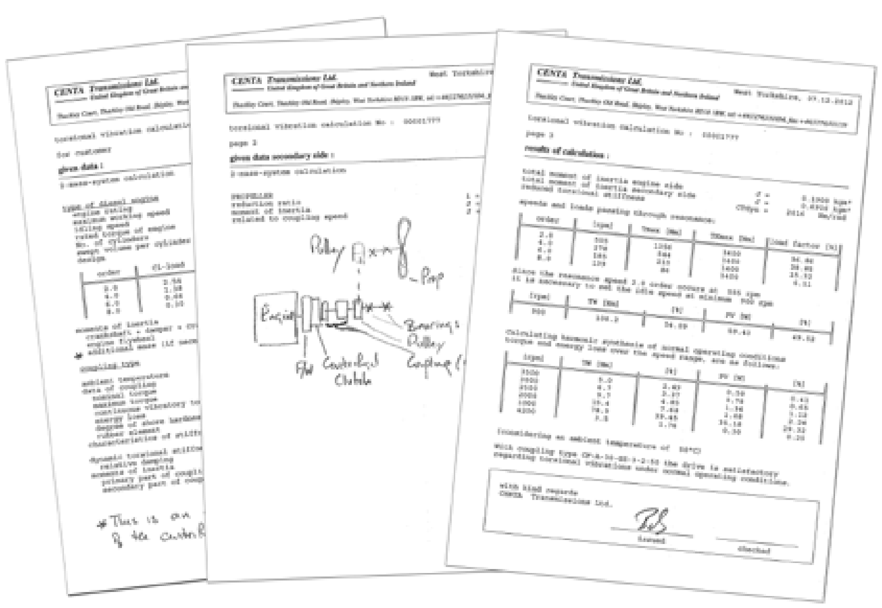
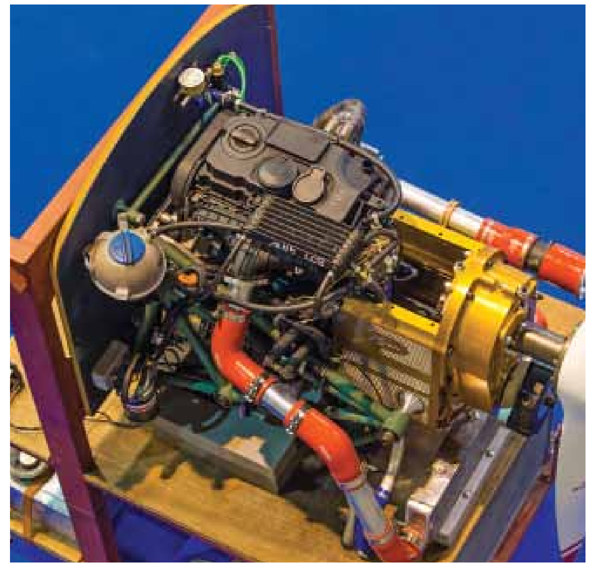
Hang on a minute lads, I've got a great idea...

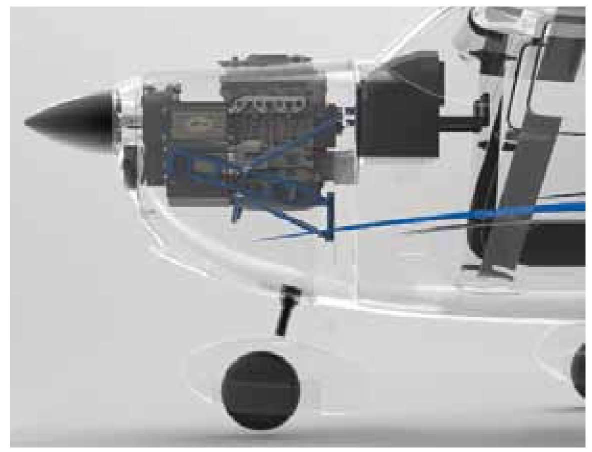
Engineering | Making your own diesel aero engine

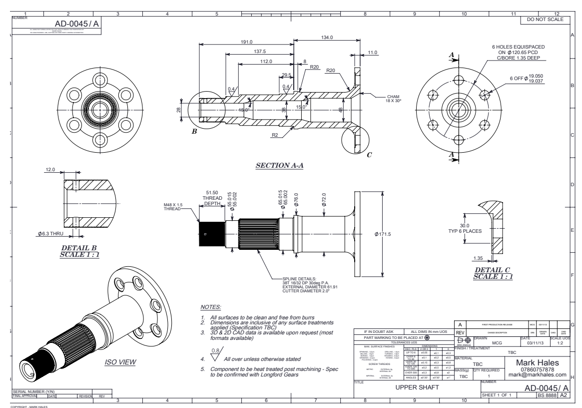
Mark Hales had an idea to create his own diesel aero engine from a ubiquitous, modern VW diesel. Just how hard could be, and what could possibly go wrong…?





