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POWER PLANT RELIABILITY ISSUES AND WEAR MONITORING IN AIRCRAFT PISTON ENGINES. PART I: ENGINE WEAR AND TBO REAL-TIME EXTENSION

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ABSTRACT

This paper introduces a method to prepare an engine for very long flights without maintenance. It also gives criteria to estimate time between overhaul by using the sensor data to have an estimation of the engine condition. In-flight refueling has introduced new challenges to UAV (Unmanned Aerial Vehicle) propulsion systems. It is now possible to run continuously an UAV without landing for long periods. For this task, it is necessary to carry a quantity of lubricant sufficient for at least one month (approximately 800h). For extremely long flights, diesel piston engines are better than spark ignition ones due to extremely low fuel consumption. A selection in the assembly line individuates those engines that are suitable for long endurance flight. This is possible because automotive engines are manufactured in thousands per day and many quality controls take place in the assembly process. Moreover, mass produced automotive engines pass several tests during the assembly process including a very short run. The results of these tests are useful for an initial selection. Then, a 25-hour trial with a very thin lubricant is sufficient to forecast the oil consumption up to 1,000 hours. The 25 hours run corresponds to the time necessary to stabilize the oil consumption rate. In addition, during the 25 hours run also the electronic infancy failures are detected. In modern engines, the electronic on board diagnosis, the full redundancy of vital sensors, electronic control units and batteries/generators, make it possible to fly safely without emergencies with random electronic failures of components and wiring. Another major requirement is to forecast the engine failure or an unacceptable deterioration in terms of mechanical performance. This paper introduced a method to evaluate the state of wear of the engine starting from a digital monitoring system. A wear model of the engine based on the real duty cycle is proposed. It is then possible to prolong the life of the engine and to increase the time between overhaul. It is also possible schedule the overhaul operation.

Keywords: piston engine, aircraft, TBO evaluation, 800h flight.

INTRODUCTION

It is now possible to run continuously an Unmanned Aerial Vehicle (UAV) without landing for long periods with in-flight refueling. Unfortunately, this is a challenge also for the propulsion systems. For example, most car manufacturers allow a maximum consumption of 0.015 kg of oil for every kg of fuel burnt by the engine. In a car, it corresponds to kg 1.5 kg of lubricant every 1000 km [1]. This travel will take 34h to a driver in Italy where the average speed is as low as 29.2 km/h [2]. In this case, the total amount of oil required for a month-long continuous run (800 h) will be 35 kg. Therefore, it is not true that any diesel will run for 800h without maintenance. It is true only for ground-based diesel APUs (Auxiliary Power Unit) that are designed to run for long periods without intervention [3]. In fact, they already have oil and coolant reservoir and a monitoring system. In order to reduce the size and the weight of oil and coolant tanks, it is strictly necessary to select engines that have low oil consumption. In fact, even in high quality automotive engines built in thousands per day, a few of these engines will need as little as 0.1 kg of oil every 100 hours; this means that they will run the whole month with the lubricant from the minimum to the maximum level of the sump. The problem is complicated by the fact that oil consumption follows a bath-tube curve [4]. Therefore, a selection method should find the engines that are best for long flights. In the engine assembly line several tests are already performed. These tests are ended by a run-in in of 3 up to 14 minutes at increasing load on the production line [5]. Afterwards a 25-hour trial with a special lubricant (SAE 0W-30 ACEAA1/B1, API SN-SM-SL-S, ILSACGF-5) is sufficient to forecast the oil consumption up to 1,000 hours [5]. This test has frequent acceleration/deceleration to maximize the engine oil consumption. In fact, oil consumption is likely to be higher when the engine is new, especially during the first 25 hours [5]. Afterwards, oil consumption increase linearly with run time. This 25 hours test (at the maximum temperature allowed for the engine coolant and for the engine compartment) eliminates also the infancy failure of electronic components, wiring and spark plugs. During these tests, the coolant consumption should be negligible. For HPPs (High Pressure Pump) and injectors, it is necessary to test them on a test bench after the 25 hours run-in. In this way, the engine will run reliably for 800 h without maintenance. In spark ignition engines, unleaded fuel avoids spark plugs fouling. A major requirement is to forecast the engine failure or unacceptable deterioration in terms of mechanical performance and wear of the engine.

The sensors data can be correlated to a wear model of the engine based on the real duty cycle. It is therefore possible to prolong the life of the engine and to increase the Time Between Overhaul (*TBO*- [h]). It is also possible to schedule the exact time in which TBO will be needed. This first part of this paper will deal on TBO forecast and engine selection and preparation for long flights. The second part will deal with engine monitoring and diagnostics. In the second part, extensive considerations about true piston engine reliability will demonstrate that a monitoring system is strictly necessary.

