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ON THE CONVERSION OF AUTOMOTIVE ENGINES FOR GENERAL AVIATION

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ABSTRACT

Automotive engines have outstanding quality controls and extremely high cost-effectiveness. This is typical to lean, mass production. For this reason, the application of these engines on aircraft is most appealing. Ultralight-sport aircraft have pioneered this approach. A few automotive-aircraft certified engines are already available on the market. However, this approach has not been as successful as foresaw a few years ago. This is due to the differences between the automotive application and the aircraft use. These differences have lead to teething problems that have been solved in almost 20 years of research work. The level now reached and the experience achieved makes it possible to convert any "successful" automotive engine into an aircraft engine. This work starts with the description of the data available from automotive manufacturers. Automotive engines have a huge background of statistical data on performance, reliability and TBO (Time between Overhaul). The correlation of these data to an aircraft application is not straightforward. Then the performance curves obtainable from the new aircraft engine are introduced. Finally, an algorithm calculates the residual life to TBO (Time between Overhaul) of an automotive engine. The method was tested on a few small last-generation CRDIDs (Common Rail Direct Injection Diesels) and spark ignition (gasoline) engines. These engines were also converted for use into small aircrafts with power ranging from 60 to 200HP. This very simple method is implemented directly in the FADEC (Full Authority Digital Electronic Control) or E-ECU (Engine Electronic Control Unit) of the engine with very few lines of C-Code (C-Language Code). It is assumed that the engine undergoes regular maintenance schedule and OBD (On Board Diagnostic) is implemented. OBD is perfectly able to foresee the imminent failure of the accessories like the starting motor, the generator, the turbocharger, the injector(s), the HPP (High Pressure Pump), etc. These parts are external to the engine and can be changed during field maintenance. Accidents, like prolonged under/overcooling, crankshaft damper failure, overspeed are monitored by the OBD and require specific maintenance actions. Ordinary problems like excessive fuel, lubricant, coolant consumption, pressures out of range... are also dealt by the OBD-related service system.

Keywords: piston engine, aircraft, automotive, general aviation, TBO.

INTRODUCTION

Several spark ignition engines are available on the market for the ultralight non-certified market.

A few of these spark ignition engines can be seen in Table-1. These engines are generally equipped with racing derived FADECs (Full Authority Digital Electronic Control) and, with the exception of the TwinAir, have a single spark plug per cylinder. However, modern spark plugs last 100,000km and, after a pre-stress test, are extremely reliable.

Table-1. A few aircraft spark ignition engine comparison (automotive conversions).

Origin	Suzuki Maruti Gypsy King G13BB	Honda Jazz L12B i-VTEC	Jeep Renegade Fiat Fire	Subaru Impreza EJ-22	Fiat Panda TwinAir
Manufacturer	Private	Private	Dieseljet Srl	Private	Aernova Srl
TO Power [kW]	75	92	85	140	100
Dry Mass [kg]	82	92	85	115	65
Power/Mass [kW/kg]	0.91	1	1	1.21	1.53
Crankshaft rpm	5,500	6,000	5,500	7,000	5,500
SFC [gr/kWh]	285	270	292 (2)	280	244
Recovery Altitude (feet)	0 (n.a.)	0 (n.a.)	0(n.a.)	0(n.a.)	10,000
Displacement (cc)	1,200	1,500	1,368	2,200	800
Certified	No	No	No	No	No

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In 1987, VM, an Italian firm, designed a brand new diesel DID (Direct Injection Diesel) engine. This engine could not be certified. Different history for the more recent (1990s) SMA DID engine. This engine is a flat, aircooled engine without PRSU (Propeller Reduction Speed Unit). From the EASA type certificate, it has a power to mass ratio of about 1.1 [HP/kg]. The maximum TO power is of 227 HP. The SFC (Specific Fuel Consumption) is about 161 g/HPh. Since the displacement is quite huge (5,000cc) this performance is really excellent. The Common Rail Direct Injection Diesel (CRDID) was introduced successfully in 1997 into the automotive market (1997). After a few years (1999) both Thielert and CRF (Centro Ricerche Fiat) began to develop an automotive conversion of the Mercedes class A and of the 1900jtd engines. In 2003, Thielert successfully certified his conversion of the Mercedes Benz Class A 1700cc engine for the general aviation market. Afterwards, in 2010 also CRF-Dieseljet brought its engine on the market. Meanwhile (2009) also Austro Engine developed and marketed a conversion of a 2 litre CRDID.

