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DIESEL ECU MAPPING OPTIMIZATION FOR AIRCRAFT AND HELICOPTER APPLICATIONS

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Abstract

Starting from a good automotive engine is always a good idea, also for brand new automotive design. In the case of automotive to aircraft conversions, the automotive engine is modified as little as possible. This approach has several advantages: reduced development time, good reliability and availability of cheap and worldwide spare parts. What it may appear a good idea is to tune up the original ECU (electronic control unit) by using one of the several softwares available on the market. However, this approach is not feasible even for ultra light aircrafts. This is due to the lack of control on the software of these ECUs. In fact, automotive software timing or ECU set-up is performed in the following way. The final ECU manufacturer (who holds the responsibility of the hardware and the software in the final car ECU) supplies to the car manufacturer a "development ECU" with a "development Software". This system is tuned on the engine and on the car to fulfill the car manufacturer requirement. When the tuning is considered satisfactory, the "maps" (the data inputted by the manufactured) are given to the ECU manufacturer. This later translates the data into the software of a "production ECU", that is given back to the car manufacturer for final validation prior to serial production of

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ECU and car. In this case, even the car manufacturer does not have a full control of what happens inside his ECU. This is logical since the full responsibility is given to the ECU part supplier. So the tuning of a serial production ECU is more than a true programming. Results are unpredictable to a certain extent that depends on the level of knowledge of the person who performed the tuning and of the software house that implemented the software. The software that truly runs on serial production ECU is a well kept secret of the ECU manufacturer, since it is the knowledge of ECU. The simpler is the software the less expensive will be the ECU and the larger the profits of the ECU supplier. Tricks are hidden inside the ECU to obtain these results; these tricks multiplied per millions of ECU give the supplier a competitive advantage.

So, even the car manufacturer has a limited control on what happens inside the real-time software of the ECU, what emerges is the engine and the car behavior. Aircraft conversions require the replacement of ECU, wirings and sensors with appropriate units. This assembly with its own software constitutes the aircraft FADEC.

Symbols

Symbol	Description	Unit
τ_{ign}	Ignition delay	ms
p_o	Combustion chamber pressure	MPa
T_o	Combustion chamber temperature	K

1. Introduction: Sporting or Aircraft FADEC Units

For this purpose, it is possible to use an airborne FADEC for CRDID (common rail direct injection diesel) or a unit that comes from the racing field. The main advantage of airborne FADEC is that they are already thought for certification. However they are usually less reliable than professional racing FADECs. The reason is simple: a racing car that has a FADEC failure has lost the race. The team requires “Absolute” reliability. The race is composed by several, very excited phases. Each one requires flexibility and reliability. Problems always arise at the worst moment and should be solved immediately. So a racing FADEC is stressed several time in a year by several cars. It may face the problem of a whole aircraft life in a single season. Another very important point is the “quality” of the professional that work on the racing FADEC. Usually they are the very top; the ECUs of any car currently manufactured derived from the racing experience. That experience dates back into the ‘70.

However, it is perfectly possible that your sporting FADEC cannot be certified. Certification means that the HW and SW manufacturer are willing to help you in the certification process. In many cases it is not the case of sporting FADEC manufacturers.

The certification process is just a serial check of performance in several well-known and well programmed tests. Having surpassed these tests does not mean to be reliable; reliability is given by cycles and failures. Another important problem is the mass. Due to EMC problems, aircrafts FADEC may be heavy. It is perfectly pointless to save 2kg in a 95kg engine, just to put on it 6kg of FADEC, as it was recently the case of an automotive DID conversion.

2. Time Scheduling

Timing scheduling is only as good as the hardware and installation. A $+/-5$ degree discrepancy in desired vs actual timing means that your engine is performing and breaking down in an uncontrolled fuzzy way. Normal accepted values are 1/10 “crankshaft degree” and many designers require an order of magnitude less. Cylinder pressure transducers are often the answer to improve performance and efficiency, and they are well worth the expense.

