PERFORMANCE OF NATURALLY ASPIRATING IC ENGINES OPERATING AT HIGH ALTITUDE

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Abstract

The loss of power and the increase of fuel consumption of naturally aspirating IC engines operating with low atmospheric pressure at high altitude as well as changes in the mixture quality with non adapting mixture formation systems are principally known. Other effects like the additional advance of ignition timing in petrol engines or the injection timing of Diesel engines as well as changes of the exhaust gas quality are usually not considered and no measures are taken in many developing countries - even when having extended highlands - for improving the economic and environmental consequences of such unfavourable engine operation.
After reconsidering the important influences and their theoretical background in high altitude engine operation some results out of road and laboratory tests with conventional petrol engines obtained in Ethiopia are shown as well as proposals for simple adaptation of engine systems.

Introduction

Some countries in Asia, Africa and Latin America have extended highlands. The influence of their ambient conditions in the operation of both stationary and motor vehicle IC engines becomes therefore quite interesting and important. Usually in developing countries many more types of new to rather old, both stationary and motor vehicle IC engines of very different origins are utilized then in industrialized countries. In order to cope with the usually lower level of service and maintenance, most of these engines do not have advanced systems for the proper adaptation of the engine operation to the ambient conditions.

Toyota for example was producing and selling a special "Africa" version of the Corolla passenger cars, model 1988, in which among other simplifications the double barrel carburetor and the ignition system are not adapted in any way for high altitude operation. The ignition timing is to be set even some degrees later than normally specified by the producer.

Cars without systems for improved exhaust gas quality (exhaust gas catalyzers, purifiers and the like) are not allowed to move around in industrialized countries, to avoid the steady pollution of the atmosphere. In developing countries the concerned authorities have not yet considered such problems and no measures are usually taken so far. The consequences are even worse when the engines operate at high altitude without any adaptation to these conditions.

After reconsidering the theoretical and practical background, based on some tests carried out on the road and in the IC engine laboratory of the Faculty of Technology of the Addis Ababa University, it is to be shown how considerable improvements can be achieved by simple adaptations of engine systems.

Conversion of Power and Fuel Consumption

The maximum work developed in the engine cylinder (indicated work) changes, despite some other influences, basically with the mass of the burnable fresh charge in it. The consequence in the effective work obtainable on the flywheel is even greater due to the action of the mechanical losses of the engine. Those matters have been widely investigated starting the late twenties because of the importance for comparing and guaranteeing engine test results obtained under different site conditions. This was also influenced by the power demand for earlier fighter planes flying at great height above ground.

Especially with respect to the medium size and big commercial engines Zinner dedicated his work partially to this field contributing much to the international standardization of conversion formulae for IC engines [1, 2, 3, 4] .

For naturally aspirating (not supercharged) IC engines the conversion of maximum power and specific fuel consumption from one site to another is valid and reliable only if the quality of the mixture is maintained for the different conditions to be compared. In the simplest case it is assumed that the power of the mechanical losses P_m of the reference (atmospheric) condition (subscript r) equals to that of the variable conditions (subscript v) so that the differences between the indicated power P_i (power developed in the engine cylinders) and the effective power P_e (net power on the flywheel) are equal too:

$$P_m = P_{ir} - P_{er} = P_{iv} - P_{ev} \qquad (1)$$

from where follows :

$$P_{ev} = P_{iv} + P_{er} - P_{ir} \qquad (2)$$

The conversion of the indicated powers is given by the conversion factor k considering the atmospheric (absolute) pressures *(p)* and absolute temperatures *(T)* :

$$k = \frac{P_{iv}}{P_{ir}} = \frac{p_v}{p_r}\sqrt{\frac{T_r}{T_v}} \qquad (3)$$

The mechanical efficiency is generally defined by [6]:

$$\eta_m = P_e \,/\, P_i \qquad (4)$$

From eqn.(2), (3) and (4) it follows :

$$P_{ev} = P_{er}\,[1-(1-k)\frac{1}{\eta_{mr}}] \qquad (5)$$

A more general definition of the indicated power conversion factor is

$$k = (p_v \,/\, p_r)^m \,(T_r \,/\, T_v)^n \qquad (6)$$

where variations of the air humidity can be considered in the corresponding atmospheric pressures by applying the partial pressures of the dry air [2], i.e. the total pressure minus partial pressure of vapor (see also DIN 6270).