This engine has been developed both by Daimler Benz for the II-generation Class A and by Thielert (now Continental) for aircrafts. A summary of the performances of these diesel engines can be seen in Table-2.

Table-2. Available aircraft DID comparison. (1) From EASA type certificate. (2) Declared by the manufacturer.

	TAE125-02-114	E4	TDA CR 2.0 16V(3)		
Origin	Mercedes Benz Class A (W169) OM640 CRDID	Mercedes Benz Class A (W169) OM640 CRDID	FIAT 2000 Multijet 16V CRDID	Peugeot 1600 HDI	Smart CDI
Manufacturer	Continental GmbH	Austro Engine GmbH	Dieseljet Srl	Private	Private
TO Power [kW]	155 (1)	123.5 (1)	160 (2)	140	60
Dry Mass [kg]	134 (1)	185 (1)	200 (2)	115	70
Power/Mass [kW/kg]	1.15	0.66	0.8	1.21	0.85
Crankshaft rpm	3,900 (1)	3,880 (1)	3,800	5,500	5,500
SFC [g/kWh]	220 (2)	21 [lt/h](2)~191	224 (2)	214	230
Recovery Altitude (feet)	6,000 (2)	10,000 (2)	8,000 (2)	10,000	10,000
Displacement (cc)	1,991	1,991	1,955	1,600	800
Certified	Yes	Yes	In progress	No	No

This Table outputs curios data. Automotive CRDIDs have usually SFC of 200 g/kWh in their Euro "0-3" version. The numbers declared by Continental and Dieseljet are very high and may possibly be the "worst" useful case. This can be the case of full power. At full power the engine may lack of air mass. An air-fuel ratio of 17:1 is easily reached. The high mass of Austro-Engine and Dieseljet engines depends on the cast-iron crankcase and the large PSRU (Power Speed Reduction Unit) and the damper. Continental motors (Thielert) manufactured an aluminium alloy crankcase to contain engine mass [1] [2] [3].

Problems of automotive conversions: power settings

The main problems of automotive conversion came from lack of knowledge. The last aircraft piston engines were developed in the 50s. Very limited specific knowledge was available in this field in the 1980, when the conversion activity began. Another problem is the very dispersed knowledge typical of the automotive industry. The "whole figure" of how automotive engines really work is known to a handful of experts that are employed by large automotive companies. Automotive engines are typically produced in the range of millions per year. The aircraft field has smaller numbers. The extremely successful Rotax 9XX engines reached the 40,000 at the Friedriechschafen 2014 Fair event. This number was achieved in approximately 14 years of continuous production. The same number of engine (40,000) is manufactured in 10 days by the automotive industry. Therefore, the interest of the automotive companies in aircraft field is negligible. Furthermore, aircraft engine companies are continually law-suited by customers for accident related problems. Finally, the aerospace engineers are turbine-oriented people. Often they lacked of knowledge about the automotive engines. On the contrary, automotive engines are a highly specialized engineering field, where it is important to keep the pace of the continuous, daily, improvements.