The concept of DID is that this motor relies on a less precise mechanism of ignition than spark, also known as autoignition. As air inside the cylinder is compressed, it heats up to 600°C before combustion even begins. After the combustion temperatures can very briefly reach $T_1 = 3000\text{K}$. This means that the Carnot Cycle reference efficiency η_c is extremely high (1). In formula

(1) the room temperature $T_2 = 288.15\text{K}$ is ISA+0°C (international standard atmosphere) sea level.

$$\eta_c = \frac{T_1 - T_2}{T_1} = \frac{3000 - 288.15}{3000} = 0.9. \tag{1}$$

This is the reason of the very good efficiency of CRDID that can easily exceed 50%. For high efficiency, the maximum temperature should be kept as high as possible. Since engine durability depends on average temperatures, while efficiency depends on maximum temperature and high temperature peak is highly desired.

The Ideal Gas Law (2) can be rewritten for Vcc (volume of combustion chamber). Formula (2) links temperature and pressure together:

$$p_{peak}V_{cc} = RT_{peak}. \tag{2}$$

The pressure p_{peak} that is the maximum design pressure should be obtained for as many engine cycle possible, in order to keep the engine efficiency at its maximum. By the way, this condition improves also combustion efficiency. This result should be kept for any boost, any altitude, any load and any ambient condition. This is the aim of optimum mapping for aircrafts and helicopters. In the automotive case, the aim is also the fulfillment of pollution requirements that are often in contrast with efficiency. High temperatures in facts, means high NOx, that are severely treated by US and EU normative. With SCR (selective catalytic reduction) the situation has changed even in the automotive field, since high temperatures are favorable to the reduction process.

In the 180 degree compression stroke, the final 30 degrees of rotation adds the same amount of heat as in the first 150 degrees of rotation.

Once it is compressed somewhere near the top dead centre (TDC), the ECU commands a time-defined precisely-measured shot of micron-sized diesel mist under pressures up to 2300 bar. As this finely atomized liquid fuel enters the hot chamber, it quickly begins to evaporate.

Only at this point, the autoignition takes place, since liquid diesel is not combustible (not to be confused with "flammable").

The duration of the combustion depends mainly on properties like cetane and macro physical properties, such as atomization quality, cylinder temperature, and the final air charge temperature.

Some petroleum-based fuels, like gasoline and ether, can autoignite at very low temperatures (under 200°C). With these fuels, it would be possible to ignite at more than 50° before TBC (BTBC). However, this would overstress the crankshaft piston assembly.

By boosting just 1.4 bar, it is possible to more than 100 bars to chamber pressure.

So increasing boost has enormous consequences on ignition timing. Timing is calculated best by angle and rpm than speed. In fact an engine that rotates at 3000rpm will make 50 revolutions every second. In 0.002s, therefore, the piston goes through 36 degrees.

In that same 36 degree injection event, there may be a 300°C air temperature increase. As fuel is injected, it atomizes and evaporates as it moves away from the injector nozzle. Evaporation also means evaporative cooling. In general, the fuel-air ratio is high near the nozzles tip and low away from it, but the fuel-air ratio does not change uniformly within the cylinder. As the fuel vaporizes into the hot compressed air, it starts to oxidize. As more fuel vaporizes and mixes with air, the number and rate of the oxidation reactions increase in a chain reaction, until the end of the ignition delay period. This time can be evaluated by the "historical" equation from Wolfer [1] correlation is as follows (3):

$$T_{ign} = 0.44 P_0^{-1.19} \exp\left[\frac{4650}{T_0}\right]. \qquad (3)$$

Equation (3) shows that the delay in exponentially proportional to the temperature. The dependency from pressure is less important.

In the premixed combustion phase ignition occurs at many locations independently and combustion propagates very rapidly in regions, which have fuel-air ratios in the combustible range. At typical full-load operation, this initial combustion consumes about 5% to 10% of the fuel used by the engine. Injection continues and fuel continues to vaporize and mix with air, aided by the heat release and turbulence generated by the initial combustion and by the high swirl in the combustion chamber. This quickly generates more gas with the required fuel-air ratio and combustion continues with exponential law. In the mixing controlled phase the remaining fuel should be consumed before partially oxidized droplet meet the “cold” piston wall. It this happens incrustation will narrow the size of the combustion chamber and the fuel “free travel”, this would rapidly reduce engine efficiency and power output.

