THE EFFECT OF MIXTURE QUALITY ON THE EXHAUST GAS EMISSIONS OF A PETROL ENGINE

BY

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by

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SUMMARY:

Reported here is the first part of an investigation, supported by the Science Research Council, into the effects of mixture quality and mixture preparation in the induction tract of a petrol engine on the mass rate of emissions of carbon monoxide, carbon dioxide, nitric oxide and hydrocarbons in the exhaust gas.

Mixture quality or the method of supplying the fuel to the induction tract is shown to be relatively unimportant at steady loads and speeds when the loads and speeds are high. At low speeds and part throttle, particularly at idling, a well prepared fully evaporated or finely divided fuel-air mixture will allow operation at mixtures which are weaker than those with a heterogeneous mixture. The rate of mass flow of hydrocarbons is not affected greatly but the carbon monoxide level is reduced significantly at the weaker mixtures.

An anomaly in the levels of carbon monoxide and carbon dioxide, similar to that reported by three other laboratories, is discussed in detail. No adequate explanation can yet be offered but the problem is receiving further attention.
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ILLUSTRATIONS
1 INTRODUCTION

1.1 An investigation into the effect of mixture quality on exhaust gas emissions began, with the support of the Science Research Council, early in the year 1968. At that time it was well known that a major reduction of the emissions of carbon monoxide and unburnt hydrocarbons of an untreated engine could be obtained by supplying the engine with a fuel-air mixture wherein the fuel is finely divided or completely evaporated. Experimental evidence suggested that the improvement was mainly due to better distribution of the fuel, that is, the engine is provided with a mixture strength that is consistent from cycle to cycle and from cylinder to cylinder. Less obvious at that time, was the influence and importance of mixture quality - a term to describe the homogeneity of the dispersion of the fuel in the air and the physical state of the fuel - when the effects of distribution are insignificant.

1.2 Investigations by Jones and Gagliardi (Ref. 1), Nonnenmann, (Ref.2), and other unpublished work suggested that for a given air-fuel ratio, the effects of mixture quality were mainly to extend the range of combustible mixture in the weak region where carbon monoxide is at a very low level. The results of Nonnenmann suggest also that mixture quality can influence the levels of carbon monoxide with rich mixtures. There was little evidence in the literature of the effect of mixture quality on the emissions of the oxides of nitrogen and almost a complete absence of tests at idling conditions.

1.3 Although it was recognised that mixture quality may have only a secondary effect, the importance of such effects cannot be ignored when legislation requirements are very stringent. For this reason the work of this report was undertaken in order to give more comprehensive information on the fundamental effects of mixture quality in the induction tract of an engine. At the request of the Science Research Council, the main attention was given to the emission of carbon monoxide and the oxides of nitrogen with less attention to unburnt hydrocarbons.

2 ENGINE INSTALLATION

2.1 Basic data and modifications to the engine

2.1.1 All tests were made on a four cylinder, water-cooled 1978 cc engine with a Heron combustion chamber, a bore and stroke of 85.6 mm and a compression ratio of 9.0 to 1. The engine was converted to single cylinder operation by removal of the pistons and connecting rods of cylinders 1, 2 and 3, and the appropriate cam followers of the valve gear. A cylinder head with separate induction and exhaust ports was fitted to allow the use of simple single exhaust and induction pipes without branching or pockets.

2.2 Coolant circuit

2.2.1 Modification of the engine coolant circuit was made in order to obtain a rapid warm-up and stable coolant temperatures. The circuit is shown diagrammatically, Fig.1. To improve the water circulation passed the firing cylinder No.4, the main water outlet is re-sited at the rear of the cylinder head. A by-pass of the thermostat at the outlet can be diverted, if
required, to a heat exchanger in the induction system (see paragraph 2.5). The engine circuit and coolant header tank, Fig. 1, are in a closed loop. The coolant temperature is controlled by a manual valve or by a thermostat that drains hot water from the header tank. A ball valve introduces a similar quantity of relatively cold water from the main laboratory system which is also a closed circuit. Untreated water was used for coolant throughout the engine tests.

2.3 Fuel systems

2.3.1 Two fuel systems were used, Fig. 2. Normal carburation was provided by an Amal 376 carburettor with a variable main jet and needle to allow the control and adjustment of the air-fuel ratio while the engine is running. The alternative system is based upon a Simms-Marvel-Schebler petrol injection pump with manual control.

2.3.2 In each case the fuel is gravity fed from the main tank to a float chamber. From the float chamber it flows to a glass burette and on to the reservoir of the primary pump of the fuel injection equipment or through an electric lift pump to the carburettor according to the system in use.

2.3.3 Fuel is supplied to the injection pump at a pressure of 50 lbf/in$^2$ gauge, approximately, from the primary pump. Bleedback from the three injectors not in use (four injectors when carburation is used) is returned to the reservoir of the primary pump. The injection pump was driven at half engine speed at the original mounting for the distributor. Timing of the injection could be altered easily by turning the pump on its mounting but it was normally set to commence nominally at top dead centre of the piston and the beginning of the induction stroke. The characteristics of the pump, given in Appendix 1, are such that the injection period and timing varies with the setting of the controls or the quantity injected.

2.3.4 Pure normal iso-octane fuel was used throughout the tests.

2.4 Ignition system

2.4.1 A conventional simple coil and contact breaker were used to provide the high voltage spark. To avoid undue electrical interference from unwanted sparks, the contact breaker cam was made by grinding off all but one of the cam lobes of the standard distributor. Subsequently, it was found to be necessary to reform part of the cam profile in araldite in order to avoid excessive heat dissipation in the coil when the contact points were closed for too long a time at slow engine speeds. The contact breaker was driven from the front end of the overhead camshaft.

2.4.2 A manual adjustment of the ignition timing was provided by swivelling the body of the contact breaker. A stroboscope triggered by the electrical pulses of the ignition low tension circuit and shown on a graduated scale on the flywheel and a fixed pointer on the engine block, was used to indicate and set the timing of the ignition.