Clockwise from above
1: Looking down. Top cover is removed to show internals, small radiator alongside the cam cover is to cool the fuel returning to the tank
2: Simulated Cessna installation. It's almost impossible to find accurate drawings so this is from a model aircraft. The engine does actually fit beneath the cowl in the real thing
3: Top shaft and propeller flange. It's a big lump but it carries all the gyroscopic forces so it needs to be
4: In amongst the calculation pages, sometimes a sketch helps with understanding whats involved
5: Early drive ideas realised in plywood, plastic water pipes, cardboard and hot glue
6: Exploded view drawn from the CAD modelling. Boom type engine mount since revised
7: Engine on the stand where it has done all the initial running on a mount designed to fit an Auster. The water radiator will move for the aircraft installation, probably to a pod under the fuselage





At the recent *Flyer* Live event, there were a couple of questions which the majority asked; what was the base engine, followed by how much does the whole lot weigh ? Several also wanted to know how many aircraft it had already powered which I guess is quite flattering. Those questions answered, the next was inevitably, in what aircraft was it going to be fitted ? Only a couple asked the slightly more direct question which is, why did I do it at all ? The first ones are easy; VW Golf Mk5 tdi 170PD, about 500lbs at the moment and none so far. The last two might take a few pages...

Why did I do it? The main reason was reducing the cost of operation, which may be a flawed premise but it was certainly motivation. In days gone by, I felt able to afford the 40 (or even 60) litres an hour required to feed the bigger Continentals and Lycomings; fuel was cheaper then and I was better off, and besides, fuel was certainly not the biggest expense. In addition to lower cost, there was too a real desire to sit behind a modern engine, of which there are few if any available to individuals. Traditional American engines are without doubt fantastically reliable but they are neither modern nor efficient and they are disproportionately expensive to overhaul. I'd already trawled the various publications and websites in search of automotive conversions and found plenty on offer, most of them in the 100hp division, but it soon became clear that while they might fulfil the 'modern' requirement, they tended to be heavier and they weren't that much cheaper to buy or operate.

And then it dawned. I could do it myself and use a modern, automotive diesel and enjoy the technical challenge... I could go for the 180-250hp sector and go back to a bigger aeroplane where any extra weight is less critical, and enjoy extra room at Jodel-running-costs because the diesel uses half the fuel. The hardware for a bigger engine wouldn't cost any more than for a smaller one, and if there was ever a commercial opportunity in the future, there's only the 230hp SMA out there and it's €100,000. Convincing myself was so very easy, added to which, finding an airframe to put it in would surely be an enjoyable search. That decided, there was the technical side to consider: direct drive or reduction? Gears, chain or belt? ▶

Electronic or mechanical injection? In a world where we are only just seeing electronic ignition creeping in for spark-ignited engines, the idea of complete electronic control of all engine functions is still a problem to some. On the other hand, total electronic control of most things in our lives is a reality, so why not aero engines?

Mechanical injection is seen as the 'safe' option because there are no electronics involved. The traditional, pre-1990s diesel featured a mechanical shuttle pump, which injected atomised diesel fuel into the cylinder, usually via a pre-combustion chamber. Pressures were relatively low (about 200bar/2,900psi) and the injection interval was hard to regulate accurately. Modern engines have a pump which generates much higher pressure (around 2,000bar or 29000psi), usually feeding a rail connecting all the injectors. These are then switched by solenoids controlled by the engine's ECU; a smaller amount of fuel is injected directly into the combustion chamber with much better control of timing (the exact point in the cycle) and if necessary, more than once. It's cleaner and more efficient and is one of the reasons why modern diesels don't rattle quite like they did.

