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FUEL EFFECTS ON ROAD TRANSPORT ENGINES - EMISSIONS AND COLD STARTING

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ABSTRACT

This paper describes a test programme to assess the cold start characteristics, gaseous and particulate emissions, to the European 13-mode test procedure, from a range of seven heavy duty diesel engines when operated with eight different fuel formulations. The results showed that engine design features were the predominant influence on both cold start and emissions characteristics. Fuel formulation was found to exert secondary influences, the most significant of which was the effect on particulate emissions of fuel sulphur content and fuel volatility.

1. INTRODUCTION

Throughout the major diesel engine markets concern is being expressed over the levels of environmental pollution caused by road traffic sources and measures to control gaseous and particulate emissions are in force in many countries.

Any change in the road transport fuel composition could potentially affect gaseous and particulate emissions of diesel engined vehicles. To assess the extent of these effects, the Dutch Ministerie van Volkshuisvesting Ruimtelijke Ordening en Milieubeheer (VROM) commissioned Ricardo to study the published information and attempt to identify the effects on performance and emissions of changes in individual fuel properties. However, overall trends could not be reported with adequate confidence due to the overriding influence of engine design parameters and the close interrelation of many fuel properties (Ref 1).

A practical study was therefore commissioned by VROM to investigate the effects of various diesel engine fuel compositions on a range of heavy duty diesel engines. To strengthen the practical focus of the work and to ensure that input from the relevant interests was available, VROM established a steering committee, which included representatives of CCMC and CONCAWE, to monitor and control the project.

2. FUEL MATRIX

The fuel matrix for use in the test programme was defined in conjunction with Concawe and was intended to be representative of the likely range of fuel compositions that may be available throughout Europe during the next decade.

In order to fully define the fuel properties expected in future years, projections of the anticipated range of cetane number, boiling range and density were made. This was combined with knowledge of the potential crude oil sources and processing routes, including cetane improvers, into an eight fuel matrix as shown in Figure 1.

A reduction in fuel sulphur level has been promoted as one means of assisting engine manufacturers in meeting low exhaust particulate limits and low sulphur fuels are currently being used in the USA. The effect of fuel sulphur level was addressed in the matrix through the use of two fuels with 0.29 and 0.07% wt, representing typical current and proposed sulphur levels respectively. The low sulphur fuel was a standard production fuel produced by a commercial UK refinery which was then doped with Benzothiophene to increase the sulphur level to the current norm for European fuels.

A baseline fuel was incorporated into the matrix and was formulated to be equivalent to the current reference fuel RF-03 specified for emission certification tests.

3. ENGINE MATRIX

The majority of engine production for the current European heavy duty diesel engine parc falls broadly into two size ranges of c. 1 and 2 litres swept volume per cylinder. The size range and level of engine technology employed is dictated by a combination of the power requirement of the vehicle, the application and the market requirement. At the higher power outputs the use of turbocharging with the addition of aftercooling for the highest ratings is common due to packaging, efficiency and emissions advantages. However, at the lower power requirements where vehicle and engine cost assume greater importance the use of naturally aspirated engines is typical and expected to continue for the foreseeable future.

All heavy duty engines use direct injection combustion systems but two alternative design concepts are employed: swirling or quiescent. The majority of production engines in Europe utilise the former, but there are also significant numbers of quiescent engines in use and a much higher proportion in the USA, therefore this type was included in the engine matrix.

In the development of heavy duty diesel engines to meet low levels of emissions legislation, manufacturers are adopting high pressure fuel injection equipment with some degree of timing control to achieve optimum flexibility and emissions over the operating range. An engine of this type was included in the matrix to enable the emissions potential of this type to be assessed, together with its fuel quality tolerance.

The selected engine matrix consisted of seven engines, all supplied through the cooperation of CCMC and other engine manufacturers and selected on the basis of production numbers. This is shown in Figure 2 together with the abbreviations used for each. The results of the work were submitted to each participating engine manufacturer who confirmed that they were representative.

