International Journal of Automotive Technology, Vol. 1, No. 1, pp. 1–8 (2000)

1229-9138/2000/001–01

FUTURE GASOLINE AND DIESEL ENGINES – REVIEW

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(Received 12 June 2000)

ABSTRACT–This paper reviews the main drivers forcing change and progress in powertrains for passenger cars in the coming years. The environmental drivers of emissions and CO2 will force better technical performance, but customer demand for increased choice will force change in the basic engine design and provide opportunities for alternate configurations of powertrain. Gasoline engines will embody refinements of valve train actuations as well as developments in combustion, especially direct injection and possibly a lean booated form of direct injection. Nevertheless, the conventional, port injected engine will continue to be the dominant engine for some years to come. The high speed direct injection diesel will very soon supplant its indirect injection predecessor completely. It will take an increasing share of the total powertrain market as improved specific power and refinement make it even more attractive to the customer. Car manufacturers will provide diesel models to satisfy this customer demand as well as using the efficiency of the diesel to enable them to meet their fleet CO2 commitments. Both gasoline and diesel engines will see an increasing degree of electrification and partial hybridisation as efficient flywheel mounted electrical devices become available.

KEY WORDS : Gasoline, Diesel, Light duty, Emisions

1. INTRODUCTION

For most of the last century car makers believed that oil reserves were limited and that the internal combustion engine had a limited life expectancy. Although there is the prospect of real competition to the conventional engine in the form of the fuel cell, it is now generally believed that oil reserves are sufficient for over 40 years (BP Amoco, 1999). the drivers shaping the future of the internal combustion engine are environmental, in the form of ever stricter emissions legislation, the need to limit CO2 output and the need for recyclability, and, in addition, they will be market created as the customer demands more choice within an evermore refined vehicle and the manufacturer is forced to get new products to the market in a shorter and shorter timescale.

Emissions legislation is now beginning to converge round the world (Figure 1) so that the global manufacturer can use similar technology for all his markets. This convergence applies to the diesel as well as the gasoline engine (Figure 2). The US federal Tier 1 standards for light duty diesels require almost identical technology for compliance as that needed for Euro III. Tier 2, due to be introduced in the next 3 years appears to be more demanding in terms of NOx and less demanding in terms of particulates than Euro IV, but in practice similar techniques and control devices can be used to reduce the emissions and the weighting of the controls adjusted to comply with the target legislation. Although fuel economy has always been a market-created driver and CAFE regulations have been in

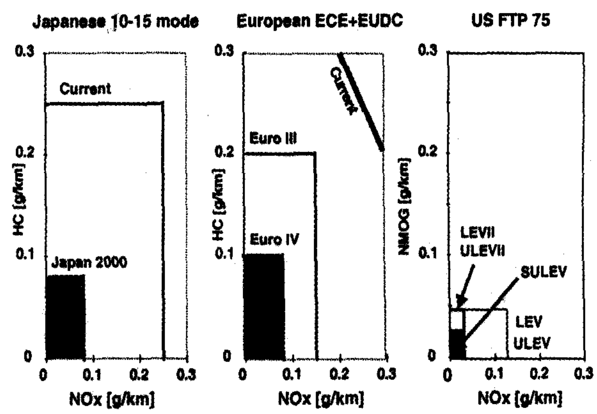

Figure 1. Global emissions convergence.

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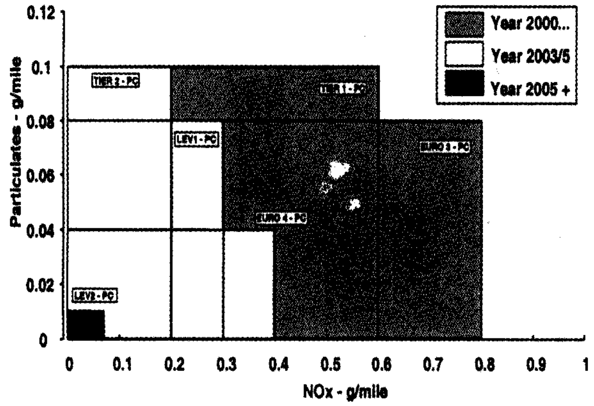

Figure 2. Comparison of USA & european diesel passenger car emissions legislation.