Automotive Engine Durability

Modern automotive engines have quite long maintenance interval. In the automotive field, 2 years or 30,000 km are common in European cars. An average car-driver of in Italy drove for km_{year}=11,448 km in 2016 at an average speed of $\boldsymbol{v_{ave}}$=29.2 km/h. Having to be serviced every two years, the engine will be taken to the shop with a *TBM* (Travel between Maintenance) of 22,896 km (1) and a *TIM* (Time Interval Maintenance) of 784 h (2).

$$TBM = km_{year} \times TBM = 11{,}448 \times 2 = 22{,}896\,km \tag{1}$$

$$TIM = \frac{TBM}{v_{ave}} = \frac{22{,}896}{29.2} = 784.11\,h \tag{2}$$

At *TIM*, checks are made battery, oil and filters are replaced and shop full diagnostic software is run. In fact, a smaller On-Board Diagnostic (OBD) software runs continuously on car Electronic Control Unit (ECU). Engines that are more sophisticated have an oil condition sensor that prolongs the oil interval on-condition. The term on-condition refers to a diagnostic system on oil wear that replaces the usual time interval or mileage for oil replacement. The oil condition sensor measures temperature and quality. The engine management system in the ECU evaluates these measurements. With the oil quality sensor, the electrical properties of the engine oil are evaluated. These properties alter when the engine oil shows signs of degradation and aging. The oil quality sensor consists of two metal tubes that are inserted one into the other to serve as electrodes. The engine oil is the dielectric medium between the electrodes. In fact, the electrical material properties of the engine oil change as the engine oil wears and ages. An electronic evaluation unit embedded in the sensor converts the measured capacity into a digital signal. This digital sensor signal is sent to the engine ECU. The engine management system in the ECU uses the signal for internal calculations (e.g. condensate in the engine oil). In a common commercial sensor, the temperature sensor is also seated on the housing of the oil condition sensor. The spark plugs will be replaced every (*SPRT* - Spark Plug Replacement Time) 3,400h in most cars (3).

$$SPRT = \frac{100{,}000}{v_{ave}} = 3{,}424.6\,h \tag{3}$$

The engine will run up to its natural end (in term of reliability) of approximately 120,000 km (4,109h at 29.2 km/h). This data come from Insurance Companies [2] as the mileage during which it is highly improbable to have Class A Mishaps. A class A mishap is a full stop of the vehicle due to a failure in the propulsion system [7]. The current car engine design life or TBO is 250,000km or 8,561h. Negligible coolant level consumption is accepted. All modern cars are liquid cooled, since emission requirements ask for an extremely rapid warm-up phase. Therefore, modern car engines already run for nearly 800h without any maintenance except coolant and oil level restoration. The challenge is to make them run reliable to the higher load factor typical of aircraft (0.77); the car load factor is about 0.44 [8-12]. First, some myths are to be debunked. The duration of a motor does not depend on the number of revolutions or the number of thermal cycles, it depends mainly on the average piston speed and secondly on the maximum operating pressure. It is not true that slow, large engines will last longer than fast smaller engines. This fact can be easily demonstrated even theoretically. In fact, the *MPS* (Mean Piston Speed [m/s]) depends on stroke (*Stroke* [m]) and crankshaft speed (*RPM* [rpm]) (4).

$$MPS = \frac{2 \times Stroke \times RPM}{60} \tag{4}$$

The piston travels in its maintenance interval (TBO [h]) a distance equal to *Length* [m] (5).

$$Length = 2 \times MPS \times RPM \times TBO \times 60 \tag{5}$$

With the same load factor, duration depends only on the tribology of the contact and the quality of the lubricant. Wear of journal bearings and on cylinders depends on temperature and velocity. Sliding velocity has well defined limits. Slow speeds means reduced bearing capacity, while excessive speed means excessive local temperatures. In fact, it is not rare to find seizure in slow engines were speeds are too low. In small engines, it is also possible to decrease the lateral piston thrust by lengthening the connecting rods. This means higher ratio $\boldsymbol{\lambda}$ between connecting crank-throw and rod lengths (distance between centers. In addition, the slow motor has to distribute the power delivered on a smaller number of cycles. Therefore, a larger bore is necessary. As the displacement increases, the thicknesses of the piston and of the heads increase with a cubic power of the bore, with further aggravation of the inertial stresses and increase of the lateral thrusts. In particular, the maximum acceleration of the piston $\boldsymbol{A_p}$[m/s^2] to the top dead center is given by equation (6).

$$A_p = \left(\frac{2\times\pi\times RPM}{60}\right)^2 \frac{Stroke}{2}\left(1+\frac{1}{\lambda}\right) \quad (6)$$

Usually the stroke of a piston engine is expressed as a fraction of the bore.