For this reason, some problems were overestimated. An important aspect is mechanical reliability. Automotive engines are highly reliable. Statistically, the problems are really very few and they are related to the beginning of the serial production, to the electronic equipment (ECU+sensors+wiring), to accessories or to mistakes of the automatic quality control system. These last events are very rare and they are well known both to the manufacturer and to maintenance

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system. Since a crankcase failure should never occur, the maximum rpm of automotive engine is commonly reduced by 15%. For the same reason the maximum torque is often reduced by 15%. The dreadful combination of low rpm and high torque, that is common in automotive engine in motorways, is absent in aircraft/helicopter engines. This low-speed, high-load condition is particularly critical for journal bearings and tribology problems in general. Furthermore, the classical overheating situation of a car towing-a-caravan on a steep-slope in a very-hot-day is also not common in aircrafts. In fact, the pilot can adjust the climb rate to avoid protracted overheating. Aircraft engine are well cooled by airspeed and they work at the maximum power output for a few minutes per flight at take-off. The second very important aspect is the maintenance. In general aviation, a qualified mechanic makes the daily inspection and signs the maintenance book. The professional pilots are trained to make a pre-flight check with a walk around. The aircraft engines are much more controlled than the automotive ones, where the common driver never takes a look at the engine. The automotive repair shops are not certified and often maintenance is not made for 100,000 km. In this period the engine is left to the EOBD (Electronic On Boars Diagnostic) system. This system is quite reliable, but it does not have any redundancy for extreme reliability. Therefore, ECUs, wiring, sensors and EOBD should be substituted for an extremely reliable aerial vehicle conversion. Extremely reliable material for this purpose comes from the automotive and marine racing field.

Automotive reliability data

Automotive engines change continuously during manufacturing. It is common to have different engines, nominally identical, in the same day. This is due to several factors. The most important factor is cost. Automotive engineers try continuously to reduce automotive costs. This process is mainly made on "accessories" that are purchased through outsourcing. These accessories may also be very fundamental parts of the engines, like sprockets, chain, belts, camshafts, pumps, etc. Engines are manufactured by thousands per day and parts arrive into the manufacturing site with an advance of hours (lean manufacturing approach). In fact, automotive process has high volumes, but manufacturing and quality controls work on batches. In many cases, materials and processes are identified by batches. This means that for a single batch everything about manufacturing is known and controls are made by samples. Different batches may be used in the same day. Outsourcing works with same philosophy. Batch of products are purchased and installed on engines from a pure cost-effectiveness basis. The great advantage in this complicated situation is that the spare parts should be available for the specific vehicle for a period varying from 10 up to 20 years. For this reason, the chassis number bears all the information necessary to individuate the batches. In this way the highly automated spare part supply system individuates the "failures" of the single engine by the spare parts sold. This is extremely important since these data are available to the manufacturer. Another important issue is that an engine type lasts much more time than a car model. A few engines have been in production for more than 50 years. The design and manufacturing of a completely new engine is so expensive that automotive companies tend to be conservative on this subject. In fact, cars are sold by power, design and configuration and not by engine technology. The combination of production rate, spare part sold and engine design conservation is the key for engine reliability assessment. The most difficult part is to assess how many hours an engine has worked. In modern engines a lot of data are stored in the ECU (Electronic Control Unit). Unfortunately, these data are rarely available even to the manufacturer. However, the culture of retrieving these data is slowly growing among the automotive companies. An enormous amount of data is available from US Department of Transportation, Black-boxes of Insurance Companies, ACI (Italian Automobile Club), Italian and European fonts. Affordable average annual distances travelled (km) per vehicle type are available (Table-3).

Table-3. Average annual km per vehicle type.

vehicle type	km x year US	km x year EU
Class 8 Truck	100,000	100,000
Transit Bus	55,000	50,000
Delivery Truck	50,000	50,000
Police	25,000	30,000
Car (diesel)	-	20,000
Car (gasoline)	22,000	10,000
Motorcycle	4,000	2,000

Far more interesting are the values that are within 68% standard deviation away from the mean in a normal distribution (Tables 4 and 5).