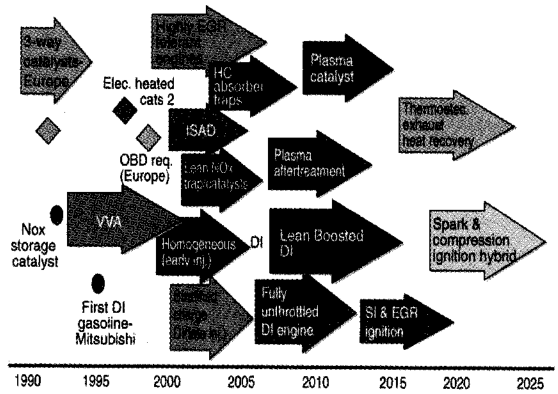

Figure 4. Gasoline engine developments.

force in the USA for some time, the phenomenon of Global Warming is now leading towards legislative pressure to control CO2. In Europe ACEA has come to a voluntary agreement to reduce fleet average emissions to 140g/km by 2008 and the possibility of achieving 120g/km by 2012 will be reviewed in 2003. There is little doubt that if progress is not made within the voluntary agreement the European Commission will pass legislation to ensure that progress is really made.

Figure 3 shows the results of a study carried out on the 1995 Volkswagen fleet. The sales in that year gave an average of 177g/km. By 'replacing' part of the sales with High Speed Direct Injection diesels(HSDI's) and part by Direct Injection Gasoline engines and then by allowing for a 10% improvement in fuel consumption from better transmission matching, vehicle weight reduction, etc. it was possible to achieve a fleet average of some 150g/km. Introducing increased sales of 90g/km cars similar to the Lupo was the most effective way of achieving further reductions. A 14% penetration of these vehicles was needed to reach 140g/km and 48% to reach 120g/km. Other manufacturers face similar challenges and it is this pressure which is going to shape the vehicle and its powertrain over the next few years.

The technologies foreseeable for the gasoline engine are shown in Figure 4. From the point of view of economy and refinement, the most important of these are probably the developments in direct injection technology and ISAD (Integrated Starter Alternator Damper) while the developments in aftertreatment are crucial to enable compliance with future emissions standards.

Figure 5 shows the equivalent 'technology roadmap' for the light duty diesel. As for the gasoline engine ISAD type developments are important for economy and refinement and, similarly, aftertreatment progress

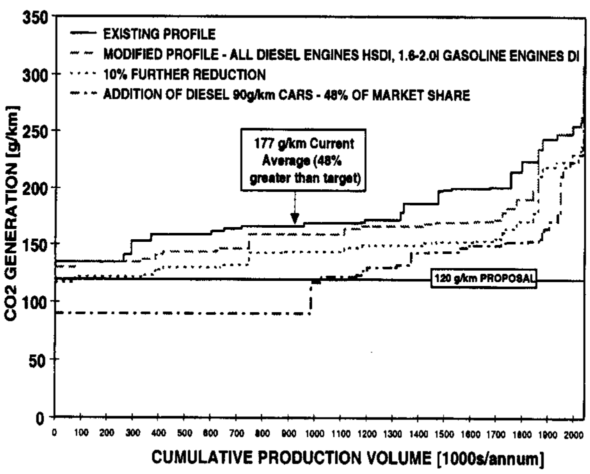

Figure 3. Fleet composition for CO2 reduction.

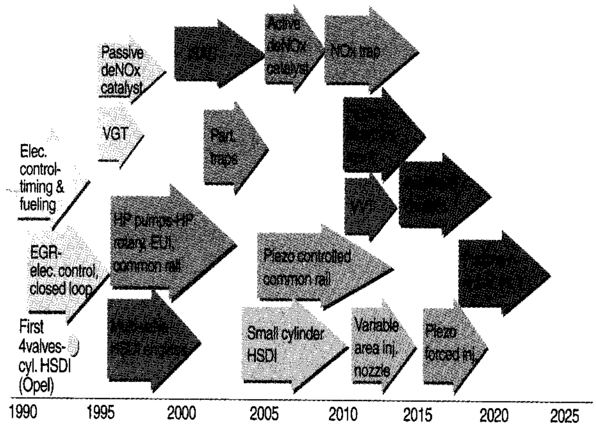

Figure 5. Diesel engine developments.

is necessary for emissions control.

