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COMMON RAIL DIESEL - AUTOMOTIVE TO AERIAL VEHICLE CONVERSIONS: AN UPDATE (PART II)

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ABSTRACT

Back to the 1997 when this activity began, it was generally thought that CRDIDs (Common Rail Direct Injection Diesel) would have completely replaced the piston gasoline engines used in aircrafts within a decade. This fact did not happen for several reasons. This paper tries to individuate these reasons. The more updated solutions to the many problems that almost stopped this application are also introduced. In this second part of this paper engine selection concepts and TBO (Time between Overhaul) are introduced.

Keywords: Diesel Common Rail; conversion; avionization.

RECENT HISTORY OF DIESEL IN THE AERONAUTICAL FIELD

Back in the 80s, VM, an Italian firm, specialized in Direct Injection Diesel (DID) engines, designed a brand new diesel engine. It was a flat engine, like the Continental and Lycoming gasoline piston engines. This engine met difficulties in the approval procedure and could not be used in general aviation aircrafts. Different history for the more recent (1990s) engine that comes from the French diesel school and it is now manufactured by SMA. This engine is aircooled, without PRSU (Propeller Reduction Speed Unit). From the company flier, it has a power of 227 HP and a mass of 206 kg, the power to mass ratio is then 1.1 [HP/kg]. The SFC (Specific Fuel Consumption) is 161gr/HPh. Since the displacement is 5000cc, these data are really excellent. After the extremely successful introduction of the Common Rail Direct Injection Diesel (CRDID) into the automotive market (1997), both Thielert and CRF (Centro Ricerche Fiat) began to develop an automotive conversion of their engines. This brought into the general aviation market the Thielert conversion of the Mercedes Benz Class A 1700cc engine. Finally, after much more work on the engine, also CRF participated company Dieseljet brought its engine on the market. Meanwhile also Austro Engine developed and marketed a conversion of a 2 litre CRDID.

A summary of the performances of these engines can be seen in Table-1.

Table-1. Available aircraft DID comparison. (1)From EASA type certificate. (2) Declared by the manufacturer. (3) Yet to be certified.

	TAE125-02-114	E4	TDA CR 2.0 16V(3)	SR305-230E
Origin	Mercedes Benz Class A (W169) OM640 CRDID	Mercedes Benz Class A (W169) OM640 CRDID	FIAT 2000 Multijet 16V CRDID	- DID
Manufacturer	Technify Motors GmbH	Austro Engine GmbH	Dieseljet Srl	Société de Motorisations Aéronautiques (SMA)
TO Power [kW]	155 (1)	123.5 (1)	160 (2)	169 (1)
Mass [kg]	134 (1)	185 (1)	200 (2)	207 (1)
Power/Mass [kW/kg]	1.15	0.66	0.8	0.81
Crankshaft rpm	3,900 (1)	3,880 (1)	3,800	2,200 (2)
SFC [gr/kWh]	220 (2)	21 [lt/h](2)~191	224 (2)	0.36 [lb/HP](2)~219
Recovery Altitude (feet)	6,000 (2)	10,000 (2)	8,000 (2)	10,000 (2)
Displacement (cc)	1,991	1,991	1,955	5,000

Table-1 outputs curios data. First, the SMA SFC is better than many CRDID. This is a dubious data. Automotive CRDID have usually SFC of 200 gr/kWh in their Euro "0" version. The numbers declared by Technify and Dieseljet are very high and may possibly be the "worst" useful case. This can be the case of full power or at 10% power. At full power the engine may lack of air mass. In this case, the FC (Fuel Charge) is set to a condition before the black-smoke. At low loads the HPP (High Pressure Pump) and the high-compression ratio piston assembly take a lot of power. The SFC of a Euro 6 engine of Daimler Benz is shown in Figure-1. This engine does not use the SCR (Selective Cathalic Reduction) and the Euro 6 emission requirements reduce both efficiency and power by lowering engine volumetric efficiency.