Automotive design engineers have many objectives, while adhering to government-regulated restrictions. Very fast warm up of the engine is a primary objective. Heat is taken everywhere, even from alternators, to heat-up the thermal plant in the minimum time possible. Maximum torque at low rpm is the first requirement, along with acceptable exhaust gas temperature (EGT), minimal noise emissions and maximized economy/efficiency. The engine should survive for a sufficient number of cycles to this hellish environment. From Alaska’s permafrost winters Sumatra’s high humidity summer, timing must be corrected constantly. Aircraft designers will stop the aircraft for the least time possible for warm up. Then high power at full rpm (take off) and automatic timing corrections for different altitudes and different power setting are required. Hot restart and full throttle authority are also important.

3. Location of Peak Pressure (LPP)

It has already been determined that the maximum torque (maximum efficiency) is obtained when the location of peak cylinder pressure, LPP, occurs between 10 and 16 degrees ATDC (after TDC). The standard reference optimum LPP for internal combustion motors is 12 or 14 ATDC, depending on the referenced study. BTDC injection timing should be adjusted to fulfill this value. The new common rail injectors will have a pressure sensor embedded in order have a direct feedback. In fact, peak pressure affects directly SFC (specific fuel consumption). An optimized indicated cycle for a CRDID is shown in Figure 1:

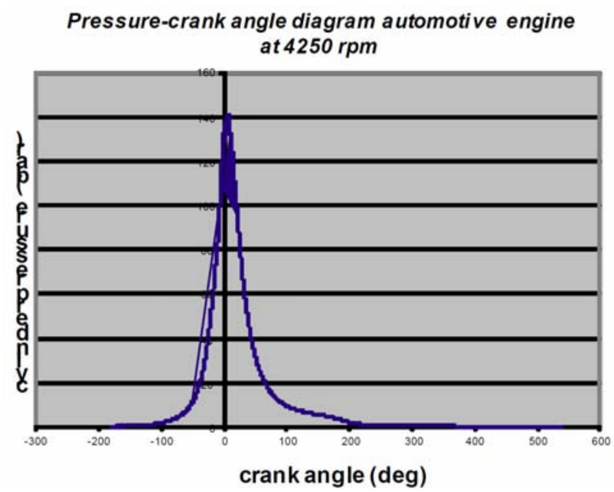

Figure 1. Optimum indicator diagram CRDID.

4. Cetane Number and Ignition Delay

Delay and combustion duration are governed by chemical properties and the environmental factors, temperature and pressure.

Since cetane number is a measure of how shortly after start of injection, the fuel autoignites. The engine requires an increasingly higher cetane number fuel to start easily in the cold. By the way, the noise level is affected by the cetane content. In the US a minimum of 40 ASTMD975 cetane number requirement is a minimum of 40 is required. Consequently, engine noise is higher in US than in Europe, where it is should be more than 45. In fact the source of the noise is the rapidness of the pressure rise. If fuel has a long ignition delay period, when it finally ignites it faces a higher charge temperature. The hotter environment accelerates ignition and increases the pressure raise (see Figure 2). A low rpm (2000 <), it is possible to attenuate the effect by pilot injection. A tiny quantity of fuel is injected in large advance before the main injection(s). Pilot injection increases the chamber temperature and reduces noise.

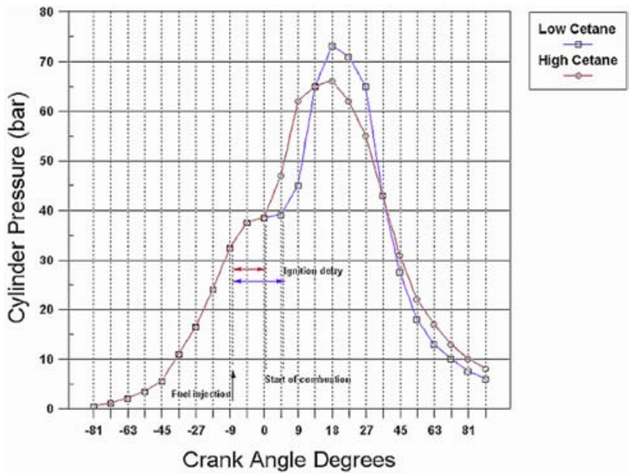

Figure 2. Ignition delay and cylinder pressure reduction with cetane [2].