An interesting development is the emergence of the small cylinder size HSDI which offers advantages in almost all aspects of operation.

2. GASOLINE ENGINES

Variable valve actuation(VVA) has been available for some years (Alfa Romeo, 1987). So far all the systems have been fully mechanical and hydraulically or electronically controlled and this has meant that no fully variable system has been produced since compromises are needed in terms of the degree of timing or lift variation used. Electrical Valve Actuation (EVA) offers a method of varying timing and lift much more flexibly so that improvements in torque curve, emissions, fuel consumption and refinement can be obtained over the whole of the load and speed range. Figure 6 shows a typical EVA system while Figure 7 shows experimental results obtained with a fully flexible research system.

Cylinder disablement has been explored many times in the past and although substantial fuel economy gains have been claimed (Hughes and Gill, 1980), it has not been popular due to the impact on emissions and refinement. EVA offers the possibility of permitting cylinder disablement in a much more flexible manner. By disabling cylinders in a varying pattern the combustion effects due to cylinder cool down are avoided and a much more gradual approach can be taken to the number of cylinders disabled so that the impact on refinement is much reduced.

The benefits of EVA would apply to both MPI and direct injection engines, but the power consumption of present day systems has prevented them getting beyond the research stage. Improvements in actuator design and more efficient electrical generation on board the vehicle are the keys to future success.

The Integrated Starter Alternator Damper(ISAD) is another device which offers benefits to MPI and direct injection engines. (Figure 8) It consists of a high efficiency, high power motor-generator mounted on the flywheel. The efficiency and power come from the electrical construction and, in some versions, from the use of high voltage. Efficiencies of well over 80% and powers of 5-10kW are available from several prototype devices (Zeyen and Pels, 1997). This high efficiency and power means that engine cut-off at idle is feasible without the disadvantages found in previous attempts. (Essentially undetectable stop-idle transition is achieved by starting times of the order of 200ms.) The high efficiency on board power generation permits many more of the ancillary devices such as water pumps and air conditioning compressors to be

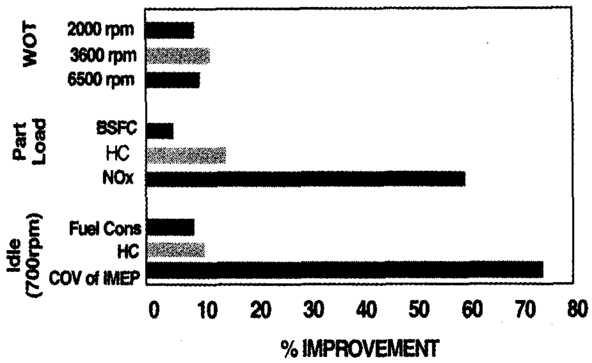

Figure 7. Effects of variable valve actuation.

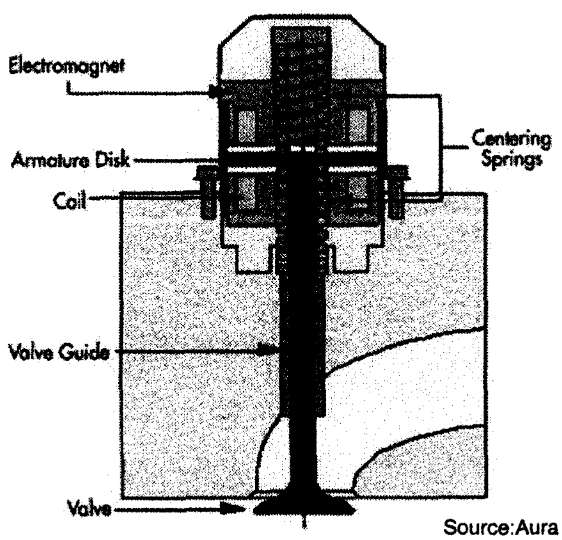

Figure 6. Typical EVA system.