In fact, the stroke ratio is given by *f* =Bore/Stroke. For example, slow, long-stroke engines have a smaller bore than its stroke giving a ratio value of less than 1. At a given engine speed, a longer stroke increases engine friction and increases stress on the crankshaft due to the higher A_p. The smaller bore also reduces the area available for valves in the cylinder head, increasing the intake pressure drop. However, long-stroke engines have larger torque at lower crankshaft speed than oversquare ones due to their longer crank throw and higher piston speed. For the same class of engine, with the same stroke ratio *f*, the mass of the piston m depends on the cubic power of the bore. Therefore, the piston inertia force F_i [N] depends on the square of the angular velocity and the fourth power of the stroke (7).

$$\begin{aligned} &F_i = m\times A_p = m\times\left(\frac{2\times\pi\times RPM}{60}\right)^2 \frac{Stroke}{2}\left(1+\frac{1}{\lambda}\right) \quad (7)\\ &\Rightarrow F_i \propto f^3\times Stroke^3\left(\frac{2\times\pi\times RPM}{60}\right)^2 \frac{Stroke}{2}\left(1+\frac{1}{\lambda}\right) \propto RPM^2\times Stroke^4 \end{aligned}$$

Therefore, large displacement, slow engines are not advantageous for aircraft propulsion. In fact, in aircraft engines the propeller need power only at high speed and engines tend to run at high speed.

TBO Evaluation: The Load Factor (LF) Method

The Load Factor (*LF*) methods [11] assumes that if you are using the fuel in less time you are taking more power out of your engine and it will last less time (shorter TBO). The classical duty cycle for small general aviation aircraft is that they will make all identical flights of 3.8h[13]. This standard flight starts with 3 minutes of 100% power (max rated power) for take-off and initial climb. Then a 92% power climb lasts for the following 30 minutes. When levelled, the aircraft cruises for 180 min at 73% power. Finally, the approach takes 60% of the power for the last 15 minutes. The fuel consumed in this reference cycle is divided by the fuel consumption of the engine at max continuous power (100%) to calculate the load factor. The resulting *LF* is from 0.65 to 0.77 depending on the engine *SFC* (Specific Fuel Consumption) curve. This curve is to be obtained on a traditional test bench and not on a propeller-braked rig. A good average value of *LF* for aircraft engines is $LF_{\mathbf{aircraft}}$=0.7. The typical automotive (car) load factor is 0.44. The assumption is that the load factor reduces life with a quadratic law. Then the 4,109h of the car TBO is reduced to 1, 623h (10).

$$TBO_{aircraft} = \frac{TBO_{car}\times LF_{car}^2}{LF_{aircraft}^2} = 1{,}623h \quad (9)$$

However, the load history of an engine is never the standard one, therefore it is possible for the FADEC (Full Authority Digital Electronic Control) or the digital engine monitoring system to calculate the true engine load factor and to compare it to the reference TBO with LF=0.7. This more accurate value depends on the true LF of the engine. In this way, in most cases, it is possible to prolong engine TBO. Since the Load Factor Method is based on the assumption that the engine efficiency is approximately constant, the result is conservative. The true TBO will be longer.

RUN IN AND ENGINE PREPARATION RUN

Modern automotive engines run-in in the assembly line can be as short as 3 minutes [5]. After this phase, the engine is kept idle for the final checks and then the performance curves (Power to engine speed) and (SFC to engine speed) are measured to check whether the engine is acceptable (within tolerances).

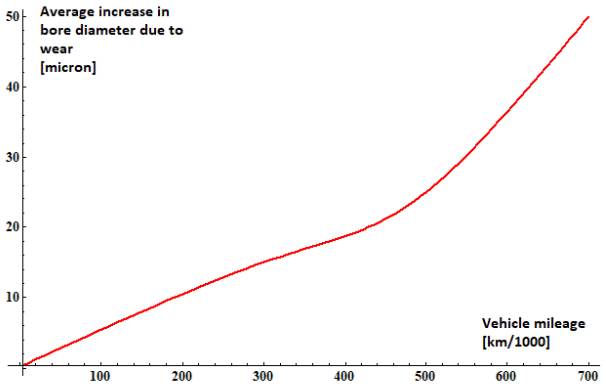

Figure-1. Average increase of the bore diameter due to wear [μm] versus mileage [thousands of km] in a small truck diesel engine [15] [16].

After the run in, oil is changed and checked for coolant, fuel and other contaminants. If the engine is selected for long run without maintenance (800h), oil consumption and blow-by should be evaluated and electronics should be checked. As described above, the additional run-in of TR=25h (Time Run-in) in a climatic chamber at the maximum admissible temperatures will also reduce infancy failures of sensors, actuators, ECUs, Spark plugs. The test cycle used has a LF larger than the standard aircraft cycle (LF=0.7). This accelerated-test-cycle is composed by 5 minutes of 100% power, 30 minutes at 92% and 15 minutes at 73% power. An idling period of 5 minutes completes the test. This accelerated cycle has an approximate LF_{acc}=0.85. The true load factor depends on engine efficiency at the different load levels.

