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Benjamin, S.F. , Haynes, C.D. and Tidmarsh, D.H.

Published version deposited in CURVE June 2013

Original citation & hyperlink:
Benjamin, S.F. Haynes, C.D. Tidmarsh, D.H. (1986) Lean burn engines for low exhaust emissions. Proc IMechE Conf. on Petroleum Based Fuels and Automotive Application. London UK; 01/1986
http://www.imeche.org/

Additional note: Please note Professor Benjamin was working at BL Technology Limited at the time of publication.

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C320/86

Lean burn engines for low exhaust emissions

S F BENJAMIN, BSc, PhD, ARCS, **C D HAYNES**, BSc(Eng), CEng, MIMechE and
D H TIDMARSH, BSc, PhD, CEng, MIMechE
BL Technology, Warwick

SYNOPSIS BL Technology has carried out a long term investigation into the development of lean burn gasoline engines with the object of meeting future emission standards at minimum cost and with best vehicle performance and fuel economy. To date the 4V engine appears to give the best lean burn performance and the use of such an engine in a low emission vehicle concept is described in this paper.

INTRODUCTION

BL Technology Ltd. have been engaged in combustion research for a number of years. The objectives of these investigations have been to research and develop combustion systems giving improved economy, better performance and reduced emissions. In particular, over recent years, attention has focussed on achieving these objectives whilst complying with the legislative requirements governing fuel quality and emission levels. This paper describes the philosophy behind the adoption of four valve combustion chambers for lean burn engines and the use of such an engine to meet Phase 1 of the draft EEC Exhaust Emission Directive levels for vehicles up to 1.4 litre capacity.

HIGH COMPRESSION LEAN BURN STRATEGY

To meet the demand for fuel efficient low exhaust emission engines a study was initiated to investigate the potential of achieving these requirements using a high compression lean burn strategy.

It is well known that raising the compression ratio will improve thermal efficiency but increase the tendency for end gas detonation when operating at high loads. Hence the chamber design needs to be optimised to operate at the highest compression ratio possible consistent with the antiknock properties of commercially available fuels.

Lean burn offers the prospect of both improved fuel economy and reduced emission for part load operation. At lean mixture ratios thermal efficiency is increased whilst emissions of nitrogen oxide and carbon monoxide are reduced. However, with excessive charge dilution abnormal combustion may occur due to either misfire or flame quenching. Under such circumstances fuel consumption deteriorates, engine instability occurs and hydrocarbon emissions increase.

Hence the combustion strategy involves the design of combustion chambers capable of stable operation at lean mixture ratios at the highest compression ratio consistent with commercially available fuels.

EVALUATION OF COMBUSTION CHAMBER DESIGNS

To meet these objectives a study was initiated during which many different combustion chambers were evaluated on a single cylinder facility to determine those chambers showing potential for future development.

The combustion chambers covered a wide range of configurations including compact chambers, bowl-in-pistons, high swirl chambers and 'open' 4 valve designs.

Not only was chamber performance evaluated in the conventional sense but detailed studies were made of the in-cylinder flow fields and flame propogation rates using a combination of analytical and measurement techniques.

In particular it is of interest to compare the lean burn potential of four quite dissimilar chamber types. The chambers may be broadly classified as:

Chamber	Type
A	Open (4V)
B	Compact
C	High Swirl
D	Disc

Results presented below for these chambers refer to 12:1 compression ratio. This work was carried out before the move to unleaded fuel in Europe.

Figure 1 provides plots of emissions against BSFC as a function of mixture ratios for these chambers. Emissions are shown for both NOx and for HC + NOx. The latter reflects the draft emission directive criteria. The results are presented for engine operation at 2000 rpm, 2 bar BMEP.

Both chambers A and B achieve low levels of NOx by operating at lean mxiture ratios. The AFR needed to attain a given NOx level however is higher for both chambers. The graph showing (HC + NOx) against fuel consumption shows that these chambers satisfy the criteria outlined earlier for good lean burn potential.

optimised 'lean burn' performance. The stability requirement would necessitate tuning at relatively high levels of (HC + NOx) albeit at the point of minimum BSFC.

Chamber D could be tuned to give comparable emissions of (HC + NOx) to chambers A and B at the expense of inferior part load economy. It can be seen from this that a four valve chamber possesses considerable potential for future development.

