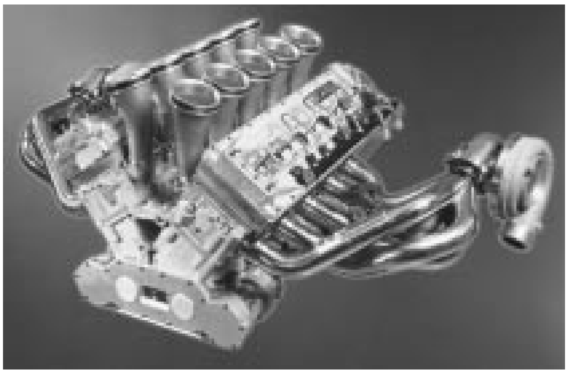
V10-Dieselmotor für Le Mans

V10 Diesel Engine for Le Mans



In endurance events such as the Le Mans 24 hour race, a high-speed diesel race engine has definite competitive advantages over a petrol equivalent of similar power, in terms of both fuel economy and tractive effort. The adaptation of a petrol race engine structure, together with operation at high engine speeds, allows maximum cylinder pressure to be controlled, leading to a lightweight engine without the weight distribution problems of approaches based on the development of heavy passenger car engines.

By Richard Cornwell, Dave Morrison and Steve Sapsford

1 Introduction

In 1931, Clessie Cummins entered a Packard-bodied Cummins Diesel Special in the Indy 500 in Indianapolis and finished 12th. In 1953, a Cummins Diesel Special took pole position but later retired. Other successful diesels competing in that era included the "Green Hornet" powered by a 6-cylinder, 6.6-litre supercharged 340 bhp engine, which set a qualifying lap at 130 mph (208 km/h) in 1951.

There were also land speed records set by diesel cars as early as 1949, when Manufacture d'Armes de Paris (MAP), a French precision engineering company, took six world records in the unlimited diesel class, including the 200 km event at an average speed of 191.7 km/h. More recently, BMW, VW and Volvo diesels have competed in track and rally events and have shown themselves to be worthy competitors against petrol cars, especially in endurance racing.

Last year, diesels were given a new opening in the form of top level sports car racing at the 24 hour Le Mans race with the publication of the 2004 Automobile Club de l'Ouest (ACO) regulations permitting diesel engines in the LMP1 category for the first time. Contemporary road car diesel engines are now delivering impressive performance and, together with anticipated pressures due to environmental concerns, have resulted in studies to promote alternative fuel and "clean racing" – including diesel.

Taurus motorsport entered a V10 diesel-powered Lola in the LMP900 class in the 2004 24 hour Le Mans and the European Le Mans Endurance Series. This limited-budget entry used a modified 5-litre VW V10 taken from a VW Touareg. Although the car raced in some events, it never had a chance to show any potential benefit from economy gains, as it never finished a race. Due to lack of development, smoke-limited performance was also an issue, as was excessive weight. Nevertheless, the team gained its place in history as the first LMP900 diesel.

Diesel racing is certainly becoming more popular in Europe in many different forms of motor sport, and the US and Japan could well follow, as car makers realise the marketing benefits from promoting their new diesel products in this way. However, all current diesels used in motor sport are essentially structurally derived from road engines, operating at typically high diesel cylinder pressures (160 -180 bar) and consequently still considerably heavier than their petrol counterpart. Alternatives to this approach form the basis of a truly competitive diesel engine for endurance racing.

2 Diesel Racing – Why Do It?

The massive growth in diesel passenger car sales in Europe is well known [1]. But what is the reason for such growth? The fuel economy advantages of diesel fuelled cars are well understood, but ultimately appeal only to a relatively small "hard core" of the car buying public whose annual mileage maximises the economic benefit of lower fuel consumption. Ricardo analysis has shown [2] that a more significant factor in diesel market penetration growth is the improvement in diesel car performance, refinement, driver appeal and environmental acceptability, via the application of the technologies currently in the diesel developer's toolbox. In simplistic terms, drivers can now enjoy equivalent – and in some cases superior – driving performance from diesel-fuelled vehicles compared to their petrol equivalents, whilst maintaining the inherent fuel consumption advantages.

