design, which requires a shop visit for retrofitting of affected engines. This caused significant delays and disruption to deliveries of A320NEOs from the Airbus production line in early 2018, as P&W prioritised support of in-service engines.

In isolation, each of these introductory issues, would not be so much of a concern. However, cumulatively it is concerning that there have been so many teething issues. Nevertheless, in public, P&W are confident that they are on-top of these issues and have design fixes in place. They believe the final fixes will result in an engine which is to the same standard as engines manufactured with the final fixes incorporated from new production. In the event these early build engines are repaired and retrofitted to the same standard as production engines incorporating final fixes for these issues, there should be no long-term value impairment to these earlier build engines.

From a lessor and owner's aspect the most concerning issue could be the combustion chamber liner distress. It is unclear if the current production design will allow engine operation up to its anticipated on-wing time for performance restoration, particularly for those engines operating in harsh environments. If not, the performance restoration shop visit interval could effectively be reduced, meaning that the effective maintenance cost per flight hour is increased. Bearing in mind that quite a lot of aircraft lease contracts for this aircraft type are already issued with specific maintenance reserve rates based on P&W published intervals, this could result in some leases having sub full maintenance life aircraft at redelivery.

3.1.3. PW1100G-JM- Life Limited Parts

The cost of the full stack of rotating life limited parts on PW1127G-JM engines is slightly more expensive than the full stack of LLPs on the V2527-A5 engines. This is offset by the cyclic life limit being significantly higher. This results in a per cycle cost saving of over 15%. These are in 2018 economics and could change in future years depending on list price escalation policies for the different engines.

Note that the actual cyclic life limits of the LLPs may be lower than the target limits. The figure in the preceding paragraph assume the LLP limits have reached their targets. At initial entry into service of an engine type, it is often the case that the engine manufacturer does not have sufficient data to validate the life limit of the LLP reaching the full life limit target. The target life limits may be validated prior to a particular design of an LLP reaching its below target life limit, or it may require improvement of the LLP design itself. If the LLP design requires updating for it to reach its target life, it could be the case that earlier build engines are disadvantaged with installed LLPs having a lower life expectancy.

3.2. LEAP-1A26 maintenance costs

3.2.1. LEAP-1A26 overhaul

The LEAP-1A architecture is a complete re-think of the CFM56-5B it replaces. The two engine types have little commonality. The LEAP-1A26 has been developed to deliver a higher bypass ratio, and therefore it has a larger fan with a higher bypass ratio (11:1) than the CFM56-5B4 engine (6:1). In turn, this enables greater efficiency and consequently lower fuel consumption. A larger fan also means a need for less stages in the LPC (1 less), but spinning a larger fan more slowly requires more stages in the LPT (3 more) than the CFM56-5B engine has. CFMI also chose to develop a two stage HPT, which is one additional stage compared to earlier CFM variants. Consequently, the HPC also has an additional stage, to keep up with the HPT in the high-pressure spool (N2 spool). Compared to the CFM56-5B, which has 18 stages, the LEAP-1A has a total number of 22 stages: 3 (LPC), 10 (HPC), 2 (HPT) and 7 (LPT). The increased number of stages would be expected to pose a disadvantage from a maintenance cost point of view.

The LEAP-1A operates at higher temperatures. CFMI has adopted the use of ceramic matrix composites (CMC), a type of composite material first brought to commercial aviation by the GE Global Research centre. CMCs are one third the weight, durable and can handle higher temperatures (300-400°F more) than the super-nickel alloys traditionally used in engine hot sections. CMCs are used in the HPT shrouds where they can withstand the high thermo-structural requirements of the HPT. Moreover, they need less cooling than metal to operate in these conditions. The use of CMC is being researched for the rotating parts of the engine as well.

Other new technologies include the use of Ti-Al blades in the later stages of the LPT. The first stages in the LPT are made of heavier nickel alloys to withstand the high temperature, but as the temperature drops in the later stages of the LPT, a lighter Ti-Al alloy is used. Lighter materials in the rotating part of the turbine, also leads to a reduction in the rotational inertia, which means they will commence rotating easier. The Ti-Al alloy, denoted as 48-2-2, used in the LEAP-1A LPT blades is one of the most successful second generation Ti-Al alloys. Its manufacturing is very well established and the LEAP-1A benefits from the experience gained with use of the Ti-Al alloy blades on the GEnx engine.