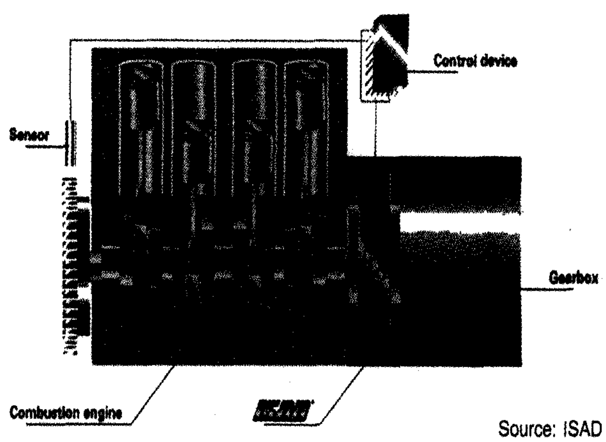

Figure 8. ISAD principles.

electrically driven. The ability to feed power into and out of the motor-generator at high frequencies means that torque fluctuations can be smoothed out and the same ability means that regenerative braking can be adopted and a degree of hybridisation achieved. Of course, as mentioned above, these devices also make the adoption of EVA much more feasible.

Direct Injection gasoline engines are now in production and their characteristics have been well documented (Niefer et al. 1999). If the direct injection engine is run as a fully stoichiometric engine it can give some 5% improvement in fuel consumption and torque curve and the emission control technology is fully compatible with that of MPI engines. However, a fully stoichiometric strategy does not take full advantage of the lean burning characteristics potentially available from direct injection. Figure 9 illustrates the impact of lean and rich operation on knock limit. As the equivalence ratio is reduced below unity the knock limit lifts and a higher compression ratio can be used. Unfortunately the rich running means that the efficiency advantage of the higher compression ratio is lost. Running leaner with equivalence ratios greater than unity has the same effect on knock limit and the higher compression ration does then give greater efficiency. Unfortunately the lean running reduces power output. The solution is to boost the engine. With the concept of a lean boosted DI we can enter a 'virtuous circle'. Boosting the engine improves the lean limit and this gives a lower octane requirement. This permits the use of a higher compression ratio or more boost and the latter then further im proves the lean limit.

Single cylinder tests carried out at Shoreham indicate the a four cylinder, lean boosted DI of 1.12 litres capacity would be able to match the torque curve and power output of a current naturally aspirated DI of 1.83 litres. It would also be able to match the power output of a 1.77 litre HSDI diesel although the driveability would be inferior due to the lower maximum torque. Figure 10 shows the torque curves for these three engines. What is particularly interesting is the predicted performance of this small, lean boosted DI in a 'C' class car of 1362kg inertia class. Figure 11 illustrates the simulated emissions and fuel consumption. It can be seen that the lean boosted DI actually gives lower CO2 emissions than the HSDI.

Although the lean boosting technology is still under development, it does, for the first time, represent a way of enabling the gasoline engine to match the diesel's CO2 performance and will undoubtedly be the subject of further studies.

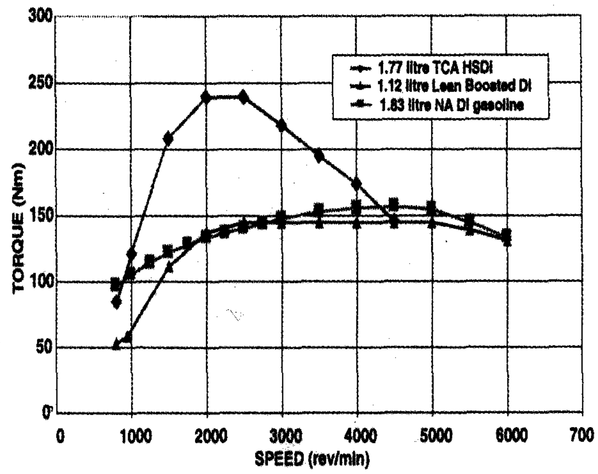

Figure 10. Contructed torque.