Table-4. US 68% standard deviation from the mean (average annual km).

vehicle type	km x year	km x year
Class 8 Truck	70,000	160,000
Transit Bus	20,000	90,000
Delivery Truck	30,000	150,000
Police	15,000	80,000
Car (diesel)	-	-
Car (gasoline)	2,000	120,000
Motorcycle	500	9,000

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Table-5. European 68% standard deviation from the mean (average annual km).

vehicle type	km x year	km x year
Class 8 Truck	70,000	140,000
Transit Bus	20,000	90,000
Delivery Truck	20,000	120,000
Police	5,000	70,000
Car (diesel)	5,000	100,000
Car (gasoline)	2,000	40,000
Motorcycle	500	4,000

About average speed, statistical data from insurance black-boxes are available. For example, an Italian from Emilia Romagna spends 1 hour and 15 minutes a day in the car at an average speed of 38.6 km/h, the Italian national average is 30 km. Among these, Ferrara, with an average speed of 43 km/h and Ravenna by 41 km/h. The average speed in Germany is 40 km/h. For delivery trucks the average speed is 40 km/h in Italy and 60 km/h in Germany. This data is particularly interesting since it is possible to assess that a delivery truck will take 5 years to reach engine TBO (250,000km). A diesel car will take 12.5 years, while a gasoline car engine will last an average of 25 years. The life of an average modern car is about 10 years. Therefore, most gasoline car will not reach engine TBO, while less than half of the diesel car will reach this limit. An Italian diesel or a gasoline car will travel for 250,000/30=8,000 hours to reach TBO, while a German delivery small truck will reach the TBO in 4,000h. This means that a TBO of 4,000h is the minimum average for an automotive engine. In fact, class 8 tracks use very different engine that are conceived for a TBO between 500,000 and 1,000,000 km. Their technology is a special type of "common rail" that does not have a single high pressure rail for the engine. These heavy duty engines are unsuitable for aircraft or helicopter use due to poor power to weight ratio. Automotive engine for aircraft conversions should be chosen among those that are used in small delivery trucks. Reliable data will be available after 5 years for 4,000h TBO or 2.5 years for 2,000h TBO. Small spark ignition engines are penalized by these statistics since they usually do not reach the TBO. However, it is possible to extrapolate the data available to obtain statistical data also in this case. Cars are a difficult issue. In the European Union diesel and gasoline high mileage cars tend to be used one year and then sold in the second-hand market. European high-mileage gasoline cars tend to run on natural gas o LPG.

Data extrapolation for TBO evaluation

Historically TBO has been expressed in “hours” or "cycles". The meaning of these terms depends on the vehicle type. In heavy vehicles the number of cycles is the total number of revolutions of the crankshaft measured by a device installed on the crankshaft. In light aircrafts, the number of hours is the total time the engine ignition has been running. In the automotive field, the duration parameter is the road travelled by the vehicle. Modern automotive and aircraft engines have the FADEC (aircraft name) or ECU (automotive-name) (Full Authority Digital Electronic Control - Electronic Control Unit) with OBD (On Board Diagnostic). It is possible to implement on these small control computers a relatively sophisticated algorithm to evaluate residual life and TBO [4] [5] [6] [7]. However, since TBO is strictly related to the engine reliability and the aircraft safety, this algorithm should be kept as simple as possible. A very simple algorithm to calculate residual life is introduced herein.

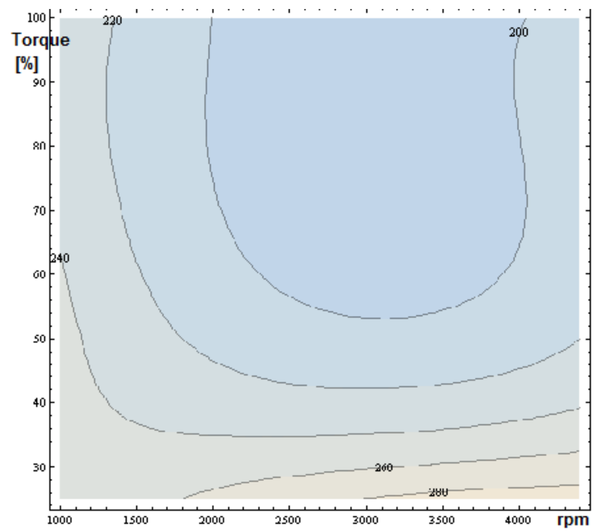

Figure-1. SFC [g/kWh] of an automotive derived CRDID.