The design of the four valve chamber can be conducive to good lean burn for several reasons. The spark plug is centrally located and therefore provides short flame paths. By optimising the port system, swirl can be readily generated in the cylinder and can be modified and transformed into turbulence in a controlled way at the point of ignition. In particular swirl can be generated efficiently without over restricting total flow. The combination of short flame travel and controlled turbulence allows the flame to propogate in an orderly and efficient manner as required for operation at weak mixture ratios.

The four valve layout, does of course, also give considerable breathing advantages over other designs with the inherent benefits of better torque and power and reduced pumping losses. The open nature of this chamber type also avoids pockets of end gases and minimises the tendency to detonate. This is also aided by the short flame paths inherent in this design.

FOUR VALVE DEVELOPMENT

Having selected the four valve chamber for further development various studies were performed to exploit the inherent advantages of such a design.

In particular extensive work was performed to optimise the chamber geometry and in-cylinder flow fields.

Geometric investigations included affects of valve angles, squish bands, piston crown profiles and plug position. Various port and valve sizes were investigated to study the effect of swirl and turbulence levels within the chamber.

These studies demonstrated that from the basic design an optimised system depends critically on the interaction between the in-cylinder flow field and chamber geometry if a controlled flow field is to be achieved.

VEHICLE APPLICATION

At an intermediate stage of the 4V chamber development described previously it was decided to build a three cylinder 4V engine for use in a research vehicle with an added target being the achievement of the phase 1 of the draft EEC Exhaust Emission Directive levels for this class of vehicle.

It was also decided that the targets would be achieved with the minimum of sophistication and additional hardware. To this end a single downdraught twin choke carburetter was chosen rather than petrol injection as used in other builds for this vehicle. No exhaust catalyst or exhaust gas recirculation was required although a was used. A constant depression carburetter was tried initially but it was not felt that in the short time available for this project that it would be possible to resolve the tuning problems created by the pulsing nature of the induction air with three cylidners to one carburetter. The compound carburetter used made it easier to separate the full and part load fuelling requirements of the engine.

Basic engine data are given in table 1. The engine incorporated lightweight components including weight reduced pistons and connecting rods. The piston assembly weight was 288 gm, compared with a previous production design of 476g, whilst the connecting rod was reduced from 612 to 512g. Valves are operated from a single camshaft operating the valves via rockers. This layout gives a compact engine of low overall height and also gives the possibility, not used in this example, of using roller followers to reduce friction. This is difficult to achieve with direct operation and would lead to a further increase in engine height.

The engine did not feature a balancing shaft of any form since this was considered expensive both in terms of cost and friction and hence fuel economy. The out of balance primary couple which remains with 50% balance of the reciprocating

Table 1 Basic Engine Data

Capacity cc	1184
Bore mm	76
Stroke mm	84
CR	10.3
Valve Timing (measured at junction of flank and ramp)	Inlet Opens 14° BTDC Inlet Closes 54° ABDC Exhaust Opens 54° BBDC Exhaust Closes 14° ATDC
Maximum Power kW	54
Maximum bmep bar	11.4
SFC at 2000 rpm 2 bar g/kW.hr	361
Carburetter	Single downdraught twin choke compound carburetter
Inlet Manifold	Water heated - carburetter with heated air intake. No electric manifold heating
Head	4 valves/cylinder - aluminium
Valve Operation	Single overhead camshaft operating valves by rockers
Block	Aluminium with pressed in cast iron liners

parts is dealt with by supporting the engine/gearbox unit under its centre of gravity, reacting torque by a rod above the centre of gravity, and by the use of soft mounts at either end of the engine/gearbox allowing the ends of the unit to move in a rotary motion with the centre of gravity relatively stationary. This gave a degree of engine refinement superior to most 4 cylinder engines.

The engine drives the vehicle via a five speed gearbox. Although fifth gear is not relevant to the results quoted in this report it is of interest to note that the vehicle was at times fitted with a modification to the standard gearbox to give an automatic operation of the change between fourth and fifth gear. In this system the manual change lever had only four forward positions and fifth gear was engaged automatically depending on manifold vacuum and vehicle speed. This automatic operation enabled the use of a higher fifth gear than was desireable in a manual change where it is necessary to avoid the need for an excessive number of gear changes and this gives better fuel economy in motorway, constant speed, running. Designs have been produced for 2 and 3 shaft gearboxes.