Similar to the PW1100G-JM, the LEAP-1A incorporates blisks. The front five out of ten stages in the HPC are made of titanium alloys and manufactured as blisks. The last five of the ten rotating stages, which handle increasing temperatures, is a one-piece spool based on nickel alloys. Blisks are not used in the turbines but their potential is currently being researched.

CFM56 series engines have generally been recognized as being more economical than competitors from a life cycle maintenance cost point of view. Similar to the PW1100G-JM series engines, we are relying on OEM projections for the estimate of shop visit costs and intervals on the LEAP-1A26 engines.

From a maintenance cost aspect, the most significant change would appear to be the additional stage in the HPT operating at a higher temperature. Refurbishment of the HPT is, generally, the largest element of a shop visit cost (e.g. $1 million to $1.5 million for a CFM56-5B). Therefore, with an additional stage in the LEAP-1A HPT, operating at a higher temperature, there are concerns that this could adversely affect shop visit costs. The use of CMCs to mitigate high temperatures, is relatively new, and it remains to be seen how this will impact on maintenance costs over the full aircraft life cycle.

Other technologies introduced, such as composite fan blades and lightweight Ti-Al in the LPT, could also affect maintenance costs.

CFMI has publicly stated it is committed to keeping the LEAP-1A total life cycle maintenance costs similar to the CFM56-5B costs.

Customers can contractually ensure similar maintenance costs on the LEAP by entering into FHAs (flight hour agreements) with CFMI, whereby CFMI will accomplish shop visits at a fixed cost per flight hour flown. It is becoming more common that FHA programmes are being entered at the time of sale of the engine.

The maintenance costs on a flight hour basis are expected to be significantly lower during the initial years of aircraft operation, up until completion of the first shop visit, as discussed further below. Therefore, CFMI could enter into FHAs with operators for the first 8 or 10 years of use (which could coincide with the initial lease term) at relatively low cost per flight hour, taking advantage of lower initial maintenance costs. With this in mind, aircraft owners need to ensure that the life cycle maintenance costs are appropriately reserved for from initial entry into service of the engines. Otherwise, the aircraft owner could then be left with the issue of being inadequately covered for the significantly higher maintenance costs for second and subsequent shop visits. As of now, there is no hard data on what those maintenance costs will be.

3.2.2. Introductory issues

The LEAP-1A engines have had fewer reported entry into service issues than the PW1100G-JM engine.

Early build LEAP-1A engines suffered problems with the booster performance in the compressor section. This caused higher than expected EGT margin loss and consequent time on wing shortfalls. A new booster has been developed and is incorporated on production engines from mid-2017. Nevertheless, this has necessitated costly retrofit of the booster on early build engines.

A number of LEAP-1A engines have suffered coating loss in the HPT section. The coating is on the CMC (ceramic matrix composite) shrouds, and its function is to mitigate the impact on the base material of the high temperatures in this area. The coating failure triggers an EGT (exhaust gas temperature) margin loss, possibly due to increased blade tip clearances, which leads to an early engine removal. CFMI plans to introduce a new bonding process for the coating, which it is claimed will address the root cause of the issue. However, engine shop visits will be required to retrofit the improved durability bonding process on in-service engines. This will, at the very least, represent a significant cost and industrial challenge for CFMI. CFMI have stated that the CMC material itself is performing as expected.

EASA has issued an airworthiness directive to remove a batch of the HPT stage 2 disk life limited part from engines before they reach 1,200 cycles in service. EASA report that this is due to a manufacturing deficiency during the forging process, which may have caused hidden defects in the disk bore. This will necessitate shop visits to replace these disks.

As of early 2018, CFMI's deliveries of LEAP-1As to the Airbus production line were running about four weeks behind schedule. This is believed to be due to delays with some suppliers, albeit not related to the supply of the more advanced materials in the engines, like the CMCs. Airbus is publicly pressurizing CFMI to get back on schedule with deliveries, which CFMI expects to do by later in 2018.

None of these introductory issues should result in a significant impact on the longer-term maintenance costs for this engine type. It remains to be seen if the advanced materials introduced in the LEAP-1A or the higher temperatures, cause any unexpected issues as these engines begin to clock up significant hours on wing.