This accelerated test is equivalent to a standard run $TR_{equivalent}$of 37h (10).

$$TR_{equivalent} = \frac{TR \times LF_{acc}^2}{LF_{aircraft}^2} = \frac{25 \times 0.85^2}{0.7^2} \approx 37h \tag{10}$$

The accelerated cycle proved to be better that a full load cycle (LF_{full}=1) that theoretically would last a longer equivalent time of 51h (11).

$$TR_{eq\_full} = \frac{TR \times LF_{full}^2}{LF_{aircraft}^2} = \frac{25 \times 1}{0.7^2} = 51h \tag{11}$$

This is because the variable power cycle varies the temperature of valves, liners, pistons cyclically. The opening and closing of the clearance between the parts increases the wear. The car would have to run for about *Travel*=4,000 km (12) to reach the equivalent $TRe_{quivalent}$=37h of a standard aircraft cycle (12).

$$Travel = \frac{TR_{equivalent} \times LF_{aircraftl}^2}{LF_{cart}^2} \times v_{ave} = \\ = \frac{37 \times 0.85^2}{0.44^2} \times 29.2 = 4{,}000\,km \tag{12}$$

In this mileage, a medium car with the higher admissible oil consumption will require 6 kg of oil [12]. The amount of oil consumed becomes therefore easy to measure.

Oil Consumption Evaluation: The Linear Law

The basic hypothesis is that the engine needs to be overhauled when the oil consumption exceeds the prescribed limits or the power output is below the minimum acceptable. This is typical of well-designed and fully developed engines. Many modern piston engines have cast-iron cylinders with plateau-honing surface-finish and high-chromium alloyed steel piston rings. High chromium stainless alloys is common for intake valves, and 21-4N (EV8) or Inconel 751 (HEV3) alloy for exhaust valves. Stellite is standard for valve seats. The steel head gaskets are also widely diffused. With this technology, after the run-in, the wear is approximately linear, up to a mileage when the engine tends to wear out with increasing blow-by (Figure1). In this case, the wear is measured as an increase in bore diameter. The same happens for the oil consumption (Figure-2) that begins to grow more than linearly just before the mileage of the knee of Figure-1. The truck began to increase the oil consumption figure just after 400,000km. The piston/liner clearance began to grow in a significant way after 450,000km. This means that it is perfectly possible to predict engine TBO in terms of oil consumption by knowing the starting point and the slope of the curve of Figure-2. The starting point depends on the engine and varies in a significant way from each unit in the same production line. This fact happens also when selective assembly is adopted. Unfortunately, only run-in and test will find the starting point of the curve of Figure-2. The slope is a characteristic of the surface-finish, the materials, the heat treatment and the oil type and it is approximately the same for all the identical engines coming out from the same production line.

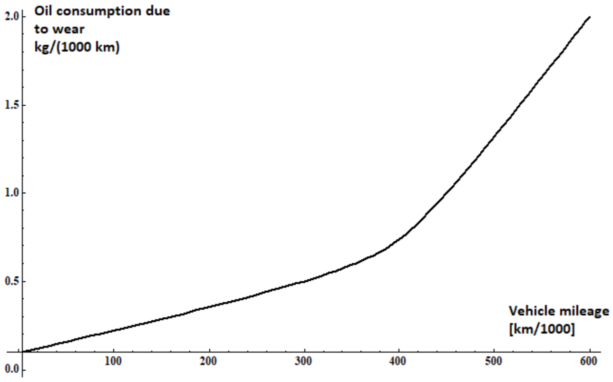

Figure-2. Oil consumption due to wear [kg every 1000km] vs mileage [thousands of km] for the engine of Figure 1 [13] [14].

Therefore, it is perfectly possible to select the engines form the production line that will show minimal oil consumption. By measuring the differential pressures between the inside the head (camshaft level), the crankcase and Outside Air Pressure (OAP) it is possible to monitor if one of the two blow-by is going out of control.

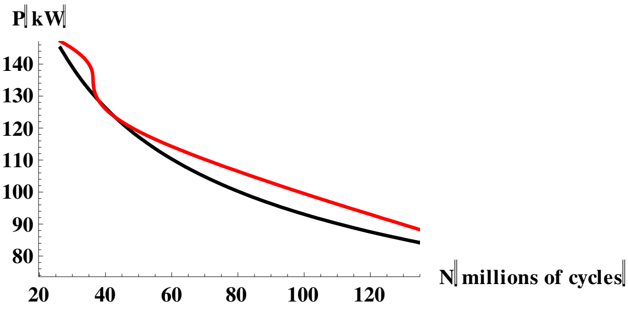

Figure-3. Experimental curve of maximum power output P[kW] for a given life expressed in number of cycles N [number/10^6](red). The approximation of this curve with a cubic law (black).