The Energy Conservation Vehicle (ECV) is a low drag vehicle (Cd 0.25) with an unladen kerb weight of a little under 1750 lbs. This low weight and low drag combined with the low speed/acceleration of the ECE cycle mean that the emission - fuel economy cycles are driven at a very low load factor. Table 2 shows a prediction of the time spent in a full ECE test at various load - speed combinations. The extreme importance of loads below 1, or even $\frac{1}{2}$ bar is perhaps surprising to many people - 41% of the total time is idle or below 0.5 bar, 68% of the time at idle or below 1 bar (deceleration is not counted in the idle time).

Table 3 shows the percentage of emissions which are emitted in various speed/load bands from a vehicle of similar power/weight to the ECV. This further emphasises the importance of the low speeds/loads. Approximately 25% of the emissions and 35% of the fuel usage occurs at loads above idle but below 1 bar.

The engine was therefore tuned on an engine test bed with particular reference to these light load conditions with best economy being the primary intent. There were some limitations in that there was a relatively short period of time available and this did not permit specific carburetters with dedicated idle progression drillings to be developed.

The engine was then fitted to the car and tested over various emission cycles. An immediate problem that was encountered was that there were unacceptable spikes of high NOx mass emission immediately off idle. This was found to be due to mixture going from rich of that which gave peak NOx emission at idle to weak of the peak NOx mixture on load. This resulted in the engine being on load at peak NOx mixture for a short while. It was also found later, when the engine was mapped, that areas of richer than intended mixture existed in this tune. These spikes were lowered by ignition retardation in very local areas. The full electronic ignition system enabled this retardation to be local so that the effect on fuel economy was minimised and kept to approximately 1 mpg on a hot ECE test. To further reduce the NOx emissions, with some impairment of HC levels, the mixture was also weakened from the best economy settings.

Table 3

Percentage of Emissions and Fuel Usage at Various Speed/Load Combinations for 1.6l Engine in ECE Test

Engine Speed rpm	Load Bar	% HC	% CO	% NOx	% Fuel
500 - 1000	Negative	23	12	4	11
750	Idle	24	31	1	18
1500 - 2500	0 - $\frac{1}{2}$	13	21	16	22
1500 - 2500	$\frac{1}{2}$ - 1	13	6	22	15
1000 - 1500	$1\frac{1}{2}$ - 2	7	9	5	8
2000 - 2500	$3\frac{1}{2}$ - 4	20	21	52	26

Table 2 Time Spent at Various Speed/Load Combinations in the ECE Cycle by ECV

BMEP (BAR)

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0

RPM		SECONDS																OVER - RUNS		
0	250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	250	0
250	500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	250	500	0
500	750	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	500	750	4
750	1000	273	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	750	1000	8
1000	1250	0	0	0	16	4	8	0	0	4	0	0	0	0	0	0	0	1000	1250	12
1250	1500	0	0	0	0	8	8	0	0	4	0	0	0	0	0	0	0	1250	1500	12
1500	1750	0	56	0	0	8	4	4	4	4	0	0	0	0	0	0	0	1500	1750	12
1750	2000	48	0	0	0	0	8	0	12	4	0	0	0	0	0	0	0	1750	2000	28
2000	2250	0	0	0	0	0	4	0	12	4	0	0	0	0	0	0	0	2000	2250	20
2250	2500	0	144	0	0	0	8	0	4	0	0	0	0	0	0	0	0	2250	2500	8
2500	2750	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2500	2750	0
2750	3000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2750	3000	0
3000	3250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3000	3250	0
3250	3500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3250	3500	0
3500	3750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3500	3750	0
3750	4000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3750	4000	0

Fuel Economy and Emission Test Results

	COLD ECE 15.04 EMISSIONS (g/test)				HOT ECE 15.04 EMISSIONS (g/test)				FUEL CONSUMPTION (mpg)	
	CO	HC	NOx	HC+ NOx	CO	HC	NOx	HC+ NOx	COLD ECE 15	HOT ECE 15
ECE 15.05 Limits	45	-	6 Max	15	-	-	-	-	-	-
ECV 3-1200 Petrol 800kg Test Wt.	8.7	10.0	3.7	13.7	5.0	7.9	3.5	11.4	39.4	45.2
As previous test but 910kg Test Wt.	7.9	8.6	5.2	13.8	-	-	-	-	-	-

This gave results presented in Table 4. It can be seen that because of the lean operation the CO levels are well under the proposed standard whilst the HC + NOx levels are just under the proposed levels. This is true at both the correct vehicle test weight of 800 kg and at 910 kg which is a more probable vehicle test weight for production engines of this capacity.