2.5 Induction system

2.5.1 The system used for all but the preliminary tests is illustrated by Fig. 3. Included in the simple induction pipe is an engine oil cooler which was adapted for the transfer of heat from the engine coolant to the inducted air or
mixture. At all times the air or mixture tends to be agitated or mixed during its passage through the heat exchanger. The supply of engine coolant could be cut off when no charge heating was required.

2.5.2 The carburettor stays in position and provides the throttle valve when operating with fuel injection. Preliminary experiments were carried out to assess the effects of pressure waves in the induction system and reverse flow through the carburettor. Experimental and theoretical work with side branches and various pipe lengths showed that the pressure conditions in the port could be influenced readily but the problem of flow reversal in the carburettor was not resolved. Eventually the decision was that the induction pipe should be made simple and that it should be extended at least ten inches before the carburettor in order to avoid a loss of fuel during flow reversals. The overall pipe length is such that the engine is receiving the optimum ram effect at crankshaft speeds of about 1900 to 2000 r.p.m., that is, about the upper speed range of the tests reported here.

2.5.3 Generally, the cross section of the induction pipe is circular and about 1.25 inch diameter. For a length of about eight inches, however, flat walls were built into the sides of the pipe to allow a visual inspection of the mixture quality downstream of the heat exchanger. Near to the induction port two small windows were fitted so that light could be transmitted across the tract for photographic observation of the mixture motion.

2.6 Exhaust system

2.6.1 A simple pipe from the exhaust port enters an expansion and mixing chamber about fifteen inches downstream of the exhaust valve. The capacity of the chamber is about 10,000 cubic centimetres or twenty times the capacity of the cylinder. Tappings for the exhaust gas analysis were normally taken downstream of the mixing chamber but tappings were available also from upstream of the chamber and from the chamber itself.

2.7 Additional equipment to aid testing of the engine

2.7.1 Several devices have been fitted or they are available for long-term experiments on the engine. Although these devices have not all been used for the work reported here they are included for completeness. They are listed as follows:

1) Ionisation gaps, amplifiers, timing gates and punch or print out equipment for the detection and measurement of flame travel times.

2) Piezo-electric pressure transducers and amplifiers for the indication of pressure variations in the induction tract.

3) An externally triggered stroboscope for a "slow motion" visual examination of the injector spray characteristics.

4) An accurately slotted disc, photo-electric cell and electronic timing unit which can be used for accurate timing of the engine events in crankshaft degrees.

5) A magnetic pick-up is fitted at the camshaft for the triggering of a stroboscope or oscilloscope.
6) A variable lift intake valve has been designed, built and fitted to the engine. This device will be described in detail in a later report when engine tests now in progress are complete.

7) The balance weights of the Avery weighing machine of the English Electric brake dynamometer, used throughout the tests, were reduced in order to increase the brake load sensitivity by a factor of about ten. This modification has been very useful for light load tests of the single cylinder.

3. OPTICAL EQUIPMENT FOR THE OBSERVATION OF MIXTURE BEHAVIOUR

3.1 Illustrated by Fig. 4 is the optical and recording system set up for the photographic observation of the mixture quality and motion in the induction tract. The system is similar in principle to that reported in the N.E.L. Report 331.

3.2 The windows in the induction tract, described briefly in paragraph 2.5.3, are recessed to avoid, or at least, to reduce the deposition of fuel droplets on the surfaces. Two brass tubes, which carry the windows, are bonded into opposite sides of the induction tract and project into the tract for a short distance on either side. The internal projection and the sharp rims of the tube were designed to prevent large quantities of fuel, which often runs along the walls of the induction tract, from streaming across the optical path and so obscuring the liquid particles in the air flow.

3.2 Continuous and stroboscopic light sources are available but, up to now, results have been obtained with the continuous source only. The light beam is focussed at the nodal point of a high speed cine camera and the camera focussed on a suitable plane near the centre of the induction tract. The passage of light through a droplet and the scattering of light from the periphery of a droplet gives a sharp image on the photographic film. A Fastex camera was used at speeds up to about 5000 frames/sec.

4. EXHAUST GAS ANALYSIS - GENERAL COMMENTS

4.1 The detection and recording of the concentrations of carbon monoxide, carbon dioxide, oxides of nitrogen and hydrocarbons as equivalent hexane were obtained with a four-channel Grubb-Parsons infra-red gas analyser. Because all the testing has been at steady engine loads and speeds a channel for high concentrations of hydrocarbons has not been necessary. For the purpose of estimating the air-fuel ratio the oxygen content of the exhaust was monitored with a Servomex OA 150 paramagnetic analyser.

4.2 During the preliminary experiments a flame ionisation detector was used for an assessment of the total hydrocarbon emissions. Before the work began it was thought desirable to analyse the hydrocarbon emissions by a gas chromatograph in order to establish the reactivity index of factor according to the composition of the hydrocarbons in the exhaust. Neither the flame ionisation detector nor the gas chromatograph, a Perkins Elmer F11, has been used extensively. The results of the flame ionisation detector tended to vary in a similar manner to the levels recorded as equivalent hexane. Since a pure hydrocarbon fuel was used throughout the tests and there was more
interest in comparative levels from one test to another, the flame ionisation measurements were not taken during the main programme of tests. The decision to not use the chromatograph was influenced mainly by the modification and development necessary for complete separation of hydrocarbons and the excessive time required to analyse a sample but also by the secondary importance of hydrocarbons that was suggested by the sponsors of the project.

4.3 Although the flame ionisation detector was not used for the main series of tests, the development of the detector for the measurement of total hydrocarbons may be of interest to other investigators in this field.

4.4 The Perkin-Elmer F11 chromatograph with a flame ionisation detector was adapted for this purpose. The fifty metre capillary column, for the separation of hydrocarbons, was removed and replaced by a 3 inch length of capillary tube. For the purpose of establishing the optimum flame conditions, the relation between flow rate, as measured with a soap bubble flowmeter, and the inlet pressure for the hydrogen and air paths were established and plotted, Graph 1. With these figures available the inlet pressures for good flame conditions were set according to the manufacturers recommendation of about 400 ml. air per minute and 30 to 35 ml. hydrogen per minute.