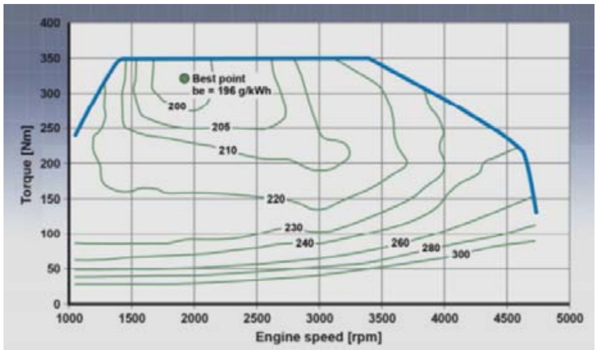

Figure-1. SFC [gr/kWh] of Mercedes -Benz OM 651 DE22 [1].

The BSFC (Best Specific Fuel Consumption) is much lower (better efficiency) than the value declared by Technify and Dieseljet and closer to the values of Austro Engines.

Figure-1 shows the point of best efficiency, designed for maximum gear (6^{th}) and economy motorway speed. Even for this engine, highly penalized by the "Euro 6", the Best SFC area is very large, from maximum torque down to 30% load and up to 77% rpm. The "Euro 0 SFC" of the same engine should be much better with its improved volumetric efficiency especially at high rpm. Air mass flow increment with a larger turbocharger is needed for aerial-vehicle "Euro 0" CRDIDs. However, looking back at the automotive data, the best and last automotive DID of the Fiat Chroma had far less power and had much higher SFC than its successor, the 1900jtd 8V. So it comes the question: why aircraft CRDIDs do not have the same (huge) advantage on the SMA DID?

The reasons of this suboptimal performance of aircraft CRDID are several. Since the automotive experience in terms of bench tests and mileage should be brought to the aircraft field, the aircraft people made the lowest number possible of modifications on the original automotive CRDID. This is not a good strategy since automotive CRDID are optimized for the best SFC/Torque point shown in Figure-1.

AUTOMOTIVE AND AIRCRAFT PERFORMANCE

In automotive engines a mass flow sensor (debimeter) measures the air mass flow toward the engine. In some conditions a butterfly valve partially closes the air flow and the exhaust is recirculated into the intake (EGR). In the case of aerial vehicles the butterfly valve and the debimeter can be eliminated. The air mass into the engine can be indirectly but efficiently measured by the Intake Air Temperature (IAT) and Intake Pressure (or Boost Pressure) sensor. Butterfly valves are installed before the two intake valve ducts. A duct is for the swirl, that is fundamental for efficient combustion and the second duct is for the air charge. The "swirl" duct is optimized for a certain Re, which is correlated to engine rpm. The swirl rate can be controlled by the duct valves. In case of aircraft engines a fixed position is given to these butterfly valves. This position depends on ducts geometry. Another option is to rework the ducts for optimum swirl at 70% rpm with full load. This is the normal cruise condition. Automotive high-production-rate castings can be polished and the swirl rate can be reduced. Often, due to defect tolerance, the valves are slightly smaller than the maximum possible. So valve diameters can be increased. This tuning operation is dangerous since it reduced duct wall thickness. For this reason it is necessary to check if the head is still under the allowable stress level. This should be done with FEA (Finite Element Analysis). Hyping and pressurized checks for coolant seal can also be done on the head. In the automotive CRDID after the turbocharger catalysts and the particle filter narrow the exhaust. These additional "nozzles" produce an additional backpressure at the exhaust.

In Figure-2, it is possible to see the exhaust of the TDA CR1.9 8V from Dieseljet. This engine is a conversion of the FIAT
1, 900 jtd 8V automotive engine.