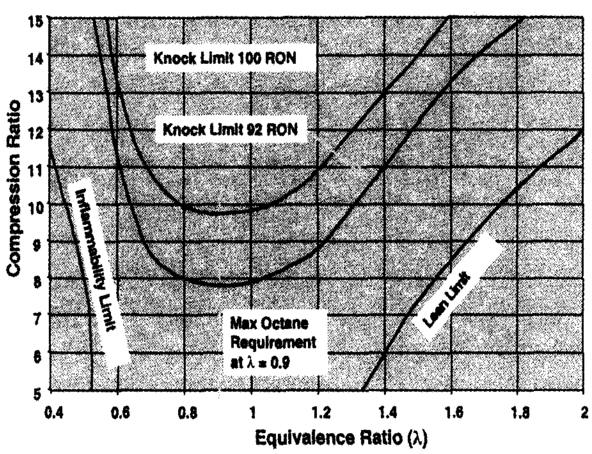

Figure 9. Limits to operational range.

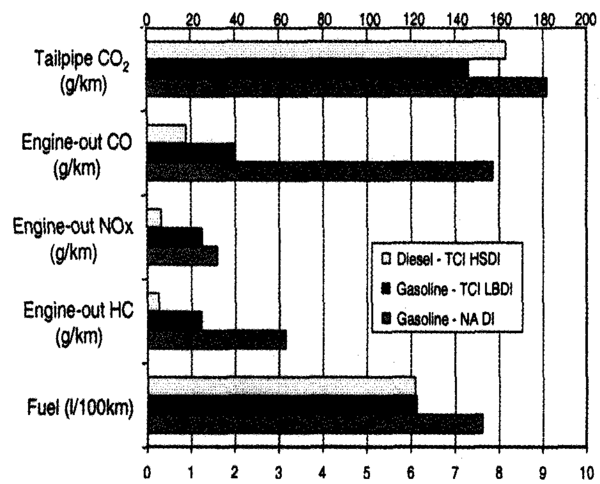

Figure 11. Simulated vehicle results.

3. DIESEL ENGINES

The light duty diesel is steadily increasing its share of the market in Europe. There are three main reasons for this. Firstly, the diesel offers a combination of economy and driveability that is especially attractive to the european customer faced with high fuel prices and widely varying driving conditions. Secondly, the range of diesel offered is now sufficiently broad to appeal to all sectors of the market. Thirdly, the diesel? image has changed from that of a noisy, smokey, but economical engine to that of the powerplant which can help provide a solution to Global Warming.
This image has been marred from time to time by fears of health effects due to the particulates emitted by diesel engines. These have been allayed by the dramatic reductions in engine-out particulates (Figure 12) and the prospects of viable particulate traps (Carletti, 1999).

OEM? such as Daimler-Chrysler (Figure 13), BMW and Audi are now offering diesel versions of their top of the range cars. The particulate and NOx reductions shown in figure 12 have been achieved with little or no aftertreatment. The investment in premium diesel in only undertaken in the belief that aftertreatment technologies can be developed to enable the diesel to meet future emissions legislation without sacrificing any of its virtues. Experimental results support this view and there are now two main approaches to diesel aftertreatment. These are shown diagrammatically in Figure 14. In the first, and currently favoured approach, a DeNOx trap is fitted upstream of a particulate filter. The DeNOx trap can be active or passive depending on the vehicle configuration and degree of NOx reduction needed. The particulate trap in this configuration needs special attention since it is downstream of one or two catalyst blocks and thus sees lower exhaust temperatures. In the second approach, a particulate trap is followed by a NOx reducer using Selective Catalytic Reduction and then an oxidation catalyst to provide final clean-up and protection against ammonia slippage. This system means that the particulate filter can be regenerated more easily but it is necessary to supply ammonia in the form of liquid urea. This system has been found to be very effective in controlling heavy duty engine emissions (Marguardt et al., 1999) but it is not really favoured for light duty applications due to the possible logistics problems of supplying and using urea in the light duty market. Both approaches are sensitive to the amount of sulphur in the fuel. Some configurations need less than 10ppm sulphur, but there are indications