4.5 Experiments were then followed to optimise the gas sampling system with the following objectives in view:–

a) a rapid response;

b) no separation of hydrocarbons;

c) a sharp peak. Because the sample volume and flow rate is constant the hydrocarbon concentration could be read directly as a peak height.

d) Adequate electrical output without the need for high amplification;

e) maintenance of good flame stability.

4.6 To achieve these objectives various sample loop volumes, connecting capillary diameters and carrier gas flow rates were tried. Suitable values were found to be:

- Sample loop: 5cc.
- Capillary diameter: 0.010 inch
- Carrier gas flow rate: 60 ml. nitrogen per minute

A calibration curve, which is almost linear, is given as Graph 2.

The amplifier sensitivity can be altered if required for the measurement of higher or lower concentrations.

5. INFRA-RED GAS ANALYSIS EQUIPMENT

5.1 For carbon monoxide, carbon dioxide and hydrocarbons the system supplied by the manufacturers was found to be adequate providing that a regular calibration procedure was adopted. However, the sensitivity or cross response of the nitric oxide detector to water vapour was considerable. A high and erratic response was found to be due to variations of the temperature of the water bath and the small size of condenser tubes which were normally
immersed in the bath of ice/water.

5.2 The problem was solved inexpensively by the installation of a refrigeration unit (extraction rate 700 B.t.u. per hour). A thermostatically controlled water/antifreeze mixture is continuously circulated through the standard water bath, as provided by the manufacturer, and an auxiliary bath with a much larger water trap in the exhaust gas sample line, see Fig. 5.

5.3 To establish the possible error due to 'hunting' of the thermostat and, consequently, small variations in the temperature of the antifreeze mixture, measurements were made of the response of the nitric oxide channel to air plus water vapour at various mixture temperatures. Saturated air at ambient temperature was drawn into the analyser through the condenser coils for each test. The results, plotted as Graph 3, show that the water bath temperature is very significant.

5.4 It was found that the thermostat was capable of maintaining the antifreeze mixture at temperatures between 0°C and 2.5°C. Reference to Graph 3 suggests that the response to water vapour will be the equivalent of about 145 ± 30 ppm. of nitric oxide. A figure of 145 ppm was subtracted subsequently from all observed readings of the nitric oxide concentration.

6. SAFETY PRECAUTIONS

Care was taken to reduce the risk and consequences of an accidental escape of toxic nitric oxide gases into the laboratory. Stainless steel regulators were used to avoid corrosive deterioration when nitric oxide was used for calibration purposes. All the analyser outlets were vented to atmosphere outside the laboratory. Other precautions included the installation of a powerful fume extraction fan, an emergency exit from the laboratory, and breathing and resuscitation equipment.

7. ENGINE TEST CONDITIONS

7.1 All the tests described in this report were at steady speeds and loads. Three methods of mixture production were employed:

a) petrol injection with a 60° cone of fuel sprayed directly towards the inlet valve - that is, position 1 on Fig. 3.

b) petrol injection upstream of the heat exchanger and close to the carburettor - position 2 on Fig. 3.

c) a carburetted mixture upstream of the heat exchanger.

For each method of mixture production the engine was tested at two temperature conditions, that is, at an ambient temperature of about 24°C or with the charge heated to about 60°C. In practice it was found that there was very little difference in the emission levels for methods b) and c). Since considerable difficulty was experienced in setting the carburettor accurately at part load conditions it was convenient to base the comparison of mixture quality on methods a) and b) only for most test conditions.
7.2 Engine loads and speeds were selected to be representative of those thought to be important in a driving cycle. These were:

a) idling at a crankshaft speed of about 800 r.p.m.

b) full load (W.O.T., wide open throttle), 60 lbf.in\(^{-2}\) and 30 lbf.in\(^{-2}\) brake mean effective pressures at engine speeds of 1500 and 2200 r.p.m.

7.3 For each load and speed and method of mixture production the mixture strength of the engine was varied in increments from a very rich setting to the leanest limits of engine operation without a serious misfire. Ignition timing was set at the minimum advance for the best torque (M.B.T.) at each load and speed. To maintain a constant b.m.e.p. it was, of course, necessary to adjust the throttle position according to the mixture strength. For this reason and to conform to current practice the emission results are given in terms of mass per unit time and not in terms of concentration. The Spindt (Ref. 3) equation was used to calculate the mixture strength according to the level of the exhaust emissions, see Appendix 2, and the mass emission rates were calculated according to the equations given in Appendix 3. In each case the level of total hydrocarbon emissions was assumed to be twice that measured as equivalent hexane. A simple Fortran IV program, included as Appendix 4, was used to reduce the experimental data.

8. COMMENTS ON MIXTURE CONDITIONS

8.1 Although visual observation was not possible, when the fuel is injected onto the back of the valve the residence time of the fuel in the port is so short that the mixture must be very heterogeneous with a considerable amount of wall flow in the ports and on the surfaces of the valve. Some indication of these conditions can be seen in the shadow photographs, Fig. 6a and Fig. 6b, taken downstream of a valve under steady state conditions in a cold flow rig. An extreme condition at low velocities of flow is illustrated by Fig. 6b. It is unlikely that the mixture quality will be affected greatly under these conditions by the temperature of the charge air.

8.2 With injection or carburation upstream of the heat exchanger, without heating the charge, the increased surface area and flow disturbance was sufficient to give a cold relatively well mixed charge which showed a slight wetting of the glass walls of the induction tract. Heating the charge to about 60\(^\circ\)C, was sufficient to give complete evaporation with no wetting of the walls.

8.3 As with all previous experiments on mixture quality the description of the mixture lacks precision. A quantitative description in terms of the percentage of fuel flowing on the wall, the percentage of the fuel evaporated and the mean droplet size in the main air flow would be very difficult to achieve and, with hindsight, hardly justified by the practical significance of the values. Preliminary results with the optical system described under Section 3 suggest that much could be learned about the qualitative behaviour of the mixture in an induction pipe by cine photography.
8.4 With a continuous light source the films lack quality and definition. Nevertheless, the images of small droplets at relatively low speeds can be seen clearly, Fig. 7. Small high speed droplets cannot be distinguished separately but the general pattern of the mixture motion, acceleration, deceleration and flow reversals, can be observed. At times in the cycle, individual droplets can be seen to be travelling away from the inlet valve and subsequently to reverse their direction back towards the cylinder.