For naturally aspirating engines the amount of fresh charge induced into the working cylinder changes with the atmospheric pressure so that $m = 1$. Other than what is known from Thermodynamics the mass of fresh charge depends not only on the absolute temperature but also on the volumetric efficiency which is defined as the relation of the actually sucked charge to the theoretical one according to the working displacement volume of the engine. The volumetric efficiency was found to increase with the temperature to the power of 0.2 up to 0.3 only [2] which is mainly an effect of density and viscosity changes. Then the product of temperature and volumetric efficiency variations has to be considered in the conversion factor as follows :

$$\frac{T_r}{T_v}\,\frac{\eta_v}{\eta_r} = [\frac{T_r}{T_v}]^{1-(0.2...0.3)} \qquad (7)$$

so that the exponent becomes finally
n = 0.7 ... 0.8 [2].

Out of these investigations the exponent 0.75 was introduced into the conversion formulae for stationary, ship and locomotive Diesel engines of the German standard DIN 6270. (For more extended and specific considerations of power conversion of turbocharged IC engines see [3, 4, 5] and the like).

As already given in equation (3), in the conversion factor for naturally aspirating motor vehicle engines the temperature change was considered by $n = 0.5$ only and was introduced in this form into DIN 70020.

With respect to the load of the engine, the mechanical losses consist in reality of a constant and a variable part. With changing atmospheric conditions the pressure level inside the working cylinder can be considered in the conversion formulae by a coefficient " α " which is near 0.07 [2]. With it the final conversion formulae for the effective power P_{ev} and the specific fuel consumption b_{ev} of naturally aspirating IC engines can be written as

$$P_{ev} = P_{er}\,[\,1 - (\,1 - k\,)\,\frac{1-\alpha}{\eta_{mr}}\,] \qquad (8)$$

$$b_{ev} = \frac{b_{er} - k}{1-(1-k)\frac{1-\alpha}{\eta_{mr}}} = b_{er}\,\frac{k\,P_{er}}{P_{ev}} \qquad (9)$$

Petrol Engine Operation at High Altitude

For Addis Ababa (about 2500 m above sea level) and the Ethiopian highlands around it the above mentioned power loss will be about 30 % or even more. Ambient temperature and relative humidity will not be considered here because they don't differ much from standard conditions. In addition, since many of the popular even new passenger cars are not provided with devices capable of adapting automatically mixture quality and ignition timing to the low atmospheric pressure (the above given equations don't apply then), an even greater power loss and increased fuel consumption must be expected.

Influence of Mixture Quality

The mixture quality is usually defined by the air ratio "λ" which is the relation of the actually sucked air mass in the mixture with a certain fuel mass, over the theoretically correct air mass for complete combustion of a given fuel mass (stoichiometric mixture relation). This dimensionless ratio is widely used in European literature and describes the operation with rich mixtures below and for lean mixtures above λ = 1 (whereas the Americans prefer either the air fuel ratio AF or its inversion FA [7], both being somewhat cumbersome because they are not dimensionless and depend on the composition of the fuel used).