Despite this, the diesel engine still suffers a negative image. The extension of this improvement in diesel performance to the racing environment is a logical conclusion to redress this problem.

3 Le Mans Regulations

The Le Mans 24 hour endurance race is regulated by the Automobile Club de l'Ouest (ACO). In 2003, regulations were issued for the following year's racing that aimed to allow diesel-fuelled vehicles to compete on an equal footing to the petrol mainstream. Diesel-fuelled engines are permitted in category LMP1 for vehicles with a minimum ballasted weight of 900 kg. Diesel engines are not permitted in category LMP2, where the minimum weight is 750 kg. The key regulations that impact engine performance concern air restrictor and boost pressure limitations. They are as set out in **Table 1**.

The other important limitation placed on LMP1 vehicles is the fuel tank capacity, which is limited to 90 litres for any fuel. Restricting diesel-fuelled vehicles to a lower fuel tank capacity to compensate for the superior fuel consumption characteristics of the diesel engine is certainly a debatable point. However, there is no precedent for restricting fuel capacity for other types of fuel-efficient engines, e.g. direct injection petrol engines, and such a limitation could form a serious disincentive to the development of any type of fuel-efficient motor sport.

4 Approach

A competitive power level for LMP1 (900 kg) vehicles is in the order of 600 bhp based on petrol experience. Typical petrol racing engines will achieve this power at speeds between 6,000 rpm (turbocharged) and 7,500-11,000 rpm (naturally aspirated). The resulting BMEP levels for these engines will be relatively low; approximately 13 bar for the naturally aspirated engine rising to approximately 25 bar for the turbocharged petrol engine. These levels of rating allow for lightweight engine structures commensurate with good weight distribution and optimal race car dynamics.

For the designer wishing to achieve competitive power levels with a diesel engine, a fundamental choice has to be made: should a production-based diesel engine be modified to produce the required power, or should an established racing engine be modified with a diesel combustion system?

The vast majority of passenger car diesel engines achieve their rated power in the range of 3500-4000 rpm, and their block and bottom end structures are designed to cope with maximum cylinder pressures in the order of 160 bar. As an example, the VW V10 TDI engine has a swept volume of five litres and may be considered suitable for modification as a racing engine. However, with a rating of 303 bhp, corresponding to a brake mean effective pressure (BMEP) of 15 bar, this may be considered a heavily over-engineered design. The dry weight of the VW V10 TDI is 367 kg. Achieving competitive Le Mans power levels while maintaining a rated engine speed of between 3750 and 4000 rpm implies a BMEP level of between 27 and 29 bar, which would require the retention of the heavyweight engine structure. A further consequence of maintaining the rated speed at "typical" diesel levels is that the torque to be accepted by the transmission at rated power is significant.

Therefore, the alternative approach of adapting a lightweight racing engine to suit the characteristics of a diesel combustion system becomes attractive. Ricardo adopts this approach for the Ricardo-Judd V10 engine.

An engine structure designed for the relatively low (compared to passenger car diesels) maximum cylinder pressures of petrol racing engines together with the air limitations imposed by the regulations impose unconventional limitations on the diesel combustion system, and these are described below.

3 Le Mans Regulations

Table 1: ACO regulations for Diesel engines

	1 Ø Restrictor (mm)	2 Ø Restrictor (mm)	Max boost pressure (mbar)
Up to 4000 cm³	55.9	39.9	3870
Over 4000 cm³ and up to 4250 cm³	55.9	39.9	3680
Over 4250 cm³ and up to 4500 cm³	55.9	39.9	3500
Over 4500 cm³ and up to 4750 cm³	55.9	39.9	3340
Over 4750 cm³ and up to 5000 cm³	55.9	39.9	3190
Over 4000 cm³ and up to 5250 cm³	55.9	39.9	3060
Over 5250 cm³ and up to 5500 cm³	55.9	39.9	2940