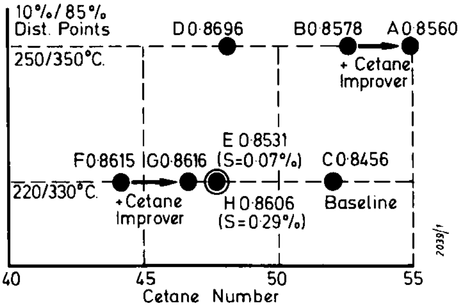


FIG 1 FUELS MATRIX

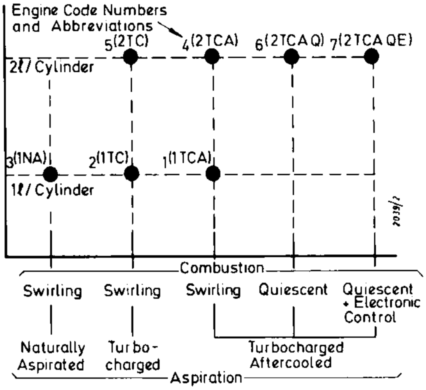


FIG 2 ENGINE MATRIX

4. TEST PROCEDURE

The test fuels were evaluated in each engine over the ECE Directive 88/77 13-mode steady state test cycle, measuring gaseous emissions and particulates. The 13-mode test procedure currently relates to gaseous emissions only, although draft regulations for the measurement of particulates have been formulated. At the time of carrying out the study, the single filter paper methodology for particulate measurement over the 13-mode cycle was not fully developed so a separate filter paper was used for each mode. The overall cycle result was computed by weighting and summing the individual mode results in the same manner as for gaseous emissions. This method has been used successfully at Ricardo and other laboratories for many years and has the additional advantage that fuel effects and particulate composition at each individual mode may be analysed if required.

The selected engines were tested on each of the fuels in the matrix in turn, beginning with the baseline fuel. At the end of the tests on each engine, a repeat test was performed on the baseline fuel to assess the long-term repeatability and variability of the emissions results. To assess the response of each engine to injection timing retard and any fuel effects on retardability, tests were carried out at three injection timings where possible. Two engines used in the study incorporated unit injectors operated directly from the engine camshaft and for these engines injection timing responses could not be obtained. For each engine, all tests were carried out at constant mass fuelling at the maximum power condition, the reference level being that obtained with the baseline fuel. This procedure was adopted to eliminate the known effects of changes in mass fuel delivery brought about by changes in fuel density and viscosity, thus ensuring that the minimum air/fuel ratio selected by the engine manufacturer remained constant.

5. COLD STARTING

Cold start tests were carried out on three engines selected from the study, the 1TCA, 2TCA and 2TCA(QE) types. All were turbocharged and aftercooled as these engines generally employ lower compression ratios than other methods of aspiration and the use of air-to-air aftercooling is likely to prolong the effects of cold ambient temperature on engine operation. A temperature of -10°C was selected for the cold start testing as this was considered to be low enough to illustrate any effects of fuel properties without requiring the use of specialist cold start aid systems. Where appropriate, the cold start aids fitted to the engines as standard were used to the manufacturer's recommendations for the test temperature.

After a period of soak at the test temperature, the engine was started and run up to governor run-out speed. Thereafter the engine speed was returned to a fast idle during warm-up. The clearance of white smoke and hydrocarbon emissions were monitored as the coolant temperature increased.

6. COLD START RESULTS

Under cold start conditions, where combustion may be marginal, the ignition quality of a fuel is of prime importance.

The effect of cetane number on cold starting properties is shown in Figure 3. Engine design parameters can also significantly affect the cold start performance of an engine and the results obtained provide a good demonstration of this. The 2TCA(QE) engine, having an electronic control system, which allows the injection timing to be optimised under all conditions, started readily on all the test fuels and reached governor run-out in the shortest time. This engine showed minimal sensitivity to fuel changes, demonstrating that timing optimisation under cold starting is a major influence.

The 1TCA and 2TCA engines showed more sensitivity to cetane number changes but again the engine design had a major influence. The 1TCA engine was fitted with a large manifold heater matrix which is pre-heated before commencement of cranking and continues to be energised after cranking finishes. The 2TCA engine has less pre-heating, using two glow-plug type elements, and no post-cranking assistance. Accordingly, the 1TCA engine gave short times to first combustion, but rather longer times to self sustained running and