One only needs to look at the challenges another engine OEM, Rolls-Royce, are currently facing on the Trent 1000 engine, powering the Boeing 787, to realize that just because an engine has a relatively trouble-free entry into service, does not mean costly and disruptive problems will not materialize later in an engine's life.

3.2.3. LEAP-1A26 – Life Limited Parts

In the LEAP-1A26, the LLPs in the compressor and HPT have a target limit which is the same as the CFM56-5B LLPs in this area of the engine. The target life limit of the LLPs in the LEAP-1A26's LPT have been extended, compared to the -5B, so that they will coincide with the limit of the LLPs in the fan. The target limits of the LLPs in the fan are the same for both engine types. Note that this is the target life, which can be different to current certified limits, but CFMI expects to have approval to extend the target lives in advance of the fleet leader LLPs reaching their life limit.

By having LLPs with two different limits, the LEAP-1A26 should have a more simplified shop visit management strategy compared to its predecessor engine, which has three different limits. Additionally, it should lead to less loss of LLP life due to the need to discard significant remaining stub life.

The stack price of the LEAP-1A's LLPs is quite a bit higher than that of the -5B engine. However, this differential is significantly reduced when it is compared on a cost per flight cycle basis, using target limits, due to the increased limits of the LPT's LLPs in the LEAP-1A.

3.3. Engine shop visit costs determined by OEM pricing policy

Part provision as well as repairs of installed materials can represent 80% to 90% of a shop visit cost of current generation engines. In the initial years of an engine's programme the only source of replacement material is generally the OEM. Used serviceable material does generally become more widespread, but not until a significant number of engines have had their first overhauls and more becomes available when a large number of engines have been parted out. This may not happen in significant quantities until an engine programme is 15 to 20 years in service.

Proprietary data to develop repairs to materials are more tightly controlled by the OEM in current generation engines, such as V2500-A5 or CFM56-5B, compared to engines developed previously such as CF80, PW4000 or CFM56-3. OEMs charge significant fees to independent MROs to licence these repairs.

The cumulative effect of the control by the OEM of the parts supply market as well as the control of the cost and availability of repairs for parts, is that the OEM can strongly influence and, for all intents and purposes, control the cost of shop visits, for the initial decades of an engine programme's life.

It is for this reason advisable to exercise caution with drawing firm conclusions from assessing the inherent maintenance costs of an engine due to its underlying design and architecture. In reality, the OEMs exert such control over the maintenance cost, that they can ensure an engine meets particular maintenance cost expectations, due to commercial considerations rather than technical considerations, if they so choose.

3.4. Growing coverage of engine maintenance by PBH agreements

It is expected that for their initial years of operation more than 65% of LEAP-1A engines and 80% of PW1100G-JM engines on the A320 NEO will be covered by OEM power by the hour (PBH) agreements. Rolls Royce is the leader in providing these agreements and already is more than a decade ahead of the other engine OEMs in terms of tying operators into comprehensive PBH agreements. PBH agreements are becoming more and more prevalent on current generation engine and aircraft deliveries.

From an airline's perspective, they provide certainty of costs and coverage, and allow for predictable payment of maintenance costs on a regular basis. However, the cost per flight hour being paid by an airline may not represent a true cost per flight hour which needs to be accrued to cover all the maintenance cost over the life of the engine.

OEMs can take advantage of longer first run intervals, less expensive initial shop visits, as well as spreading the cost over the duration of the agreement term (which may be longer than shop visit interval), to cover the cost of the shop visit. Upon expiry of the agreement, and redelivery of the aircraft, the owner can then be left with a situation where cost of maintaining the engine is not adequately covered for shop visits during the latter part of the engine's life.

3.5. Airframe Maintenance Costs

On the airframe side, there have been relatively few changes that are expected to lead to significant maintenance cost differentials between the NEO and the CEO. The heavy check workscopes should be reduced slightly, while the smaller checks such as A-checks and C-checks are projected to see marginal cost reductions. One notable system difference, which should help reduce airline delays, and line maintenance costs, is the replacement of the pneumatically controlled engine bleed air system with an electrically controlled one.

Significant components such as the APU and landing gear are unchanged. Although Airbus did introduce a new gear in 2015 across all A320 variants, which features a 20% longer overhaul interval. As you would expect with a new larger engine variant, the thrust reversers are different on the NEO and are expected to be more expensive to overhaul.

