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diesel fuel aromatic content and its relationship with emissions from diesel engines

Prepared for the CONCAWE Automotive Emissions Management Group and based on work carried out by the Special Task Force on Diesel Fuel Emissions, (AE/STF-7).

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ABSTRACT

This report provides the results of a research programme designed to investigate the influence of diesel fuel aromatic content and cetane number on diesel engine exhaust emissions.

A representative range of seven current light-duty vehicles, together with two heavy-duty engines, was tested using European test procedures with six fuels having aromatics contents in the range 15 to 37% volume. The test fuels were produced by deep hydrogenation of the base fuel. This process influences other fuel quality parameters, including density, sulphur content and cetane number. To balance these changes the matrix included sulphur and ignition improver additive-doped fuels. A hydrocracked fuel was also included in order to study the influence of aromatic type.

The study found a significant influence of fuel properties on carbon monoxide and particulate emissions from light-duty vehicles. The strongest correlations were obtained with cetane number. Inclusion of aromatics terms in correlation equations with cetane number gave no improvement over correlations incorporating only cetane number.

KEYWORDS

diesel fuel, aromatics content, mono- di- and tri- aromatics, density, sulphur content, cetane number, emissions

NOTE

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SUMMARY

The aromatic content of diesel fuel has been suggested as a factor influencing emissions from diesel engines. CONCAWE therefore decided to study the influence of aromatics and cetane number on diesel engine emissions performance. Gaseous and particulate emissions were measured for a range of contemporary diesel vehicles and heavy-duty engines, operating on a carefully designed matrix of diesel fuels.

The investigation was conducted using European test procedures with six fuels having aromatics contents in the range 15 to 37% volume. The test fuels were produced by deep hydrogenation of the base fuel. This process influences other fuel quality parameters, including density, sulphur content and cetane number. To balance these changes the matrix included sulphur and ignition improver additive-doped fuels. A hydrocracked fuel was also included in order to study the influence of aromatic type. Seven modern light-duty vehicles and two current heavy-duty engines were included in the programme.

The study found a significant influence of fuel properties on carbon monoxide and particulate emissions from light-duty vehicles. The strongest correlations were obtained with cetane number. These correlations appear to hold for both "natural" and additive-induced cetane numbers. A trend has been observed between hydrocarbon emissions and cetane number, but no strong correlation has emerged. No overall trend has been observed for nitrogen oxides emissions, which are strongly influenced by engine type.

Correlations of emissions species with aromatic content are less significant than correlations with cetane number. This applies for both total aromatics and condensed (di- and tri-) aromatics. Inclusion of aromatics terms in correlation equations with cetane number gives no improvement over correlations with cetane number alone.

For the heavy-duty engines little correlation of fuel properties with emissions was apparent.

1. INTRODUCTION

The aromatic content of diesel fuel has been suggested as a factor influencing emissions from diesel engines. In both the US and in Europe there is pressure to introduce aromatic content limits in diesel fuel specifications.

European research work in this area has included two cooperative programmes: one carried out on behalf of the British Technical Council for the Motor and Petroleum Industries (BTC), the other by the French Motor Industry (UTAC). US research work includes a heavy-duty engine programme, using the US transient test procedure. This project was conducted on behalf of the Coordinating Research Council (CRC). All these studies concluded that cetane number is a significant variable affecting gaseous and particulate emissions, whilst some of them also concluded that aromatics content may have an effect.

In order to investigate the influences of aromatics and cetane number, the Special Task Force on Diesel Fuel Emissions (AE/STF-7) was requested by the CONCAWE Automotive Emissions Management Group to set up a programme. The objective of this study was to determine the amount and nature of gaseous and particulate emissions from a range of diesel vehicles (cars and light vans) and heavy-duty diesel engines.

This report summarizes the CONCAWE findings on the influences of diesel fuel cetane number, aromatic content and aromatic type on diesel engine emissions. The work described was carried out in the laboratories of five CONCAWE member companies. Additional analytical studies were sub-contracted to Ricardo Consulting Engineers as an integral part of the programme. Every attempt was made to standardize test and analytical procedures throughout the programme, such that a consistent body of data be made available.

Detailed analytical data on the composition of the particulates generated in this programme will be provided in a separate report.

2. CHOICE OF DIESEL VEHICLES AND ENGINES FOR THE PROGRAMME

The number of diesel vehicles and heavy-duty engines was limited by fuel availability/cost constraints. Subject to these limitations, the programme covered a range of European light- and heavy-duty diesel engines including naturally aspirated (NA), turbocharged (TC), turbo-charged and inter-cooled (TC/IC), indirect injection (IDI) and direct injection (DI) types.

The characteristics of the vehicles and engines employed in the programme are as follows:

VEHICLES

Vehicle No 1	1.6 litre	NA/IDI	Passenger Car
Vehicle No 2	1.8 litre	NA/IDI	Passenger Car
Vehicle No 3	1.9 litre	NA/IDI	Passenger Car
Vehicle No 4	2.5 litre	TC/IDI	Passenger Car
Vehicle No 5	2.3 litre	TC/IC/DI	Passenger Car
Vehicle No 6	2.0 litre	TC/DI	Passenger Car
Vehicle No 7	2.5 litre	NA/DI	Light Van

Vehicle No 1 was equipped with an oxidation catalyst; vehicle No 4 was fitted with an electronic control system optimizing fuel injection timing for given engine operating conditions.