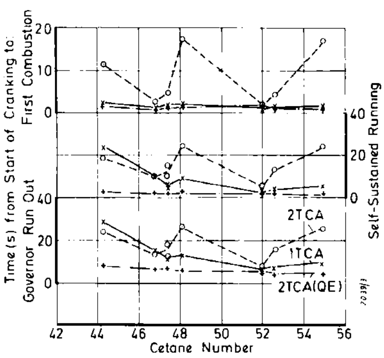


FIG 3 EFFECT OF CETANE NUMBER ON COLD START PERFORMANCE

governor run out than the 2TCA(QE) engine. In general, the 2TCA engine with less pre-heating required longer cranking times and took longer to achieve a given speed and demonstrated more sensitivity to cetane number changes. Both 1TCA and 2TCA engines took longer to start as the cetane number was reduced, a trend that was not unexpected. However, longer start times were recorded for some of the higher cetane fuels and subsequent examination of the fuel properties showed that the fuels concerned (cetane numbers 48.1, 52.6 and 54.9) were in the higher boiling point range, suggesting that volatility also influences the cold start behaviour. Whilst the engine was warming-up the decay in white smoke and hydrocarbon emissions was monitored, the time to reach selected levels being recorded. These results are shown against cetane number in Figures 4 and 5. Under warm-up conditions, the effects of fuel properties and engine design influences were more pronounced. As had been observed previously, the sTCA(QE) engine, having the benefit of a flexible control system, required the shortest time to reach a given smoke or hydrocarbon level, particularly at low cetane numbers. The two other engines required longer times to reach a given level and also showed a marked sensitivity to cetane number, lower cetane fuels requiring longer times for emissions to fall to a given level. It is noteworthy that the 1TCA engine, which had demonstrated short starting times, due to the large amount of pre-heating, required longer for smoke or hydrocarbon emissions to decrease than the 2TCA engine, which had less pre-heat assistance and therefore took longer to start, providing further evidence of the influence of engine design choices on engine operation under cold conditions. The influence of fuel volatility was again demonstrated, these fuels (cetane numbers 48.1, 52.6 and 54.9) requiring longer times to reach given emission levels.

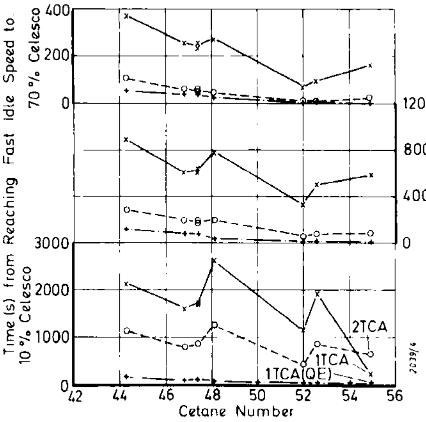


FIG 4 EFFECT OF CETANE NUMBER ON COLD START SMOKE COLD START

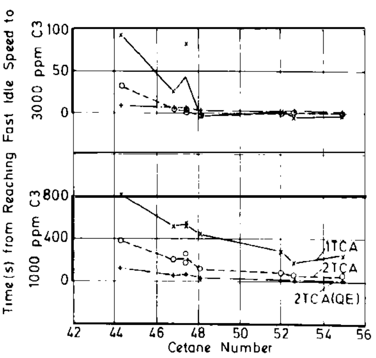


FIG 5 EFFECT OF CETANE NUMBER ON HYDROCARBON EMISSIONS

7. 13-MODE EMISSION RESULTS

The test results are presented in the form of trade-off curves against 13-mode NOx as this parameter is one of the primary criteria constraining the development of diesel engines to meet legislated limits. The fuel effects were not consistent between engines and therefore it was considered more useful to present results as overall bands rather than individual results. The bands of fuel responses are shown as shaded areas on each curve, with the baseline fuel result for each engine highlighted.

7.1 NOx

The effect of fuel on NOx emissions is shown in Figure 6 for the different injection timings tested. There was a large spread in NOx levels between engines, due to engine design influences and the method of aspiration (ie NA, TC, TCA). The fuel effects on different engines varied with the type of engine and the injection timing although the effects were smaller for those engines having lower NOx levels.

7.2 Hydrocarbons

The trade-off between NOx and hydrocarbon emissions is shown in Figure 7. All engines for which a timing response could be obtained exhibited the expected trend for hydrocarbon emissions to increase as the NOx level was reduced, as the combustion system was operated away from the optimum design condition. The level of hydrocarbon emissions depended upon engine design, the TCA engines tending to give lower emission levels than the other types tested. The effect of fuel on hydrocarbon emissions was generally similar at the lower hydrocarbon levels but those engines giving higher levels appeared more sensitive to fuel changes. The sensitivity was found to be of similar magnitude across the range of timings for each engine.