Because the purely mechanical system can't meter the fuel as accurately, the engine uses more and you don't get the same energy from it, and if you try, you'll get smoke, which is something of a no-no. So, electronic it had to be, and I was asked by someone in authority if I could fit two sets of injectors and two ECUs, just to be sure... To be fair, he then answered his own question, saying that would probably be introducing problems rather than avoiding them, adding, ""Well, my car's diesel and it's never gone wrong." The choice of the VW PD was then fairly logical. It is a modern, electronically-managed, four-valve, twin-cam featuring a very high-pressure injection system, uniquely via a third cam in the cylinder head operating shuttles which inject directly into the combustion chambers, switched by solenoids; hence the name Pumpe Düsa. I reckoned the shuttles would be more tolerant of any variations in fuel quality than a rotary pump.

The cylinder block is iron, which adds weight, but is immensely strong and as proof there is the VW Fun Cup endurance championship, which had already converted to diesel using the PD engine. Most of the races are six to 12 hours with a 25-hour event at Spa. If the engines could stand that amount of time flat out, in between regular over-revs, and do it for the whole season, a propeller would be easy. More important, a French company had made a stand-alone ECU and loom for the series, much simpler than the Bosch unit in the car, featuring only the controls needed for engine operation.

Twist & shake

As for the drive question, direct is extremely simple and suits a traditional aviation engine, which has to be large in displacement because it can't turn very fast. It's possible for a car engine to drive a propeller directly (the French Delvion is a successful example), but although a typical two-litre turbo diesel's torque peak is between 1,700 and 2,500, horsepower is torque times rpm, so you need both. A direct-drive engine would also be extremely heavy for about 110hp, which wasn't enough. Another decision made. Gears are then the more compact and somehow more sophisticated option, but a belt is cheaper, lighter and simpler, and most important, there's no lubricating oil to leak out.

Spiky output

I already knew that the killer of a great many automotive conversions is torsional vibration, a term which doesn't really describe the problem. It's the twisting of a shaft in both directions and a diesel is a worst case because the compression ratio and combustion pressures give the reciprocating parts a real shock each time the piston approaches top dead centre. I got a suitably qualified chum to plot the spikes, for which he had to know the rotational inertia of the engine, and the propeller. Hoffmann Propeller obligingly provided a generic number for the latter, but the former might well have been the combination for the Bank of England's safe. I called in a favour via the press corps and we got the number, after which Peter discovered that the spikes don't occur throughout the range but at certain points, the worst one at 555rpm where the twist is ten times the maximum torque the engine can produce. According to the Jaguar Land Rover engineer to whom I chatted at *Flyer* Live, torsional vibration is still pretty much the biggest source of problems he has to deal with and it's why modern diesel cars have a dual-mass flywheel, which has to be replaced along with the clutch. The cure for the 555 spike was to avoid it, using an off-the-shelf centrifugal clutch, which is common in industry for diesel-driven refrigeration pumps. Without it the engine apparently won't start and just oscillates until it breaks something.

There was another spike at 3,200rpm, which we couldn't avoid (like the area on the rev counter for some Lycomings), so transmission specialists Centa specified a pair of the company's flexible doughnut couplings. Centa conducted their own torsional vibration survey and Bob took a real, practical interest, even reviewing my design sketches to make sure the couplings exactly fitted the role. Although one could handle the torque, the size of the spike required a diameter too large for the engine's 4,200 max rpm, so a pair of smaller ones had to be installed in series. There are those who huff and puff about the exclusive nature of aviation, but my experience has been that industry has already encountered most of the problems and if you give the specialists all the information they need, there's often a solution on the shelf.

By then, the drivetrain was looking far too long, especially when added to the dimensions of an in-line four, so I came up with a concentric shaft arrangement; this took the drive from the first coupling forward to the second, then back to the bottom pulley, which drives the Gates Poly Chain. This is a carbon-fibre, reinforced, toothed belt, which is more compact for a given amount of torque; the motorbike drag racers who use them say they have never had a problem. The PD engine has another spike (almost equal in size to the 555) but it's at 4,300rpm, where the engine doesn't go. Well, I won't, but the Darkside Developments guys – PD diesel performance specialists

Above: Front flexible coupling clearly seen below the propeller shaft
Left: Throttle assembly, using a pair of mobility scooter speed controllers
Right: An early run, before we discovered the missing boost pressure

who supplied a lot of the ancillaries – have a SEAT Arosa drag race car fitted with a turbo from a massive John Deere agri machine, which is half as big as the engine and forces it to produce 350hp plus, revving to 5,200rpm. Has it ever blown up? "No" Do you do anything special to the engine? "No, it's out of a breaker, we put it straight in." Anyway, for us, that was two spikes avoided, one defended.

