TURBOMATCHING OF SMALL AIRCRAFT DIESEL COMMON RAIL ENGINES DERIVED FROM THE AUTOMOTIVE FIELD

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ABSTRACT

Common rail automotive (Direct Injection) Diesels (DID) are always turbocharged. This engine works at limited altitude and should output torque at low rotational speeds. Not so for engines that work coupled to propeller and fans. This is the case of aircraft and helicopter engines. In this case it is important to have high output power at high rpm and to keep throttle authority and power at the higher altitude possible. Some basic concepts to achieve this result are introduced in this paper. Single turbocharging systems are introduced and an option to improve the altitude performance is discussed. Far from being exhaustive, this paper is an initial step in the long and awkward technology of turbocharging automotive-derived engines. The basic concepts for efficiency are also discussed.

Keywords: Common rail automotive Diesels (DID), turbocharging.

INTRODUCTION

Density of air decreases with gain in altitude. At an altitude of about 20, 000ft (6, 100m) in the International Standard Atmosphere (ISA) the density of air is reduced to half of what it is at sea level. An aircraft in climb would experience a lower mass of air entering the cylinders; the result is a decrease in the ouput power of aircraft engine. Without working on the turbocharging, a DID lose 50% of its sea level power when at 20,000ft. For DID this problem may render ignition impossible with an engine full stop. Hot restarting may be also impossible.

This paper introduces some concepts behind turbomaching the modern common rail DIDs, and the advantages it gives us in performance at high altitude. Almost all the modern common rail DIDs are already turbocharged since automotive manufacturers are looking for high torque at low rpm and high power output. The air flows through the cylinder head, from the induction system to the exhaust system and then out into the ambient again. In single turbocharger systems, the induction system is composed by the air intake, the air filter, the compressor ant the aftercooler. As altitude reduces the air density it is possible to recover it by increasing boost pressure. This is normally achieved by increasing the turbocharger rotational speed. The altitude at which the nominal boost pressure can be maintained is called recovery altitude. Up this Flight Level (FL) the engine will output its original output power with a small increase of Specific Fuel Consumption (SFC) due to the increased compression work. From the recovery altitude up the DID engine will not only lose power. It will also lose the possibility of starting (not only cold starting, but also hot restarting) and the possibility of full throttle authority. So for modern turbocharged common rail DIDs five altitudes are significant. Recovery altitude (1) that is the altitude at which the engine maintains nominal full power and full throttle authority. Starting altitude (2) that is the altitude at which the engine can be started-up (hot starting). Full throttle authority altitude (3) that is the altitude at which the throttle can be freely used. From this altitude up the throttle must be kept to "continuous full". The engine will continue to run with an output power that decreases with altitude. Maximum altitude (4), that is the altitude at which the engine will continue to run (ignite). These four altitudes are meant for ISA (ISA+0°C) conditions. Offsets from this conditions define different altitudes. A common temperature envelope is (ISA-50°C)-(ISA+20°C). This means (-35°C)-(+35°C) at sea level. So an engine will have 3 sets of 4 altitudes, a set for the minimum temperature (for example ISA-50°C), a set for nominal conditions (ISA+0°C) and a set for maximum temperature (ISA+20°C). The performance (power and torque vs rpm) will be surfaces with the 3rd direction being the altitude. A family of this surface may be drawn with altitude.

Turbocharging concepts

Turbocharging runs off what is largely wasted energy; exhaust energy is given by Temperature and Speed. By keeping the speed constant it is possible to write:

$$TPR = pt5 / pt4 <= 1.0 \quad (1)$$

$$Tt5 / Tt4 = (pt5 / pt4) \wedge ((gam -1) / gam) \quad (2)$$

$$TW = ht4 - ht5 \quad (3)$$

$$TW = cp * (Tt4 - Tt5) \quad (4)$$

$$TW = nt * cp * Tt4 * [1 - TPR \wedge ((gam -1) / gam)] \quad (5)$$

So the wasted exhaust temperature Tt5 can be converted to energy (5). The drawback is the back pressure *pt4* that is increased by turbocharging. Usually inlet manifold pressure is higher *pt3* is higher than *pt4* since compressor efficiency is usually lower than turbine efficiency. When EGR (Exhaust Gas Recirculation) has to work it is necessary that *pt4>pt3* in order to permit a flow from the exhaust to the intake. Usually EGR is necessary in cars for emissions. This condition always takes place at reduced power output. In aircrafts and helicopter EGR may be used to accelerate the warm up time that is critical for DIDs. In fact this very high efficient engine usually run at idle with natural cooling (no radiator fan is necessary) and the thermostatic valve in the cooling system is strictly necessary. The lowest the compression efficiency the hottest the air to the inlet manifolds. This hot air introduced in the engine also increases the engine temperature ant the thermal stresses. These drawbacks are countered by charge-air cooling, which passes the air leaving the turbocharger through a heat exchanger called aftercooler. This is done by cooling the charge air with an ambient flow of either air (air-air intercooler) or liquid (liquid-to-air intercooler). The drawback of inter/aftercooling is its mass and volume of the cooler along with the associated plumbing and piping. This also reduces reliability and increases turbo-lag. The "turbo lag" drawback is that engine response suffers greatly because it takes time for the turbocharger to come up to speed (spool up). However, this delay in power delivery is negligible in aircraft/helicopter applications since fan/propeller inertia is the main "lag factor". However in aircrafts and helicopters also air temperature decreases as altitude increases. Since DID ignition depend on the exponential of 1/T (see (6) [1]), it may be necessary to bypass the aftercooler at high altitude, just to keep the engine working. T is the chamber temperature as the fuel is injected.

$$\tau_{ign} = 0.44 P_o^{-1.19} \exp\left[\frac{4650}{T_o}\right] \quad (6)$$

Compressors

The compressor field is dominated by centrifugal compressors. The advantages of centrifugal compressor are: good off-design performance, wide volumetric-flow range (from the surge to the choke lines) and low manufacturing costs. The main drawback is adiabatic efficiency that is typically below 80%, while axial compressors may reach 88%. Rotational speeds may be as high as 350,000 rpm. Centrifugal compressor air flow varies with an approximately quadratic law with rotational speed. It doesn't have a reliable airflow amount based on any engine RPM, because it's very design only flows air efficiently at high turbocharger RPM. On the other side it is the turbine that "controls" compressor rpm. Also the turbine power output follows a quadratic law with exhaust volumetric flow. The turbine starting condition is a "threshold difference" between turbine inlet and outlet. If the turbine is too big for the engine, the turbocharger shall not start at all, or will run at so low rpm to be detrimental to engine power output. On the other side if the turbine is too big, it will accelerate in very short time, up to a value where the velocity are so high and efficiencies so low that it will stop "naturally" or saved from exploding by the wastegate or by FADEC (Full Authority Digital Control. The FADEC may reduce fuel charge to avoid this situation. It should be noted that turbochargers manufacturers always perform containment tests to avoid physical dangers in case of turbines or compressor explosion. The situation of very small turbochargers is common in the automotive field where turbolag should be contained and high torque at low rpm is required. So although centrifugal compressors are very efficient at high RPM, they are ineffective at creating meaningful boost at lower RPM. This concept is called surge limit, or the point in the airflow vs. pressure map where the compressor can no longer flow air into the system. The other limiting is the chocking line (right side) where compressor cannot elaborate a larger air flow.

Turbine to compressor matching

On the theoretical point of view, the matching of the turbine and the compressor is easy. Equations (7), (8), (9), (10) and (11) hold

CPR = pt3 / pt2 >= 1.0 (7)

Tt3 / Tt2 = (pt3 / pt2) ^ ((gam -1) / gam) (8)

CW = ht3 - ht2 (9)

CW = cp * (Tt3 – Tt2) (10)

CW = (cp * Tt2 * (CPR ^ ((gam -1) / gam) - 1))/nc (11)

Then it is necessary that the TW=CW, however, since a bearing assembly is present, and the bearing efficiency is not negligible, the "power balance" equation turns to TW*nb=CW.