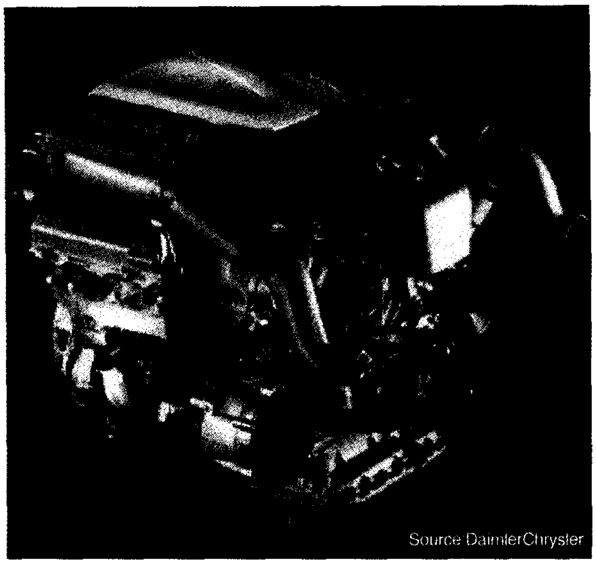

Figure 13. Mercedes V8 OM268.

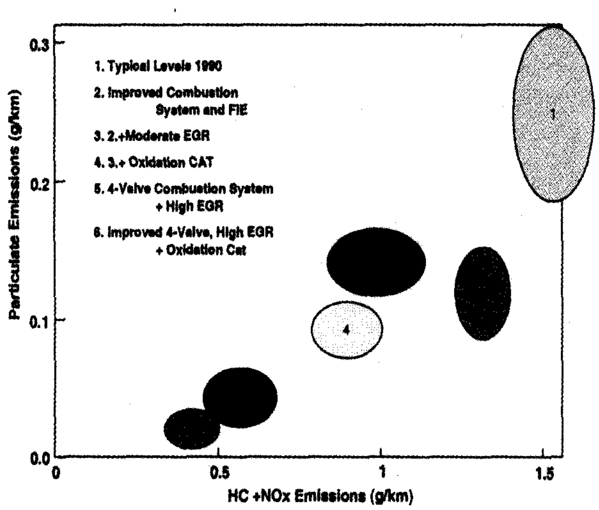

Figure 12. Reduction in vehicle particulates.

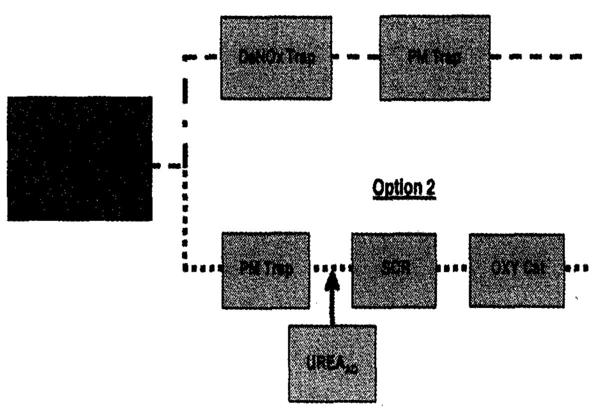

Figure 14. Diesel aftertreatment approaches.

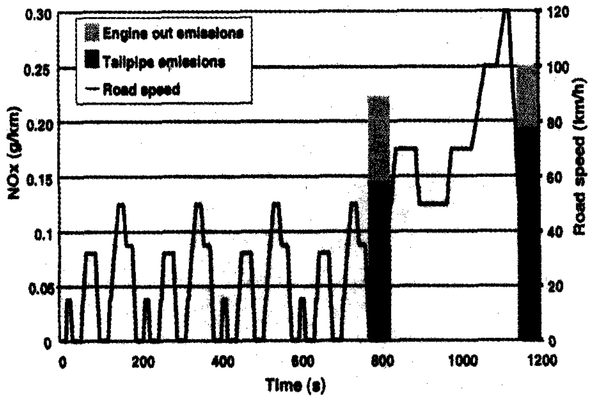

Figure 15. DeNOx effedtiveness.

that viable systems can be developed to cope with 30 or 50 ppm.

Figure 15 shows the effectiveness of an active DeNOx system applied to a 1500kg vehicle powered by 2.2 litre diesel producing some 100kW. The reducing agent for the DeNOx trap was hydrocarbons in the exhaust provided by post injection. This gave a CO2 penalty of less than 3%. As can be seen from the figure, the results are well inside the Euro IV 'box' and the effectiveness of the DeNOx system can be seen in the comparison of the engine out and tailpipe NOx emissions.