I then had to get everything drawn and was fortunate to find a bright young man with that essential additional attribute: enthusiasm. I could do my sketches, Peter did the calculations and Mat would add the measurements to create the model on-screen and between us we could manipulate it to make things fit. It's technology which in the right hands helps people like me to realise an idea, after which the screen model can be converted into something the machinists can make and I know the bolts will drop straight in. Slightly more difficult though was supplying some of the essential measurements. You'd think it would be easy to find a pattern for the threaded holes on a PD block, but that too is apparently some arcane secret guarded against all forms of industrial espionage. Fortunately, another piece of technology – the FaroArm, like some giant, upmarket Anglepoise lamp with a probe in place of a bulb, designed originally for medical use – can plot the location of the holes to within fractions of a mil in all axes and delivered them in a form that Mat could use.

The exhaust manifold was made by a local go-faster exhaust specialist and a turbo came from one of the many turbo suppliers. I had to design an engine mount, and persuade John the stress engineer to specify the tube sizes according to his calculations, then get it made by the motor sport guys, which needed a huge jig. Then ? Get the many rotating parts machined, hardened, splined... the drive housing parts had to be hobbed from a solid piece of high-grade aluminium (still the cheapest way for small quantities), engine mounts had to be specified and sourced and so on. The local blacksmith made the stand you see in the pictures and to get the engine running and prove the mechanical additions, I decided to use the car's ECU for the time being. It had all taken far longer that I wanted – partly because I had to call in a lot of favours from people whose day rate I couldn't possibly afford – and three years on, all those people who politely suggested I save the cost of diesel development and spend it on avgas for the next few years were looking pretty far-sighted.

First start

The grand fire-up came in May 2015, if you can call the press of a button followed two seconds later by the clatter of a diesel in any way grand. Maybe it was the sense of occasion, and only after I found the reason it wouldn't start was because the starter was turning the wrong way... Sounds like you might just reverse the connections. Alas not. Motorsport came to the rescue with a custom starter (and alternator) which are modified to stand the rigours of competition, and I'd already cobbled up the accelerator pedal box from the car (which turned out to be a much bigger problem later on). After that, start-up was a complete anticlimax. It ran (well, of course it did, VW spent millions making sure), but more important, the clutch engaged smoothly and there was enough thrust to blow the dustbins over. Wouldn't develop proper boost mind, a detail which the Darkside boys tackled on the test stand outside their workshop, reprogramming the ECU in stages and handing it back each time so I could read the max static rpm. Currently we reckon about 200hp, but they insist that's only a base setting. "Just tell us how much you want".

It has now been running for several hours with nothing more than a few minor installation problems – that's not including building a hand throttle that would actually talk to the ECU – the pile of pedals purchased on eBay and dismantled in search of a solution is considerable. Eventually another clever chum came up with a solution after much scanning on his oscilloscope. Carl made a neat hand-throttle using a pair of mobility scooter hand controls and some circuitry to feed the ECU, one sending exactly ▶

E-Conditions

In the middle of the development, there emerged the Professional Experimental category, now E-Conditions Category. This is an enlightened initiative by the Royal Aeronautical Society and the CAA which allows an individual (like me) to certify an aeroplane up to test flight without having to satisfy the British Civil Airworthiness Requirements. It having begun to dawn that a suitable test bed was likely to be outside the budget, E-Conditions seemed like manna from heaven. I met Alan Carter, the CAA's GA Head of Airworthiness, and the LAA's Francis Donaldson at Turweston to discuss the project's future underE-Conditions, and as Carter put it, a crusty old 172 or 182 is an obvious test bed whereas an RV-10 would be an extravagance. Amen to that, even old, unloved Cessnas are fine aeroplanes but they are cheap as chips because they are now completely uneconomical to operate unless you have a real use for them.

Messrs Donaldson and Carter clearly wanted the diesel to work, so I kind of feel I've let them down, but it subsequently became clear that the word 'Professional' was the key. It didn't have anything to do with the standard of design or workmanship, more the status of the company, which in turn implies the enterprise has to have a properly commercial future. A group of potential investors then decided that the engine was not likely to be certified, and so the promise of light aviation in areas of the world where there's no petrol, let alone avgas, was unlikely to be realised; and the government changed and the likelihood of a couple of grants about which we were reasonably optimistic, disappeared overnight. In the meantime, we had found a nice, straight-back G-Reg Cessna 175 which had sat at the back of a hangar for a while but was in really good condition.