TBO Evaluation: The Power to Cycle Law

The Load Factor (LF) is an approximate, very conservative, method. With this method, the overhaul will be anticipated. A better evaluation of the remaining engine hours to overhaul can be obtained by using the Power-to-cycle curve of the specific engine. This curve displays the maximum number of cycles N allowable for the engine at a certain power setting P [kW]. This means that the engine will sustain a certain number of cycles on the x-axis while outputting the corresponding power in the y-axis. Since it is possible that the same P_i power level is obtained at different engine speed and throttle settings, only the full throttle curve will be used. Therefore, the curve is drawn at the minimum engine speed at which the engine outputs that power. It is the condition of maximum thermal load. This condition is the worst possible for the engine for a given power load [19]. Figure-3 shows a power-to-cycle curve of an automotive-derived diesel engine converted to aircraft use by the authors. It is a direct derivative of a very popular diesel car engine. This four in-line 1,560 cc turbo-diesel has 16 valves. This engine has been progressively upgraded form the original 82 kW (110 HP) up to the final 147 kW (200 HP) of the aircraft version. This is possible because the original automotive engine has catalysts, a soot filter and a throttle butterfly valve in the intake. Automotive engines needs as much torque as possible at low engine speed, while aircraft engines needs power (and torque) only at high engine speed. This requirement of high torque at low engine speed along with the necessity that the car fulfills the Euro 6x requirement is a huge penalty on maximum power output and fuel consumption. Another basic requirement of automotive engines is low noise especially at low audio frequencies. This requirement is not fulfilled in aircraft engines where power (and torque) is necessary only at high engine speed and engine noise at low frequencies is covered by propeller noise. No emission requirements are actually present for aircraft engines. The red curve of Figure-3 is based on a few known experimental points (Table-1). The continuous rating for this aircraft engine is P_2=112 kW@4,000 rpm. This rating has been successfully kept for 500h of continuous operation. The number of cycles $\boldsymbol{N_2}$ elapsed in 500h is 60 million (13). For economical reasons the authors use the 500h continuous run. It is a long run that lasts 21 days (three weeks) on a specialized test bench. After this test, the engine is disassembled and checked for wear of the main parts. The test is considered passed if the parts remain within the manufacturer's tolerances with the exception of the valve guides. In fact, valve guides are normally out the maximum tolerances after the 500h run.

$$N_2 = 500 \times 4{,}000 \times 60/2 = 60 \times 10^6 \tag{13}$$

The red curve of Figure-3 requires many tests. The longer one takes more than two months (1500h -135 million cycles). In absence of more data, the power to cycle curve can be approximated by a cubic law (black line of Figure-3) that is drawn from the point P_2=112 kW@4,000 rpm.

Table-1. Experimental data.

Million of cycles	Power [kW]
26.4	147
36	137
60	112
135	92

With the cubic law, any point $\{N_i, P_i\}$ of the curve will be calculated with equation (14).

$$P_x = \frac{N_2^{1/3} \times P_2}{N_x^{1/3}} \tag{14}$$

In the specific case of the engine of Figure-3, it is possible to check the level of approximation of the cubic law by evaluating the maximum power output P_{max} of the engine at $\boldsymbol{N_1}$ = 26.4 million cycles (15). From the first raw of Table-1, P_{max} should be 147 kW instead of 145 kW (15). The error is below 2%.

$$P_{\max} = \frac{N_2^{1/3} \times P_2}{N_1^{1/3}} = \frac{60^{1/3} \times 112}{26.4^{1/3}} = 145\,kW \tag{15}$$

With the power-to-cycles curve, a rule similar to the one of Palmgren-Miner's [17-18] for the fatigue of structural components (16) can be used also to evaluate the time to overaul.

$$\sum_{i=1}^{n_{tt}} \frac{n_i}{N_i} = 1 \tag{16}$$

The Palmgren-Miner law (16) is based on the damage concept. If the engine runs for ni cycles at P_i power, the engine will be damaged for a fraction equal to n_i/N_i. The number of cycles $\boldsymbol{N_i}$ is taken from the power-to-cycles curve (Figure-3). Adding the damage as it takes place, it is possible to evaluate the total damage of the engine. When the damage is unitary, the engine should be overhauled. Below 40% of maximum power the power to cycle curve is not valid. The minimum load of 40% comes from the automotive experience. In fact, if the LF is 0.44 for a car it is possible to assume that the car will run with this LF for the standard-automotive-life of 250,000km. An Italian driver living in Rimini (Italy) will run at an average speed of 29.2 km/h. The engine will then last 250,000/29.2=8,561h. If the LF=0.44, the engine will run at approximately at 44% of the maximum engine speed of the car engine (0.44 3500=1540 rpm). Therefore, the car engine will run for 395 million cycles. The output power of equation (15) will be about 58kW (80HP) or 40% of the maximum power. Therefore, it is necessary to evaluate the value of N_{idle} when the engine runs below 40% of the maximum power.