In the true work the problem is not so easy. In fact, compressor and turbines maps are made by measurement of a few points and the other are interpolate, incompatibility problems may coming during testing of the turbocharger group. Turbine should be "larger" than compressor since the turbocharger should accelerate. However a too larger turbine may arrive at its limit too soon and will limit compressor performance. Other problems come from compressor and turbine casings geometry and volumes. The turbocharger should work in a wide range of temperatures of intake and exhaust. Bearing efficiency is not constant and depends by several factors. Turbocharger dynamic map is not the turbocharger static map; numbers from mono-dimensional simulation never truly match true engine performance. For these reasons, it is better to use well known, widely diffused and well proven turbochargers. They should be used as an assembly, concentrating the work on compressor efficiency and engine matching, avoiding further problems that may require data that are not commonly available and that are difficult to obtain. The only operations that can be easily performed are changing on materials of wheels and casings, in order to obtain better temperature performance (titanium alloy compressor) or lighter unit (Inconel sheet welded turbine casing). However, in this case, resonance tests on shaft and containment tests should be performed.

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The turbochargers chosen for an automotive engine rarely is adequate for aircraft or for helicopter use, as it can be seen in Figure-1. The data for the automotive use (blue color) come from a presentation of Cummins about "vehicles" [2]. The same data for cars are to be moved on the left side. The more powerful the car is the more on the left it moves. The data for aircrafts (red color) come from the Flight Manual of the Cessna 172 "Skyhawk" equipped with Lycoming IO-360 engine. Helicopter engines work all the time at nearly constant rpm and variable load. For aircrafts there is no reason to have high torque at light rpm, since propellers and fans absorb energy with a quadratic law with rotational speed (crankshaft speed). Propeller and fan acceleration can't be very fast since inertia is high. This is an advantage for engines. In fact speed means good lubrication of bearings; the high inertia forces on piston reduce the peak load of combustion, reducing the overall load on crankshaft. So it is usually possible to improve the engine output from the "original automotive" value. Another important factor is emissions. Modern automotive engines are designed for emissions. This stringent requirement means EGR (Exhaust Gas Recirculation) and important restrictions especially on exhaust (Catalysts, Diesel Particulate Filter (DPF), Throttle…). Aircraft and helicopter do not need to meet this requirement. More, they worked in "fixed" point condition. To improve SFC at these points it is necessary to work efficiently, with a "weak" mixture, this means efficient combustion and low emissions. However, on "fixed points emissions", a whole paper can be easily written. Just by eliminating all these nozzles on intake and exhaust, it is possible to improve the performance, if the new points are inside the compressor (and turbine) map(s) and are in the "high efficiency" areas. So an automotive and aircraft conversion should always output a more performant engine.

Component optimization

In the intake to exhaust ideal chain each component should be optimized for performance, the first is the air intake and the filter.

Dynamic air intake (RAM air intake)

The ram-air intake is designed to transform the intake air kinetic energy into pressure. This is obtained by increasing the cross-sectional area of the intake ducting. From the Bernoulli's Law, when gas velocity goes down the pressure inside the duct is increased. The increased static pressure in the plenum chamber has a positive effect on the compressor, both by moving the chocke line to the right and also by the improvement on the total pressure ratio CPR. However the energy recovered depends linearly with air density, so the amount of pressure recovered should be evaluated. In fact ram air intakes are difficult and expensive to realize and the net result is brilliant only if the design is optimized and the manufacturing is accurate. The ram air intake of the Messerschmitt Bf109G has a drag of 0.71% of the total of the whole airplane [3]. This airplane was optimized during several years of work including tests in the full wind tunnel in Chalais-Meudon near Paris, just after France was occupied by the germans during WWII (1940). So of the 1475 HP of the Daimler Benz 605 engine, more than 10 HP were lost due to the air intake drag. Another example is the Ferrari 312T that suffered from a significant drag due to the ram air intake (see Figure-2). The same air intake boost pressure was obtained through the two Naca air intake in the front (see Figure-3) with negligible additional drag due two the air intakes. This optimization was performed in several tests and hours in the wind tunnel and on practice tests.