8.5 Individual frames show the droplets to be elongated in the direction of flow. This distortion is partly due to the relatively long exposure time of the camera even at its maximum speed. Better definition may be obtained by synchronising an intermittent spark source of light with the rotating prism of the camera so that the exposure time is reduced by a factor of about one hundred. Time did not permit further development of this technique since the results were unlikely to add significantly to the prime objective of the investigation.

9. ENGINE TEST RESULTS AND COMMENTS

9.1 Repeatability and significance of results.

All investigators of engine exhaust emission have experienced difficulty as a consequence of a lack of repeatability which can be very significant at steady loads and speeds when the levels are low and the changes to be observed are small. Graph 4 gives an indication of the variation of the recorded mass emissions for a particular engine load and speed on three separate occasions when the differences in the ambient temperature, barometric pressure, and ambient humidity were insignificant. To reduce the effects of the lack of repeatability as much as possible comparisons between the various methods of mixture production were made for a particular load and speed during one continuous run of the engine. The results taken for a particular run of the engine were plotted on the same graph. This should mean that small differences between curves on the same graph will be more significant than small differences from one graph to another.

9.2 Idling test results

9.2.1 A series of tests run at 800 r.p.m. and "no-load" are illustrated graphically by Graphs 5 to 10; Graphs 5 to 8 give the mass rate of emission for four ignition timings of 10° B.T.D.C., 5° B.T.D.C., T.D.C. and 5° A.T.D.C. Comparisons of the two extreme ignition timings, for a particular method of fuel supply, are given in terms of the mass rate of emissions, Graph 9, and the concentrations by volume, Graph 10.

9.2.2 It is well known that a retarded ignition timing is effective for the reduction of hydrocarbons. The gain, which appears to be independent of mixture quality, is illustrated by Graphs 9 and 10. According to Graph 9, the mass rate of emissions of nitric oxide is greater when the ignition is retarded. In comparison to other modes of a driving cycle, however, it is clear that the mass rate of emissions of the oxides of nitrogen are negligible during idling.
9.2.3 Clearly, with reference to Graphs 5 to 8, the main effects of the various methods of fuel preparation in the induction tract during idling is the extent to which lean mixtures can be utilised. With fuel injected upstream of the heat exchanger and well upstream of the inlet valve, position 2 on Fig. 3, low levels of carbon monoxide can be obtained by running the engine with a stoichiometric or slightly weaker mixture. At this position for injection the residence time or the mechanical mixing of the induction tract was sufficient to give a mixture quality that was not improved significantly by heating the charge. Injection at the back of the valve, whether the charge was heated or not, requires the mixture to be rich. This causes a substantial increase of carbon monoxide in comparison with that when injection is well upstream. The observed effects of mixture quality on the oxides of nitrogen was not significant for these tests since the observed differences are within the limits of experimental error, that is, the cross response to water vapour etc.

9.3 Full load and part load test results

9.3.1 The results for engine speeds of 1500 r.p.m. and 2200 r.p.m. are illustrated by Graphs 11 to 18 and Graphs 19 to 24 respectively. In all cases the mass rate of emissions follow the known trends with mixture strength; the nitric oxide showing a maxima at mixture strengths between about 15.5 and 17.5 to 1, or equivalence ratio between about 0.95 and 0.85; where the hydrocarbon levels tend to be a minima and the mass emissions of carbon monoxide are low. In general, the mass emissions of nitric oxide increase with speed and load and the maxima tend towards weaker mixtures as the speed and load increases.

9.3.2 Also expected was an increase in the emissions of nitric oxide when the charge is preheated. This increase was observed at the higher engine speed but the full load results at 1500 r.p.m., Graphs 12 and 13, in particular, show the opposite trend. An explanation could be that the concentrations are higher with a heated charge but at this speed the reduction in charge density and charge mass flow, as indicated also by the reduction in b.m.e.p., is sufficient to cause a net reduction in the mass emissions. On the basis of equal power, the difference is quite insignificant.

9.3.3 Graphs 11 to 24 indicate clearly that the various methods of mixture production had little or no effect on the mass rate of emissions of carbon monoxide, hydrocarbons and the oxides of nitrogen when the engine is operating at steady loads and speeds. This finding has been reported elsewhere (Ref. 4). The small differences that were observed are relatively insignificant compared with variations due to instrument errors and the problems of good repeatability.

10 GENERAL DISCUSSION OF RESULTS AND PROGRAMME OF WORK

10.1 According to the results and comments given in paragrapy 9.3.3. it could be the interpretation that the mixture quality in the induction pipe, when the engine is running at steady speeds and loads, is of little or no significance as far as combustion and the exhaust emissions of a petrol engine are concerned. Results of a previous investigation (Ref. 5) at the A.S.A.E., however, give a clear indication that extreme conditions of mixture quality will result in considerable differences in the level of exhaust gas emissions. To understand
the differences between one investigation and another a description based upon observations and a little imagination, can be offered for the means by which a fuel-air mixture is prepared before the start of combustion in the cylinder.

10.2 Irrespective of the method used for the introduction of fuel to the induction tract it is quite evident from shadow photographs downstream of the valve (Ref.6) that the flow through the valve induces considerable turbulence in the mixture. The mixture motion can be very effective in the production of a good quality homogeneous mixture as a consequence of the mixing process and the break-down and evaporation of fuel ligaments leaving the surface of the valve. The preparation of the mixture by the valve is most effective when the pressure drop across the valve or the rate of gas flow is high and much less effective when the pressure drop and rate of flow is low at low engine speeds and part throttle operation.

10.3 Mixture preparation in the induction tract will most likely depend upon the mixture motion and turbulence, the temperature of the mixture and the walls of the tract, the pressure of the mixture, the relative 'humidity' in terms of the fuel vapour present and that required for saturation, residence time in the duct, wetted surface area and the degree of initial atomisation of that fuel that is not deposited on the wall during its passage down the tract. A homogeneous and well evaporated mixture is more likely to be produced when the mixture motion and turbulence is great, the temperature of the mixture and walls of the tract is high, the residence time of the fuel in the tract is long, the wetted area of the tract is large, the mixture pressure is low and the fuel is finely divided and well dispersed in the air stream.