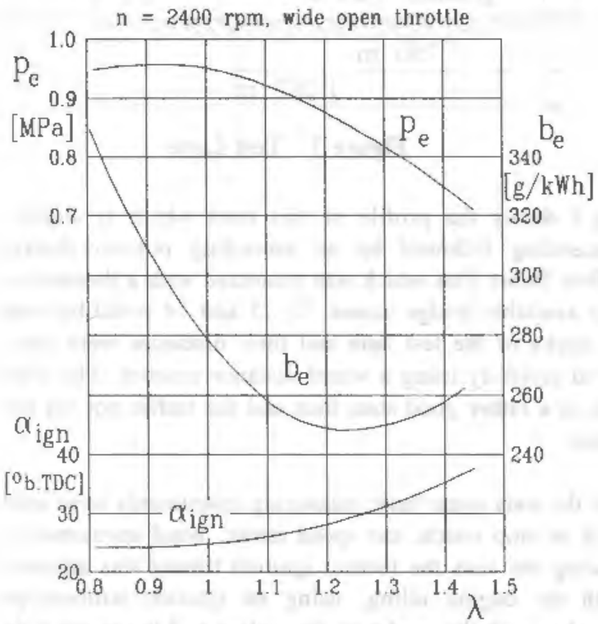

Figure 1 Air Ratio Influence in Engine Parameters

Fig.1 shows the influence of the air ratio on the mean effective pressure p_e (= *bmep*) and specific fuel consumption b_e of a one cylinder petrol test engine when running at wide open throttle at 2400 rpm [8]. The results were obtained with optimum ignition timing for which the characteristics are indicated on the bottom.

Such test results are principally true for any 4 stroke petrol engines at any operation point. It follows that the mixture for maximum power should be near the stoichiometric one, slightly in the rich field for which an increase in the fuel consumption has to be accepted. For best efficiency (minimum specific fuel consumption), the mixture should be lean at about λ = 1.2, which should apply for all part load operation points. The leaner the mixture the earlier would be the optimum ignition angle to make up the somewhat slower flame travel velocity, which is maximum at about the stoichiometric mixture.

In addition to Fig.1, Fig.2 shows the influence of the mixture quality, again represented as air ratio λ, on the exhaust gas quality. These test results were obtained with a 1.7 liter four cylinder four stroke engine at throttle valve angle 40° (upper part load), 2500 rpm, always with optimum ignition advance [8]. Such behaviour is again very typical for four stroke engines.

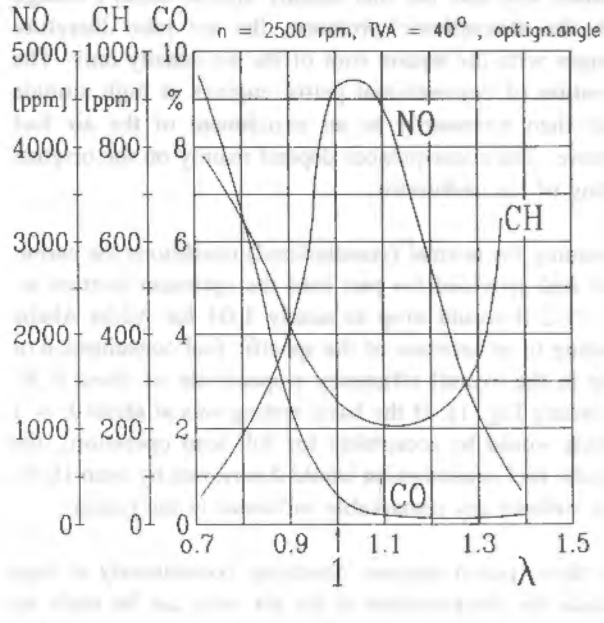

Figure 2 Air Ratio Influence in Exhaust Gas Quality

Fig. 2 shows that the operation at about λ = 1.2 is somewhat optimum too (compare with minimum specific fuel consumption, Fig.1), as far as these exhaust gas components are concerned if no other measures are taken to improve totally the exhaust gas quality. Modern mixture quality concepts, with even lower content of harmful exhaust gas components, are derived from the stoichiometric mixture relation where a reduction of nitrogen monoxide (NO) in the so called 3-way catalyzer supplies the oxygen for oxidizing almost completely the remaining carbon monoxide (CO) and the different unburned hydrocarbons (CH).

The mixture relation provided by a carburetor is given by the mass flow of air through the venturi tube and that of the fuel trough the main jet. According to the elementary carburetor theory the same pressure difference between atmospheric and static pressures in the throat of the venturi applies for the two flows. (For more details see for example [7, 9]). Therefore it can be shown that the air ratio is determined by the effective areas (including the discharge coefficients) of the venturi A_v and the main jet A_j, the actual densities of air ρ_a and fuel ρ_f and the stoichiometric mass relation of air and fuel according

$$\lambda = \frac{A_v}{A_j}\sqrt{\frac{\rho_a}{\rho_f}}\,\frac{1}{\left[\frac{m_a}{m_f}\right]_{stoich}} \qquad (10)$$

Since the areas and the stoichiometric mass relation are constant and also the fuel density almost doesn't change with the atmospheric pressure, the air ratio therefore changes with the square root of the air density only. The operation of conventional petrol engines at high altitude leads then necessarily to an enrichment of the air fuel mixture. The consequences depend mainly on the original setting of the carburetor.

