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INFLUENCE OF FUEL VARIABLES ON THE OPERATION OF AUTOMOTIVE OPEN AND PRE-CHAMBER DIESEL AND SPARK IGNITED STRATIFIED CHARGE ENGINES: A LITERATURE STUDY COVERING PETROLEUM AND SYNCRUDE DERIVED FUELS, EXECUTIVE SUMMARY

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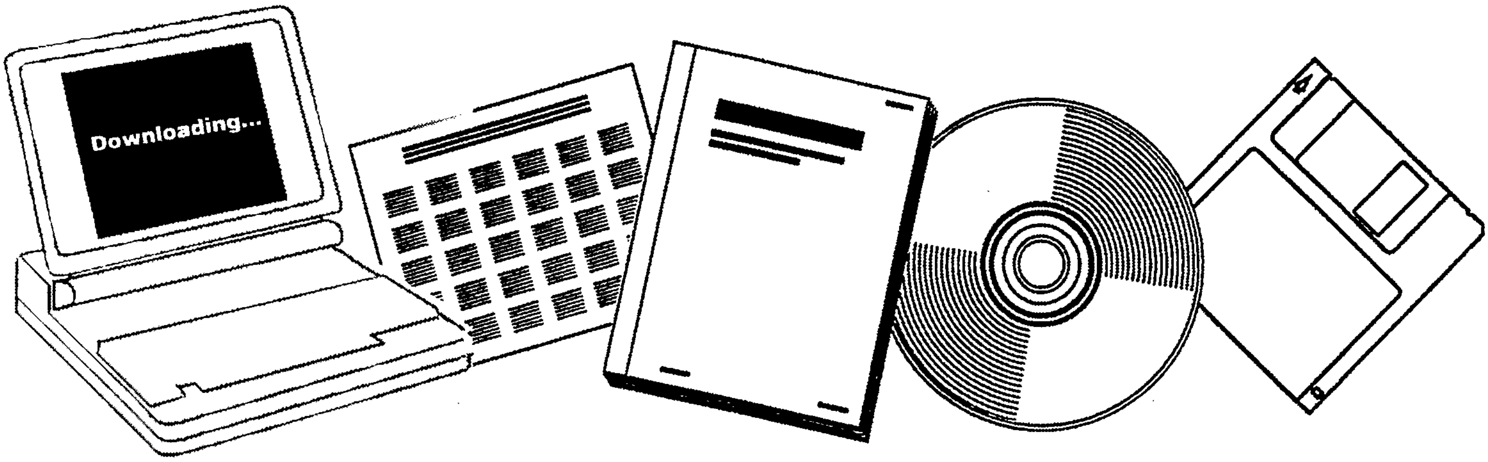

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The Influence of Fuel Variables on the Operation of Automotive Open and Pre-Chamber Diesel and Spark Ignited Stratified Charge Engines:

A Literature Study Covering Petroleum and Syncrude Derived Fuels

Executive Summary

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ABSTRACT

A literature study has been carried out to ascertain the influence of fuels and fuel variables on the operation of automotive diesel and spark ignited stratified charge engines with a view to understanding the impact of future fuels derived from syncrude. The findings from the search were presented and discussed in detail in the main report (Ricardo DP.81/539). In this executive summary, the conclusions and recommendations from the main report are presented.

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1. INTRODUCTION

Recent future energy projections for domestic supplies within the United States suggest that unrestricted exploration and development of new sources of natural gas and oil would only result in a temporary escalation of energy production peaking in the period 1990-95. The fall in output after this period dictates that the US must develop a syncrude industry by the 1990-95 era to avoid reliance upon the vulnerable option of high import levels.

In embarking upon an energy policy incorporating the use of alternative fuels such as syncrude products, it is prudent to study the potential impact of these fuels upon the systems that will be exposed to their use. This is particularly valid for the automotive engine.

This executive summary provides a synopsis of the main report (Ricardo DP81/539) which presented and discussed data pertaining to the fuel/engine relationship that could be extracted from a search of published and Ricardo in-house literature and aimed to assist with the understanding of the potential impact of future automotive fuels upon power plant operation and requirements. The main report provided a precursor (Task 1) to a complementary test programme under the same contract (Tasks 2 and 3). The range of data incorporated was broadly restricted to fuels and engine types regarded as pertinent to the proposed test programme.

The complementary test programme, Tasks 2 and 3, is divided into a preliminary screening study, Task 2, followed by a more fundamental study, Task 3.