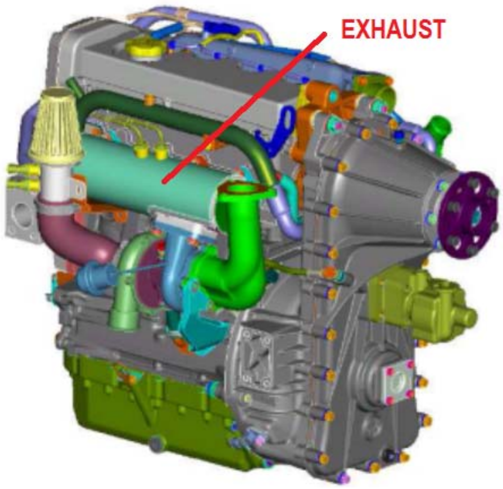

Figure-2. The exhaust of the Dieseljet engine [Diseljet flier].

In the design of a turbocharged CRDID the selection of the most effective exhaust configuration of the turbocharging system is very important. In fact engine performances are affected by the gas flow unsteadiness. In this case the "constant pressure" turbocharging system was chosen. If it is possible, the exhaust ducts should be divergent to reduce velocity and recover pressure. A maximum angle of 7° is advised and a trumpet shape is better. In the "constant pressure arrangement" the fluctuating gas flow from the cylinders is damped so that the conditions at the turbine entry are the most steady possible with time, providing a nearly constant pressure turbocharging. Since the mass flow is relatively constant, high efficiency of the turbine and the compressor is achieved.

TURBO CHARGER (TC) SELECTION

Just by removing the “Euro XX” obstructions in the intake and the exhaust, without even touching the head of the original engine an increase in output power of about 15% may be achieved. This value is limited by the TC performance. In fact this unit is optimized for the best efficiency point and for the turbolag reduction and not for maximum power. Several turbochargers are available from the automotive and racing field. Especially for small output power (< 200HP) commercial TCs lack of boost.

This is due to the fact, that, in order to achieve more power. The intake boost of aerial vehicle conversion may arrive at 4 to 1, with an average value of 2.2:1. These are the usual values for racing application. It is then possible to find in the aftermarket special racing units with increased compressor wheel diameter with improved boost. Another way to improve boost is to enlarge the compressor and turbine casings. However this approach penalizes the weight and it is not convenient. The more the boost, the higher is the recovery altitude (critical altitude). After this altitude power and throttle control are progressively reduced. Over the limit altitude the engine will not ignite any more. Reduced throttle control means that you can reduce throttle to a limited amount otherwise the engine will not recover the rated power for that altitude. This allowable throttle reduction is progressively reduced to zero as altitude increases. To reduce this problem the aftercooler can be bypassed and the intake manifold is thermally insulated. Figure 3 (Austro Engine) shows altitude performance for a few engines.

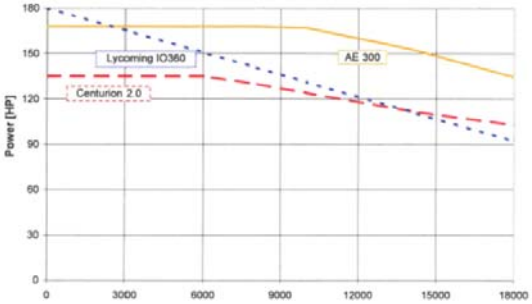

Figure-3. Altitude performance (from Austro Engine Web Site).

From Figure-3 a few evaluations can be made. Since AE300 (E4) recovery altitude is around 10,000ft and a reasonable boost pressure is 2.2bar, the maximum boost of the AE300 (E4) TC may be (3)

$$Boost_{\max} = \frac{\rho_{sealevel}}{\rho_{10,000\,ft}} Boost_{sealevel} = \frac{1.225}{0.904} 2.2 = 2.98 \quad (3)$$

That is a good value for an automotive-derived turbocharger. With specially designed units it is possible to arrive up to 10:1 (Figure-4). With this limit value of boost, it is possible to calculate the maximum single-stage recovery altitude (4)

$$\rho_{\min} = \frac{Boost_{sealevel}}{Boost_{\max}} \rho_{sealevel} = 42{,}000[\,ft] \quad (4)$$

A compressor with such a high compression ratio is not very efficient and it also has a very narrow surge-to-choke area. This means that the CRDID would have problem of TC starting and turbocharger efficiency at sea level. Two stage intercooled turbocharging is then more convenient from 6:1 compression ratio up. The practical maximum single stage recovery altitude is then (5)

$$\rho_{\min} = \frac{Boost_{sealevel}}{Boost_{practical\max}} \rho_{sealevel} = 0.45[kg/m^3] \Rightarrow 30{,}000[\,ft]\,ISA + 0°C \quad (5)$$

6:1 boost usually requires a special turbocharger, specifically designed for this purpose.