Assuming for normal (standardized) conditions the carburetor had provided for part load the optimum mixture at $\lambda = 1.2$ it would drop to nearly 1.04 for Addis Ababa (leading to an increase of the specific fuel consumption or drop in the overall efficiency respectively of about 9 %, according Fig. 1). If the basic setting was at about $\lambda = 1$ (which would be acceptable for full load operation), the specific fuel consumption would deteriorate by even 16 %, here without any remarkable influence in the power.

For those petrol engines operating continuously at high altitude the deterioration of the air ratio can be made up easily by an adaptation of the effective main jet area according to eqn. 10. It should be decreased with the square root of the air density change (to be approached by the atmospheric pressure change at constant temperature). The effective diameter of the jet should then be decreased approximately with the fourth root.

The much lower pressure level with part load inside the engine cylinder leads to a considerable decrease of the flame propagation velocity. This is usually counteracted by the vacuum ignition advance of any conventional passenger car petrol engine. Since such systems compare the pressure drop, due to the throttling, in the intake manifold only, they cannot adapt an additional change in the atmospheric pressure. Therefore an additional (static) ignition advance has to be considered for high altitude.

Road Fuel Consumption Tests

Since maximum power is seldom required for normal driving at moderate velocities the average road fuel consumption becomes then the most important parameter for the evaluation of the entire vehicle economy, whereas for more detailed investigation in the test bench, despite the power output, the specific fuel consumption and exhaust gas quality are the parameters to be considered mainly, as shown above.

A Toyota passenger car Corolla XL 1.3 l, model 1988, was selected for some road fuel consumption tests to be carried out on the rather plain and straight road between Dukam and Debre Zeit. (The tests were carried out during the Final Project of Amdemichael Retta, AAU, 1990).

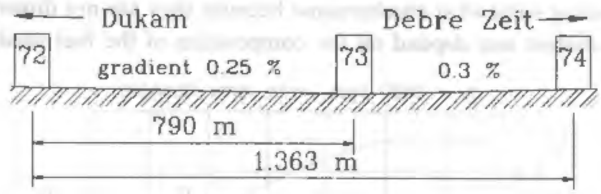

Figure 3 Test Lane

Fig.3 shows the profile of this road which is slightly descending followed by an ascending portion shortly before Debre Zeit which was measured with a theodolite. The available bridge stones 72, 73 and 74 could be used as marks of the test lane and their distances were measured carefully using a wheel distance counter. The road was in a rather good state then and the traffic not yet too dense.

For the tests some basic measuring instruments were used such as stop watch, car speed meter, wind anemometer. During the tests the (static) ignition timing was adjusted with the engine idling, using an ignition stroboscope together with the marks on the pulley and the angle scale on the engine block.

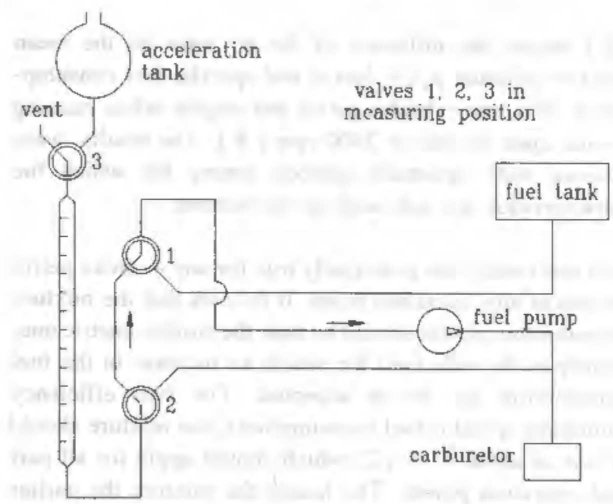

Figure 4 Fuel Consumption Measuring Device

Fig.4 shows the fuel consumption measuring device which was assembled in the workshop of the Faculty of Technology using an available 200 ml scaled glass tube with acceleration reserve tank. With this tube volume a maximum measuring distance of 2 km could be applied even with bad engine setting. The device with two additional two-way valves on a plywood board was installed in front of the co-drivers seat and connected with 3 hoses to the car fuel system. With the engine running, four different valve settings were applied:

- fuel supply to the engine directly from the tank
- additional filling of the tube
- acceleration of car to desired velocity with fuel from the acceleration reservoir
- measuring position of all valves

In every case the fuel was supplied to the carburetor through the fuel pump, thus maintaining fuel flow pattern and engine operation conditions while changing the valve positions. The acceleration reserve tank that is usually not provided with similar test devices is used to approach the desired velocity before test begin. It serves mainly to improve the measuring exactness since the (fast) turning of valve 3 at the beginning of the test doesn't interfere at all in the engine operation.

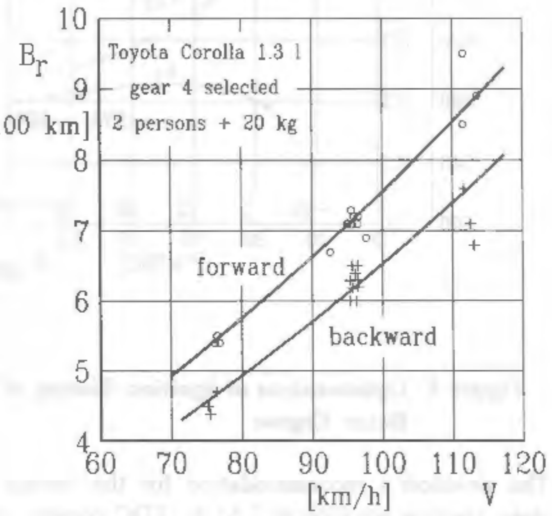

Figure 5 Road Fuel Consumption with Changed Velocity

Fig. 5 shows initial test results with the expected sharp rise of the fuel consumption with increasing velocity. Because of the additional wind resistance forces which are encountered frequently in Ethiopian highlands the forward tests (toward Debre Zeit) cause higher road fuel consumption. When running with 120 km/h (tachometer reading), the measurement exactness was far less than with lower velocities (see different scattering of measured points in Fig.5), mainly because of the disturbances by the normal traffic. Therefore all the following tests were carried out several times forward/backward at 100 km/h. Out of it the average values were taken for further evaluation.

The optimization of fuel consumption and ignition timing

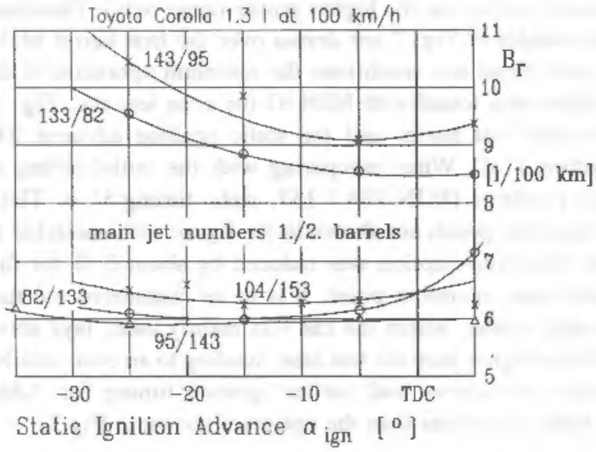

Figure 6 Optimization of Main Jet and Timing

is shown in Fig. 6. For these tests a number of different main jets were interchanged for the two barrels of that carburetor directly on the road. Previously a simple flow measuring device was made and the main jets were calibrated with it after their manufacture thus obtaining the efective diameter in 1/100 mm (main jet number MJN). For every main jet setting the ignition timing was changed on the road with the engine idling thus giving the static ignition advance as parameter. (It is then superimposed by the vacuum and centrifugal advances under normal operation). Out of the test data the indicated characteristics were traced.