Task 2 will explore the operation of two standard, multi-cylinder, contemporary, light duty diesel engines representing indirect (IDI) and direct injection (DI) combustion systems. With these engines, a relatively narrow range of fuels will be utilised to screen the influence of such fuel variables as ignition quality and volatility upon performance and emissions without undertaking any fuel/engine optimisation.

The fundamental study, Task 3, will examine the influence of fuels upon several combustion systems encompassing IDI and DI diesel, and spark ignited stratified charge (TCCS, MAN FM, spark ignited Comet IDI diesel). This will be accomplished utilising a single cylinder engine and injection and/or ignition timing will be suitably varied to achieve a degree of optimisation for each fuel. Fuels will have wide ranging specifications.

2. OBJECTIVES

In compiling the main report, the objectives of the study were stated as follows:-

a) To perform a literature search of published and Ricardo in-house data relating to the use of alternative liquid fuels in internal combustion engines.

b) To survey the literature and to extract where confidentiality permits the data regarded as pertinent to the proposed test programme.

c) To analyse the pertinent data and to present the findings, recommendations and conclusions in a report in order to understand more fully the fuel/engine relationship.

3. SCOPE OF THE LITERATURE SEARCH

The literature search was based on an examination of the following sources:-

a) Ricardo Library catalogues and indexes, including in-house databases, containing references from a wide range of published and unpublished literature. The latter covers Ricardo reports which were utilised when confidentiality permitted.

b) Published abstracts and indexes such as British Technology Index (B.T.I.), Motor Industry Research Association abstracts (M.I.R.A.), Institution of Mechanical Engineers Index (I. Mech. E.), American Society of Mechanical Engineers Index (A.S.M.E.) and Society of Automotive Engineers Index (S.A.E.).

c) External on line computer databases such as Compendex.

Utilising these sources, potentially useful references covering the use of alternative liquid fuels in internal combustion engines were located. These references were screened for information regarded as pertinent to the test programme using the selection criteria reported in section 4. The literature search covered the period 1940 to c.June 1980.

4. PERTINENT DATA - SELECTION CRITERIA

The selection criteria for those data regarded as pertinent for inclusion in this study were broadly based upon the contents of the proposed test programme as follows.

4.1 Pertinent Fuels

For the complementary test programme, it has been decided to explore the fuel/engine relationship with a range of fuels whose leading parameters fully encompass the potential specifications of future broadcut fuels derived from syncrude. In the absence of actual syncrude products, it is proposed that petroleum derived diesel fuel and straight run naphtha will be blended to provide simulated broadcut fuels. In addition, the individual base fuels will also be evaluated.

The range of leading fuel parameters that will be studied are a function of the base fuels that will be utilised and are listed as follows:-

	No. 2 Diesel Fuel	Straight Run Naphtha
Cetane No.	c.45	c.27
Research Octane No.	c.30	c.70
Distillation Range °F	c.400-700	c.190-400
Aromatic Content % Vol.	c.30	c.15
Sulphur Content % wt.	c.0.4	c.0.003
Gravity ° API	c.34	c.52

Broadcut blends of these fuels have intermediate properties dependent upon the blend ratio.

Notable by its absence from this scheme is high octane gasoline. This omission is deliberate and based upon the rationale that the most economically produced future broadcut fuels would not utilise high octane gasoline for blending, since the production of high octane gasoline is energy intensive owing to the various upgrading processes employed. Furthermore, power plants for which broadcut fuel will be designated will not include the conventional spark ignition gasoline engine thus eliminating the high octane requirement.

Based upon these experimental fuels for the complementary test programme, data that were regarded as pertinent for this study were defined by liquid petroleum fuels with the exception of data relating to the evaluation of syncrude products which were naturally included. Such fuels as alcohols,liquid gases and vegetable oils were therefore excluded.

In addition, the influence of fuel additives such as cetane improvers, cold flow improvers, smoke suppressants, etc., were also not expressly studied. Data involving the use of cetane improvers were however included when utilised for specifically studying the influence of ignition quality.

4.2 Pertinent Engines

Pertinent engines were isolated primarily by three major factors; namely: type of combustion system, means of fuelling and application.

4.2.1 Pertinent Combustion Systems

The following combustion systems based upon reciprocating piston engines have been designated for the test programme and were therefore regarded as pertinent to this study:-

a) Indirect injection diesel - IDI
b) Direct injection diesel - DI
c) Spark ignited, indirect injection diesel - (Ricardo Comet).
d) Spark ignited, direct injection - MAN FM.
e) Spark ignited, direct injection - Texaco Controlled Combustion System, TCCS.