10.4 The relative importance of mixture preparation by the valve and by the condition in the induction tract are suggested by the results given in this report. At the relatively high speeds of 1500 r.p.m. and 2200 r.p.m. and at the higher loads, the valve effect is predominant. At the idling condition the valve is less effective and conditions in the induction tract are more significant. It is clear that a good mixture, which can be produced without the necessity to heat the charge, is effective in extending the weak range of burnable mixtures. The minimum mass rate of hydrocarbon emissions does not seem to be greatly affected by mixture quality, but Graphs 3 and 8 tend to show the lowest levels with a long residence time and a good quality mixture. This trend is seen in Table 1, the results of an investigation (ref.5) at the A.S.A.E. on the single cylinder of a six cylinder water-cooled engine of 2550 cc capacity with a wedge combustion chamber in the head and a compression ratio of 8.3 to 1. The figures for 'idling', that is, closed throttle at 600 r.p.m., show clearly that the residence time is generally the most important factor but good atomisation of the fuel becomes essential with short residence times, that is, when the fuel is supplied near to the valve. There is a severe penalty in terms of carbon monoxide levels for poorly formed mixtures at idling and closed throttle conditions at any speed.

10.5 A very 'coarse'mixture represented in the extreme by dripping fuel on the back of the valve, is undesirable even when the preparation by the valve becomes more significant, see Table 1. A drip feed will obviously be modified considerably if the residence time is increased or the motion of the mixture is increased. As acknowledged by Dodd and Wisdom, the drip feeds
### TABLE 1

425 cc cylinder, wedge combustion chamber; and compression ratio of 8.3 to 1

<table>
<thead>
<tr>
<th></th>
<th>600 R.P.M.</th>
<th></th>
<th>1200 R.P.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Full Throttle</td>
<td>Closed Throttle</td>
<td>Full Throttle</td>
</tr>
<tr>
<td>Fuel injection towards back of valve (7&quot; upstream of valve)</td>
<td>570 (2.0)</td>
<td>900 (7.0)</td>
<td>320 (1.4)</td>
</tr>
<tr>
<td>Fuel injection into induction tract (13&quot; upstream of valve)</td>
<td>650 (2.8)</td>
<td>680 (1.4)</td>
<td>330 (3.2)</td>
</tr>
<tr>
<td>Drip feed (7&quot; upstream of valve)</td>
<td>370 (4.7)</td>
<td>600 (1.6)</td>
<td>440 (4.9)</td>
</tr>
<tr>
<td>Drip feed (13&quot; upstream of valve)</td>
<td>350 (4.0)</td>
<td>450 (1.5)</td>
<td>430 (6.0)</td>
</tr>
<tr>
<td>Drip feed onto back of valve (1&quot; upstream of valve)</td>
<td>1200 (1.2)</td>
<td>1430 (5.4)</td>
<td>700 (7.2)</td>
</tr>
</tbody>
</table>

**Notes:**

1) The figures given are minimum hydrocarbon concentrations in p.p.m. as measured with a flame ionisation detector.

2) In brackets are the percentage concentrations of carbon monoxide by volume.

3) Closed throttle was set to give a 'mean' manifold pressure of 10.5 inch of mercury vacuum in each case.

4) Ignition timing was fixed at 4° B.T.D.C.

5) Iso-octane was used for all tests.

6) Repeatability was less satisfactory than for the experimental results plotted on Graphs 4 to 24.
used in their tests will be conditioned appreciably by a throttle plate downstream of the feed and, in one case, the fitting of a plenum chamber between the fuel supply and inlet valve. With practical methods of fuel supply, preparation by the valve at 'high' engine speeds and loads is such that the degree at atomisation is relatively unimportant when transient operation of the engine and manifold distribution is not significant.

10.6 Once transient operation of the engine is required the quality of the mixture is almost certainly decided by the need to accelerate or decelerate the fuel and air together. A fully evaporated mixture or a short residence time is indicated by common sense and practical experience. A short residence time is obtained by fuel injection on to the back of the valve but some means of improving the mixture in the cylinder is desirable at idling and slow speed closed throttle conditions.

10.7 Plotting the nitric oxide levels as a mass rate (gm. per hour) indicates clearly that these are much greater at high loads and speeds. Although the concentrations may be reduced by retarded ignition, exhaust gas re-circulation etc., the increased throttle required to restore the engine power may largely offset the gain. The most practical means for reducing the nitric oxide level would seem to be the use of a rich mixture allied with an efficient oxidation of hydrocarbons and carbon monoxide in the exhaust pipe at wide throttles and high speeds. Weak mixtures could be used at part and closed throttle.

10.8 It is possible that a greater turbulence in the cylinder at part load conditions, particularly at low speed, would be effective in giving a better mixture at the time of ignition, a faster flame speed and a reduction of the thickness of the quenched hydrocarbons at the surfaces of the combustion chamber. Work now in progress and the second part of the investigation are concerned with the improvements obtained by throttling with a variable lift valve, the device mentioned previously under item 6 of paragraph 2.1.1.

10.9 An important factor in an emissions experiment is the degree of repeatability. Variations of the order of 100% have been noted in other investigations. Although significant compared with the small changes being observed, the reliability and repeatability of the tests reported in this investigation were more reasonable. The most likely explanation is that the use of a pure single hydrocarbon fuel, without additives, gave stable running conditions of the engine. When examined after several hours of running, the deposits in the combustion chamber were very light and easily removed with a dry cloth. The usual precautions of regular calibration of the exhaust gas analyser were taken. As described previously, particular care was taken to avoid non-representative exhaust samples and the cross response to water vapour. Nevertheless, the measured concentrations of carbon monoxide and carbon dioxide show anomalies which defy an adequate explanation in terms of engine and fuel characteristics. Similar anomalies have been reported by at least two other laboratories working independently.