Table 5 shows the percentage emissions which are emitted in the various speed load bands for this vehicle at 800 kg wt. when tested over the ECE cycle.

Table 5
Percentage of Emissions Emitted at Various Speed/Load Combinations for ECV in the ECE Test

Engine Speed rpm	Load Bar	%HC	%CO	%NOx
500-1000	Negative	17	23	4
500-1000	Idle	13	16	2
1500-2000	0-½	4	5	5
2000-2500	½-1	17	17	12
1500-2000	1-1½	8	7	4
2000-2500	1-1½	8	6	10

Although the vehicle did not undergo full development cold start and other necessary evaluations for production vehicles it was driven in a wide range of conditions with totally acceptably driveability and performance on unleaded gasoline of 95 RON (ULG 95).

The engine was then removed from the vehicle and fully mapped over the speeds - loads that are of interest for cycle emission and fuel economy tests.

Fig. 2 shows the full throttle performance of the engine as installed in the vehicle. Maximum power is 54 kW (60 bhp/litre) and maximum bmep is 11.4 bar. The performance above 3000 rpm, particularly for s.f.c., is compromised by a rich tune which was not corrected since the main interest at this time was in the emission performance at lower loads.

Fig. 3 which shows the air fuel ratio at which the engine runs shows areas as weak as 24:1 with much of the map at 20:1 or weaker. The difficulties of obtaining the desired air fuel ratios can be seen in the part of the map in the 0 to 1/1½ bar area where there are large variations in air fuel ratio with small changes in load or speed. A longer development period may have allowed these variations to be reduced.

The s.f.c. map (fig. 4) does not show the absolute minimum s.f.c. of the engine since this occurs at a higher load than was of interest for emission purposes. The 2000 rpm/2 bar level of 361 g/kW.hr. is excellent for operation on 95 ULG fuel. The noteworthy feature of the HC contour map (fig. 5) is the rapid increase in specific HC emissions as the bmep is reduced which implies that lowest HC emissions will occur if the engine is operated at high load - low speed rather than vice versa. A further deduction is that in order to meet the HC + NOx standard of 15 with a 1.4l engine the 2000/2 bar HC emission should be below 7g/kW.h.

The NOx contours, fig. 6, show high NOx emission at 1750 rpm between 0.5 and 1.5 bar and also show an unusual increase in NOx levels as load is decreased. This is due to the undesireable air fuel ratio characteristic in this area with mixture strength as rich as 15 to 1 and much of this local area at mixtures of around 17:1 which gives maximum NOx. This area would be a prime target in any retune which might be necessary if it were necessary to meet lower emission standards.

Specific CO emissions are indicated in Fig. 7.

Since this work has been carried out further improvements have been made to the lean limits which can be achieved with 4V engines.

CONCLUSIONS

The results reported here indicate that an open chamber 4V engine with suitable combustion chamber layout and port generated swirl can give excellent fuel economy and power whilst still meeting the proposed phase 1 draft directive emission standards without the need for expensive and potentially power consuming add on devices. In addition such a system gives a more stable emission level with time than does a catalyst approach and is likely to give lower total emissions over the vehicle life and a lower cost of ownership. The work to date does, however, indicate that significant further reduction in these proposals will require the use of such undesireable additional features.

It must be stressed that in order to obtain good lean burn performance with 4V engines requires careful optimisation of chamber and port and that many 4V engine designs do not exhibit such good lean burn characteristics as those reported here.

ACKNOWLEDGEMENTS

The authors wish to thank the directors of BLT for permission to publish this paper.