Although in the test programme the IDI diesel will be represented by a Ricardo Comet V swirl chamber combustion system, it was decided not to restrict this study solely to this system but to include other developed forms of swirl and pre-chamber engines.

Similarly, the test programme will also utilise a toroidal swirling DI engine and, by adopting the same philosophy as for the IDI diesel, data relating to the use of other developed forms of DI engine e.g. quiescent chamber, were incorporated.

The three spark ignited systems are all of the 'late' injection type (i.e. injection commences later than 50° BTDC on compression stroke). Of these, the MAN FM and TCCS processes represent two of the most developed, late injection, open chamber, stratified charge engines. Other stratified charge processes with multi-fuel capability, e.g. Mitsubishi MCP and Deutz AD, were acknowledged in the main report but not studied in detail.

The choice of these combustion systems is entirely logical. IDI and DI diesel engines currently represent the most fuel efficient power plants for automotive applications. For the future, it will be desirable to retain this advantage provided the specification of fuels permits. A study of the fuel/engine relationship for these combustion systems was therefore essential in order to be able to define acceptable minimum fuel requirements. The spark ignited systems chosen for detailed study all represent designs which have demonstrated multi-fuel capability although they have to date reached different levels of development status. All of these systems represent unthrottled, late injection, stratified charge engines. By being unthrottled like the diesel engine, high thermodynamic efficiency is obtained in the interests of good fuel economy. By employing late injection, excessive levels of pre-mixed combustion can be avoided with the resultant elimination of fuel octane requirement. The addition of a positive ignition source in the form of a sparking plug also avoids the necessity to use fuels of high cetane number. By using the sparking plug for ignition, thereby not relying on the natural cetane number of the fuel to attain compression ignition, as in the case of the multi-fuel diesel engine, wide fuel tolerance is achieved with favourably lower compression ratios. This provides the direct advantage of lower mechanical stresses and hence lighter engines and attenuated high friction levels characteristic of the diesel engine.

4.2.2 Pertinent Fuelling Methods

In keeping with the test programme, engines utilising pertinent combustion systems and fuels but incorporating dual fuelling, whether in the form of dual injection or aspiration with pilot injection were also excluded. Data were therefore restricted to single fuel, single in-cylinder injection systems.

4.2.3 Pertinent Engine Applications

For this study, only engines classified as light to heavy duty, high speed automotive were included. Non-automotive and low/medium speed engines for marine and locomotive applications were therefore omitted. This is a generalised statement since in a few isolated cases data obtained from small non-automotive diesel engines were included to provide corroborative support for results obtained from automotive types.

4.3 The Relevance of Omitted Data

The omission from this study of any fuel, combustion system, method of fuelling or engine application was not intended to suggest that similar studies of fuel/engine relationships covering these areas would not be beneficial. In fact they would be essential to encompass and comprehend fully the entire scenario.

These equally important areas were not studied in the main report because it was considered that the inclusion and analysis of such data lay outside the scope of the work defined in the current contract.

5. ANALYSIS OF PERTINENT DATA

For analysis, the data were broadly subdivided into two major classes as follows:-

- compression ignition combustion

- spark ignited combustion

5.1 Compression Ignition Combustion

Analysis in this category was carried out to develop information relating to the way in which leading fuel parameters influence the operation of compression ignition engines. This was achieved, where data permitted, by extracting the reported effects of fuel parameters, or fuel type, on the following topics:-

- Cold starting characteristics
- Exhaust smoke following cold starting
- Exhaust smoke at normal engine operating temperatures
- Performance, fuel economy, combustion characteristics, etc.,
- Gaseous exhaust emissions
- Exhaust particulate emissions
- Potential health hazards of emitted particulates
- Noise
- Exhaust odour
- Engine deposits and wear
- Fuel injection equipment considerations

These topics were thought to represent areas of current interest. The format of the listing was not intended to indicate relative importance.

For each of these topics, where appropriate, the influence of the following fuel variables were investigated:-

- Ignition quality - cetane number
- Volatility
- Chemical composition
- Viscosity
- Density
- Impurities
- Low temperature performance
- Alternative fuels

Alternative fuels aside, the individual fuel variables have been investigated by various workers in differing degrees of isolation, as permitted by the complex nature of liquid hydrocarbon fuels and the strong inter-relationship of several of the variables. For this reason, fuel sets have frequently been utilised with wide ranging variables and the engine observations treated statistically, together with the fuel variables, to obtain the strongest relationship.