ENGINES

Engine No 1	6.0 litre	TC/IC/DI
Engine No 2	9.6 litre	TC/IC/DI

3. PROVISION OF TEST FUELS FOR THE PROGRAMME

A fundamental problem which arises in studies of the influence of changes in fuel characteristics on engine performance lies in the inherent intercorrelation between fuel properties. As a consequence, it is frequently difficult to change one fuel characteristic without altering other properties of the fuel. In this study, despite careful design of the fuel matrix, it was not possible to remove the influence of intercorrelated fuel characteristics. The correlation characteristics of the individual fuel properties are shown in **Appendix 1**.

The base fuel was prepared at high aromatic content, in a refinery of a CONCAWE member company, by blending suitable components. The aromatic content of this base fuel was reduced by deep hydrogenation (hydro-dearomatization) in the research laboratory of a second CONCAWE member company. The conditions of this hydrogenation were such that the aromatics content was significantly reduced from 37% to 15% volume. It should be emphasized that no full-scale plant of this type exists in the European Community.

This range was considered to be sufficiently wide to enable any influences of aromatics content on emissions to be detected. Furthermore, data from a recent European diesel fuel survey[1] demonstrate that this range reflects the spread of European commercial fuel quality, as shown in **Figure 1**. Whilst the base fuel contains 1, 2 and 3 ring (mono-, di- and tri-) aromatics, the hydrogenation process used gives preferential reaction with 2 and 3 ring aromatics. Thus the product obtained contains only 1 ring (mono-) aromatics.

Since the hydrogenation process reduces fuel sulphur content, all fuels were doped to a constant sulphur level (about 0.2%) using tert-butyl disulphide. This ensured that the influence of sulphur content on particulate emissions remained consistent. In an attempt to separate aromatics and cetane number effects, two fuels were treated with 2-ethylhexyl nitrate ignition improver additive, to give cetane numbers equivalent to those of the fuels of reduced aromatic content. Lastly a hydrocracked fuel was used, containing a low level of mono-, di- and tri- aromatics, for comparison with the hydrogenated fuel containing only mono- aromatics.

The aromatic content range of 37% down to 15% was chosen to correspond approximately to a cetane number range of 45 to 55. In other respects the fuels were designed to have typical current European qualities.

Analytical data on the six fuels used in the programme are given in **Table 1**. These data are mean values calculated from individual results obtained in the laboratories of the CONCAWE member companies involved in the programme. The fuel matrix used is shown in diagrammatic form in **Figure 2**.

4. PROVISION OF LUBRICATING OIL FOR THE PROGRAMME

In order to eliminate any influence of lubricating oil quality on the amount or nature of particulates generated in this programme, a commercial lubricating oil was chosen which satisfied the short-term test requirements of each engine employed in the programme. This oil, which was of SAE 15W/40 quality meeting API SF and DB 227.1 requirements, was used throughout the test programme.

Inspection data on the unused oil are:

REFERENCE L90/1544

GRADE SAE 15W/40, API SF, DB 227.1

Pour point	°C	-24
Sulphur content	% mass	0.77
KV 40°C	mm^2/sec	108
KV 100°C	mm^2/sec	14.5
KV 150°C	mm^2/sec	5.7
Viscosity Index		137
Volatility (DIN 51581) 1 hour, 250°C	% mass	12.3
Phosphorus	% mass	0.10
Calcium	% mass	0.22
Magnesium	% mass	0.10
Zinc	% mass	0.12

Hydrocarbon Distribution

IBP	°C	329
FBP	°C	550

5. VEHICLE AND ENGINE TEST PROCEDURES

The procedures used in this programme were those adopted for EC legislation covering emissions from diesel vehicles. Thus, for the vehicle tests, the ECE-15 test cycle was used followed by the EUDC (extra urban driving cycle). All test procedures were carried out in duplicate, using a random order of fuel testing in each laboratory. Vehicle tests were carried out in four CONCAWE member companies' laboratories, and engine tests in two.

Details of the vehicle test procedures used are as follows:-

1. Change lubricating oil to the standard AE/STF-7 lubricant.

2. Carry out a lubricating oil and injector nozzle pre-conditioning programme using CEC reference fuel RF-03-A-84, with a total driving distance of 1000 km. This programme has a duration of two days (500 km/day), 33% running on a freeway at 130 km/h (about 165 km/day) and 67% road driving at an average of 60 km/h (335 km/day).

3. Pre-condition the vehicle under test using three EUDC cycles, followed by an 8 hour soak period.

4. Cold start, followed by the ECE-15 procedure, measuring gaseous and particulate emissions, using either Whatman or Pallflex filters.

5. Change the gas sampling bag, but NOT the filter, and proceed with the EUDC procedure, again measuring gaseous and particulate emissions.