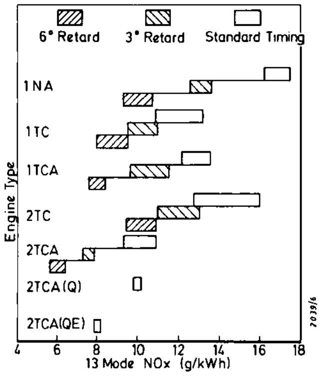


FIG 6 13-MODE NOx OVER THE ENGINE, FUEL AND TIMING MATRIX

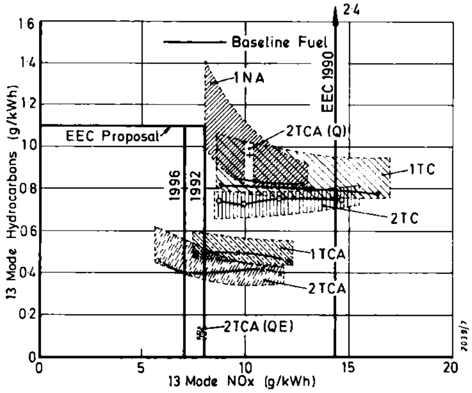


FIG 7 13-MODE NOx-HC OVER THE ENGINE, FUEL AND TIMING MATRIX

7.3 Carbon Monoxide

The trade-off between NOx and carbon monoxide is shown in Figure 8. The diesel engine operates at air/fuel ratios well above stoichiometric and therefore produces very low levels of carbon monoxide. Hence, the level of carbon monoxide produced over the 13-mode cycle is, in turn, a function of the engine air/fuel ratio at full load conditions, this being a function of the specific engine rating. Therefore, engines that operate at relatively low air/fuel ratios would be expected to produce the highest levels of carbon monoxide and this was observed for the naturally aspirated engine (1NA). This engine also exhibited the greatest sensitivity to fuel changes of all those tested although the 2TCA(QE) engine showed changes of a similar order of magnitude due to the changes in cycle power caused by the correction to equal mass fuelling.

7.4 Fuel Consumption

The trade-off between NOx and 13-mode cycle fuel consumption is shown in Figure 9. All engines showed increased fuel consumption as the injection timing was retarded away from the optimum in order to achieve low NOx levels. The adoption of turbocharging and aftercooling improves the trade-off due to the engine being less sensitive to timing changes but even the engine with the best cycle fuel consumption trade-off would incur a penalty of approximately 5% from its current level in order to meet future NOx limits of 7 g/kWh. Fuel composition changes produced variations in cycle fuel consumption of typically 5 g/kWh for most engines after correction for density variation. The 2TCA(QE) engine gave variations larger than this but these were attributable to the large cycle power corrections needed with this engine over the others.

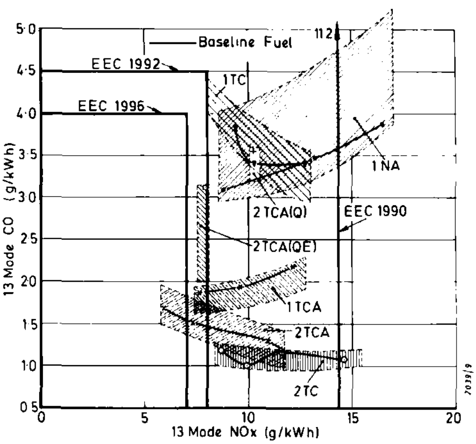


FIG 8 13-MODE NOx-CO OVER THE ENGINE, FUEL AND TIMING MATRIX

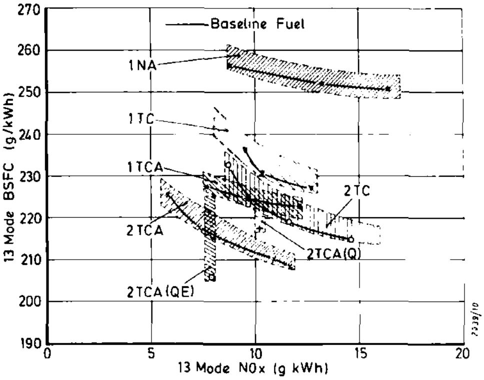
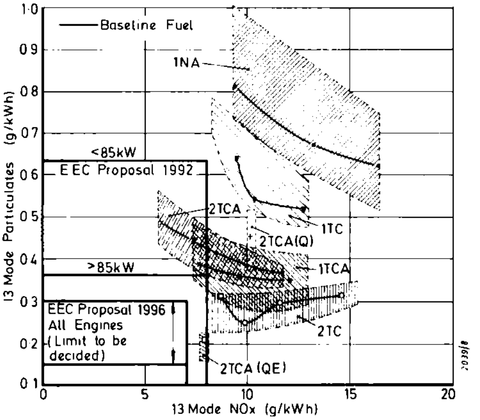