The inclusion of alternative fuels was made to cover data relating to the use of, for example, jet fuels and gasolines in compression ignition engines. In this case all fuel variables can markedly differ. In the case of jet fuels, which can have specifications closely akin to diesel fuel, the results of the other "controlled" experiments could probably be used to predict their performance with varying degrees of reliability. In the case of radically different fuels however such as gasoline, major leading fuel variables generally lie outside the ranges explored during the "controlled" studies, and hence predictions of their performance could not reliably be made in all areas. Resort must therefore be made to the actual operational results. Furthermore, the simultaneous interaction of several variables, as in the case of alternative fuels, may provide completely different operational characteristics, making the validity of predictions from the "controlled" experiments suspect. In short, the results of the "controlled" and alternative fuels studies were viewed in unison to provide a complete picture.

The analysis of these data revealed at an early stage that there were several major areas of disagreement, or differences in sensitivity regarding the influence of fuel variables upon the various facets of diesel engine operation. No doubt in many cases such differences could be more fully understood if comparisons of relative injection timings, or other leading engine parameters, could be made between test engines. Unfortunately, such valuable data were all too frequently not reported. Because of these areas of inconsistency between the reported observations and the lack of supporting data, it was not thought possible to develop an engine/fuel model, so this was not attempted. The various data were therefore presented in some detail within appendices to the main report to illustrate this point. Predictions were only made where general agreement of observations permitted, although speculative comments were included. Owing to the differing sensitivities such predictions were generally only of a qualitative nature.

5.2 Spark Ignited Combustion

Reported data for the three spark ignited stratified charge systems of direct interest to this project were analysed under the following topics for the different fuels utilised where results permitted.

- Combustion characteristics
- Performance
- Fuel economy
- Gaseous exhaust emissions
- Response to gaseous exhaust emissions controls
- Exhaust particulate emissions

- Exhaust odour
- Noise
- Cold starting characteristics

For these combustion systems, the various topics were examined for the influence of fuel type where data permitted and, in addition, comparisons with the compression ignition engine were made.

5.3 Additional Analysis

From the findings of this search, it was clear that the analysis could not be fully developed to cover comparisons of the various combustion chambers operating with different ranges of fuels. Consideration to the selection of suitable combustion systems for ranges of fuels was however given in the report discussion.

6. CONCLUSIONS AND RECOMMENDATIONS

In this section the overall conclusions drawn and the recommendations made as extracted from the main report are presented.

The overall conclusions and recommendations were drawn from detailed discussion and conclusions presented in the main report and itemised under the following topics:-

i) Cold starting characteristics

ii) Exhaust smoke following cold starting

iii) Exhaust smoke at normal engine operating temperature

iv) Engine performance

v) Gaseous exhaust hydrocarbon emissions (HC)

vi) Gaseous exhaust carbon monoxide emissions (CO)

vii) Gaseous exhaust nitrogen oxide emissions (NOx)

viii) Exhaust particulate emissions

ix) Noise

x) Exhaust odour

xi) Other considerations:

- Engine deposits and wear

- The influence of fuel impurities upon exhaust emissions
- The potential health hazard of exhaust particulate

xii) Suitability of combustion systems for future fuels.

These detailed conclusions are presented in the appendix to this document.

6.1 Overall Conclusions

a) Considering the extensive worldwide utilisation of diesel engines with a variety of combustion chambers and different applications, there is relatively little information available from structured programmes on the detailed effects of fuels and fuel variables related to the many facets of engine operation.

b) In the available literature there are many conflicts and areas of insufficient data and it is impossible to predict the overall effect of fuel variables upon diesel engine operation.

c) Insufficient data are available to evaluate syncrude derived products or to know whether syncrude products, having the same basic specification as petroleum derived products, behave in a similar fashion.

d) The data currently available on the influence of fuels and fuel variables have been acquired without recourse to engine re-optimization for fuels. In addition, the light duty IDI diesel engine requires more detailed attention. Future work should therefore cover a wider range of diesel engines and optimization of the engines for the various test fuels used.

e) i) For fuels of very low ignition quality spark ignited stratified charge engines will probably be required as they have been demonstrated to have good fuel tolerance.

ii) For fuels of relatively high ignition quality, re-optimized diesel engines should be suitable.

iii) For fuels of intermediate ignition quality i.e. c.30-35, it is not clear without further data which type of combustion system would be most suitable.

f) A significant reduction in fuel ignition quality will require considerable design and development effort, either to adapt diesel engines or to apply spark ignited stratified charge engines on a large scale.

g) A large amount of carefully structured test work is required to obtain detailed information to understand fully the implications of future fuels upon the operation of engines with various combustion systems.