Low Load TBO

Archard's expression (16) [19] states that, under a certain amount of load and within an interval of speed, wear does not depend on load W [N].

$$Q = k \times W \times DS \qquad (16)$$

Where Q is the volumetric wear [mm^3], k is the wear factor [mm^3/(m x N)] and *DS* is the sliding run distance [m]. In modern automotive engines the distance *DS* is equivalent at least to twice the normal car engine life (250,000km). In this case, a reasonable value is around *TBO_idle*=16,000h. Most automotive engines will be idling at around 1,000rpm. Therefore, a typical engine will run at least N_{idle}= 50 million cycles (17).

$$N_{idle} = 16000 \times 1000 \times 60 / 2 \approx 50\, million\ cycles \qquad (17)$$

With this more accurate approach, it is possible to evaluate the number of cycles to *TBO* for the standard cycle *Total#StandardCycles* (Figure-4) and the standard time interval elapsed for each engine cycle in standard conditions *Δt_standard*. This evaluation can be performed by the digital monitoring system of the engine. This algorithm is shown in Figure-4. While the engine is running and the *Load*>40% the new *TimeToOverhaul* [h] is evaluated. Entering the While cycle,t hat is run at fixed time intervals *Δt*, the number of cycles *n* totaled in this interval and the ***Powe***r is read by the algorithm.

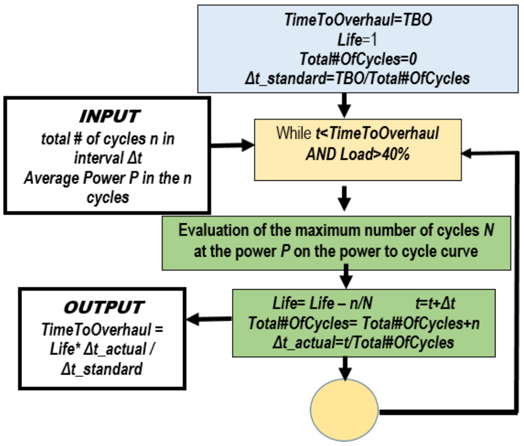

Figure-4. Block diagram of TBO algorithm.

If the *Load* (that is the ratio between the maximum rated power and Power) is less than 0.4, the algorithm goes to the next cycle. If *Load*>0.4 the maximum Number of cycle *N* at *Power* is evaluated on the power-to-cycle curve. This curve is similar to the one of Figure 4 and it is specific for every engine type (see the example of Figure 3). Then the variable *Life* is reduced by the ratio *n/N*. This is the application of equation (12). It is then possible to calculate the new T*BO=TimeToOverhaul* of the engine. For intervals ***Δt*** below 40% load it is then possible to integrate the algorithm of Figure 4 with an additional branch in which the residual life is reduced by *n/Nidle*.

Thermal Cycling Fatigue TBO

Another important factor in engine TBO is the thermal cycling. As the car engine reaches the temperature of full-power-mapping, the thermal cycle begins. This cycle stops when the engine is turned off. Modern automotive engines are all liquid cooled and have a relatively short warm up phase. This is necessary for emission requirements. For the same reason the engine should stay warm. Therefore, the problem of overcooling at idle is eliminated by engine and installation design. In old engines, especially air-cooled ones, on descent the engine tends to overcool. This fact has two adverse effects. The first one is thermal cycling that reduces engine life. The second adverse effect is that the unburnt fuel passes into the lubricant through the gap between piston and liner of the cold engine. This dilution reduces lubricant capability and bearing life. Therefore, thermal cycling should not be underestimated. For example an air cooled engine on an aerobatic aircraft that will make 8 minutes flights is much more stressed than the same engine on a general aviation aircraft. In automotive engines, the thermal cycling is calculated with 6 cycles per day for a 10 years life (18). An Italian car driver will use his car an average of 288 days a year [2]. Then the maximum design value for a car engine is about $N_{thermal}$=18,000 thermal cycles.

$$N_{thermal} = 288 \times 6 \times 288 \approx 18{,}000\, cycles \qquad (18)$$

The digital engine monitoring system can easily measure coolant or head temperature cycles and estimate the reaming time to overhaul based on thermal cycling fatigue.