FIG 9 13-MODE NOx-BSFC OVER THE ENGINE, FUEL AND TIMING MATRIX

7.5 Particulates

The trade-off between NOx and particulates is shown in Figure 10. As the injection timing was retarded, all engines showed increased particulate emissions, due partly to higher smoke levels under these conditions and also to the increased hydrocarbon levels. The different types of engine also gave different orders of response with timing. Those engines that employed higher injection pressures had a smaller penalty in particulate emissions as the timing was retarded than those with lower injection pressures. Thus the 1NA and 1TC engines have steeper trade-offs with timing than the other engines tested due to the poorer fuel atomisation with the relatively lower pressure injection systems. The two swirling aftercooled engines (1TCA and 2TCA) both produced similar levels of particulate emissions, indicating that engine size need not be a limiting factor in producing low emission levels. A similar effect was observed with hydrocarbons. One of the lowest particulate emission levels was produced by the 2TC engine, an unexpected result as turbocharged and aftercooled engines generally give the best emission trade-offs.

The response of the test engines to fuel changes was more marked than for hydrocarbons. Again, the engines with the lower emission levels generally showed less variation in particulate emissions than those engines with higher emission levels, although the 1TCA engine gave larger changes in emissions than other engines of similar emission levels.



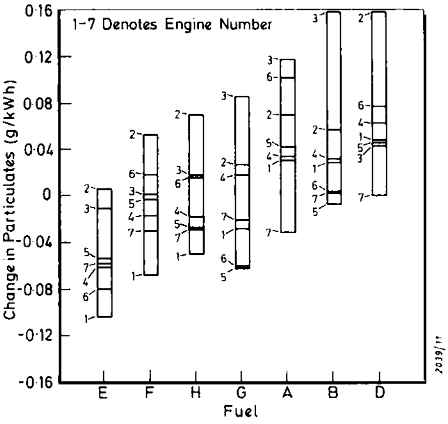


FIG 10 13-MODE NOx-PARTICULATE OVER ENGINE, FUEL AND TIMING MATRIX

FIG 11 MODEL PREDICTED CHANGE IN THE 13-MODE PARTICULATES FROM THE BASELINE FUEL FOR EACH ENGINE

8. DETAILED ANALYSIS OF RESULTS

From the measured engine data presented above, it was clear that although engine type, and to a lesser extent injection timing, were the dominant factors in determining overall emission levels, fuel type also influenced the results from each engine. However, with the exception of the low sulphur fuel, which in general gave the lowest particulate results, none of the test fuels appeared to exhibit a sufficiently consistent response across the engine range to identify either particularly 'good' or 'bad' fuels in respect of the measured parameters. This lack of a clear response was not particularly surprising in view of the deliberate 'commercial' nature of the fuels matrix.

To investigate whether any underlying fuel effects were present which may have been masked by the dominance of the other factors, it was necessary to use a more advanced analytical technique. An established statistical modelling method (Ref 2) was therefore employed which enabled the contribution of each individual parameter (eg fuel, engine, timing etc) of an overall result to be identified relative to a selected reference condition. This method thus provided a convenient means of isolating the effect of fuel type relative to the baseline fuel. The use of the model technique had the additional advantage of providing some smoothing of the measured results, thus limiting the significance of any results which were towards the limit of the typical test accuracy range. In general, it was found that the model results closely reflected the measured values.

The statistical model analysis was carried out for the 13-mode cycle results of particulates, NOx and hydrocarbons and the peak torque and rated speed exhaust smoke values, these parameters being the major area of interest in the work under review. An example of the results obtained is shown in Figure 11 which demonstrates the model predicted change in 13-mode particulates for each fuel in each engine relative to the predicted results for the baseline fuel in each engine for the standard timing condition.

The data in Figure 11 is presented in histogram form in ascending order of increase in particulate, based on the worst case result from any of the engines for each fuel. Thus, an initial means of ranking fuel effects becomes apparent although it could correctly be argued that this method is very engine specific and accounts only for the worst case result and ignores fuel effects in the remainder of the engine matrix. To account for these effects, alternative methods of ranking were investigated both to improve confidence and to provide a means of indicating the magnitude of the fuel effects. These included averaging and weighting methods, all of which gave similar trends so averaging was used for the further analysis to enable a more quantitative indication of fuel effects to be presented.

The same analyses were carried out for the NOx, HC and smoke results and again a high degree of similarity between methods was demonstrated. The influence of fuel composition on exhaust smoke was found to be minimal and hence is not reported in detail.