6.2 Recommendations

On completion of the compilation of the main report, the following recommendations were made.

a) Continue to update the literature study particularly as regards synfuel operation because more data are likely to be generated in this area in the near future.

b) Give high priority to making synfuels available for future test programmes.

c) Give consideration to other potentially fuel tolerant combustion systems.

d) Define a test programme which will provide the required information in the areas where insufficient data currently exist.

e) Study the trade-off between the refinery implications of maintaining fuel quality so that existing diesel engines and design philosophy can be retained against reducing fuel quality with the attendant research and design/development implications, particularly with regard to lead time for production.

APPENDIX

This appendix presents the detailed conclusions reached within the main report and are presented under the itemised topics listed in Section 6.

i) COLD STARTING CHARACTERISTICS

a) Low temperature flow performance of future fuels will need to be comparable with current fuels. The relative importance of cloud, pour and cold filter plugging points will need to be determined.

b) Ideally, future fuels for diesel engines should have cetane numbers of c.42 minimum to ensure the retention of acceptable cold starting characteristics. The adoption of a more volatile broadcut fuel with this ignition quality may in fact tend to improve starting, providing excess fuel delivery characteristics are maintained.

c) Reducing cetane number to c.35 will generally adversely influence cold starting characteristics. In the case of heavy duty DI applications, it is considered that the implications may be tolerable to the driver, but have commercial repercussions for the operator. In the case of the light duty IDI diesel with more stringent acceptability standards, it is speculated that these standards may not be reliably met at low ambient temperatures with current designs.

d) To obtain acceptable cold starting at low ambient temperatures with fuels of c.35 cetane, engines may require modification to incorporate higher compression ratio or revised valve timing. This will have adverse implications upon engine rating or in some cases require redesign with attendant frictional and weight penalties. To overcome this, the wider adoption of external aids will be required and in the case of the light duty IDI, the use of larger capacity heater plugs or plugs which stay energised after key release should prove beneficial.

e) For fuels of even lower cetane number, i.e. c.30, DI engines will require design modifications and the widespread adoption of external aids. In the case of the IDI engine, design modifications will prove beneficial although continuously energised heater plugs should continue to be adequate.

f) For fuels of very low cetane number i.e. c.20-25, the spark ignited stratified charge system becomes attractive in respect of cold starting.

g) Increased volatility assists in offsetting lower cetane number. Limited evidence suggests however that a broadcut fuel of c.35 cetane will provide difficult starting in a standard light duty IDI vehicle.

h) Attention must be paid in the future to ensure that lower viscosity broadcut fuels do not penalise excess starting fuel delivery characteristics due to internal pump leakage.

i) With more volatile broadcut fuels, hot starting may prove difficult due to vapour locking if pre-start purge facilities are not made available.

ii) <u>EXHAUST SMOKE FOLLOWING COLD STARTING</u>

a) The maintainance of current diesel fuel ignition quality in combination with more volatile broadcut fuels may improve cold smoking tendency beyond current levels.

b) Reduction in fuel ignition quality below current standards will aggravate cold smoking tendency.

c) More volatile broadcut fuels should assist in moderating cold smoking tendency with lower cetane fuels although the latter parameter will probably remain dominant.

d) To alleviate cold smoking tendency with lower cetane fuels, diesel engines will require adapting by such means as raising compression ratio, optimising injection timing, raising exhaust back pressure and insulating combustion chambers. Exhaust gas recycle may also prove beneficial.

In the case of IDI engines, the retention of energised heater plugs may impart considerable improvements.

e) With very low cetane fuels, i.e. less than c.30, the DI engine may continue to smoke at idle even up to normal operating temperatures. In this case a cure may be effected by employing significantly higher compression ratio and levels of exhaust back pressure but with adverse implications in other respects. For IDI engines, the continued application of energised heater plugs may be adequate.

f) For very low cetane fuels, the spark ignited stratified charge engine may prove very successful in respect of cold smoking.

g) Results exist to understand the implications of lower cetane fuels upon the cold smoking tendency of diesel engines. Similar trends are also available for the influence of volatility. Data have not been uncovered however to assess possible future fuels which encompass both appreciably lower ignition quality and higher volatility i.e. possible broadcuts. Similarly, the potential moderating influence upon cold smoke with lower cetane fuels of engine modifications such as increased compression ratio, optimised injection timing etc., is not known. In addition, the potential benefits of the spark ignited stratified charge engine in respect of cold smoking are also not known.