Maximum pressure and temperature are also dependant from cetane number. The lower the higher pressure and temperature. Therefore, power output should be reduced when cetane number is law. This is a problem with Jet(A1) fuels where a minimum cetane number is not guaranteed.

5. Engine Start-up (Cranking)

Specific maps control the start-up procedure called "*cranking*".

Usually at start-up the engine outputs unspent fuel that can be seen as white cold smoke.

To avoid these phenomena special glow plugs are now available. They are controlled through a specific electronic power unit by a PWM (pulse width modulated) signal by the ECU. This glow plug may reach temperature up to 1200K eliminating the problem that is both of time and pollution. A fuel that combusts more readily will require less cranking to start an engine.

A small capacity rain will reach the required pressure (usually a few hundred bars) in less time rendering the procedure faster. A fast igniting, quite running engine at start-up is felt by the driver has a good engine. This fact is neglected in aircraft engines, where the minimum ignition rpm (around 300rpm) is delayed by the propeller inertia. Low capacity rails reduce pressure smoothness and overall efficiency.

6. Optimization Basics: BTDC Main Injection Control

A non-common rail DID engine has an optimum autoignition temperature of 450°C for our diesel platform. With a fixed 15 BTDC injection pulse at 2000rpm, the ignition event reasonably begins at around 10 degrees BTDC@250bar, with a delay value of 5 degrees. If the ignition lasts 40 degrees, then 10 degrees are on the negative side and 30 degrees of positive torque, resulting in 20 degrees of net positive torque.

As the entry air charge heats up, the delay is reduced increasing the negative side and decreasing the positive one. The reduction of the positive side is further increased by a reduction in combustion time due to higher chambers temperatures and pressures.

As engine charge temperature rises, the cylinder gets progressively hotter, with a further reduction in combustion delay. The process of overheating is usually dampened by an increase in engine blow-by with further power loss.

In CRDIDs the problem is solved by a corrective map(s), usually based on IAT (intake air temperature) and water temperature (CT - coolant temperature), the map(s) reduce(s) timing with factors that tend to reduce ignition timing and fuel amount.

7. BTDC Main Injection Control: RPM

A faster moving piston requires more timing advance because it arrives at LPP in less time than a slower moving piston. To prepare fuel spray for complete combustion at the same crank angle position, it must be injected sooner to have the same amount of time to be combustible near TDC. The advance timing should be roughly proportional to as rpm. This phenomenon is contrasted by the fact that the compression is more adiabatic and the temperatures at the same crank angle are higher. RPM increase alone, reduces the load. In fact, more active cycles are available for the same power output. This is the case when the pilot manually changes the propeller pitch.

8. BTDC Main Injection Control: Load

Load is the peak pressure level that can be measured inside the cylinder. As load increases, exhaust gas temperature increases with these higher pressures and fuel charge. With more energy to be recovered in the turbocharger, the resulting boost available increases. Higher pressure and temperature with higher load decrease the ignition delay period. If corrective actions are not taken, ignition delay can range from 3 degrees under high load, to as much as 8 degrees during “cold” low load cruise. This fact suggests the need for retarding injection advance for higher load. However, higher load normally requires a longer current pulse (in case of single pulse injection), up to 600% longer time duration than a low load pulse. This fact requires an advance to keep LPP in position, so the effect of load, and the longer pulse that is associated with load, tend to cancel each other out. But the net result is a small ignition retard, requiring reduced advance. As load increases, premix combustion duration becomes smaller, yielding to diffusion controlled combustion. This fact explains why, at low rpm, high fuel events require very low timing numbers.