Table 1 summarises the overall results in terms of the change in 13-mode emissions from the baseline fuel due to fuel effects alone for the standard injection timing condition. To put the magnitude of the changes due to fuel type into perspective, the table also shows the average emission levels over the engine matrix with the baseline fuel and the corresponding maximum and minimum percentage change of these average levels.

	Better <—— Fuel Ranking ——> Worse							Average level all engines baseline fuel	Max % change +/-
	Average Change in Emission g/kWh								
	A	B	D	E	H	F	G		
NOx	-.584	-.453	-.278	-.158	-.139	.14	.233	12.14	-5 - +2
	E	F	G	H	B	A	D		
Particulates	-.052	-.007	-.006	-.003	.04	.052	.063	0.397	-13 - +15
	A	B	E	F	G	H	D		
HC	-.014	-.003	.012	.046	.054	.057	.058	0.61	-2 - +9

TABLE 1 MODEL PREDICTED AVERAGE CHANGE IN EMISSIONS DUE TO FUEL EFFECTS COMPARED WITH THE MODEL PREDICTED AVERAGE EMISSIONS WITH THE BASELINE FUEL

The use of a percentage term to describe the changes in gaseous and particulate emissions (with the exception of the effects of fuel sulphur level, as discussed later) is considered correct as any changes due to fuel type are most likely to occur on a proportional basis. Thus any changes due to fuel type will be more significant in absolute terms for those engines exhibiting the highest emission levels, particularly where these engines may be close to any proposed legislative limits.

Inspection of the test data here confirms this observation. Taking the case of particulates, for example, engine 2TCA(QE) which showed the lowest overall levels, typically 0.2 g/kWh, gave a total spread of results for the fuels tested of 0.034 g/kWh or ±9%. In contrast, the highest levels, typically 0.65 g/kWh occurred on engine 1NA which resulted in a fivefold increase in the spread of fuel effects to 0.16 g/kWh but a similar percentage change, ±12%.

To test the significance of the effects shown in Table 1 it is useful to compare these with the repeatability level for the various parameters. From the extensive emission tests carried out at Ricardo the following repeatability levels are typical: NOx ±0.1 g/kWh HC ±0.02 g/kWh Particulates ±0.02 g/kWh. For the average levels shown in Table 1 these values correspond to NOx ±1%, HC ±3%, particulates ±5%. It is clear from these values that the following effects were significant (in decreasing order) when compared to the baseline fuel

1. Reductions and increases in particulate
2. Increases in hydrocarbons
3. Reductions in NOx (small significance)

8.1 Relationship with Fuel Properties

It was not a prime objective of this programme to relate any changes in emissions to specific fuel properties. Indeed, the programme was initiated largely because of the problems encountered in other programmes which did have this objective and the difficulty found in characterising fuel properties. However, because the fuel matrix was composed of a range of expected commercial products, a range of fuel properties was present (Figure 1).

Initially, the statistical model data shown in Table x was compared with the major fuel properties to identify any trends or relationships and this analysis is reported here. Subsequently, a more rigorous regression analysis was carried out by the sponsor (ref 3). The first approach identified some separation of the effects in relation to step changes in the property groups for the fuels (eg sulphur content, volatility etc) as discussed below, whilst the second approach attempted to establish mathematical relationships across a range of properties. This in general led to the same conclusions but with some variation in emphasis.

8.2 Sulphur Content

Reduction in the fuel sulphur content from 0.29% w/w (fuel H) to 0.07% w/w (fuel E) gave a consistent reduction in particulates for all engines as shown in Figure 12. The regression coefficients demonstrate the near linearities of the response at the three timings assessed whilst the coefficient of determination (R^2) in each case is excellent. Thus, for the standard timing condition, a reduction of fuel sulphur content of 0.22% w/w reduced particulates by 0.036 g/kWh indicating that the conversion rate to sulphate was similar for all engines (typical value 1.5%) and demonstrating the increasing significance of sulphur content as overall particulate levels are reduced by other means.

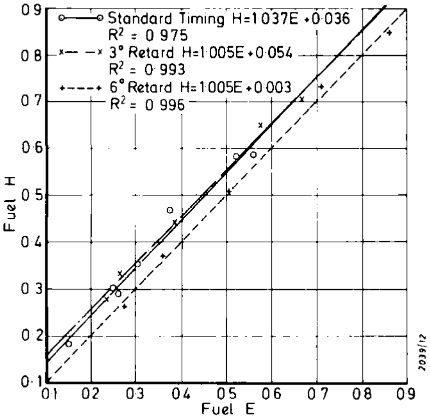


FIG 12 MODEL PREDICTED 13-MODE PARTICULATES. EFFECT OF SULPHUR CONTENT FUEL E (0.07%) V FUEL H (0.29%)

The effect of sulphur content on particulate levels at the most retarded timings was consistently close to zero, due to the increase in particulate with the low sulphur fuel being greater than that with the standard sulphur fuel when compared to the standard timing condition. No explanation for this effect can be offered and is probably of little significance as a timing retard of 6° is unlikely to be the sole means of engine emission control.