h) Much more work must be carried out in the context of cold smoking tendency to appreciate fully the implications with respect to future fuels.

iii) <u>EXHAUST SMOKE AT NORMAL ENGINE OPERATING TEMPERATURES</u>

a) Assuming that future fuel specifications may differ from those of current diesel fuels, the data available does not enable reliable predictions in all areas relative to the smoking performance of diesel engines. This is because of major areas of conflict and the fact that re-optimisation for fuels has not been carried out. Further comprehensive test programmes are therefore required before the full implications upon smoke and smoke limited power output can be evaluated.

b) Reducing cetane number will tend to aggravate blue smoke experienced with many diesels at light load. Engine modifications will help to alleviate this problem. With very low cetane fuels, blue smoke will be most apparent unless major steps are taken in the form of engine modifications to effect a cure. In this instance, the spark ignited stratified charge engine may prove beneficial although light load smoking tendencies for this class of engine are not fully reported.

c) It appears that fuels of higher volatility will assist in moderating light load blue smoke. In the case of the MAN FM engine, volatile fuels are required to cure light load smoke.

d) Published data generally suggest that more aromatic fuels increase smoke output from diesel engines.

e) The effects of cetane number upon black smoke output from diesel engines at higher load factors cannot reliably be judged from the conflicting data available. A similar situation exists regarding the influence of fuel volatility.

f) Limited data available for synfuels with specifications similar to current diesel fuels demonstrates that no major impact upon smoke is apparent. Coal derived products with very low H/C ratio have been used as extenders for diesel fuel and provided significantly worse smoke performance. Shale fluids as diesel extenders seem acceptable as regards no adverse influence upon smoke limited power output. Much more work with synfuels is however required.

g) The spark ignited stratified charge engines under direct consideration in this study should return improved smoke limited output with fuels more volatile than diesel fuel.

iv) ENGINE PERFORMANCE

a) Low ignition quality fuels need not penalise fuel consumption provided that diesel engines are suitably adapted to compensate for longer ignition delay and to maintain the timing of peak pressure relative to TDC at optimum. Such adaptation will be required automatically for other considerations such as emissions and noise. Thermal efficiency may therefore be maintained within acceptable limits.

b) There is little experimental evidence to suggest that fuel volatility, viscosity or chemical character influence economy. The possible influence of volatility and chemical character should be examined in more detail for clarification. Viscosity effects if evident should automatically be compensated for when optimising diesel engines for future fuels.

c) Data regarding the influence of synfuels upon fuel economy are limited. It is speculated that providing engines are suitably optimised for such fuels then fuel consumption will not suffer. If however future synfuels are allowed to have appreciably lower H/C ratios compared with current diesel fuels, it is speculated that fuel economy will be penalised. These speculations require experimental verification.

d) The spark ignited Comet, TCCS and FM combustion systems appear resilient to wide ranging fuel specifications in respect of brake specific fuel consumption. In the case of the TCCS system, this resilience has also been demonstrated over the 1975 FTP test and although experimental evidence is not available, it is anticipated that the other two systems will behave similarly.

e) The maximum torque output of both diesel and these spark ignited stratified charge engines will be governed by the influence of fuel upon smoke output, as each engine type has a smoke limited rating.

v) <u>GASEOUS EXHAUST HYDROCARBON EMISSIONS (HC)</u>

a) Fuel injection characteristics may require re-optimsiation, along with air swirl matching, to assist in minimising any potential adverse effects upon HC emissions. Owing to positive ignition, spark assisted stratified charge engines may be somewhat less sensitive in this respect.

b) Fuels having higher volatility or lower ignition quality with respect to diesel fuels will tend to increase HC emissions in current diesel engines. In respect of volatility, attention must be focused on minimising uncontrolled volumes at the injector tip and further reducing combustion chamber lost volume to minimise the penalties. In respect of lower cetane number, the extent to which HC control can be regained by taking action to combat the longer ignition delay and avoid late combustion cannot be ascertained from the literature. More work is therefore required in this area.

c) More work is required to generate reliable trends linking fuel chemical composition and HC emissions.

d) Limited data regarding the use of diesel synfuels suggests that HC emissions were only influenced in comparison with regular diesel fuel to an extent that would have been expected of petroleum products of the same specification. Diluting diesel fuel with hydrogenated creosote oil of low H/C ratio increases HC emissions due to reduced rates of combustion.