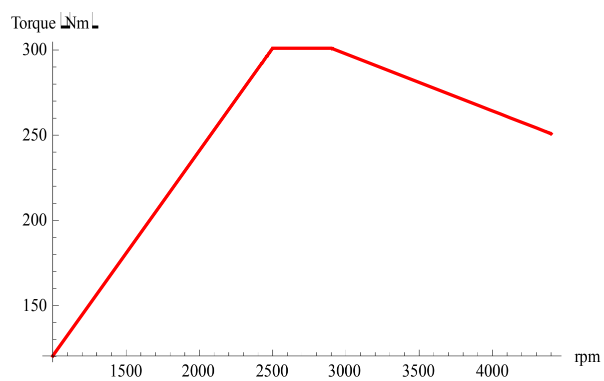

Figure-2. Torque of a 150HP automotive -aircraft converted CRDID.

As an example, from Figures 1 and 2 it is possible to obtain Table-6.

Table-6. Theoretical fuel consumption with a constant efficiency propeller.

Fuel consumption [lxh]		**rpm**
Max Take Off (100%)	27	4,400
Max Continuous (92%)	24.6	4,084
Cruise (73%)	18.8	3,781
Approach (60%)	15.3	3,542

The procedure to calculate the fuel consumption for the "cruise" line is described herein.

A constant-efficiency propeller absorbs the power in a cubic way. Therefore, it is necessary to run the engine at 3,781 rpm (2) to have 73% of the maximum power available (150HP).

$$rpm_{cruise} = \left(\frac{P_{cruise}}{P_{\max}} \times rpm^3_{\max} \right)^{\frac{1}{3}} == 3781[rpm] \quad (1)$$

At rpm_{cruise} the maximum torque available from the engine is about C_{rpm_cruise}=270Nm (figure2). The torque required by the propeller is (2)

$$C_{cruise} = \frac{P_{cruise}}{rpm_{cruise}\pi / 30} == 203[rNm] \quad (2)$$

The load on the engine is then (3)

$$Load == \frac{C_{cruise}}{C_{rpm\_cruise}} 100 = 74[\%] \quad (3)$$

From Figure-1 it can be seen than the SFC (Specific Fuel Consumption) at this point 195 [g/kWh] (Figure-1). The fuel consumption per hour at cruise will then be evaluated (4).

$$FC_{cruise} == P_{cruise} SFC_{cruise} == 15.7[kg] = 18.8[l] \quad (4)$$

A typical aviation aircraft work cycle ("standard flight") is the following: 100% power will be required for take-off up to about 1,000ft ASL (Above Sea Level) (3 min.). At this point, the power is pulled back to 92%. Then the airplane will climb to about 12,000ft ASL (0.5 h). Then it will cruise for 3 hours at 73% power. Then the power will be pulled back to about 60% on the approach to landing (15 min.). From Table-1, it is possible to calculate an approximated fuel consumption of 73.8 lt. In this durability model, an engine has a lifetime that can be compared to the mass of fuel used. The Load Factor (LF) represents the relationship between fuel burned and the number of hours the engine takes to burn it. In this case, the flight lasted 3.8 h. At max continuous power, the fuel burned would have been 27*3.8=102 l. Hence, the LF can be calculated (5).

$$LF = \frac{Fuel_{Burnt}}{Fuel_{\max ratedpower}} = \frac{73.8}{102} = 0.7 \quad (5)$$

The typical automotive load factor is 0.5. It is then possible to calculate the load factor ratio LF_{ratio} (6).

$$LF_{ratio} = \frac{0.7}{0.5} = 1.4 \quad (6)$$

On a pure LF basis, the aircraft engine will last 2,000 h (7).

$$TBO_{aircraft} = \frac{TBO_{automotive}}{LF^2_{ratio}} = \frac{4000}{1.4^2} \approx 2{,}000\,[h] \quad (7)$$

Automotive engines have the necessity of high torque at low rpm. A common optimization point for automotive engines is the motorway-optimum-speed point. This means low rpm, highest speed and 120km/h. In this condition the crankshaft speed is the minimum possible to contain fuel consumption. This means low oil flow rate and limited cooling of pistons and journal bearings. Furthermore, the automotive engine should pass the standard cycle for the EURO 6 emission tests. In the case of aerial vehicles, the used range is from 50% to 100% at EURO 0 and the cruise power is the critical point. For this reason, it is possible to install larger turbochargers and obtain a higher output power.