3.6. Maintenance Costs Summary

The preceding maintenance sections have delved into and discussed the potential maintenance cost differences between the A320NEO and the A320CEO. As was explained, at this stage of a re-engined aircraft programme, forecasts of future expected maintenance costs are largely reliant on OEM projections. The actual maintenance cost outcomes, in turn, can be heavily influenced by the engine manufacturer's parts pricing policy and level of control of the aftermarket. For typical operations, we see the V2527-A5 powered A320CEO as being around $400,000 more expensive annually to maintain than the CFM56-5B4/3 equivalent. Based on our review of available OEM data, it looks like both the PW1127G-JM and LEAP-1A26 powered A320NEO variants could fall within a similar range of maintenance costs. However, it is more likely that on the A320NEO, the CFMI powered variant will be the more expensive to maintain.

4. Landing Fees

Several regulatory organizations such as International Civil Aviation Organization (ICAO), Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) have introduced recommendations for reducing noise and pollutants. Policy makers have introduced several programmes to limit the impact of aviation on the environment. For example, the European Commission envisages among its goals for 2050 a reduction of 75% in CO_2 emissions, 90% in NO_X emissions and 65% in perceived noise emissions. These goals are relative to the equivalent emission levels of aircraft manufactured in 2000 (European Commission, 2011).

The aviation industry is aware of the environmental goals and both the public and regulatory agencies' expectation of reduced emissions of CO_2, NO_X, NO_2 and noise. According to Boeing's comprehensive, although not exhaustive, list of airports that levy environmental charges, less than 20% these airports are taxing noise (128 out of 651 airports) and a small number charge emission as well (25 out of 651) (The Boeing Company, 2018). As emission charges are relatively low fees and only levied at a small number of airports, for this study, we focus only on airports that tax noise, which is typically levied via runway fees. The airports reviewed have in common additional environmental considerations like APU charges, curfews and run-ups. Some of them also have emission charges. They are mainly located in the US and Europe.

All types considered in this study, the A320CEOs powered by CFM56-5B4/3 and V2527-A5 and the A320NEOs powered by LEAP-1A26 and PW1127 satisfy the current Chapter 4 noise certification standard (EASA, 2018). Chapter 14 was introduced by ICAO as a further refinement of the existing Chapter 4 standard, applicable for aircraft first submitted for new certification from 31 December 2017. Current build A320CEOs and all A320NEOs are expected to meet the new Chapter 14 standard. The global operational reference standard is Chapter 3, and all marginal noise improvements are calculated relative to the Chapter 3 limits, which vary depending on the certified weight of the aircraft. For an A320 with a 77,000kg maximum take-off weight the Chapter 3 limits are: lateral (96.9), fly over (91.7) and approach (100.7), for an overall cumulative limit (289.3). The limits are measured in Effective Perceived Noise Decibels (EPNdB). Per the current standard, A320CEOs at 77,000 kg maximum take-off weight classify as Chapter 4. Chapter 4 represents a 10 EPNdB cumulative reduction of Chapter 3 standards, while Chapter 14 represents a further 7 EPNdB reduction.

A few airports incentivise new technology performance by charging less for significantly quieter aircraft. Heathrow airport has one of the most expensive charging structures when it comes to differentiating aircraft with varying noise levels. According to the new criteria, if powered by a CFM56-5B4/3 (typical cumulative 16.4 EPNdB reduction), A320CEO classifies as Chapter 4-Base, and if powered by a V2527-A5 (typical cumulative 19.6 EPNdB reduction), it classifies as Chapter 14-High. Equivalently, an A320NEO at 77,000 kg maximum take-off weight, powered by a LEAP-1A26 (typical cumulative 30.2 EPNdB reduction) or a PW1127 (typical cumulative 29.3 EPNdB reduction), is categorized as Chapter 14-Low. This classification results in a significant reduction in the landing charges between CEOs and NEOs at Heathrow airport. Annualized charges for each of the four types are summarized in Figure 5. The reduction is close to $500k between a V2527-A5 powered A320CEO and a NEO, and close to $750k between a CFM56-5B4/3 powered A320CEO and a NEO in the scenario of one landing per day through the year at Heathrow airport.