10.10 Graphs 26 and 27 illustrate that the measured concentrations of carbon monoxide with rich mixtures fall into a broad band when plotted against mixture strength. The results tend to correlate in two main groups; part load at 2200 r.p.m. and all other loads at 1500 r.p.m. and 2200 r.p.m. Results at idling tend to fall between the two. It can be seen on graph 26
that the part load results at 2200 r.p.m. compare closely with the levels expected with the assumption of a water-gas reaction equilibrium at 3000°R. The lower levels of carbon monoxide at 1500 r.p.m. and full throttle, 2200 r.p.m. graph 27, would correlate fairly well with an equilibrium composition at about 2400°R.

10.11 The differences in the engine operating conditions would not appear to justify the suggestion that the cycle conditions were very different. For example, part load conditions at 2200 r.p.m. correlate at a high level of carbon monoxide whereas part load at 1500 r.p.m. correlate better at a low level. In general the results appear to be more dependent on load and speed than on the method of fuel supply to the engine. An exception to this generalisation is that the lowest levels of carbon monoxide were obtained at 1500 r.p.m. and 30 b.m.e.p. with fuel injection on to the back of the valve. This is in agreement with Nonnenman (Ref. 2) who observed a shift which was apparently dependent upon the method of fuel supply. He attributes the shift to lower cycle temperatures as indicated by the temperatures of the sparking plug. The differences that he measured at a particular mixture strength are far greater than those reported here and it is most unlikely that they can be explained by a change of equilibrium composition or kinetic reaction rates according to temperature changes only.

10.12 The levels of carbon dioxide, plotted on Graphs 28 and 29 do not help to explain or clarify the situation. It is shown that no results at rich mixtures, with the possible exception of part load at 2200 r.p.m., correlate well with an equilibrium composition. An anomaly occurs in the weak region also but again the part load results at 2200 r.p.m. correlate more nearly with a composition that assumes that the dry products of combustion are carbon dioxide, oxygen, argon and nitrogen only. All the results at other loads and speeds are low by more than one percent of carbon dioxide. Similar discrepancies have been reported (Ref. 4) by Dodd, at M.I.R.A., and Wisdom, at E.R.A. Limited.

10.13 Various possibilities for the apparent discrepancy have been considered. Clearly, the presence of hydrocarbons, nitric oxide etc., in the exhaust emissions would account for a discrepancy in the carbon monoxide and carbon dioxide levels but the difference would be much smaller than those observed. Dilution by leakage of air into the exhaust or exhaust sampling system can be discounted since the oxygen level, Graphs 28 and 29, is no greater than would be expected when account is taken of the small fraction that is present at all mixture strengths. Plotting the sum of the carbon monoxide and dioxide concentrations, Graph 25, tends to suggest dilution or an error in the estimation of the effective mixture strength but the dioxide levels alone, Graphs 28 and 29, show clearly that a shift of the results towards weak mixtures is not acceptable. A careful check of the gas valves of the infra-red gas analyser has eliminated the possibility of dilution by nitrogen which is used as a purge gas for the instrument.

10.14 It is important that the results of emissions experiments should be understood fundamentally. Further thought and experiment will be given to this anomaly in future work. The practical significance of the comparisons of the methods of fuel preparation reported here and elsewhere are unlikely to be affected but until an adequate answer is found the absolute values of the
concentrations measured cannot be accepted with complete confidence.

11 CONCLUSIONS

11.1 Normal methods of fuel supply and mixture production have no significant effect on the mass rate of emissions of carbon monoxide, carbon dioxide and nitric oxide at engine speeds and loads other than idling. This observation is in agreement with the finding of other workers in this field. Extremes of mixture quality have an undoubted effect but a poor mixture may be improved considerably by the residence time in the induction tract and by its turbulent passage into the cylinder.

11.2 At low engine speeds and part throttle operation, particularly when idling, the preparation of the mixture by its flow through the valve may be inadequate. At conditions such as these the method of mixture preparation affects the lean limits of combustion. Lower carbon monoxide levels can be obtained by improving the mixture quality so that the engine will run at weaker mixtures.

11.3 Mixture improvement and better combustion are likely to be obtained by increasing the turbulence in the combustion chamber. Work in progress, employing a variable lift valve, is expected to add to the knowledge of this factor.

11.4 An improvement of the mixture in the induction pipe can be obtained, if necessary, by physical means. A large wetted surface area and a small flow disturbance is sufficient to give a relatively dry mixture without heat.

11.5 The mass rate of emissions of nitric oxide increases considerably with load and speed. According to the tests reported here, the maximum rate for a given load and speed occurs at weaker mixtures as the load and speed increases. Heating the inducted mixture to 60°C increased the concentrations of nitric oxide but did not significantly affect the mass rate of flow per horsepower. Retarding the ignition at idling reduces the concentrations of nitric oxide but the mass rate of flow may increase. The low mass rates of flow at idling, however, are insignificant compared with those at other operating conditions.

11.6 The general repeatability of the results, a problem in most emission experiments, was reasonable. This was mainly attributed to the use of a pure hydrocarbon fuel and the absence of deposits in the combustion chamber. Particular care was taken to reduce the cross response of the infra-red gas analyser to water vapour.

11.7 A cine photographic technique has been successfully employed for the observation of mixture behaviour in an induction tract.

11.8 A satisfactory explanation cannot be offered yet for the low levels of carbon monoxide and carbon dioxide at many loads and speeds of the engine. Similarly, low levels of carbon dioxide have been reported by at least two other laboratories working independently. A third has reported differences in the carbon monoxide levels that lack an adequate explanation. Further attention will be given to this anomaly in future work.
**REFERENCES**

1. **JONES, J.H. and GAGLIARDI, J.C.**
   Vehicle exhaust emission experiments using a pre-mixed and pre-heated air fuel charge

2. **NONNENMANN, M.**
   The influence of external mixture formation on the performance of the four-stroke petrol engine.

3. **SPINDT, R.S.**
   Air-fuel ratios from exhaust gas analysis

4. **DODD, A.E. and WISDOM, J.W.**
   Effect of mixture quality on exhaust emissions from single-cylinder engines

5. **BLURTON-JONES, T.J.**
   Mixture quality effects on exhaust emissions

6. **BEALE, N.R.**
   A study of fuel atomisation in the induction tract of a fuel injection spark ignition engine
APPENDIX 1

INJECTION PUMP CHARACTERISTICS

The injection pump used throughout the tests is of the distributor type with a single reciprocating and rotating plunger.