The "constant torque" method makes it possible to calculate an approximate value of the ultimate power for the aircraft converted engine. The simplified hypothesis is that the maximum torque can be kept up to the maximum allowed rpm by boosting more pressure into the intake. This is obtained by turbocharging. Furthermore, the conversion from Euro 6 to Euro 0 eliminates several pressure drops in the intake and in the exhaust of the automotive engine. In particular, the debimeter, the intake butterfly valve, the catalysts and the particulate filter can be removed. As seen before, both the torque and the maximum crankshaft speed can be increased of 15%. Therefore, an increment of 32% is commonly possible (1.15x1.15=1.32). The ratio between aircraft power and automotive power is P_{ratio}=1.32. The $TBO_{aircraft}$ can then be calculated (8).

$$TBO_{aircraft} = \frac{TBO_{automotive}}{P^3_{ratio}} = \frac{2000}{1.32^3} \approx 900[h] \quad (8)$$

This is the minimum in the worst case possible.

Another important factor that reduces engine life is thermal cycling. As coolant inside the engine is heated over 40°C a thermal cycle begins. It ends when the coolant is cooled again below 40°C. Automotive engines are calculated to last 5 years. It corresponds to about 800 thermal cycles per year for a total of 4,000 thermal cycles in engine life. From tribological tests, every single cycle that exceeds this limit takes 2h to engine life. In aircraft engines the automotive cycle limit is rarely overcome with the exception of aerobatic and paratrooper launching.

Reliability increase in terms of fatigue

A 15% increase of torque from automotive to aircraft applications may appear a large value. It is not. In fact, the load application velocity (stress rate) greatly affects fatigue life of components. Low varying load (low stress rate) tends to reduce fatigue life more than fast varying loads. Therefore, a crankshaft designed to withstand 15% overload at low rpm (1,200-2,000 rpm) will be much more resistant at top speed (over 3,000 rpm). As it was shown in the previous part of the paper this is the case of aircraft engines. The steady state working conditions, typical of engines running at nearly constant rpm, is also greatly favorable both for engine parts and accessories. Therefore, aircraft engine are less stressed than their automotive counterparts. However, several treatments can be applied to improve fatigue life of engine components. Hot and cold hyping are among the most commonly used. Nitriding and shot peening of critical spots is also possible.

Methods to increase engine TBO

For a longer TBO several options are available. The simplest one is to change the original oil to a more performing one. For example, a more viscostatic oil reduces hydrodynamic friction. Oil additives further improve TBO. Low temperature additives reduce friction at startup and in valve trains at low rpm. High temperature ones reduce friction and wear for the piston assembly. In general, additives improve engine performance with the drawback of more frequent oil substitution. However, automotive oils are generally of good quality and oil-service-interval may be as long as 500h. Table-7 summarizes the improvements obtainable starting from a top quality commercial automotive engine.

Table-7. % increase in TBO.