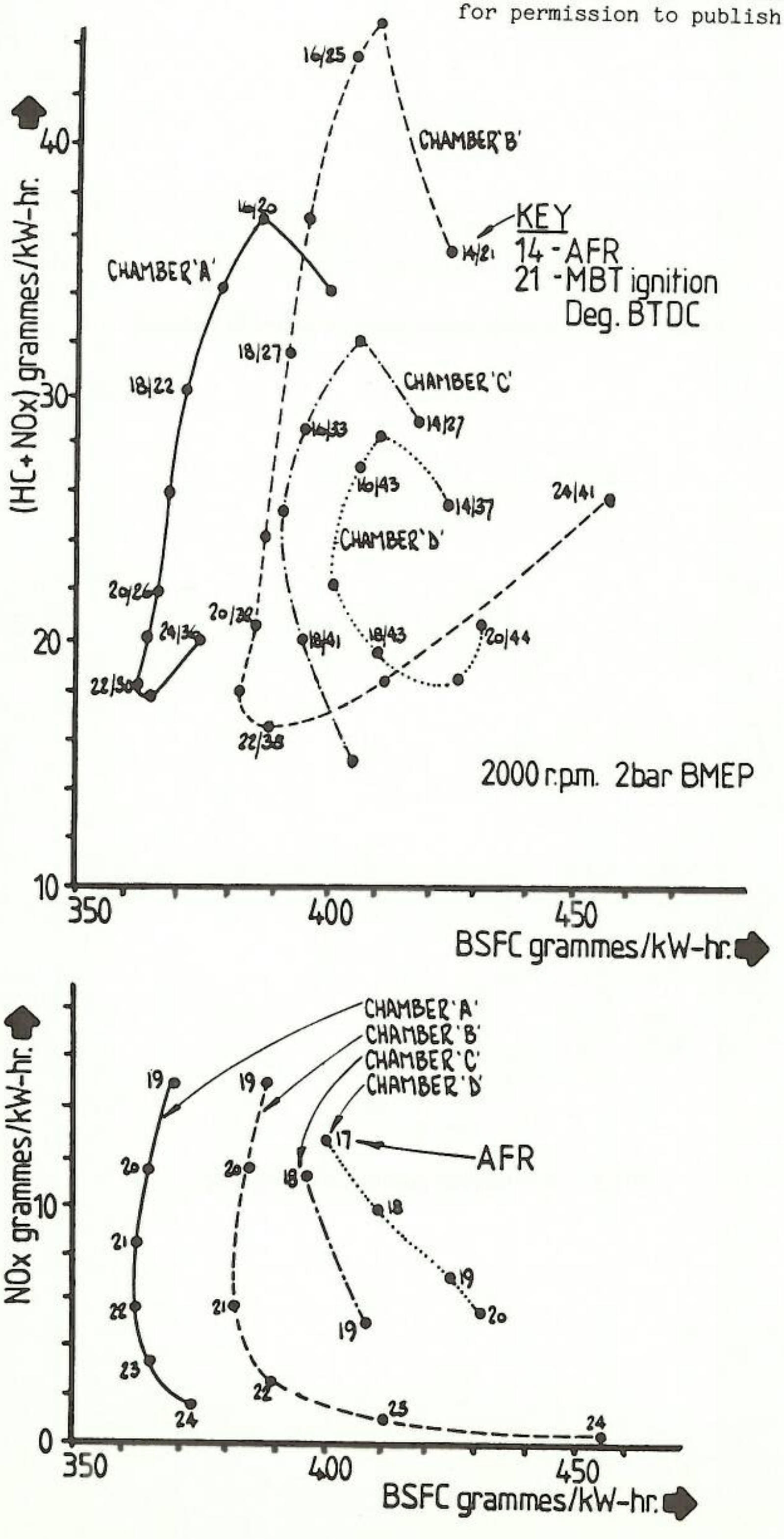

Fig 1 Comparison of four combustion chamber types

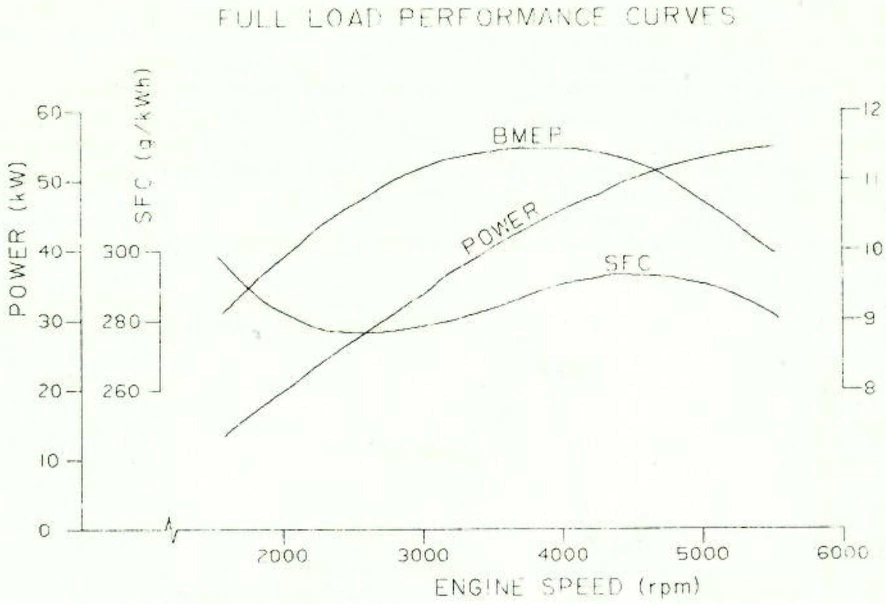

Fig 2 Full-load performance curve of engine as installed