The E-Conditions criteria were absolutely clear; I could test but not travel anywhere, couldn't carry passengers, then when the testing was finished (nominally a 12-month interval), the engine would have to come out and the aircraft would be scrap. It could not return to any previous European status. As the man said, this is not a convenient sidestep for existing regulation. So the 175 will return to EASA regulation, with the original O-300 on the nose. E-Conditions really is a great initiative, but as it turns out, not for me.

Below: Another view of the Cessna installation. There's a lot of room in the cowl for an intercooler and pipework and the noseleg is mounted directly on the firewall which makes the design of an engine mount much simpler

half the other's voltage. We will be replacing the car ECU with a fully programmable one as soon as possible.

Which aircraft?

But now, the second most asked question, and much more interesting, in which aircraft will I put it?

It had to be something that was already accommodating a 360 Lycoming, or preferably a 540, or a Continental O-470, all of which weigh about the same as the AD200 diesel. I really wanted to avoid a lump of lead in the tail and endless calculations about how much fuel you could put in on every trip. There's a lot of focus on weight in aircraft for obvious reasons, but somebody came up with the great term 'mission weight'. If the new aeroplane and engine combination can match the existing one's range and performance at a similar all-up-weight, it doesn't matter how the weight has been added. Since the diesel burns half the fuel, you can carry half as much with the reduction in cost being the obvious additional benefit. The question though, was still, 'Which aeroplane?' I was already well aware of the restrictions governing certificated aircraft, so the LAA route was the obvious one, but what seemed like an entertaining search in prospect turned out to be an extreme source of frustration (Full Throttle pg 25). It might make me sound naive, but my initial assumption still seems reasonable; that anything on the Annex II list and therefore technically an orphan, should be automatically eligible for an LAA Permit. Not, as it turns out.

The 'E' Conditions category option ('E' for 'experimental') had emerged along the way and sounded great in prospect but sadly that too is not going to work for me (see 'E-Conditions' box). So, it will have to be something that is already LAA-approved and the choice of larger-engined aeroplanes is pretty limited. Almost all are still certificated and the most annoying thing is that some of the obvious candidates in Annex II (which are in theory, I stress 'in theory', eligible for LAA oversight) are only certificated because someone bought or assumed the Type Responsibility. When I last investigated, it was certainly not clear what level of product support had to be provided to maintain that responsibility or whether anybody in authority ever checked. It all turned out to be rather disappointing but you can't exactly blame the LAA. The CAA's ruling is that as long as someone holds the Type Responsibility, any aircraft which is entitled (note the word 'entitled') to a Certificate must have one in order to fly. The wording of the FAA's rules is interesting by comparison. Paraphrased, it states that if an aircraft cannot meet the criteria of the Type Certificate (because you have modified it) then it is no longer entitled to the privileges that go with that certificate. It is however, eligible for an Experimental Certificate provided it is safe for flight.

The fundamental difference as I see it is that the FAA is willing to devolve the responsibility for safe operation to the pilot or owner, irrespective of any previous certification. We have heard the phrase, 'EASA won't let us,' applied to a few situations of late but a man who is in a position to know, said, "The CAA can do anything they like..." Given that a few other Commandments that have endured for so long have recently been subject to Damascene conversion, I choose to believe him. The CAA has recently allowed some aircraft to transition – even though there is a TRA in place – and owners can choose whether to stay on a National C of A or apply for an LAA Permit. In the most recent case, the TRA holder agreed, but it's still not completely clear why the CAA was minded to change the policy, which it had thus far resolutely defended. A welcome change but we'll have to see whether the Authority continues down the path.

So where to go from here? There are some obvious improvements to be made: a different turbo and exhaust manifold, ground-adjustable propeller, a single-screen dash display and, especially, a dedicated ECU, plus some obvious weight saving including a new engine mount. All of them are specified and available.

It would be great though, just to get it flying, which I'd be happy to do 'as is'. As another time-served observer said, that is almost more important than continuing to improve it on the ground. I know what he means but I still need something in which to put it... It also depends on whether I'm doing this for me, or to create something to sell, which is pretty much where I came in. The trouble with any project that takes a long time – which in aviation is most of them – is that circumstances (business, personal, financial) all change over time. We'll see what the New Year brings. Hopefully you'll be able to read about it in these pages.

"Total electronic control of equipment is a reality, so why not in aero engines?"