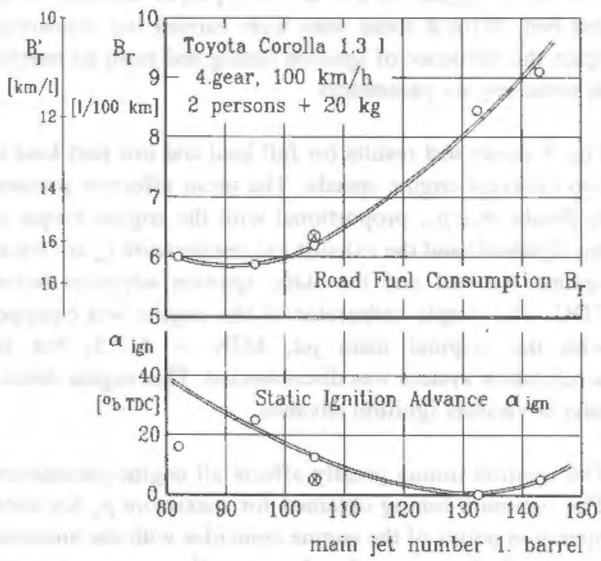

Figure 7 Optimum Road Fuel Consumption

For the evaluation it was assumed that the second barrel would not be functioning since the power required for 100 km/h is about 12 kW only. (In such carburetors the second barrel applies for the higher power range only). Therefore the results of Fig. 7 are drawn over the first barrel MJN. Under these test conditions the optimum operation of the engine was found with MJN 95 (or even less acc. Fig. 7) for the first barrel and the static ignition advance 24° before TDC. When comparing with the initial setting of the producer (MJN 104 / 153, static timing 5° b. TDC, concerned points are shown in the figure with encircled x) the fuel consumption was reduced by about 8 % for this particular operation point. It is to be considered too that Addis Ababa, where the car was mainly used, lays about 500 m higher than the test lane, tending to an even smaller main jet number and earlier ignition timing for Addis Ababa conditions than the optimum shown in Fig.7.

An even greater effect was found in long distance tests. Before the modifications the car used to consume as an average slightly above 10 l/100 km (overall fuel consumption), which applies for inner city operation with normal loads in Addis Ababa mainly, including few long distance trips. After the modifications of carburetor and timing (now MJN 95 / 143, timing 24° b.TDC) the car has an overall fuel consumption of about 7.7 l/100 km (= 12.9 km/l). At long distance trips usually 6 l/100 km (i.e. 16.7 km/l) are consumed.

Laboratory Engine Tests

In the machine hall of the Faculty, a stationary 1.2 liter VW boxer engine (25 kW at 3600 rpm) is mounted on the test bed. With it some tests were carried out concerning again the influence of ignition timing and main jet number in some engine parameters.

Fig. 8 shows test results for full load and low part load at two different engine speeds. The mean effective pressure p_e (*brake m.e.p.*, proportional with the engine torque on the flywheel) and the exhaust gas temperature t_{ex} are traced against the real and the static ignition advances before TDC. The simple carburetor of this engine was equipped with the original main jet, MJN = 117.5, but the acceleration system was disconnected. This engine doesn't have a vacuum ignition advance.

The ignition timing greatly affects all engine parameters. The optimum timing obtained for maximum p_e for every operation points of the engine coincides with the minimum specific fuel consumption b_e (since the mixture quantity and quality were almost constant for every operation point) and coincides also with minimum unburned fuel components of the exhaust gases, some being converted into the toxic carbon monoxide and different hydrocarbons.