Figure-1. The Ferrari 312 T ram air intake.

The designer, Ing. Mauro Forghieri, it still wandering whether the performance result was worth of the amount of work.

Figure-2. Ferrari 312 T2 with NACA ram air intakes.

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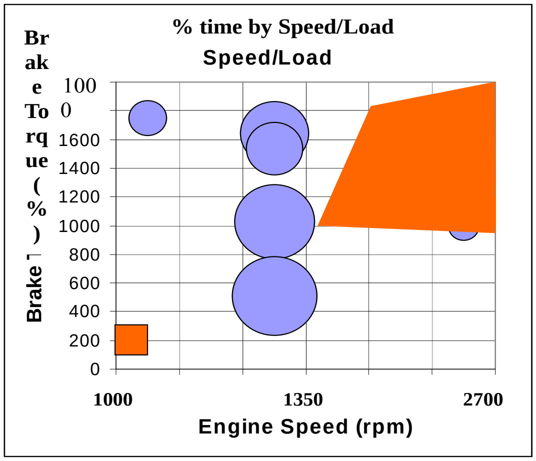

Figure-3. Differences between automotive (blue) and aircraft use (red).

However ram air intakes have a drag and an additional weight, since an alternative intake with a proper air filtering for operation near ground level is still necessary. Also the icing problem should be considered. Air filter are not a huge problem. A modern multiple-layers oiled-cotton fabric filter can captures the airborne dirt particles. These dirt particles cling to the fibers of the filter and actually become part of the filtering media. This depth-loading process allows modern air filter to retain significantly more dirt per square inch than a paper filter with an efficiency of more than 96% for particles 10 to 20 microns in size. Conically shaped commercial filters fit perfectly the air compressor intake. Icing problems are absent due to the vicinity of the engine. Even if not ideal, this solution is efficient and lightweight. The only notable exception is for helicopters that operate near the ground in a very "dusty" environment like a sand desert. In this case the filter clogs in short time quickly reducing the air flux and the output power. In this case a more efficient filtering system should be used with cyclonic type pre-cleaners.

Materials

In aircrafts and helicopters, high pressure single-stage turbocharging usually requires expensive materials as titanium alloys on the compressor side. Also the other turbocharger components too, such as the turbine, bearings, shaft seals, the casings and their connections, are exposed to higher thermal and mechanical stresses as a result of the pressure ratios being far higher than those of common automotive turbochargers currently on the market. By using the available Finite Element Analysis (FEA) and Computational Fluid Dynamic (CFD), it is now possible to verify whether the commercial unit can substain the different working conditions. The advantage of using titanium compressors is without doubt the fact that no additional structural measures for cooling are needed. However, the big disadvantage is the substantially more difficult material from the fatigue point of view. In this case hot hyping is required. In many cases it is possible to increase the rotational speed of 15%-20%. In this way the maximum pressure is improved along with altitude performance. It is also possible the use of optionally coated parts, that may improve performance. Today centrifugal turbocharger use both ball bearing and plain bearings, supported by a squeeze oil damper in the bearing flanges. Plain bearings remain the most reasonable option in terms of costs and operational reliability [8] also for the new high-pressure turbochargers. An improved balancing and an accurate assembly upgrade the turbocharger unit to the maximum performance level reasonably obtainable. CFD simulation makes it possible to estimate the new part of the map that is not available.