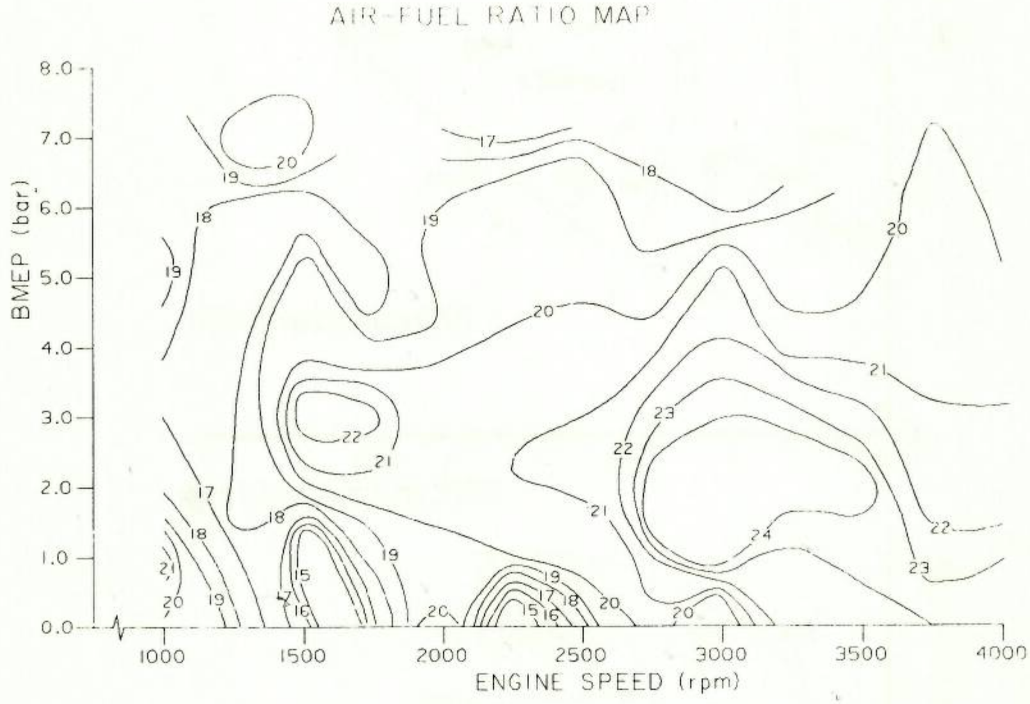

Fig 3 Contours of constant air–fuel ratio

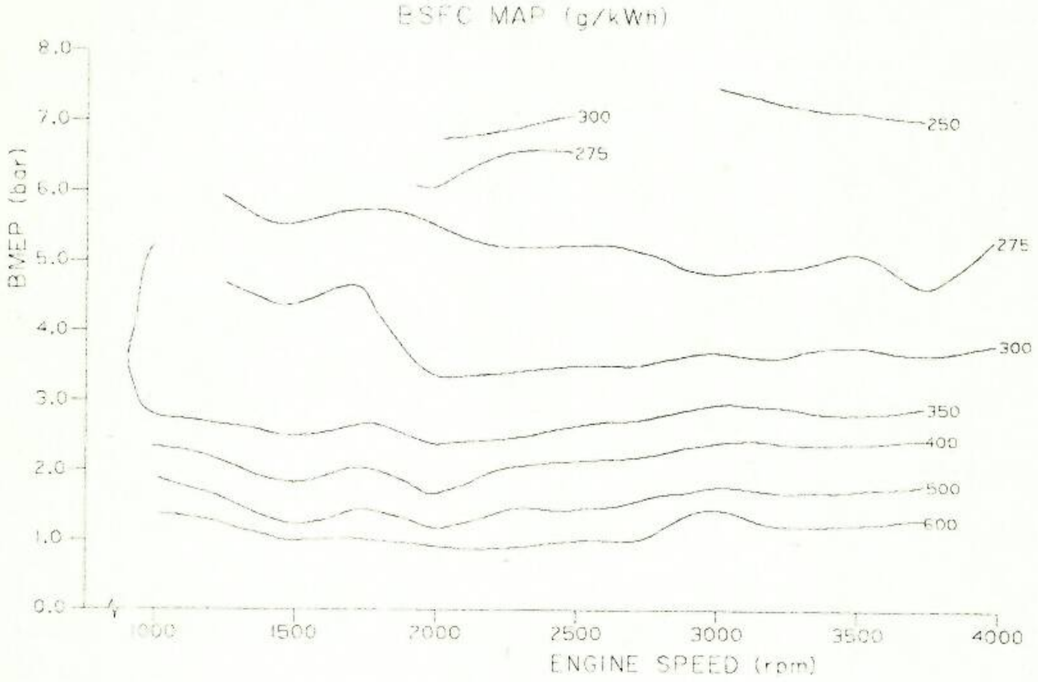

Fig 4 Contours of constant specific fuel consumption