The low sulphur fuel was also found to distort some other fuel property group relationships in respect of hydrocarbon emission as noted below.

8.3 Volatility (T_{90}°C) and Viscosity

There was a strong interrelation between volatility (T_{90}°) and viscosity, with the fuel matrix falling into two distinct groups; fuels A, B and D (T_{90} 357-359°C, viscosity 4.26-4.51) and the remainder (T_{90} 331-343°C, viscosity 3.14-3.34). The two terms are thus substantially interchangeable and for convenience volatility is used throughout.

Figure 13 shows that there was a clear separation of particulates in respect of the two volatility groups with the lower volatility fuels (A, B and D) resulting in increases in particulates of similar magnitude to the reductions obtained with the low sulphur fuel and hence must be regarded as significant. Conversely, these fuels produced some reduction in NOx which is consistent with a degradation in combustion conditions and thus, to a small degree, are self compensating on a NOx/particulate trade off basis. However, as timing is the dominant factor in NOx production for a given engine, this observation is of little practical significance.

There was no relation between hydrocarbon emissions and volatility, with fuel D producing the largest increase in hydrocarbons whilst fuels A and B produced the largest reductions.

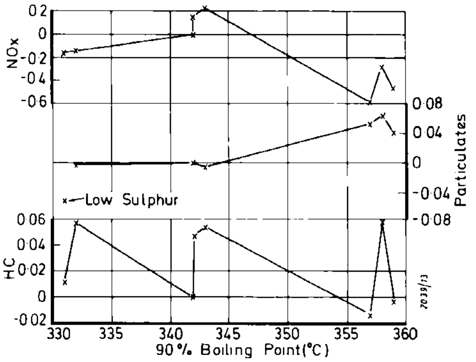


FIG 13 MODEL PREDICTED CHANGE IN 13-MODE EMISSIONS V 90% BOILING POINT

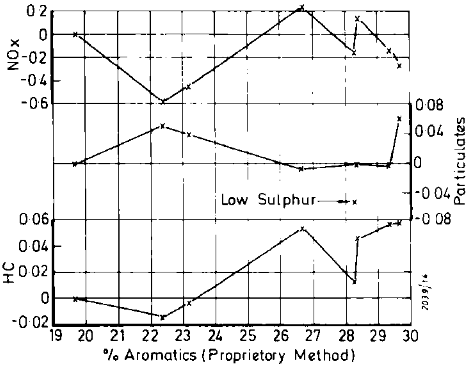


FIG 14 MODEL PREDICTED CHANGE IN 13-MODE EMISSIONS V AROMATIC CONTENT

8.4 Aromatics

The range of aromatic content of the fuel matrix was relatively small at 20-30% by a proprietary test method or 25-33% by the draft IP PM-AY method. The ranking of aromatic content was similar by either method with the proprietary method being reported here.

The role of aromatics in emission generation is very topical at present with somewhat conflicting information being presented by various researchers. The data from this programme is presented in Figure 14. It can be clearly seen that for this fuel matrix no relationship existed between either NOx or particulates and aromatic content (neglecting the effect of the low sulphur fuel in the case of particulates). Some separation of the data is evident in the case of hydrocarbons, with the higher aromatic levels producing the highest increases, with the exception of the low sulphur fuel.

8.5 Cetane Number

Some separation of the hydrocarbon effects and to a much lesser extent the NOx effects was evident for two cetane number groups (44-48 and 52-55), as shown in Figure 15. The effects were in line with general diesel combustion theory, where reducing the cetane number leads to an increase in the delay period and the pre-mixed burning fraction, resulting in increased NOx and hydrocarbon emissions.

There was no relationship between cetane number and particulate emissions. The use of cetane improving additives did not distort the data. Again the low sulphur fuel was an anomaly in respect of hydrocarbon effects.

8.6 Density

Figure 16 shows the data for the effects of density on hydrocarbon emissions which again fell into two groups with the lower densities producing substantially no change whilst the higher densities showed increases.

There was no correlation between NOx or particulate and density.