Exploration of the combustion requirements of smaller and smaller HSDI's has revealed that small cylinder sizes can give a better emissions/performance trade off than the traditional, approximately 500cc cylinder. This quite surprising finding is due to the reduction in thermal loading which the greater surface to volume ratio of the smaller cylinder gives. It thus becomes possible to obtain greater specific power from the smaller cylinder for a given thermal loading. The increased surface to volume ratio leads to a degradation in indicated specific fuel consumption, but the ability to uprate means that the brake specific fuel consumption virtually unchanged. The control of the fuel air mixing process given by high pressure injection systems means that the specific emissions also remain unchanged.

Figure 16 shows how a rating of 50kW/l from a 500cc cylinder is broadly equivalent to 60kW/l from a 300cc cylinder. Ricardo tests with a 1.21 HSDI with four cylinders of 300cc have shown that a rating of 66kW can be achieved at 4000 rev/min when the specific fuel consumption remains at only 233g/kWh. The maximum torque of the engine is 200Nm(22bar bmep). The emissions results from single and multi-cylinder tests are shown in Figure 17. It can be seen that Euro IV engineering targets are achievable

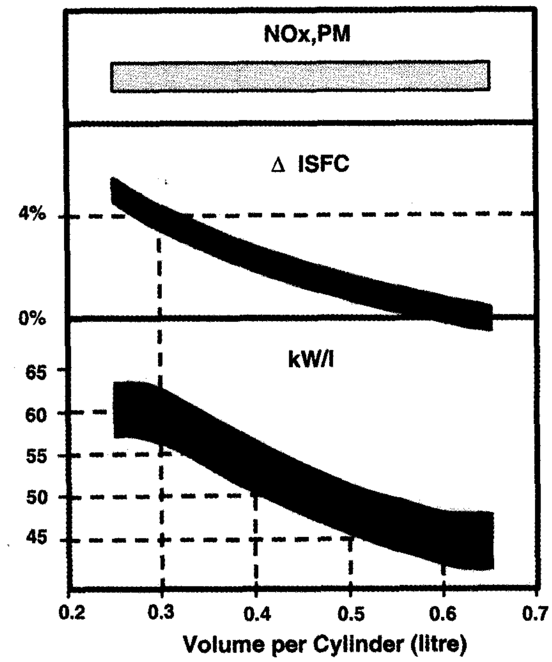

Figure 16. Downsizing of diesel cylinders

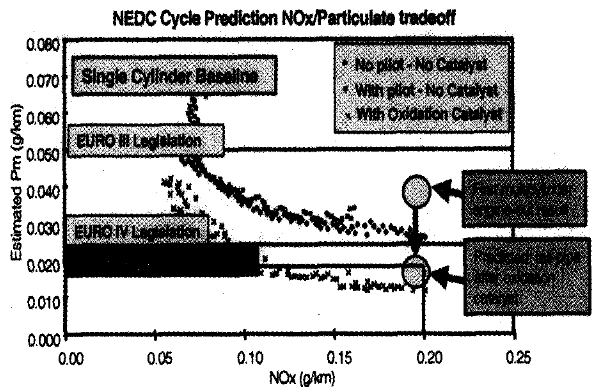

Figure 17. Small diesel emissions.

with only an oxidation catalyst.

We can thus see the emergence of a new generation of small cylinder HSDI's rated at over 60kW/l giving very good fuel consumption in real driving conditions, excellent driveability due to their high torque capability and, of course, full emissions compliance.

The immediate development in HSDI design can be predicted as a move towards open deck, aluminum cylinder blocks. This construction gives excellent bore cooling and is sutable for high volume manufacture using high pressure die casting. For the highly rated engines the cylinder centers are increased slightly to give a cooled interbore capability. With aluminum

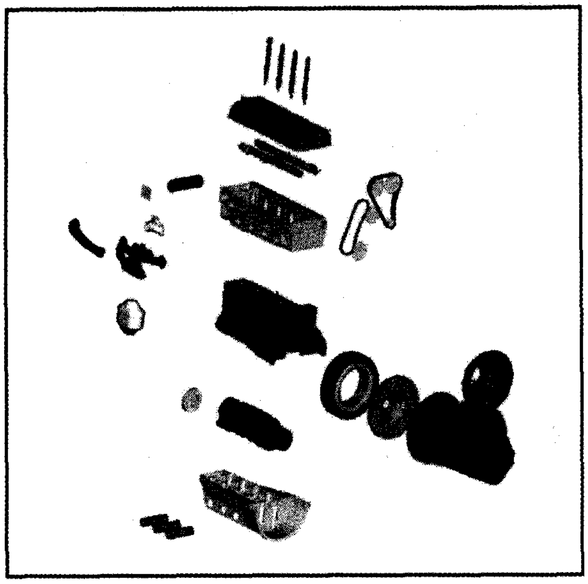

Figure 18. Integrated engine design concept.