Much more data need to be acquired concerning the use of synfuels to understand fully the situation.

e) The spark ignited Comet engine requires higher cetane fuels for low light load HC emissions.

f) Insufficient data exists for the MAN FM engine concerning HC emissions and fuel tolerance. It is speculated that a trade-off exists with volatility, with fuels of intermediate distillation characteristics to either diesel or gasoline having the potential for lower light load HC emissions. Work is required in this area.

g) More volatile fuels appear to increase generally HC emissions with the TCCS combustion system.

vi) GASEOUS EXHAUST CARBON MONOXIDE EMISSIONS (CO)

a) It must be anticipated that CO emissions will rise if the ignition quality of future fuels is allowed to reduce. The possibilities of restoring CO emissions by engine re-optimisation for lower ignition quality fuels should be examined.

b) The influence of fuel volatility upon CO emissions is contradictory. The influence of wide ranging distillation characteristics representative of broadcut fuels have not been examined and an examination in this area is required. Limited 1975 FTP test results obtained with broadcut fuels suggest that CO emissions will increase even if reasonable ignition qualities are maintained.

c) The relationship between CO emissions and fuel chemical composition is also not clear as contradictions exist and therefore requires controlled experimental evaluation.

d) Data with synfuels in respect of CO emissions are again limited and need strengthening. The data uncovered for this study suggest that diesel synfuels will not materially affect CO emissions outside of what may be expected of petroleum derived fuels with similar specifications. The blending of hydrogenated creosote oil obtained from coal with diesel fuel increases CO emissions. The low H/C ratio of this dilutent and the unacceptable reduction in smoke limited output due to slow rates of combustion would not make such a dilutent extender for diesel fuel attractive.

e) The use of more volatile fuel in both the spark ignited Comet and TCCS spark ignited stratified charge systems favour lower CO emissions. The response of the MAN FM system in this respect is not known and needs evaluating.

vii) GASEOUS EXHAUST NITROGEN OXIDE EMISSIONS (NOx)

a) There is reasonably strong evidence to suggest that reducing cetane number to c.30-35 in current diesel engines will adversely affect NOx emissions. It is thought that the longer ignition delay is responsible. Whether or not engine optimisation to reduce delay with low cetane fuels will restore NOx emissions is not known. Test work is required to clarify this point.

b) The influence of volatility upon NOx emissions cannot be accurately judged from the available data due to various contradictions. Some evidence suggests that more volatile fuels suppress NOx emissions from pre-chamber engines. If truly characteristic this will favour the use of broadcut fuels. Additional studies are required in this field however for full clarification.

c) Fuel viscosity has not been related to NOx emissions. The influence of fuel chemical composition upon NOx emissions requires clarification to determine whether or not aromatics per se influence NOx formation.

d) Data relating to the use of very low ignition quality, highly volatile gasoline fuels are restricted and contradictory. The characteristics of such fuels upon NOx emissions cannot be accurately judged therefore without access to further data. Other light fuels such as jet fuels, kerosenes and No. 1 diesel fuels generally appear not to affect adversely NOx in comparison with No. 2 fuels.

e) Many more data need to be generated in respect of synfuels. Limited data suggest that synfuels with specifications similar to regular diesel fuel do not adversely affect NOx formation, differences that were apparent being commensurate with differences in fuel properties such as ignition quality. Tentative data would also imply that shale fluids can be used as diesel dilutent extenders without adversely affecting NOx but that low H/C ratio coal products in the form of hydrogenated creosote oil cannot.

f) The spark ignited Comet engine favours less volatile fuels for low NOx emissions whilst the converse may be true of the MAN FM system. FTP results with TCCS equipped vehicles imply that this system is insensitive to fuel specification with respect to NOx emissions.

viii) EXHAUST PARTICULATE EMISSIONS

a) For fuels having ignition qualities comparable with No. 2 diesel fuel, there is reasonable experimental evidence to suggest that minimising aromatic content and lowering upper distillation characteristics relative to current No. 2 diesel fuel will impart significant particulate reductions.

b) Limited data available suggest that reducing ignition quality in IDI engines may reduce particulate emissions. Since light duty FTP diesel particulate emissions are largely comprised of the organic HC fraction and lower cetane fuels induce higher HC emissions, it is thought that lower ignition quality will generally increase light duty particulate emissions. This effect should however be moderated by engine re-optimisation.