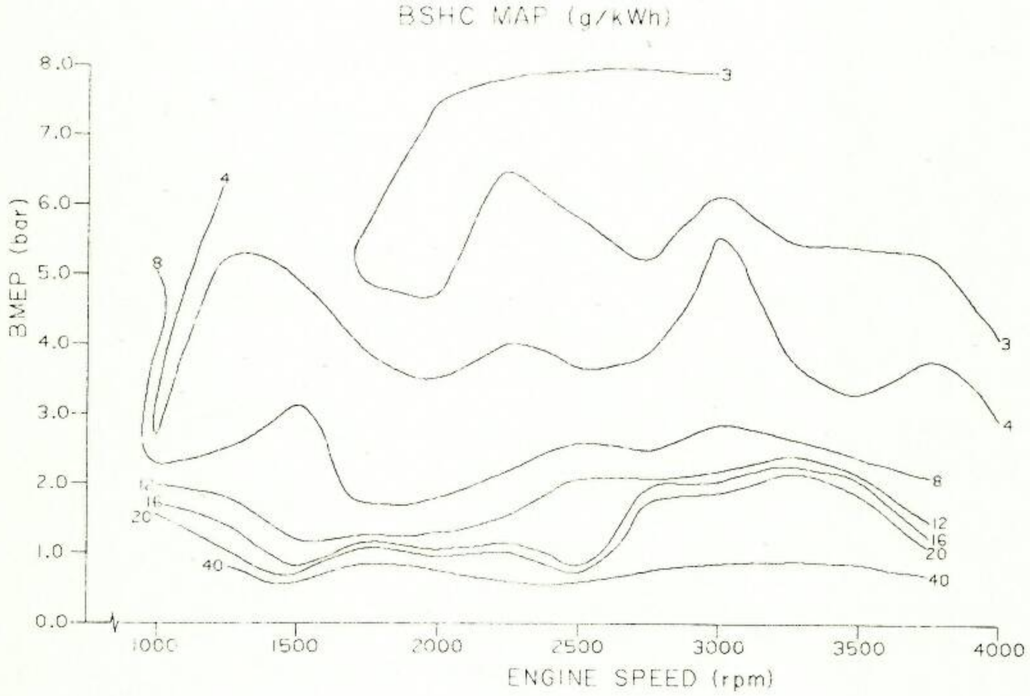

Fig 5 Contours of constant specific HC emissions

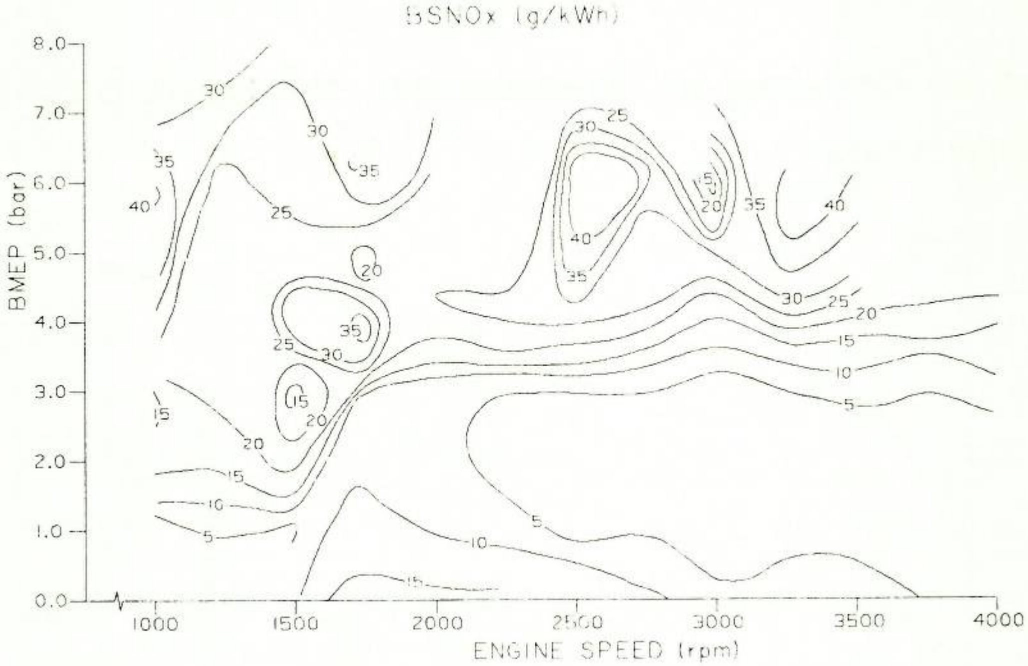