	Low T additive	High T additive	Coatings	Surface finish
Valve train	100%	-	2000%	10%
Piston assembly	10%	100%	400%	5%
Bearings	100%	-	20%	10%

For example, from Table-7, the application of the DLC (Diamond Like Carbon) treatment in the valve train (all contact surfaces) brings a 1,000% (ten folds) improvement in TBO. If also a very high quality Low Temperature additive is used an additional 100% is obtained with a twenty-fold improvement of the TBO for the valve train. The improvement of the surface finish is limited. If the original engine is an automotive top quality CRDID produced in millions, an additional 10% can be obtained for a total of 22 folds the original TBO (for valve train only). These values are taken directly from the Formula 1 engine tests and from experience in top performance engines for racing watercrafts. A more limited increase in bearing durability can be obtained through better finish and coatings. Several options are available to improve the life of liners and piston rings. In the worst case, which is the one of CRDIDs, it is possible to increase the piston-assembly life four folds. In the best one that applies to gasoline engines it is possible to increase the life of 10 folds. Several treatments are available for the valve train, a few applies also to AVGAS leaded fuel. In this specific field the life increase ranges from 4 fold up to 10 folds, depending on fuel type and automotive original materials and treatments.

A method to evaluate engine data from "low hours" statistical data

Engine manufacturers typically test the life of their engine with internal standard tests. Alfa Romeo used the "1,000 miles" test that is the cycle of an engine that runs a racing contest called "millemiglia-onethousandmile". It was an open-road endurance race which took place in Italy from 1927 to 1957. The load and rpm are expressed in terms of percentage of the maximum value possible and applied to the specific engine. In general, every automotive company runs its own tests. Commonly, a maximum power minimum endurance test and a variable load-rpm test on the style of the "1,000 miles" one. This test is run with an engine with the maximum power possible from the specific mass produced engine. In fact, maximum power and torque output of automotive engine may vary up to 15% (in a few cases even more), due to "tolerances" especially in sensors and injectors. The marketing office of each automotive company decides to declare the maximum, minimum or medium value of the maximum output power on the car brochure. The test run and the value declared by each company are well known by the specialists of automotive engines. In fact, companies often buy and test vehicles manufactured by competitors. This is a known strategy to improve product cost-efficiency. For this reason, at least one point of the curve of the cubic curve of power-to-TBO is known. The second point can be retrieved from the early statistical data if available. The automotive companies tend to use a standard maximum continuous power test for their engines. In a few cases it is 100h continuous at maximum power. This point is then known. By using the equation already described in this paper it is possible to obtain many other information about the unknown engine. If these data are not available, it is possible to make a test with the 32% overload as indicated in previous paragraph.

TBO forecast of improved automotive engines in aircrafts

From previous paragraphs the TBO of automotive engine in aircraft was evaluated. It was also pointed out that it is relatively easy to improve engine life by adopting methods that are already common in the F1 racing field. Every automotive engine has its proper failure behaviour and it weak points. However, automotive companies need a non-catastrophic safe failure mode. The engine should lose power and it should increase the oil consumption. Finally, the EOBD individuates a malfunction and the engine should be overhauled without a full stop of the car. Seizures should be avoided at any cost. For this reason, a few failure mode is common to many automotive engines. Average TBOs of subassemblies are summarized in Table-8.

Table-8. Average automotive subassemblies TBO (km).

Subassembly	Diesel	Gasoline	Failure mode
Valves	250,000	200,000	Power loss
Valve train	500,000	500,000	Seizure
Journal bearings	1,000,000	1,000,000	Seizure
Turbocharger	200,000	150,000	Seizure
Common rail System	250,000	-	Irregular starting
Injection/Ignition	-	200,000	Irregular starting
Spark/Glow Plugs	150,000	80,000	Irregular starting
Liner/rings	500,000	500,000	Power loss

The improved values are summarized in Table-9. These are general values; the specific ones should be evaluated case by case, engine by engine. For example, the material and treatments of valves are very different among engines of the same manufacturer. The type of fuel used has also an influence on the TBO of many components. Therefore, the figures of Table 9 should be taken as purely indicative.

Table-9. Improved subassemblies TBO (km).

Subassembly	Diesel	Gasoline	Failure mode
Valves	1,250,000	1,000,000	Power loss
Valve train	5,000,000	5,000,000	Seizure
Journal bearings	2,000,000	2,000,000	Seizure
Turbocharger	1,200,000	950,000	Seizure
Common rail System	300,000	-	Irregular starting
Injection/Ignition	-	300,000	Irregular starting
Spark/Glow Plugs	150,000	80,000	Irregular starting
Liner/rings	1,500,000	2,000,00	Power loss

Purely indicative, corresponding TBO values are summarized in Table-10. Again, beware to adopt it for an unknown engine, on an unknown aerial vehicle with an unknown fuel.