Anyway, the turbocharger should be selected from the aerial vehicle specifications and not from the engine ones only.

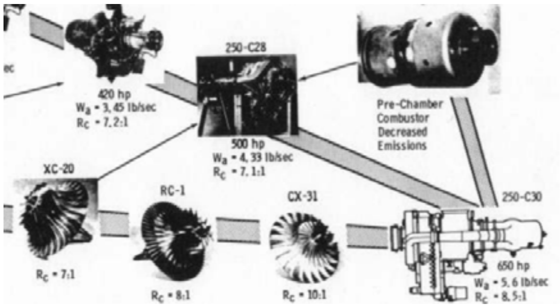

Figure-4. 10:1 compressor. From RR250 development (Rolls Royce).

AUTOMOTIVE CONVERSION CHOICES

Many automotive CRDIDs can be converted for aircraft use. The amount of modification may be kept to the minimum to cut (purchase and development) costs. When you ask to an automotive CDID specialist what is the possible increase in power output, he will likely answer that a 15% is a reasonable value. In fact automotive engines with proper tuning and improved controls on critical components can easily achieve this value. If engine durability is the question, in this case a common method coming from the marine field may be used. Both marine and aircraft engines move a propeller, so, at least in this sense, they are similar.

Table-2. Fuel consumption. (1) Manufacturer data sheet.

Fuel consumption - Austro engine E4	
Max Take Off (100%-123.5 kW)	35.1 lt/h (1)
Max Continuous (92%-114 kW)	31.5 lt/h (1)
Best Economy (73% 90 kW)	21 lt/h (1)
Approach (60% 74 kW)	19.5 lt/h

A typical aviation aircraft work cycle is the following: 100% power will be required for take-off up to about 1000ft AGL (Above Ground Level) (3 min.) where the power will get pulled back to about 92%. Then the plane would climb to about 12000ft MSL (Mean Sea Level) (0.5 h). Then it will cruise for 3 hours at 73% power. Then the power will get pulled back to about 60% on the approach to landing (15 min.). So it is possible to calculate a fuel consumption (Table-2) of 85.38 lt. In a very simplified durability model, an engine has a lifetime that can be measured in weight of fuel burned. You can run that weight of fuel through the engine in a short time period if you are extracting large amounts of power, or you can take much more time to burn the same amount if you only extract small amounts of power. The Load Factor (LF) represents the relationship between fuel burned and the number of hours you are taking to burn it. In this case the flight lasted 3.8h. At max continuous power the fuel burnt would have been 31.5*3.8=119.7 lt. Hence the LF is (6):

$$LF = \frac{Fuel_{Burnt}}{Fuel_{\max ratedpower}} = \frac{85.3}{119.7} = 0.71 \tag{6}$$

A small car used for typical automotive light duty will go for 250, 000 km without rebuild when properly maintained. At average speed (city car) of 28 km/h, this is a TBO=8, 930 h (Time Between Overhaul) The calculated Load Factor (LF) for aviation is 71%, compared to the typical car load factor which is 44% (7)

$$LF_{ratio} = \frac{71}{44} = 1.61 \tag{7}$$

The power ratio is (8)

$$P_{ratio} = \frac{P_{aircraft}}{P_{automotive}} = \frac{114}{102} = 1.12 \tag{8}$$

The aircraft engine TBO will be then (9)

$$TBO_{aircraft} = \frac{TBO_{automotive}}{P^3_{ratio} LF^2_{ratio}} = 2{,}456[h] \tag{9}$$

This TBO is too high for optimum performance. This fact explains the result of Table 1 were the CRDID were not competitive with the SMA DID engine. Let's then validate the equation (9).