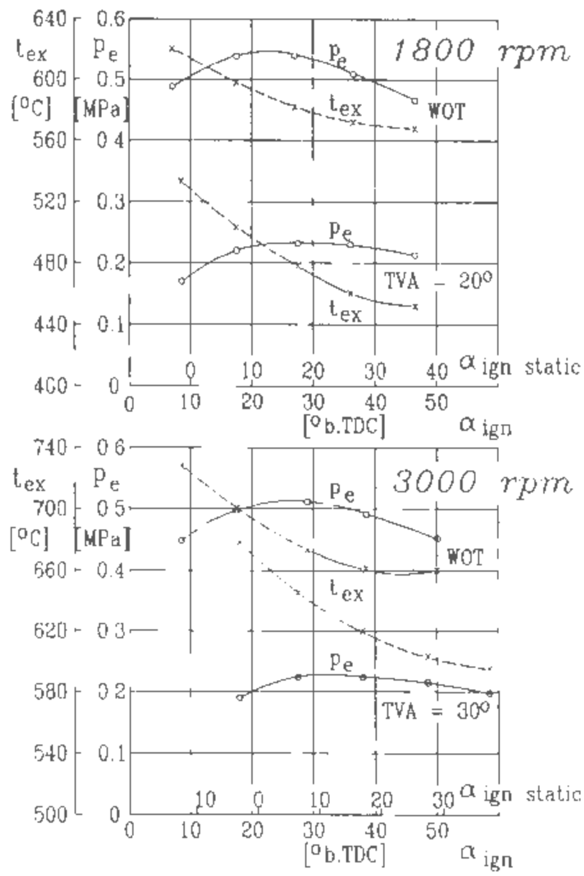

Figure 8 Optimization of Ignition Timing of VW Boxer Engine

The producer's recommendation for the setting of the static ignition advance at 7.5° b. TDC equates with the observed optimum at full load (wide open throttle = WOT) for 3000 rpm only. For the other operation points indicated in Fig. 8, the optimum setting would be much earlier. The higher the engine speed and the lower the load, the earlier is the optimum ignition timing, which indicates clearly the general need for centrifugal advance and vacuum advance systems of any petrol engines, in order to compensate for the nearly constant time delay of the inflammation period with increased speed and for the lower flame travel velocity with decreasing cylinder pressure, due to throttling at part load.

For this engine with the carburetor not yet adapted to high altitude operation, considering the too rich mixture provided, the ignition timing should be set at about 8 to 10° earlier than prescribed (compare also with road tests, 3.2). According to the indicated exhaust gas temperature behaviour, this would also be advantageous for thermal stress and lifetime of exhaust valves and other members.

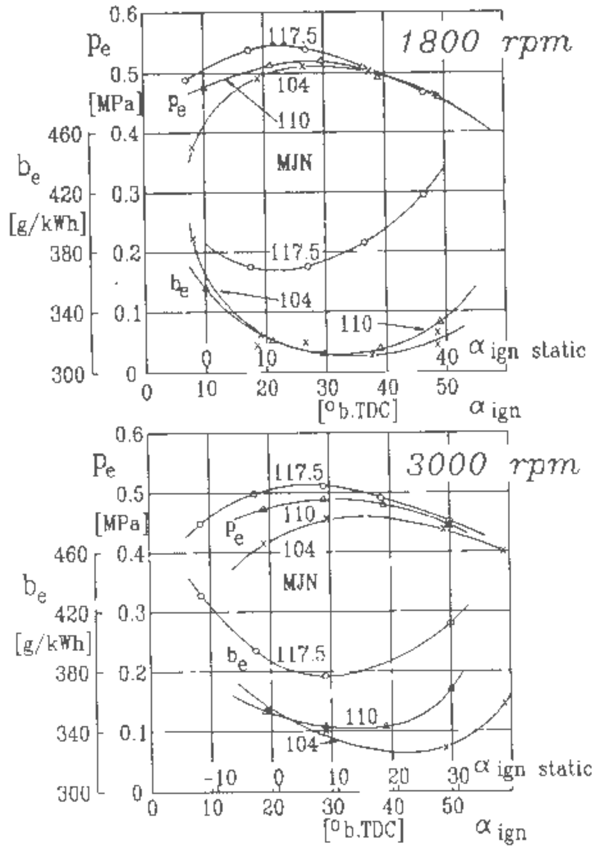

Figure 9 Full Load Optimization with Different Main Jets

Fig.9 shows a comparison of engine test resnlts for two engine speeds at full load which were obtained with different main jets. Starting with the original main jet (MJN = 117.5), the two others lead to a considerably leaner mixture. If the original main jet was correctly set for sea level then MJN = 110 would represent the right setting for abont 2500 m altitude, according eqn. 10.