Compressor maps and turbocharger choice

Even if a 1D simulation of the engine has to be performed, a first analysis of the compressor maps available should be performed. Compressor maps are usually interpolated by the manufacturer from a few experimental points. Compressor characterization is an expensive steady state activity. They are performed on prototypes whose quality may be better than the production one; also air gaps are huge problems, so do not aspect that (turbo) compressor to be perfectly repetitive with different "identical" parts and with wear. Compressors work with volumetric air flow while maps have a mass air flow on the x-axys. In fact it is a normalized volume air flow at the manifold pressure and at the reference temperature. It is the mass flow you should have in the intake manifold at the pressure (ratio) indicated on the y-axis and at the reference temperature chosen by the manufacturer. Correction formulas are indicated by the manufacturer (Garrett) for different manifold temperatures (12) (13).

$$PR = \frac{Boost + Pi + Pa}{Pa - Pf} \qquad (12)$$

$$CFR = \frac{(EngineCC/16.39) * (RPM/2) * VE}{1728} * 0.069 * PR * \frac{\sqrt{(AAT/545)}}{AP / 13.95} \qquad (13)$$

In order to use the KKK compressor maps, CFR should be divided by 132 to convert from lbm to kg/s.

CFR is a normalized volumetric air flow. So if you increase the filter pressure drop, you will move the CFR point on the right hand side, to an increase of the normalized mass flow, obviously not of the true mass flow. This is due to the fact that the "true" natural diagram should be: volumetric flow on the x-axis and pressure ratio on the y-axis. The installation of a nozzle, a filter or a butterfly valve increases the volumetric flow and shifts the maps on the right hand side.

The choice of the turbocharger is made on the compressor map. For any turbocharger the rule is the smallest the better. The compressor map is always too small. For this reason it is better to choose a variable Variable Geometry Turbocharger (VGT). The VGT is mapped in the FADEC. The variable geometry of the turbine has the effect to widen the map on the x-axys. It should be stressed that turbocharger efficiency is important for overall engine efficiency. For example a 2000 cc DID, that has a VE=0.8 and a maximum manifold pressure of 1.6bar will elaborate a volumetric flow of 0.054 m^3/s from the intake manifold to the cylinders. If the intercooler cools down the air down to 50°C and ambient temperature is ISA+0 sea- level (15°C) the volumetric flow at the air filter is 0.076 m^3/s. If the compressor has an adiabatic efficiency of 0.7, the compression work is around 6 kW. At 5000m ISA+0, the density reduction is 40%. The PR to restore manifold pressure is around 3. The power required by the compressor is around 10 kW. So it is very important to start from the cruise point. It should be in the region of maximum efficiency. Another important point it the take off point that not only should remain inside the map, but should be sufficiently inside to allow the acceleration of the turbocharger up to the required pressure level even at very lowest take off temperature. High altitude take off should also be considered. Looking around at all the flight envelope a first idea of a few "best turbochargers" can be individuated. After the full rpm envelopes have been checked, the 50% rpm envelope should also be controlled. When the turbocharger set is reduced enough, 1-D simulation of the whole engine should be used. In Figure-4 it is possible to see the working point (red point). At the maximum take off altitude (1850m) and minimum temperature (ISA-50C). This is calculated for the Fiat 1300jtd engine, with a PR of 1.6. The purple and blue point indicate the full power points at minimum (ISA-50C) and maximum temperature (ISA+35C) at the maximum design altitude (5000m). It should be noted that the choice is far from ideal, since it is probable that the turbocharger will face problems to start at take off and it is always working in the low efficiency areas of the map. Another problem will be throttle authority at medium altitude especially in cold days. The blue point is far outside of the map, may be in the choke region. This fact should be checked, along with the possibility to increase the maximum turbo rotational speed.

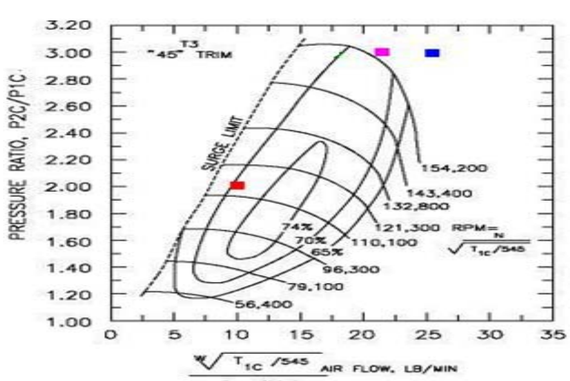

Figure-4. Full power points at maximum take off level (ISA-50) (red) and maximum altitude (purple (ISA-50), blue (ISA+35)).