From direct experience of the authors, a CRDID of the first generation (Euro 2) was geared up to 150HP from the original 115HP (P_{ratio}=1.3). Then an endurance test was performed and a continuous 500h-full-power test was carried out (LF_{ratio}=2.27). After the test, the engine was taken from the brake in perfect conditions. The tolerances were all within the limit of the manufacturer for a new engine. By using the method described above (6-9) the aircraft TBO would have been (10):

$$TBO_{aircraft} = \frac{TBO_{automotive}}{P^3_{ratio} LF^2_{ratio}} = 779[h] \tag{10}$$

So this method is too conservative. A more probable TBO would have been around 1, 000h. Even with this method, the 15% power increase, would give the following output (11).

$$TBO_{aircraft} = \frac{TBO_{automotive}}{P^3_{ratio} LF^2_{ratio}} = 2{,}254[h] \tag{11}$$

This result is too high for an aircraft conversion, which, after the approval of Authorities, would have a first TBO of 500h to be extended to a normal 1,200h as aircraft hours pile up. The power upgrade is too conservative to maximize CRDID performance, even when the engine is as "automotive" as possible to keep costs down.

PROBLEMS OF CRDID CONVERSIONS: POWER SETTINGS

The main problems of CRDID conversion come from lack of knowledge. The last aircraft piston engines were developed in the 50s. No specific knowledge was available in this field in the 1980, when the conversion activity began. Another problem is the very fractioned knowledge typical of the automotive firm. The "whole figure" of how a CRDID really works is known to a handful of experts that work for large automotive companies. They usually work for large projects for millions of items. The aircraft field is typical of small numbers. The extremely successful Rotax 9XX engines reached the 40,000 items at the Friedrichshafen 2014 Fair event. This success was achieved in several years of production (approximately from 1990). This number is meaningless for the huge automotive development costs that require millions of engines. The interest of the automotive firms is limited. The engineers working in the aircraft field were very efficient, highly specialized men. Often they lacked of the whole figure of the CRDID. This fact is common in the automotive field, where specialization is important to keep the pace of the continuous, daily, improvements.

For this reason some aspects were overestimated. An important aspect is mechanical reliability. Automotive CRDIDs are highly reliable. Statistically, the problems are really very few and they are related to the beginning of the serial production, to accessories or to mistakes of the automatic quality control system. These events are very rare and they are well known both to the manufacturer and to the maintenance people. For aircraft CRDIDs they can be easily avoided. In order to improve reliability and durability, in aircraft CRDID the maximum rpm was reduced from the automotive maximum. This was a mistake, since aircraft CRDID are well cooled (much better than cars) engines that work at the maximum power output for a few seconds per flight at take-off. Automotive CRDIDs are already derated since the maximum rpm is reduced by 15% to avoid catastrophic failures with an extremely high confidence level. 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 office shops are not certified and often maintenance is not made for 100, 000 km. That means more than 3,000 h. In this period only the lubricant and coolant levels are controlled by a fuel station operator. These men change also filters substitution when strictly necessary. The maximum rpm reduction means more mean average pressure. This fact increases the mechanical and thermal stress at the same power level. The result is a reduced power output, a reduced power-to-mass ratio and a less efficient propulsion system. These considerations partially explains why the air-cooled SMA DID is competitive with the much more efficient and powerful liquid-cooled CRDID technology.

HIGH PERFORMANCE AUTOMOTIVE CONVERSIONS

Table-3 summarizes a few special parts developed for aircraft CRDID. The improvement may be substantial with high cost for manufacturing, assembly and testing. This can be easily done in the ultralight market, where it is possible to install experimental engines. In this case the stringent requirements on engine mass and the necessity to achieve high power output to be competitive with spark ignition engine boost the research activity. These CRDID have the advantage to use the much less dangerous diesel fuel.

Table-3. Special parts available.