9. BTDC Main Injection Control: Altitude

Altitude or elevation changes air density and temperature. There is 50% less oxygen at 6,700m. If no correction is taken by increasing boost or IAT, this reduction makes the ignition longer, and injection timing must therefore be advanced to maintain a correct LPP.

10. BTDC Main Injection Control: IAT

IAT affects ignition delay (3), and speed of the ignition event. IAT speeds up fuel evaporation, reduces ignition delay and combustion duration. In this case thus injection timing must be retarded. This is especially true if IAT increases with the increase propeller load due to aftercooler inefficiency and high external temperature, in a thermal feedback relationship.

11. BTDC Main Injection Control: Humidity

In CRDIDs, humidity is frequently overlooked, with no correction for this factor.

In fact, the mass of water vapor is usually very low (see Table 1).

Table 1. Mass content of water vapor at saturation

Air temp. (°C)	Saturation mixing ratio (gr/kg)
–1.1	3.5
32.2	30.7
18.3	13.2
35.0	36.5

As it can be seen at 35°C the mass of vapor is 3.7%. In CRDID the normal mixture is 20:1, while the stoichiometric is around 15:1, so an excess of 33% of oxygen is present. In saturation at 35°C this excess is reduced to about 30% with negligible effects. However, in a rainy take off, with a standard oiled paper oil conical, little droplets of water pass through the filter. The air in this case is oversaturated. When fuel is combined with “wet” air, the combustion event progresses at smoother rate. Therefore, an advance in timing is required. This has a well-known beneficial effect on power output with an increment up to 20% [3] in power production.

12. BTDC Main Injection Control: Boost

Increasing boost creates a more oxygen rich environment in the combustion chamber. This fact is associated to higher temperatures. The result is a faster ignition results that require retard in the timing. Remember that pressure has a less relevant effect than temperature effect on ignition delay (3).

13. BTDC Main Injection Control: Fuel Temperature

Temperature affects fuel viscosity, fuel charge, injector atomization, evaporation rate. The increase in fuel charge is because a volume is injected in a time. The fuel inject is a liquid, with a density that does not change substantially with temperature. As fuel is sprayed through a nozzle the amount of fuel charge depends on the pressure differential (constant) and fluid viscosity. Another important factor is that the fuel at top admissible temperature (110°C) will atomize into drops 1/4 the size of diesel at cold start (–35°C). This also means four folds the liquid surface area initially exposed to the charge air. The larger the surface, the larger the heat transfer and the evaporation rate, leading to a faster combustible mixture. As combustion proceeds faster, injection timing retard is required.

14. BTDC Main Injection Control: Cetane Rating

A higher cetane rating results in a less consistent ignition delay and in noise reduction. A higher cetane rating the timing to be slightly retarded to maintain the same LPP.

Cetane sensors are available on the market, but not of common use.

15. An Example of Automotive Mapping: Peugeot 306 HDI Map [5]

This car has a 2.0HDI CRDID with 205Nm@1750rpm and 90HP@ 3200rpm declared by the factory. The fuel pump pressurizes the fuel up to 1350 bar (this consumes to 5HP of the output power). The pre-injection injects approximately 1mm^3 of fuel into the cylinder during the compression stroke. This fact reduces the pressure and temperature gradient inside the cylinder before the main injection event. The pre-injection, which can be run up to 2000rpm, reduces combustion noise by up to 1dB per cylinder. This also reduces the amount of time it takes for the fuel to ignite under the main injection event. This is the true fuel charge, and provides the main power stroke of the engine. Injected quantities can reach 51mm^3 per stroke at full-load. A ‘post injection’ has the purpose cool down the combustion and to contain the NOx the diesel particulate filter in order to burn off any soot which could potentially clog the filter. The boost pressure of the Garrett GT1546s turbocharger is controlled by a mechanical pressure actuator, which opens the waste gate and diverts the exhaust away from the turbine. The ECU controls the maximum amount of fuel injected per stroke as shown in Figure 3.