In the UK, apart from Heathrow airport, nearly all other major airports do not distinguish between CEO and NEO, and if they do, the difference in fees is very small. Most landing fees are calculated based on the MTOW, while noise categories contribute very little. Gatwick airport is the only other significant airport to differentiate between noise level of the NEOs and CEOs, although the fee saving is not significant- e.g. in the same scenario of one landing per day through the year, the reduction is at most $4k between a V2527-

A5 powered A320CEO and a NEO, and close to $11k between a CFM56-5B4/3 powered A320CEO and a NEO. In contrast to Heathrow and Gatwick, the majority of British airports: Aberdeen, Birmingham, Bristol, East Midlands, Edinburgh, Glasgow, Luton, Manchester, Stansted, do not distinguish between CEO and NEO noise levels.

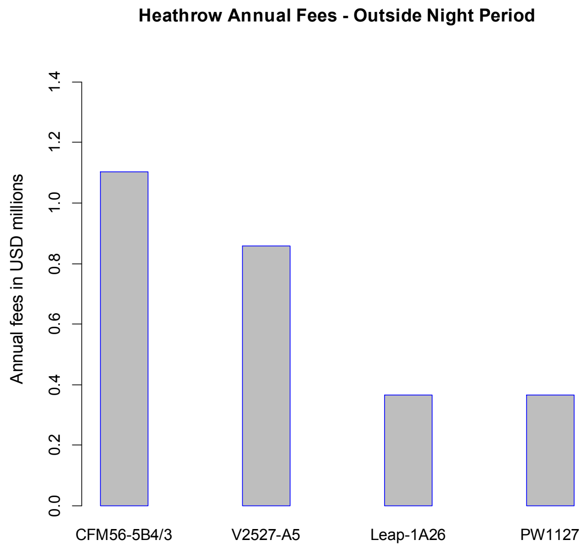

Figure 5: Noise charging at Heathrow airport for 2018 build A320CEO - 77,000 kg maximum take-off weight (CFM56-5B4/3 Chapter 4-Base, V2527-A5 Chapter 14 High) and A320NEO - 77,000 kg maximum take-off weight (LEAP-1A26 or PW1127, both Chapter 14 Low), based on new chapter designation. Annualized values are calculated assuming one landing per day through the year.

Most airports in Europe or US, offer no incentive to use aircraft quieter than the Chapter 4 standard. Some airports such as Dublin, do not charge aircraft for noise, or if they do, they charge the same for all aircraft models considered in this paper.

Overall, there is no systemic differentiation between using NEOs and CEOs at nearly all of the world airports yet. Unless flying to Heathrow, the difference in the noise charges between CEOs and NEOs is not significant. Consequently, for the vast majority of airlines, the factors mentioned in the earlier part of the paper will have a higher impact on the airlines' decision-making process when it comes to selecting fleet composition, aircraft deployment and developing marketing strategies.

5. Conclusions

- Both engine types on the A320NEO are delivering on their fuel burn improvement expectations.
- A typical operator can save around US$500k annually on fuel, by operating an A320NEO, compared to operating an A320CEO, powered by its predecessor engines, assuming a fuel price of US$2 per gallon and average utilization. This translates into a theoretical monthly lease rental increase of $21k for an A320NEO, assuming a 50% follow through of operational savings to rental premium.
- At higher utilisations, or if the fuel price goes over US$3 per gallon, these annual savings on fuel can exceed US$1M per aircraft.

- CFMI and P&W have both publicly committed to there being no increase in life cycle maintenance costs on the NEO engines, compared to their predecessor engines on the CEO.
- The architecture of the PW1127G-JM engine may enable lower maintenance costs when compared to the V2527-A5 engine.
- The design and operating temperature of the LEAP-1A26 engine, could lead to higher maintenance costs compared to the CFM56-5B4/3 engines.
- Through their control of the aftermarket, spare part provision and repair development, P&W and CFMI can use commercial means to meet maintenance cost targets for their A320NEO engines.
- Initial operators can protect themselves from uncertain maintenance costs via entering into power by the hour agreements with the engine OEMs.
- There have been numerous reliability issues associated with the entry into service of the engines on the A320NEO, particularly the PW1127G-JM engine, which are causing significant disruption to operators. The OEMs do appear to be making significant progress with addressing these problems, however it is not yet confirmed that there will be no longer term adverse value or maintenance cost impacts due to these issues.
- London Heathrow is the only notable airport where meaningful landing fee savings can be made due to the A320NEO's lower noise emissions. This could be in the region of $500k to $750k per annum for an aircraft operating there once daily.

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