Engine	Crankshaft	Ti alloy rods	Aluminum alloy crankcase	Light crankcase	camshaft	Journal bearings
Audi V12tdi	x	x				x
Audi V8tdi	x	x				x
Fiat 2000jtd	x	x	x	x		x
Peugeot 1600 HDI						x
Fiat 1300jtd			x	x		x
SmartCDI	x				x	x

AVAILABLE CRDID FROM THE AUTOMOTIVE MARKET

A few CRDIDs from the automotive market are known to the authors: their performances are summarized in Table-4. The Daimler Benz OM640 is not known to the authors but was added to the table for explanatory reasons.

Table-4. CRDIDs from the automotive field. (1) TAE125-02-114.

Engine	Automotive **power** (HP)	Naked **mass** (kg)	Ultimate **power** (HP)	Crankcase	BSFC gr/HPh (Euro 0)
Audi V12tdi	500@4,000rpm	220	900@5,200rpm	CGI	148
Audi V8tdi	327@4,000rpm	195	600@5,200rpm	CGI	148
DB OM640	140@4,200rpm	-	211@3900rpm(1)	GJL26Cr	-
Fiat 2000jtd	190@4,500rpm	114	250@5,200rpm	Cast Iron	152
Peugeot 1600 HDI	115@3,800rpm	92	200@5,000rpm	All. alloy	151
Fiat 1300jtd	95@4,400rpm	105	200@6,000rpm	Cast Iron	154
SmartCDI	54@4,400	63	100@5,200rpm	All. alloy	160

A few comments are needed on the ultimate power concept. Automotive engines have the problem of torque at low rpm. It is the torque that moves the wheels through the transmission. A common optimization point for CRDIDs in the European automotive market is the motorway optimum speed point. This means low rpm, highest gear and standard velocity, for example 2, 000rpm, 6th speed and 120km/h. This condition is particularly unfavorable for the CRDID, since the crankshaft speed is very low, this means relatively low oil pressure and problems of pistons and journal bearing cooling. For the journal bearings the peripheral velocity can be low and insufficient minimum oil thickness may take place. The peak pressure in the combustion chamber in the indicator cycle is near the TDC, usually in the range from 0 to +18° After TDC (ATDC). Inertia loads are very low and they subtract a little amount of the pressure loads induced by piston and rod at the TDC (Top Dead Center). The peak pressure load on piston and crank assembly are then at the maximum possible. In aerial vehicles this low torque low rpm point never happens since the propeller load goes in a quadratic way. In the automotive field the optimization is aimed to best efficiency during transient. This result is obtained through optimum compactness of the TC, the installation and the after cooler. Minimum sizing or under sizing is fundamental. Short ducts, small volumes are used so have immediate throttle response, more room and lower costs. From this world only the heat exchangers are really useful for the aerial vehicle field, since they are very small, efficient and reliable. Piping, fittings, TCs.... are usually too small or of insufficient quality to be used in a world where a failure means a forced landing. The other important aspect is the rpm and load range. In the case of aerial vehicles the used range is from 50% to 100%. The aerial vehicle uses full output power at every take off, the car, in many cases never needs it. In a few model of sport car, the ECU (Electronic Control Unit) had a memory to record the load history. For a few car models, produced in thousands of item, the maximum power was never reached by any car and any user. In Figure 5 it is possible to see the Automotive Torque and the Aircraft Torque for the same engine.

As it can be seen the automotive engine has high torque at low rpm. The air-engine has a larger turbo. This turbo is not working at low rpm and starts to work properly at 50% of the maximum rpm. From this point on the power output is acceptable. Near the maximum rpm, the injection starts to cut. In the automotive field, a 15% increase in design rpm from the maximum requirement is usual to obtain the required reliability level. The air engine is checked thoroughly and the balancing is done to the best possible. Pistons and rods are reworked and polished to achieve better performance. Rods may be replaced or may be treated to improve fatigue life. For all these reasons the aircraft engine has an "ultimate" maximum power higher than the automotive one.