5 Combustion Systems

The desire to reduce engine weight drives us towards higher operating speeds in order to generate the required BMEP. Ricardo research indicates that, with a correctly specified combustion system, at least 6000 rpm is possible, within the performance envelope of modern fuel injection equipment (FIE). In order to validate the expected combustion system performance at high engine speeds, Ricardo Vectis 3-dimensional CFD analysis has been used to evaluate the air/fuel mixing behaviour of the combustion system at 4000, 6000 and 8000 rpm. The boundary conditions for each speed were set to maintain output levels consistent with the 600 bhp target power. For each of the three operating speeds, the injection nozzle flow rate was re-specified in order to maintain a constant injection period.

The CFD analysis, **Figure 1**, confirms that the fuel evaporation and mixing performance of the Ricardo high-speed diesel racing (HSDR) combustion system is similar at engine speeds between 4000 and 8000 rpm. The heat release profile resulting from the fuel burn process is also similar across the operating speed range. The CFD analysis confirms the theoretical limiting air/fuel ratio across the wider engine operating speed range, allowing an estimation of the air limited performance envelope of the engine.

6 Air Limited Performance

The determination that combustion system performance can be safely extrapolated from the passenger car range of operating speeds into the wider speed range necessary for a petrol-derived racing engine allows an estimation to be made of the performance potential of different engine displacements within the constraints imposed by the air restrictor mandated by the regulations.

The brake specific air consumption (BSAC) characteristic of the HSDR combustion system is shown in **Figure 2** and is used as a boundary condition in the estimation of air limited performance. Given that the regulations permit a fixed restrictor size regardless of engine displacement, the other primary boundary condition in this process is the airflow at which the restrictor chokes. In the case examined here, the limiting airflow per restrictor for 2x39.9 mm diameter restrictors is approximately 1040 kg/hour. A secondary consideration is the displacement-dependent boost pressure limitation, which will impact the engine speed at which an engine of a given displacement will become air limited.

Figure 3 shows the expected engine power curves resulting from boost pressure limited airflow curves for the Ricardo HSDR combustion system. These curves represent the maximum possible power at the assumed level of volumetric efficiency of 100 %. Only decreasing the air/fuel ratio or BSFC would increase power above these levels.

The restrictions imposed by the regulations only enable a rating in excess of 600 bhp up to a maximum speed of 5500 rpm. Beyond that speed, engines of all displacements will be air limited and therefore a petrol race engine structure will still need to support BMEP levels in the region of 25 bar at 5500 rpm.

7 Full Load Air/Fuel Ratio and Smoke

Given that one of the reasons to attempt diesel racing at Le Mans is to convince a wider proportion of the car-buying public that passenger car diesel technology has made considerable progress in the last ten years, the emission of large quantities of exhaust smoke during the course of a race is not acceptable [3]. Therefore, the application of some kind of diesel particulate filter (DPF) to the engine would be desirable, and may well be the subject of a mandatory requirement in future years.

The air/fuel ratio (AFR) targets encapsulated within the BSAC characteristic shown in Figure 2 assumed that no DPF was in operation, but the addition of a DPF would allow a reduction in full load AFR by between 1 and 2 ratios, while still maintaining sensible filter loading with no possibility of smoke puffs. A reduction in full load AFR by 1 ratio generates the air limited power curves shown as dotted lines in Figure 3, showing the potential for rating in excess of 650 bhp at speeds up to 5000 rpm.

8 Piston Structural and Thermal Limitations

One of the most highly loaded components within a diesel engine is the piston. It has to perform the functions of pressure containment and air guidance under conditions of high acceleration with only minimal and intermittent oil cooling. Data for piston specific loading are given in **Figure 4**, including data for current production racing DI diesel engines. Taking these as an upper limit on piston performance and translating these specific loading figures into a power limit for 5-litre engines shows the maximum power to be around 700 bhp. This is above the air limited performance curve for most cases, Figure 3. Clearly, the piston specific loading guideline is only a single measure of piston durability, and is no substitute for a full programme of piston and engine structural optimisation.