Table-10. Improved subassemblies TBO ("aircraft h").

Subassembly	Diesel	Gasoline	Failure mode
Valves	4,500	3,600	Power loss
Valve train	18,000	18,000	Seizure
Journal bearings	7,200	7,200	Seizure
Turbocharger	4,320	3,420	Seizure
Common rail System	1,080	-	Irregular starting
Injection/Ignition	-	1,080	Irregular starting
Spark/Glow Plugs	540	288	Irregular starting
Liner/rings	5,400	7,200	Power loss

Table-10 shows that in CRDIDs, with the exception of glow plugs, the TBO is really impressive. Besides, glow plugs are used only for starting at temperature below 0°C. It is perfectly possible to replace these devices with external heaters that are effective down to -55°C. At these extremely low temperatures the main problem comes from the batteries. In spark ignition gasoline engines, the spark plug is the weakest element. However, it can be replaced during field maintenance as glow plugs and injection sytems.

CONCLUSIONS

Automotive engines have outstanding quality controls and extremely high cost-effectiveness. This is typical to lean, mass production. For this reason, the application of these engines on aircraft is most appealing. Ultralight-sport aircraft have pioneered this approach. The level now reached and the experience achieved makes it possible to convert any "successful" automotive engine into an aircraft engine. This paper outlined with the description of the statistical data available from automotive manufacturers. Automotive engines have a huge background of statistical data on performance and reliability and TBO. Unfortunately, the correlation of these data to an aircraft application is not easy. Furthermore, the performance curves obtainable from the converted aircraft engine are introduced.

Finally, an algorithm introduces the residual life to TBO (Time between Overhaul) of the former automotive engine. The method was tested on a few small last-generation CRDIDs (Common Rail Direct Injection Diesels) and spark ignition (gasoline) engines. These engines were also converted for use into small aircrafts with power ranging from 60 to 200HP. This very simple method is implemented directly in the FADEC (Full Authority Digital Electronic Control) or E-ECU (Engine

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Electronic Control Unit) of the engine with very few lines of C-Code (C-Language Code).

It is assumed that the engine undergoes regular maintenance schedule and OBD (On Board Diagnostic) is implemented. OBD is perfectly able to foresee the imminent failure of the accessories like the starting motor, the generator, the turbocharger, the injector(s), the HPP (High Pressure Pump), etc. These parts are external to the engine and can be changed during field maintenance. Accidents, like prolonged under/overcooling, crankshaft damper failure, overspeed are monitored by the OBD and require specific maintenance actions. Ordinary problems like excessive fuel, lubricant, coolant consumption, pressures out of range... are also dealt by the OBD-related service system.

Symbols

Symbol	Description	Unit	Default
rpmcruise	Cruise crankshaft speed	rpm	
Pcruise	Power propeller@ cruise	kW	
Pmax	Max power	kW	
rpmmax	Max crankshaft speed	rpm	
Crpm_cruise	Engine torque required at cruise rpm	Nm	
Crpm_cruise	Max engine torque at cruise rpm	Nm	
Load	Load on engine	-	
FCcruise	Fuel consumption at Pcruise and Tcruise	lxh	
SFCcruise	Specific Fuel Consumption Cruise	g/ (kWh)	
LF	Load Factor	-	
$Fuel_{burnt}$	Fuel burned	l	
$Fuel_{maxratedpower}$	Fuel burned @Pmax	l	
$LF_{automotive}$	LF automotive	-	0.5
$LF_{aircraft}$	LF standard aircraft flight	-	
$TBO_{aircraft}$	TBO with standard aircraft flights	h	
$TBO_{automotive}$	TBO automotive	h	4,000 minimum

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