Fuel delivery is controlled by restricting the movement of a spring loaded shuttle which connects with the pumping chamber. The injection commences once the initial plunger movement has displaced the shuttle to its stop, so that for a given speed the end of injection remains fairly constant, but the commencement, and hence the injection period, varies with control position.

The characteristics of the system were investigated by stroboscopic observation of the injector spray for various speeds and control settings, the results are plotted on Graph 30. The timing was set so that the mean point of injection commencement was approximately at T.D.C. (beginning of induction stroke), but it can be seen that for extreme conditions this varies between 29° B.T.D.C. and 23° A.T.D.C.
APPENDIX 2

CALCULATION OF THE RATIO OF AIR TO FUEL BY WEIGHT

Air/fuel ratios were calculated from exhaust analysis using a method developed by Spindt (S.A.E. 650507)

The basic equation for the computation is:

\[
A/F \text{ ratio} = F_b \left[ 11.492 \frac{F_c \left( \frac{1 + R}{2 + Q} \right)}{1 + R} + \frac{120(1 - F_c)}{3.5 + R} \right]
\]

where

\[
R = \frac{P_{CO}}{P_{CO_2}}
\]

\[
Q = \frac{P_{O_2}}{P_{CO_2}}
\]

\[
F_b = \text{fraction burned} = \frac{(P_{CO} + P_{CO_2})}{(P_{CO} + P_{CO_2} + P_{HC})}
\]

and

\[
F_c = \text{fraction carbon in fuel}
\]

\[
P_{CO} = \text{volume percentage CO in exhaust}
\]

\[
P_{CO_2} = \text{volume percentage CO}_2 \text{ in exhaust}
\]

\[
P_{O_2} = \text{volume percentage O}_2 \text{ in exhaust}
\]

\[
P_{HC} = \text{percent carbon in hydrocarbons on a per carbon basis}
\]

\[
= \frac{\text{ppm H}_C \text{(FID)} \times 6}{10^4} \quad \text{OR} \quad \frac{\text{ppm H}_C \text{(NDIR)} \times 12}{10^4} \quad \text{(approx.)}
\]

The accuracy of this method is independent of the amount of water vapour in the analysed gas, and the accuracy is only slightly affected by instrument errors; the method does however require the fraction carbon to be known. Since a pure hydrocarbon fuel of known composition was used throughout the tests, the method was suitable. For fuels of uncertain composition a further method employing a carbon/hydrogen balance, is available, although this method requires an estimate of the water vapour content of the sample, and is affected to a greater extent by instrument error.
APPENDIX 3

CALCULATION OF MASS EMISSION RATES

An engine produces $M_1$ gram-moles of exhaust gas per hour. After cooling or drying to remove water vapour this reduces to $M_2$ gram-moles/hour.

The moles of carbon constituent/hour are:

$$\text{Moles carbon/hr from exhaust} = \frac{M_2}{100} (\text{CO}_2\% + \text{CO}\% + 6 \text{C}_6\text{H}_{14}\%)$$

grams carbon/hr = $\frac{12.01 \times M_2}{100} (\text{CO}_2\% + \text{CO}\% + 6 \text{C}_6\text{H}_{14}\%)$

Now fuel consumption (measured) is $X$ gm/hour.

'.'. Carbon intake of engine is $F_c \times X = Y$ gm/hr

where $F_c$ is fraction carbon in fuel by weight.

hence $M_2 = \frac{100 \times Y}{12.01 (\text{CO}_2\% + \text{CO}\% + 6 \text{C}_6\text{H}_{14}\%)}$

This is the gram-moles of dried (analysed) exhaust/hr.

hence mass emissions:

$$\text{CO gm/hr} = \frac{\text{CO}\%}{100} \times M_2 \times 28.01$$

$$\text{C}_6\text{H}_{14} \text{gm/hr} = \frac{\text{C}_6\text{H}_{14}\%}{100} \times M_2 \times 86.178$$

$$\text{NO gm/hr} = \frac{\text{NO}\%}{100} \times M_2 \times 30.008$$

Atomic Weights:

12.01 = Atomic weight of carbon
28.01 = Mol weight CO
86.178 = Mol weight of Hexane
30.008 = Mol weight NO
PROGRAM LAYOUT

APPENDIX 4

61 FN#«UFC.VXFAF 21 T
62 LIST(LP)
63 SEND TO (END,PROGRAM FILE,STORF)
64 PROGRAM(C108)
65 INPUT1=CRU
66 OUTPUT2=LP O
67 END
68 MASTER EXHAUST GAS ANALYSIS
69 DIMENSION S(10)
70 DATA X1/4HDATA/,X2/4H***C/,X3/4H***Z/
71 CALL DATE (DATE1)
72 CALL TIME (TIME1)
73 WRITE(2,100),(DATE1,TIME1)
74 100 FORMAT(1H1/0/0X,29HN,REAL EXHAUST GAS ANALYSIS 10X,6HDATE AR,
75 12X,6HTIME AB,\\\\\
76 101 READ(1,102) (S(J),J=1,10)
77 102 FORMAT(10AM)
78 CALL COMP3(S(1),X3,J)
79 IF(J-1)0,111,0
80 CALL COMP3(S(1),X1,J)
81 IF(J-1)101,0,101
82 103 READ(1,102) (S(J),J=1,10)
83 CALL COMP8(S(1),X2,J)
84 IF(J-1)0,105,0
85 WRITE(2,106) (S(J),J=1,10)
86 104 FORMAT(10X,10AM)
87 GO TO 103
88 105 WRITE(2,115)
89 113 FORMAT(4X,4HBMEP,6X,3HSFC,6X,3HIGN,4X,3H%0,6X,4H%O2,5X,3H%2,4X,
90 25XPMN0,3X,5HPPMHC,3X,5HPPMHC,4X,5HC0G/H,4X,5HHCG/H,4X,5HNOG/H,6X,
91 5HFA/F)
92 WRITE(2,116)
93 114 FORMAT(65X,6HNDIR),3X,5H(FID))
94 READ(1,106) (FC, DENSF, SPPED)
95 106 FORMAT(9ED,0)
96 107 READ(1,106) (BLOAO, TIGN, CO, CO2, O2, PPMNO, PPMHCN, PPMHCF, FUEL)
97 IF(FCO2)0,101,0
98 C COMPUTE BMEP LB/SQ IN
99 C BMEP=3.7*BLOAD
100 C COMPUTE FUEL CONSUMPTION GM/HR
101 C FUELCON=127800.0*DENSF/FUEL
102 C COMPUTE FUEL CONSUMPTION LB/HR
103 C FUEL=FC+2.0466F-3
104 C COMPUTE BRAKE HORSEPOWER
105 C BHP=8.5*BLOAD*SPEED/5000.0
106 C COMPUTE SPECIFIC FUEL CONSUMPTION LB/BHP.HR
SFC=FUELMB/HHP