The results correspond in principle with Fig.1. The original main jet led to an overrich mixture under the given site conditions. For optimum ignition timing, with leaner mixture there is a small reduction in mean effective pressure (corresponding with engine torque and engine power) but a considerably better fuel consumption. MJN 110 conld be accepted as a good compromise for this engine even without additional full load (power range) enrichment systems as they are frequently used for normal car engines. They are aimed to make up the power loss at full load which would arise from the lean mixture of the part load (= economy range) mixture formation system, compare Fig. 1 (see also [7, 9]).

Since normal driving includes many more operation conditions with constant speed at part load and few (and usually short) full load cycles only, it is more important to check the part load behaviour of the carburetor. Fig. 10 indicates the test results which were obtained for low part load operation on that engine for the same set of different main jets as before.

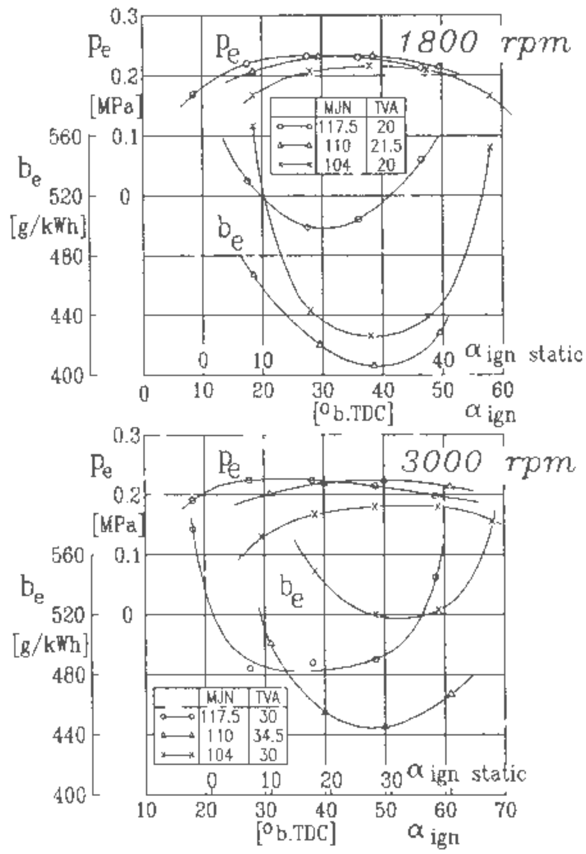

Figure 10 Part Load Optimization with Different Main Jets

The leaner mixture (obtained for example with MJN 104) leads necessarily to lower mean effective pressure, similar as in Fig.1 and 9. In order to study the effect of the leaner mixture in the efficiency of the engine at given part load working points (p_e, speed), the throttle valve angle for MJN 110 was adapted so that the same mean effective pressure was obtained as for MJN 117.5. At optimum ignition timing, the comparison with the original main jet gives a considerably lower fuel consumption for the two speeds, down to 82 % and 91 % respectively. Similar test results can be expected for all operation points of the engine. If the original ignition setting should be taken as reference, an even greater fuel saving would be observed on this engine by the adaption of MJN and ignition timing. A complete and more careful optimization of the mixture quality throughout all operation conditions of any engine in the test bed of the Faculty of Technology would require the acquisition and building-up of reliable combustion air consumption and exhaust gas component measurement devices.

Summary and Recommendations

The loss of engine power at high altitude is unavoidable (or can made up only with proper superchargers). With non-supercharged petrol engines operating continuously at high altitude, additional effects like an enrichment of the air fuel mixture and a slower combustion can be counter-acted by proper setting of main jet and ignition timing.

The test results obtained for one operation point from road tests and for four operation points in stationary engine tests obtained with real carburetors coincide principally with the theory of the elementary carburetor.

If the carburetor systems can't be adapted to high altitude then an additional advance of the ignition timing of about 8 to 10° is already an useful measure.

A better solution is the interchanging of original main jets by smaller ones where the MJN's are reduced with the fourth root of the atmospheric pressure change (for Addis Ababa to about 93 %), together with a setting of the static ignition timing by about 15 to 20° earlier then for sea level conditions. This would lead to a considerable reduction of fuel consumption, pollution of the atmosphere and thermal stresses of engine parts, as compared with the non-adapted engine.

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