9 The Ricardo-Judd Racing Diesel Engine

The technical specifications of the Judd GV5 engine, **Table 2**, show it to be an ideal candidate for conversion to diesel operation, since the inlet and exhaust valves of the bio-ethanol variants are near-vertical, which is close to ideal for a diesel combustion system. Of particular note is the engine dry weight of 135 kg, compared with 367 kg for the VW V10 TDI.

For diesel combustion, with cylinder spacings considered sensible for sufficient durability, the engine would be able to contain a maximum swept volume of 4.6 litres. Figure 3 confirms that this is well within the range examined to determine air limited performance and should be capable of an air limited rating of in excess of 620 bhp up to 5000 rpm without a DPF and in excess of 650 bhp with a DPF.

The power curves in Figure 3 were described as air limited performance curves in Section 7, assuming that the maximum boost pressure permitted by the regulations was available across the entire engine operating range, in order to maximise the airflow subject to the choking limit of the restrictor. In reality, of course, the engine's air supply will be subject to the flow map restrictions of conventional turbocharging technology, which will result in "real world" performance somewhat less than the theoretical maximum air limited power level.

Ricardo Wave 1-D simulation has been used to analyse the performance potential of the 4.6-litre Ricardo-Judd V10 diesel engine with appropriate turbo machinery from the Motorsport division of Garrett. It should be pointed out that, under ACO regulations, variable geometry turbocharging is not permitted.

Figure 5 shows the air limited and real world power capabilities of the 4.6-litre Ricardo Judd engine with the HSDR combustion system superimposed. Again, dotted lines show the performance possibilities if the use of a DPF is considered allowing reduction in full load AFR by 1 ratio. The piston limit for the maximum feasible engine bore of 94 mm is shown, and is well in excess of the air limited performance potential.

The power curve resulting from the Wave simulation shows that, under real turbocharged conditions, the actual performance at speeds below the rated speed of

9 The Ricardo-Judd Racing Diesel Engine

Table 2: Judd GV5 petrol and bio-ethanol race engine.

Configuration	72° V10
Capacity	4997 cm^3
Weight	135 kg (dry weight, includes flywheel and wiring harness but excludes clutch and exhausts)
Dimensions	Length 622.5 mm Height 417.0 mm (excluding trumpets) Width 555.0 mm
Maximum Power	Over 440 kW at 7800/min (with 2 X 32.7 mm Ø intake restrictor) Over 598 kW at 10,000/min (no intake restrictor)
Maximum Torque	603,34 Nm at 8500/min (with 2 X 32.7 mm Ø intake restrictor) 630,46 bei 8500/min (no intake restrictor)
Maximum rpm	9500/min (with 2 X 32.7 mm intake restrictor)
Engine Management System	EFi Euro 12
Cooling System	Twin water pumps (one per bank), water outlets on front of cylinder heads
Oil System	Pressure pump and oil inlet on LHS, scavenge pump and oil outlet on RHS
Chassis Mounting	Top front mounting by shear plate, all others stud fixing, including four rear mounting points
Additional Features	Can be fully stressed

5500 rpm is less than the air limited performance. Clearly, at this speed range, the engine is not being boosted to the full levels allowed by the regulations, and the achievable output is being limited by the constraints of the turbocharger. If the extra weight could be tolerated, a two-stage turbocharging system could be used to make up the deficit.

Figure 6 shows further results from the Wave performance simulation. For the 4.6-litre engine, the maximum boost pressure permitted by the rules would be 3340 mbar (absolute). The boost pressure supplied by the turbochargers is actually much less than that, as the turbocharger compressor has to compensate for the significant intake depression resulting from the airflow restrictors.

The engine's maximum cylinder pressure (pmax) was held at a nominal level of approximately 140 bar by optimising the start of combustion timing and by selecting an appropriate compression ratio of 14:1. Such levels of pmax are considered acceptable for the structure of the GV5 engine, although more reduction could be achieved by lowering the compression ratio further without loss of startability, given the use of external engine preheating systems.