It should be remembered that, for this programme, the usual effects of density (eg increased smoke) were eliminated by operation of the engines at constant mass fuelling. This was considered valid as these effects should not be regarded as true fuel effects but as an artifact of the diesel engine fuel delivery mechanism (ie volume based).

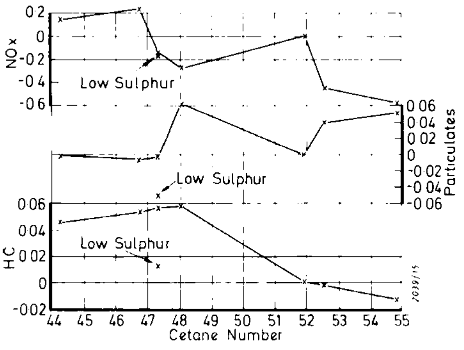


FIG 15 MODEL PREDICTED CHANGE IN 13-MODE EMISSIONS V CETANE NUMBER

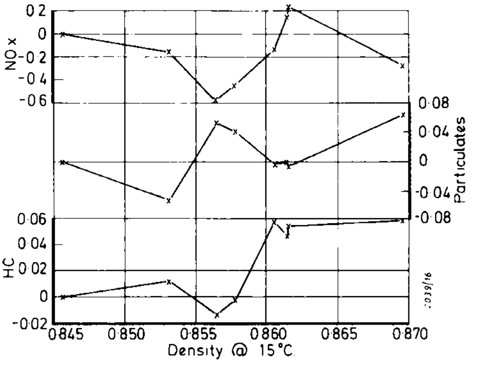


FIG 16 MODEL PREDICTED CHANGE IN 13-MODE EMISSIONS V DENSITY

9. DISCUSSION AND CONCLUSIONS

The test programme has demonstrated the dominance of engine type and technology level in controlling the level of exhaust emissions, fuel consumption and cold starting characteristics.

Before reviewing fuel effects in detail it is instructive to compare the emission levels of the various engine types with current and proposed European legislative levels (Figures 7 & 8). Considering the six engines primarily intended for the European market, whilst all easily achieved the 1990 hydrocarbon limit, the 1NA engine exceeds the 1990 NOx limit and the 2TC engine was marginal. Minor changes in timing would allow these engines to achieve compliance although the accompanying increases in smoke on the 1NA engine may introduce another legislative problem.

Whilst further injection retard would allow achievement of the 1992 NOx level (and in some cases the 1996 level), the accompanying deterioration in fuel consumption would be unacceptable and achievement of the 1992 particulate limits would be marginal. Additional development will therefore be required to achieve the 1992 limits for all engines. At this level, the secondary effects of fuel type established in this programme will begin to assume greater importance and may influence the required engine improvements. These observations are accentuated when considering the 1996 levels with the 1NA engine presenting the greatest challenge.

The measures necessary to reduce particulates will in general bring about hydrocarbon reductions making this aspect less problematic for both 1992 and 1996 levels.

The 2TCA(QE) engine, primarily designed for the US market, was shown to meet the proposed 1992 emission levels and it is known that the type of technology employed in this engine is capable of achieving compliance with the proposed 1996 level. (Ref 4)

For the two engines assessed in this programme which used quiescent combustion, this system was not shown to provide any advantage unless allied to other combustion developments (eg high pressure injection, timing control etc).

Reviewing the effects of the test fuel matrix, it should again be stressed that being essentially 'commercial' in nature no particular attempt was made to decouple the various interrelated properties in constructing the matrix. Nevertheless, two effects were observed which were considered significant, these being the reduction in particulates with reduction in fuel sulphur content and the increase in particulates (and to a lesser extent influences on cold running) for those fuels having lower volatility (or higher viscosity). These effects tended to become more apparent by separation of the effects into two blocks of fuel property. It is therefore somewhat dangerous to attempt to ascribe mathematical relationships to the observed data which implies interpolation between these blocks. The influence of sulphur content and volatility is also supported by other similar programmes (ref 5).

A similar but less significant relation between blocks of fuel properties and hydrocarbons was also observed with the higher density and aromatic fuels and lower cetane fuels all indicating higher hydrocarbon emissions. Cetane number correlated well with cold start characteristics.

No relationship was found between aromatic content and particulates which is supported by the work in Ref 5 but at variance with that reported in Refs 6 and 7. However, the range of aromatic levels assessed in this programme was small compared with the similar programmes referenced and of particular relevance did not include very low aromatic fuels as currently being considered for use in the USA. In view of the conflicting evidence available the result obtained here is therefore not unexpected.

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