SELECT HYDROCARBON READING

IF(PPMHCFC0.108,108
PPMHC=PPMHHCN*2.0E-4
GO TO 109

108: PPMHC=PPMHFC*1.0E-4

109: SUMC=CO+CO2+6.0*PHC

GMOLEX=FC*100.0*FUELC0N/(12.01*SUMC)

120: COMPUTE CO MASS EMISSION GM/HR

121: CUMPH=CO*0.2801*GMOLEX

122: COMPUTE HC MASS EMISSION GM/HR

123: HCMPH=PHC*0.86178*GMOLEX

124: COMPUTE NO MASS EMISSION GM/HR

125: GPHNO=PPMINO*1.0E-4+0.30008*GMOLFX

126: FC1=11.492*FC

127: FC2=12.0*(1.0-FC)

128: SUMHC=CO+CO2

129: C1HC02=CO/CO2

130: COMPUTE FRACTION BURNED

131: FC1=1.492*FC

132: FC2=12.0*(1.0-FC)

133: COMPUTE AIR/FUEL RATIO

134: GPMEX=FC1*(C02+0.5*CO+O2)/SUMC2*FC2/(3.5+C0C02))

135: WRITE(2,110)(NAME,SFC,TIGN,CO,CO2,O2,PPMNO,PPMHHCN,PPMHFC,C0GPH,HCG

136: 4PH,GPHNO,APF)


138: 52,F10.3)


140: 52,F10.3)

141: GO TO 107

142: CALL TIME(TIME1)

143: WRIFE(2,112)(DATE1,TIME1)

144: 112 FORMAT(///T1X,17HEND OF JOB DATE AR,2X,6HTIME AR,141)

145: STOP

146: END

147: FINISH

148: 164: FINISH

149: 165: G0#C10A Z1
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ILLUSTRATIONS

Fig. 1  Engine coolant circuit
Fig. 2  Fuel systems
Fig. 3  Induction system
Fig. 4  Optical and recording system
Fig. 5  Water bath coolant flow circuit
Fig. 6a & b  Shadow photographs downstream of a valve in a flow-rig
Fig. 7  Droplets in motion - from cine film

Graph
1. Flame detector gas flow v pressure
2. Flame detector calibration curve.
3. Cross response of nitric oxide analyser to water vapour
4. Repeatability at 1500 r.p.m. full load
5. Mass emissions 800 r.p.m. (no load) ignition 10° B.T.D.C.
6. Mass emissions 800 r.p.m. (no load) ignition 5° B.T.D.C.
7. Mass emissions 800 r.p.m. (no load) ignition T.D.C.
8. Mass emissions 800 r.p.m. (no load) ignition 5° A.T.D.C.
9. Mass emissions 800 r.p.m. (no load) injector position 2
10. Volumetric concentrations 800 r.p.m. (no load) injector position 2
11. Mass emissions 1500 r.p.m. (full load) carburation and injection
12. Mass emissions 1500 r.p.m. (full load) injector positions 1 & 2
13. Mass emissions 1500 r.p.m. (full load) injector positions 1 & 2 heated charge
14. Mass emissions 1500 r.p.m. (60 b.m.e.p.) carburation and injection
15. Mass emissions 1500 r.p.m. (60 b.m.e.p.) injector positions 1 & 2
16. Mass emissions 1500 r.p.m. (60 b.m.e.p.) injector positions 1 & 2 heated charge
17. Mass emissions 1500 r.p.m. (30 b.m.e.p.) injector positions 1 & 2
18. Mass emissions 1500 r.p.m. (30 b.m.e.p.) injector positions 1 & 2 heated charge
19. Mass emissions 2200 r.p.m. (full load) injector position 1 & 2
20. Mass emissions 2200 r.p.m. (full load) injector positions 1 & 2 heated charge
21. Mass emissions 2200 r.p.m. (60 b.m.e.p.) injector positions 1 & 2
22. Mass emissions 2200 r.p.m. (60 b.m.e.p.) injector positions 1 & 2 heated charge
23. Mass emissions 2200 r.p.m. (30 b.m.e.p.) injector positions 1 & 2
24. Mass emissions 2200 r.p.m. (30 b.m.e.p.) injector positions 1 & 2 heated charge
25. Carbon monoxide % + Carbon dioxide % v air-fuel ratio
26. Carbon monoxide % v air-fuel ratio at idle and 2200 r.p.m. part load
27. Carbon monoxide % v air-fuel ratio at 1500 r.p.m. and 2200 r.p.m. full load
28. Carbon dioxide % and Oxygen % v air-fuel ratio at 2200 r.p.m. part load
29. Carbon dioxide % and Oxygen % v air-fuel ratio at idle, 1500 r.p.m. and 2200 r.p.m. full load
30. Injection pump characteristics
FIG. 1  ENGINE COOLING CIRCUIT

FIG. 2  FUEL SYSTEM
FIG. 3 EXPERIMENTAL INTAKE SYSTEM

FIG. 4 OPTICAL AND RECORDING SYSTEM
FIG. 5 EXHAUST SAMPLE COOLING AND WATER TRAP SYSTEM
FIG. 6  SHADOW PHOTOGRAPHS DOWNSTREAM OF AN INLET VALVE
- COLD FLOW RIG

(a) at a high air velocity
(b) at a low air velocity
FIG. 7  DROPLETS OF FUEL IN MOTION
(one frame of cine film)

The sizes given are the approximate diameters