Finally, the engine torque reaches a maximum at 4000 rpm. The torque at all speeds is below 850 Nm, which is a realistic endurance limit for race car transmissions such as those successfully supplied by Ricardo to Audi and others for petrol Le Mans racing.

10 Competitive Advantages of the Racing Diesel Engine

The simulated performance curves for the 4.6-litre V10 diesel engine described above exhibit the following headline figures:
- 468 kW at 5500 rpm
- 850 Nm at 4000 rpm
- 80 % of maximum torque available between 3000 and 6200 rpm
- 14:1 compression ratio, p_{max} 140 bar
- 150-180 kg dry weight (estimate)

How competitive could such a race car be if equipped with such an engine? To answer this question, two principle aspects will be examined: fuel consumption and tractive effort. Clearly, this is not an exhaustive study of the competitiveness potential of the engine, but illustrates areas of operation in which the diesel might offer competitive advantages rather than just being an engineering curiosity.

10.1 Fuel Consumption

The relative full load fuel consumption of the Ricardo Judd V10 race diesel, with an expected range of uncertainty dependent on engine optimisation, is plotted against some petrol race engines in **Figure 7**. Engine operating speed has been normalised to rated speed. An improvement of at least 11 % is expected at rated power, rising to 20 % at 80 % rated speed, relative to the better turbocharged petrol engine.

An analysis of data logged for a real Le Mans lap for a petrol-engined vehicle allows an engine duty cycle (engine speed / power versus time) to be estimated. By incorporating suitable changes to the overall transmission gearing, the same data can be translated into the diesel engine operating speed range. A limitation of this approach is that it assumes that the driving style of the petrol vehicle, i.e. gear strategy at given points on the track, carries directly over to the diesel vehicle – an assumption that would of course need to be validated by track testing.

The resultant duty cycles are similar for both types of engine, with a major portion of the lap time spent at approximately 80 % of rated speed, corresponding to 78 % of the petrol rated power and 89 % of the diesel rated power. There are also significant periods for both engines operating at rated power and at around 120 % of rated speed, during downshifts for corners.

Knowing the proportion of time spent at each point on the power curve makes it possible to estimate the fuel burnt during the course of a lap. **Figure 8** compares the expected fuel burnt and corresponding laps per tank, assuming a fixed tank volume of 90 litres. It should be pointed out that the relatively crude duty cycle analysis described above would not be expected to produce an accurate volume or mass fuel flow estimate for the engine but instead is intended for comparative purposes only. The analysis reveals a clear fuel consumption advantage of the diesel, allowing a pit strategy with fewer fuel stops during the course of the 24 hour race.

10.2 Tractive Effort

The relative tractive effort curves of diesel and petrol race engines of equivalent power, with representative gearing (allowing the vehicle to achieve maximum velocity at rated speed in 6th gear), are shown in **Figure 9**. Between 3000 and 6000 rpm, the diesel tractive effort curve exceeds the petrol curve in all gears.

Obviously, the usability of this tractive effort advantage depends on the engine speed used at any given point on the track. Using the previously derived engine duty cycle and logged lap data, it is possible to identify gear and engine speeds at points around the track.

Figure 10 shows that, in all but a few parts of the circuit, diesel tractive effort is in excess of that of the petrol engine, resulting in improved acceleration out of corners (subject to traction limits and traction control interventions).

11 Conclusions

A diesel engine powered endurance racing car can be more than just an engineering curiosity or an "also ran". Real competitive advantages over conventional petrol race cars can be expected in the areas of cornering, acceleration/tractive effort and fuel economy. The combination of an optimised high-speed diesel combustion system, turbocharging and the regulatory framework allows competitive engine performance within a lightweight, petrol-derived engine structure. The significantly lower weight of the proposed Ricardo Judd racing diesel engine compared to a modified production V10 allows weight optimisation of the race car up to the regulated minimum weight via ballast in the usual way, rather than an excessively tail-heavy vehicle that compromises driver feel and handling. Inclusion of a partial flow DPF system ensures maximum public appeal and acceptability through the avoidance of smoke emissions.

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