blocks the liners can liners can be cast-in iron sleeves. A conventional head/block joint is used with long cylinder head bolts to provide a controllable gasket clamping force and to take the bolting loads down into the block and away from the top deck. To give rigidity the short block with and aluminum bed plate is favoured.

Figure 18 illustrates how the ISAD concept can be incorporated into a small HSDI concept in order to give advantages in terms of parts count, packaging, performance and refinement. The ISAD is built into the engine structure from the start and thus virtually all the ancillaries can be electrically driven. This permits a plain front end to the engine with only the oil pump and a torsional vibration damper driven off the crankshaft nose. The valve gear is driven by a two stage, nodal chain drive. The cylinder head and block are as described above, however the EGR cooler is housed in the cylinder head and the catalyst is attached directly to the sump.

Although the transmission is a separate unit from the engine, it is integrated with the cylinder block-ISAD housing as a design concept to give maximum rigidity. The transmission ratios and transmission control take advantage of the ability of the ISAD to feed power into (and out from) the flywheel.

4. DEVELOPMENT TOWARDS ALTERNATIVE POWERTRANS

The conventional powertranin(internal combustion engine-transmission-drive shafts) is faced with competition from hybrid concepts and fuel cells.

A continuing increase in the degree of 'electrification' permitted by ISAD type devices actually permits a single shaft parallel hybrid to be achieved very simply. The complex control and transmission systems needed for most of the 'full' hybrids are avoided and the extent of hybridisation can be adjusted by varying the size of the engine and batteries to suit particular duty cycles. The high cost of most full hybrids is likely to inhibit their market penetration and the partial hybridisation described above is the most feasible introduction route for them.

The fuel cell is the most likely direct competitor to the internal combustion engine, but the need for a liquid fuelling infrastructure and the high cost and inefficiencies associated with the use of an on board fuel reformer are likely to restrict the rate at which they supplant the conventional engines. Once sufficient volume has been achieved and once a sufficiently widespread fuel supply system is established then the cost can fall and the rate of penetration can increase. If the fuel cell were supplied directly with hydrogen, the cost of the fuel cell vehicle would be much less and the efficiency better. However the barrier to this approach is the problem of storing sufficient hydrogen on board the vehicle to give and acceptable range. A breakthrough in this area would mean that a hydrogen infrastructure could be developed. If this were to happen, then the conventional internal combustion engine could be adapted to burn the same hydrogen (Ciancia et al., 1994) and thus could remain in competition with the fuel cell.

5. CONCLUSION

(1) The main drivers influencing gasoline and diesel engines in the future will be exhaust emissions legislation, the need to limit CO2 production and an increasingly demanding customer.

(2) The port injected gasoline engine will continue to satisfy a large part of the market, but it will gradually incorporate advanced technologies such as fully variable valve actuation and cylinder disablement.

(3) The direct injection gasoline engine will continue to increase its penetration of the market as it evolves towards a truly stratified charge engine.

(4) The lean boosted version of the direct injection engine has the potential to equal the diesel in terms of CO2 production.

(5) The high speed direct injection diesel will quickly supplant the indirect injection diesel and evolve to provide very driveable, refined and economical

engine with specific powers as high as 70kW/l.

(6) The high specific power and good emissions performance of the high speed injection diesel are achieved by and evolution towards small cylinder sizes.

(7) Increased electrification of gasoline and diesel powertrains with the use of flywheel mounted electrical devices will bring emissions, efficiency and performance benefits and provide a route towards partial hybridisation.

ACKNOWLEDGEMENTS–The author would like to thank the Directors of Ricardo Consulting Engineers for permission to publish this paper. He would also like to thank colleagues for providing the detailed experimental and design information on which the paper is based.

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