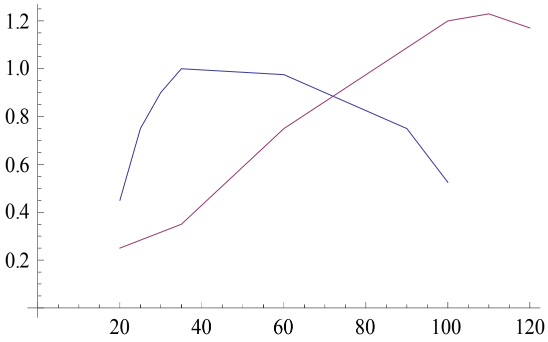

Figure-5. Automotive Torque vs. Aircraft Torque for the same CRDID. X-axis Torque/Automotive Torque. Y-axis rpm/rpmAutomotive-axis Torque/AutomotiveTorque. X-axis rpm/rpmAutomotive.

Intake and exhaust manifold are usually replaced and all the parts not strictly necessary are removed. The engine "naked" of Table 4 is the engine without accessories and turbocharger. The SFC are similar, with the exception of the one derived from the Smart CDI, that has, in this case, the maximum relative increment of output power. This is paid by a small penalty in SFC (Specific Fuel Consumption). In a few cases also the crankshaft and the camshafts are replaced. The head is also tuned up, with larger valves, polished ducts and re-worked swirl-ducts. The intake duct valves are also set in a fixed position for maximum power. Additional treatments are made were necessary for improved wear resistance. Just as a first approximation the output power of an aircraft conversion can be evaluated with (12):

$$P\max = \frac{T_{\max Auto} e \pi n_{\max} f}{30} \tag{12}$$

Where $T_{maxAuto}$ is the maximum torque of the automotive engine, **e** is a factor that takes into account that the conversion from Euro 5 to Euro 0 makes it possible to eliminate several pressure drops in the air-exhaust system of the engine. In particular the debimeter, the intake butterfly valve, the catalysts and the particulate filter can be removed. ***e*** can be around 1.15 (15% increase in torque) in many engines. *f* is the factor that takes into account of the possible increment in the maximum crankshaft speed. A reasonable value may be around 1.15 (15%). Table 5 summarizes the values calculated with (3) and the ultimate values. Just to be clear, these ultimate power values have to be reduced to take into account of several factors, among which the fuel is the most important, with cetane number and density variations.

Table-5. Summary of results of (1).

Engine	**Automotive power** (HP)	**Calculated with** (3) **HP**	**Ultimate power** (HP)	**Error**
Audi V12tdi	500@4,000rpm	842	900@5,200rpm	-6%
AudiV8tdi	327@4,000rpm	547	600@5,200rpm	-9%
Fiat 2000jtd	190@4,500rpm	336	250@5,200rpm	+34%
DB OM640	140@4,200rpm	237	211@3,900rpm	+12%
Peugeot 1600 HDI	115@3,800rpm	182	200@5,000rpm	-9%
Fiat 1300jtd	95@4,400rpm	187	200@6,000rpm	-6%
SmartCDI	54@4,400	92	100@5,200rpm	-8%

So, even with this extremely simplified method, the results are acceptable, with the exception of the FIAT 2000jtd. It should be noted that tests are to be carried out and "weak" components should be detected. It is a good rule not to remove a working engine from the brake just to send it to the wrecking yard. Failure in CRDIDs may be tricky; in fact thermal fatigue may reveal the damage at the successive start up. From Table-4 and Table 5 it is possible to see that all the CRDID approved by the Authorities for General Aviation are far from the ultimate power value achievable by the engine.

CONCLUSIONS

The Euro 6 CRDID cannot be better of a Euro 0 one in terms of power and efficiency. For several reasons the available CRDIDs available on the market for general aviation appear to be underpowered and with a suboptimal SFC. This paper tries to explain the reason for this performance. The aircraft engineers didn't “dare” enough, overestimating aircraft stresses. The TC availability also conditioned the maximum power obtainable.

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