Power rating considerations

Since no torque is required at low rpm, it is important only to consider the working points from 50% to 100% throttle. In FADEC controlled modern DIDs, idle condition is not critical. An ad-hoc algorithm keeps the engine running at the preset rotational speed. At full throttle and full rpm the the inertia forces contrasts the gas pressure. Crankshaft and rod bearing are not so stressed as in the automotive application (high torque, low rpm). The piston suffers of multiple loads, but it is well cooled by the abundance of air present. Euro 6 condition are not to be met and maximum power can be increased significantly. In modern engines with variable intakes, it is possible to lock the vanes at the minimum turbulence position, that it is optimum for maximum power output. A larger turbocharger can be installed; this will shift maximum torque upwards and improve maximum power output. This process also improves the SFC in the aircraft work area. By a careful choice of the turbocharger and an especially "weak mixtures" it is possible to reach values below the common automotive of 150 gr/HPh (203 gr/kWh). Values down to 136 gr/HPh (184 gr/kWh). The SFC common rail curve is almost flat up to the maximum power output. Altitude do not affect this Figure, since the energy at the exhaust is far to be fully utilized.

CONCLUSIONS

An important factor in the conversion of automotive common rail DIDs to aircraft/helicopter application is the optimization of the turbocharging system. In this paper the correct choice of the turbocharger has been considered. Turbolag is not important in aircraft applications, since propeller or fan inertia delay significantly the response time of the engine. For this reason a larger diameter, higher pressure turbocharger can be adopted. This turbocharger may use a titanium alloy compressor. A VGT turbocharger is the best choice to optimize engine performance in the wide working region. A well dimensioned or over dimensioned aftercooler should be used to keep air charge as cool as possible. As altitude increases the air becomes thinner and colder. The increase of turbocharger speed may compensate this fact up to the recovery altitude. In order to operate with full or partial throttle control at higher altitudes, it becomes necessary to increase the performance of commercial turbochargers. This is possible to a limited extend and requires to work on the turbocharger unit, both by improving material quality (hot hyping) and by increasing the balance level. Even by choosing the best solution possible a single unit turbocharging system is far from ideal for aircraft and helicopter performance.

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Symbols

Symbol	Description	Unit
TPR	Total turbine pressure ratio	-
Pt4	Turbine inlet pressure	Pa
Pt5	Turbine outlet pressure	Pa
Pt3	Manifold pressure	Pa
Tt4	Turbine inlet temperature	K
Tt5	Turbine outlet temperature	K
ht4	Turbine inlet specific stagnation enthalpy	J/kg
ht5	Turbine outlet specific stagnation enthalpy	J/kg
TW	Specific turbine work	J/kg
cp	Specific heat	J/kgxK
nt	Turbine adiabatic efficiency	-
gam	Specific heat ratio	-
τ_{ign}	Ignition delay	ms
p_o	Combustion chamber pressure	MPa
T_o	Combustion chamber temperature	K
Pt2	Compressor inlet pressure	Pa
Tt2	Compressor inlet temperature	K
Tt3	Compressor outlet temperature	K
nc	Compressor adiabatic efficiency	-
CW	Specific compressor work	J/kg
CPR	Total compressor pressure ratio	-
nb	Turbocharger bearings efficiency	-
Pa	Ambient pressure	Pa
Boost	Boost gauge pressure	Pa
Pi	Aftercooler+intake-duct pressure loss	Pa
Pf	Filter pressure loss	Pa
CFR	Corrected Flow Rate (Garrett)	lbm
EngineCC	Engine Displacement	cc
VE	Engine Volumetric Efficiency	-
AAT	Absolute Air Temperature	°F+460
AP	Ambient Pressure	psi