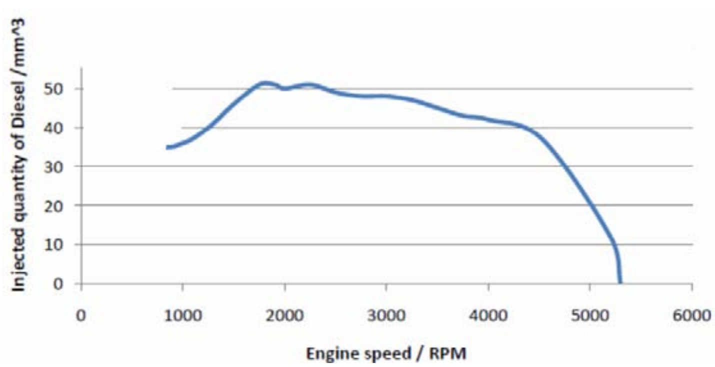

Figure 3. Fuel charge per cycle (derived from [5]).

As it can be seen the maximum injection quantity it is 51mm^3 of fuel per stroke at 1750rpm.

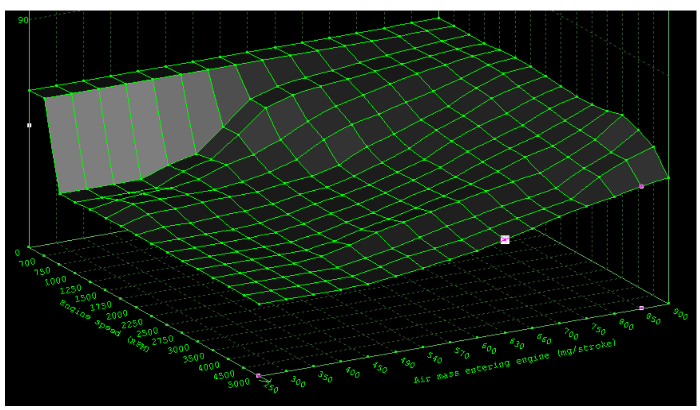

Figure 4. “Smoke” map, rpm-airmass (mg/cycle) vs fuel quantity [4].

The IQ is also limited with respect to the mass of air entering the engine. IG is given by the “smoke map” (Figure 4). This map works the following way: the ECU reads the rpm and the flow mass (debimeter), the maximum value permissible is given by Figure 4. Another map correlates the throttle position to this maximum amount. This amount is the one on Figure 3, the lower of the two is injected.

Another map that works on IQ is the fuel temperature map. This map limits IQ with fuel temperature and engine rpm. This map is controlled by two main factors: emissions and correlation between injected mass and temperature. In fact IQ is calculated on rail pressure and injection time with standard fuel temperature. As temperature increases the fuel charge (mg/cycle) increases and should be corrected to avoid “black smoke” and emissions out of control. Coolant temperature is also read and IQ is reduced by another map, other maps are available for IAT and boost pressure. All these maps result to an IQ that is the minimum of the “correction set”. Since the injector is treated by the ECU an On/Off device, this minimum IQ is related to a time of injection. At this point, the ECU calculates the timing advance. A minimum and a maximum timing advance are also set and related to rpm with separated maps. Automotive mapping follows the philosophy of maximum performance with emission control and engine durability, the true amount of torque and power output is not important. A best compromise is automatically chosen by the ECU. FADEC aircraft philosophy is reversed since a minimum amount of power should be guaranteed at any cost. If automotive ECU software is to be used, an excellent knowledge of the SW is strictly required.

16. Conclusions

CRDIDs are fully controlled by FADEC software. In this paper only single injection tuning has been treated. Only the most important variables and sensors have been introduced. An example of automotive software implementation has been briefly discussed. It is of paramount importance to keep the LPP within 12-14° ATDC. These results guarantee the maximum engine efficiency and performance. General criteria of aircraft injection mapping have been discussed, along as some hidden hints that are not reported on books. Very careful SW control should be implemented in order to avoid the criteria of automotive FADECs to preserve emissions and engine durability as primary criteria. In aircraft and helicopter operation the primary objective is safety, for this reason power reduction strategies should be applied by the PF (pilot flying) and not by the FADEC software.

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