Fuels having cetane numbers significantly lower than diesel fuels have not been examined regarding their influence upon particulate emissions.

c) Preliminary results with hydrogenated diesel fuel obtained from coal of similar specification to No. 2 diesel fuel returned competitive particulate emissions.

d) The performance of the spark ignited Comet and MAN FM combustion systems with regard to particulates is not known for any fuel and must be examined. Limited data with a TCCS engined vehicle reveal that the particulate output with unleaded gasoline as fuel is very low in comparison with what may be expected from a similar vehicle equipped with an IDI diesel engine. Shale derived gasoline and gasoline/diesel blends returned particulate emissions closely in accord with the IDI diesel. Factors other than combustion differences are thought to be responsible.

e) Insufficient data exist to predict the performance of future fuels in respect of particulate emissions where it is anticipated that distillation range and ignition quality will be significantly at variance with current diesel fuels. Experimental work with engine re-optimisation where appropriate is required. In addition, similar studies are required with actual synfuels since expected impurities may contribute to particulate output.

ix) NOISE

a) Diesel engine noise levels will rise with fuels of lower ignition qualities than current standards. It is thought that adaptation to moderate ignition delay with such fuels to avoid penalties in other areas will automatically assist in controlling noise. It is also believed that noise in synfuel operation will be characterised by the ignition quality of the fuel. Noise should be monitored during future test programmes to confirm these speculations.

b) Limited evidence would suggest that fuel volatility is not a dominant factor in noise generation. Test work to clarify this point is required however.

c) One reliable source of data suggests that noise in high speed IDI diesel engines is influenced by fuel chemical character. This point should be investigated to observe whether it is a general characteristic of diesel engines.

d) Noise from spark ignited Comet and TCCS stratified charge engines appears to be insensitive to fuel specification defined by gasoline and diesel fuels. It is speculated that the MAN FM system will also behave in this fashion although experimental evidence is not available.

x) EXHAUST ODOUR

a) Exhaust odour data are limited and at times contradictory and difficult to interpret. It is suggested that odour should be further evaluated in respect of the influence of fuels but it is considered that odour studies may adopt secondary importance to the study of other more leading parameters.

xi) OTHER CONSIDERATIONS - ENGINE DEPOSITS AND WEAR, THE INFLUENCE OF FUEL IMPURITIES UPON EXHAUST EMISSIONS AND THE POTENTIAL HEALTH HAZARD OF EXHAUST PARTICULATE

a) When considering future fuels, one must be aware of the implications of fuel specification upon such features as engine deposit and wear levels. Ignition quality, volatility and chemical character may be important factors based upon results from limited studies. An examination of these parameters must therefore be included in future test programmes since it appears that there is insufficient data available at present to allow accurate judgement.

b) In the interests of low engine deposits and wear, fuel sulphur level should not be allowed to rise significantly above current standards. Assuming exhaust catalysts are utilised in the future for particulate control, fuel sulphur levels should be maintained as low as economically possible. Exceptionally low levels of fuel sulphur may cause damage to fuel injection pump components however because of depressed extreme pressure lubricity. The lubricity of future fuels must therefore be examined for compatibility with fuel injection equipment.

c) There are insufficient data to ascertain whether or not fuel bound nitrogen contributes to NOx emissions. There are no data to ascertain whether fuel bound nitrogen contributes towards particulate emissions. Data are therefore required in this field.

d) Due regard for the influence of future fuel specifications upon the potential health hazard of particulate emissions should be given and examined in future test programmes, although in the short term this can be ascribed a low priority status.

xii) SUITABILITY OF COMBUSTION SYSTEMS FOR FUTURE FUELS

a) The response of diesel engines to fuel ignition quality appears to be the prime controlling factor which will govern the suitability of the diesel engine for future fuels.

b) If fuels of very low ignition quality i.e. c.15-25 are anticipated as being widely available in the future, then the spark ignited stratified charge engine will represent the most viable combustion system. This is based upon the view that for diesel engines to successfully operate on such low cetane fuels, considerable adaptation towards past multi-fuel developments will be required which will be commercially unattractive. In addition, the high speed potential of light duty diesel engines may be restricted and emissions characteristics may be adversely affected.

c) Assuming that the currently unresolved issues of wider fuel distillation characteristics and chemical composition upon such features as diesel engine emissions show no adverse implications, then the retention of high ignition quality for future fuels i.e. above c.40 will enable the diesel engine to continue as the most competitive automotive power plant. This view is based upon the high state of development of the diesel engine with generally better emissions levels and transient fuel economy than the spark ignited stratified charge engine.

d) For fuels of intermediate ignition quality i.e. c.30-35 cetane, a judgement cannot be made without further data. This is based upon the fact that the required degree of adaptation of the diesel engine to operate successfully in respect of performance, economy, emissions etc., has not been established to enable comparison with the spark ignited stratified charge engine.

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