Fig 6 Contours of constant specific NO_x emissions

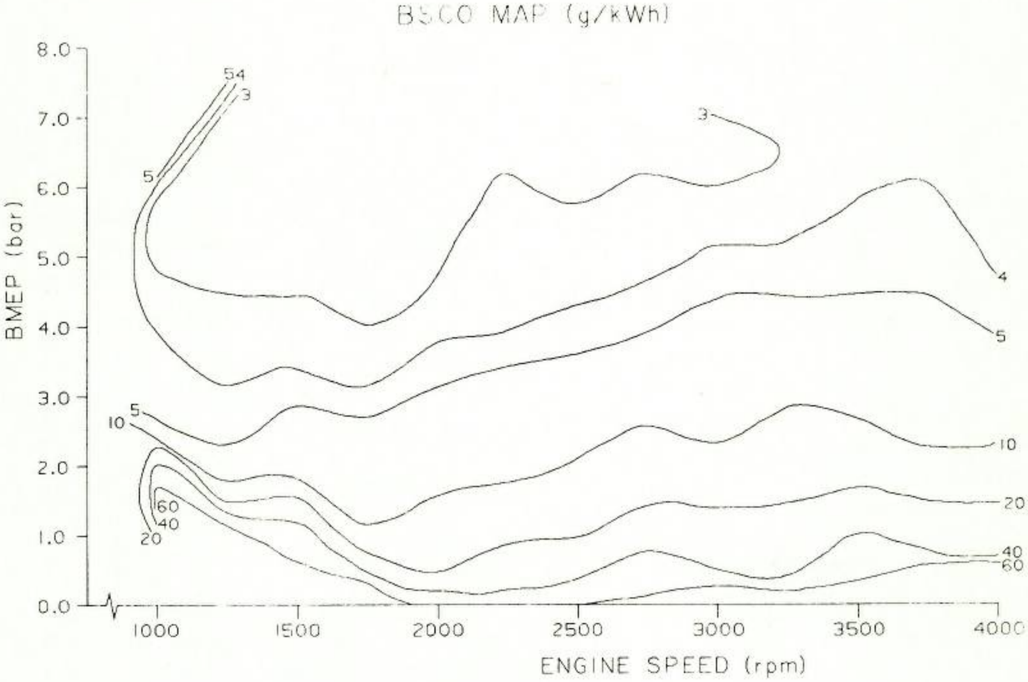

Fig 7 Contours of constant specific CO emissions

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