DISCUSSIONS

The focus of this paper is to select and prepare an engine that can reasonably fly for a week on a UAV with in-flight refueling. The power output of this engine is in the 100-500 HP power range. For this reason, turboprop or turbofan are not the best choice due to their low efficiency in this power range. Piston or Wankel engines seem to be the only reasonable choice. The selection is made from automotive engines that have many advantages on specialized aircraft engine. The main advantage is the number of tests that are made in the assembly line. In fact, with engine mass produced in thousands per day, quality is of paramount importance to avoid huge losses in the aftermarket. An additional advantage is given by the availability of many engines from different manufacturers. The best and most proven engines can be selected. These engines have cumulated trillions of hours in the hands of unskilled drivers in a very hostile environment. In fact, for noise control, the engine compartment of modern vehicles is very hot. Normally the under-hood temperature is 85-90 DEG C with peaks (thermal soak) over 110 DEG C [21]. In addition, from the assembly-line quality controls is possible to select those engine that show the minimal oil consumption. Modern automotive engine come with ECUs and sensors that already have on board diagnosis systems [22-23]. In any case, it is easy to replace the electronics with better quality ones from the aircraft or the automotive fields. The Author proposes an additional run-in of 25h with a very thin oil to stabilize the oil consumption and reduce the infancy failure of the electronics. After the run-in additional controls can be made especially on the fuel system. The whole cost of the engine and its preparation is well below the cost of a turboshaft of equivalent power.

CONCLUSIONS

In-flight refueling has introduced new challenges to unmanned aerial vehicle propulsion systems. It is now theoretically possible to fly continuously an unmanned aerial vehicle for infinite time. Unfortunately, this is a main challenge for the propulsion systems that suffers statistically of a high mishap rate. This paper introduces a method to prepare automotive derived piston engines for very long flights without maintenance. It also gives criteria to estimate time between overhaul, not as a general standard, but by correlating the engine monitoring data. A main issue is the oil consumption that is complicated by the fact that oil consumption follows a bath-tube curve. Therefore, a first selection is to select the engines that are suitable for long endurance flight directly in the assembly line. This is possible because automotive engines are manufactured in thousands per day. Afterwards, a 25-hour run in with a thin lubricant is sufficient to forecast the fuel consumption up to 1,000 hours. In modern automotive engines the electronic on board diagnosis and the full redundancy of vital sensors, electronic-control-units) and batteries/generators, make it possible to control the engines during the flight. Unfortunately, the automotive derived electronics find its limit in wiring and extremely cheap sensor selection. For this reason, for aircraft engines it is convenient to use aircraft or racing derived electronic components. A feasible target can be one-month continuous flight time: this means about 800 hours. Another major requirement is also to forecast the engine failure or an unacceptable deterioration in terms of mechanical performance. By carefully applying a few elementary algorithms on the monitoring data, it is possible to monitor the state of wear of the engine. These data are correlated to a wear model of the engine based on the real duty cycle. It is therefore possible to prolong the life of the engine and to increase engine life. It is also possible to schedule the exact time when a major revision.

ABBREVIATIONS

TBO	Time Between Overhauls
UAV	Unmanned Aerial Vehicle
OBD	On Board Diagnostic
EOBD	Electronic On Board Diagnostic
ECU	Electronic Control Unit
APU	Auxiliary Power Unit
HPP	High Pressure Pump
TR	Time Run

SYMBOLS

Symbol	Description	Unit
kmyear	Average Mileage x Year	km
vave	Average Car Speed	km/h
TBM	Travel Between Maintenance	km
TIM	Time Between Maintenance	h
SPRT	Spark Plug Replacement Time	h
MPS	Mean Piston Speed	m/s
Stroke	Piston stroke	m
RPM	Crankshaft velocity	rpm
TBO	Time Between Overhaul	h
Length	Total Piston Travel	m
Ap	Maximum Piston Acceleration	$m\ s^{-}2$
λ	distance between centers of connecting rod / Stroke	-
LF	Load Factor	-
TR	Time Run	h
Travel	Equivalent car mileage	km
OAP	Outside Air Pressure	Pa
N,n	Number of cycles	-
P	Engine output power	kW
Q	Volumetric wear	mm^3
W	Load	N
k	Wear factor	mm^3 m^{-1} N^{-1}
DS	Piston travel	m
TBOidle	Time Between Overhaul of the engine when idling	h
Nidle	Number of cycles of the engine when idling	-
Nidle	Number of thermal cycles of the engine	-
SFC	Specific fuel consumption	gr kW^{-1} h^{-1}
BSFC	Brake specific fuel consumption	Gr kW^{-1} h^{-1}

REFERENCES

[1] AA. VV. 2018. Oil consumption and oil loss, MS Motorservice Rheinmetall Automotive, 2017, https://www.ms-motorservice.com/fileadmin/media/MAM/PDF_Assets/Oil-consumption-and-oil-loss_51747.pdf, (accessed on 26 February 2018).

[2] Del Prete A. 2017. L'osservatorio UnipolSai, Resto Del Carlino ed. Bologna, 21 November 2017. (data retrieved from car black boxes by Unipolsai Insurance Company, in italian).

[3] Peng L., Tusinean A., Hofbauer P., Deylami K., 2018. Development of a Compact and Efficient Truck APU. Report #14353, U.S. Army TARDEC, 6501 E.11 Mile Rd, Warren, MI, 48397-5000 USA, 2004, http://www.dtic.mil/dtic/tr/fulltext/u2/a583072.pdf (accessed on 28 March 2018).

[4] Wilkins D. J. 2018. The Bathtub Curve and Product Failure Behavior Part One - The Bathtub Curve, Infant Mortality and Burn-in, http://www.weibull.com/hotwire/issue21/hottopics21.htm (accessed on 27 February 2018).

[5] AA. VV. 2018. In-Process Testing for Engine Manufacturing using Signature Analysis, http://www.sciemetric.com/sites/default/files/SI_Engine_IPT_Blueprint_01-12_0.pdf (accessed on 27 February 2018).

[6] AA. VV. 2018. Hard Facts About Engine Break-In, Lycoming, https://www.lycoming.com/content/hard-facts-about-engine-break (accessed on 27 February 2018).

[7] AA. VV. 2003. Unmanned Aerial Vehicle Reliability Study, U.S. Secretary of Defence.

[8] Piancastelli L., Frizziero L., Pezzuti E. 2014. Aircraft diesel engines controlled by fuzzy logic. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(1): 30-34, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA

[9] Piancastelli L., Frizziero L., Morganti E., Canaparo, A. 2012. Fuzzy control system for aircraft diesel engines. International Journal of Heat and Technology, ISSN 0392-8764, 30(1): 131-135.

[10] Piancastelli L., Frizziero L., Rocchi I. 2012. A. Feasible optimum design of a turbocompound Diesel Brayton cycle for diesel-turbo-fan aircraft propulsion. International Journal of Heat and Technology, ISSN 0392-8764, 30(2): 121-126.

[11] Piancastelli L., Frizziero L., Daidzic N. E., Rocchi I. 2013. Analysis of automotive diesel conversions with KERS for future aerospace applications. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 0392-8764, 9(1): 807-818, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA

[12] Piancastelli L., Frizziero L., Pezzuti E. 2013. Kers applications to aerospace diesel propulsion. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(5): 32-36, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA

[13] Dannenhoffer R. F., Engine Duty Cycle Estimation for Conceptual Design Aircraft. R. F., Grumman. Aerospace Corp. Bethpage, NY. AIAA/SAE/ASME 17th. Joint Propulsion Conference. Anniversary. July 27-29, 1981 /Colorado Springs, Colorado, USA.

[14] Dunst J. 2018. When Is Engine Oil Consumption Considered Excessive, https://www.bellperformance.com/blog/when-is-oil-consumption-considered-excessive (accessed on 27 February 2018).

[15] Ellerman J., Rohrle, M., Schelling H. 1981. Oil Consumption and Blowby of Truck Diesel Engines-Test Bench Results, SAE 810937, 37-45.

[16] Ishizuki Y., Soto F., Takase K. 1981. Effect of Cylinder Liner Wear on Oil Consumption in Heavy Duty Diesel Engines, SAE 810931, 1-6.

[17] Palmgren A. 1924. Die Lebensdauer von Kugelgen, Verfahrenstechnik, Berlin 68, 339-340 (in German).

[18] Miner M.A. 1945. Cumulative Damage in Fatigue, Journal of Applied Mechanics. 67, A159, 223-226.

[19] Piancastelli L., Frizziero L., Morganti E., Canaparo A. 2012. Method for evaluating the durability of aircraft piston engines. Walailak Journal of Science and Technology, ISSN 1686-3933, 9(4): 425-431.

[20] Archard J.F. 1953. Contact and Rubbing of Flat Surface, J. Appl. Phis. 24(8): 981-988.

[21] Binner T., Reister H., Ernst P., Weidmann J. 2005. Aspects of Underhood Thermal Analyses. http://www.fkfs.de/uploads/publikationen/fkfs_kfz_AD_Binner.pdf (accessed on 30 March 2018).

[22] Caligiana G., Liverani A., Francia D., Frizziero L., Donnici G. 2017. Integrating QFD and TRIZ for innovative design, Journal of Advanced Mechanical Design, Systems and Manufacturing. 11(2).

[23] Francia D., Caligiana G., Liverani A., Frizziero L., Donnici G. 2018. Printer CAD: a QFD and TRIZ integrated design solution for large size open moulding manufacturing, International Journal on Interactive Design and Manufacturing, 1st February 2018, 12(1): 81-94.