6. Carry out at least two complete ECE-15/EUDC tests. Report ECE-15 gaseous, EUDC gaseous (g/test) and combined ECE-15/EUDC gaseous and particulate emissions (g/km).

Details of the engine test procedures used are as follows:-

1. Drain, flush and re-fill the sump with the standard AE/STF-7 lubricating oil at the start of each pair of duplicate tests.

2. Carry out the ECE R49 13-mode test procedure measuring gaseous and particulate emissions, using a single filter throughout the procedure.

3. Carry out two complete ECE R49 tests.

6. EMISSIONS DATA: LIGHT- DUTY VEHICLES

The gaseous and particulate emissions data obtained from duplicate runs are shown in the form of mean values for each vehicle/fuel combination in Tables **2** to **8**.

The first three, Tables **2** to **4**, give separate gaseous emissions data (in g/test) for ECE-15 and EUDC cycles. In the second set, Tables **5** to **8**, the data are expressed in terms of total emissions (in g/km) over the combined cycle, and include particulate emission data. The "equivalent distance" used to calculate emissions in g/km was 11.007 km.

A wide range of emissions levels was obtained covering different engine and fuel injection types. The ranges for individual emissions are set out below.

APPROXIMATE RANGES OF EMISSIONS VALUES FOR LIGHT-DUTY DIESEL ENGINES/INJECTION SYSTEMS

EMISSION SPECIES	ECE-15 CYCLE	EUDC	COMBINED CYCLE	"CONSOLIDATED" DIRECTIVE LIMITS
	g/test	g/test	g/km	g/km
CO	2 - 12	0.7 - 4.8	0.3 - 1.4	2.72
HC	0.3 - 6.5	0.07 - 4.7	0.04 - 1.0	0.97
NO_x	1.8 - 24	2.1 - 20.8	0.4 - 4.0	
PARTICULATE	-	-	0.05 - 0.5	0.14

Using combined cycle data, the percentage changes across the range of vehicles and fuels are as follows:

EMISSION SPECIES	% CHANGE
CO	360
HC	2 400
NO_x	900
PARTICULATE	900

7. EMISSIONS DATA: HEAVY-DUTY ENGINES

The gaseous and particulate emission data obtained from duplicate ECE R49 runs are shown in the form of mean values (g/kWh) in Tables **9** to **12**.

For the two engines in this programme there was considerable variation in emission level, as set out below in comparison with the limits proposed in the EC "Clean Lorry" Directive.

EMISSION SPECIES	THIS PROGRAMME	"CLEAN LORRY" DIRECTIVE LIMITS	
		EFFECTIVE 1.7.92	EFFECTIVE 1.10.95*
CO	1.2 - 2.4	4.5	4.0
HC	0.30 - 0.45	1.1	1.1
NO_x	7.0 - 10.5	8.0	7.0
PARTICULATE	0.2 - 0.6	0.36/0.62	0.15/0.26

* For new models

8. CORRELATION OF FUEL PROPERTIES IN THE MATRIX

As stated in **Section 3**, it was not possible to remove the influence of intercorrelated fuel characteristics from the matrix of fuels used in this programme. Sulphur content was, however, kept constant throughout by doping.

For this fuel matrix, the strongest correlations of total aromatics are with density and cetane number (see **Appendix** and **Figure 3**).

9. STATISTICAL ANALYSES OF THE DATA

The emissions data generated in this programme have been analysed using two different approaches. The first technique considers each vehicle and engine as a separate entity for data analysis purposes. This approach recognizes the different fuel "appetites" of the different combustion systems investigated. The second technique views the light-duty vehicles as a population, using a normalization technique to reduce the spread of values for each emission. This approach ignores the different combustion systems under investigation. The second treatment could only be applied to the light-duty vehicles, as insufficient heavy-duty engines were investigated to make up a population. The results of the statistical analyses are discussed in Sections **11** and **12**.

The normalization technique used was to calculate an average value for each emission for each vehicle (or engine) over the six fuels. Each emission level was then re-calculated by dividing the individual value by the mean emission level for that vehicle or engine. These normalized values were then averaged to provide normalized mean values for each fuel (see **Tables 5** to **12**).

The statistical criteria used in this work to assess the models are as follows:

1. Adjusted R^2 - the proportion of the variance of the data explained by the regression model. Unadjusted R^2 is the percentage of the sum-of-squares explained by the model and takes no account of the degrees of freedom. Thus the former expression is the appropriate one to employ.
2. Student's T-value - is used to assess the significance of an individual coefficient in a regression model.
3. Fisher's F-value - is used to assess the significance of the complete regression model.

Significant values of T and F are given below for 3 and 4 degrees of freedom. For both T and F, significance increases with numerical value.

Degrees of freedom	3	4
T (95% confidence)	3.2	2.8
T (99% confidence)	5.8	4.6
F (95% confidence)	9.3	6.4
F (99% confidence)	29.4	16.0

10. DATA ANALYSIS - INDIVIDUAL VEHICLES AND ENGINES

In order to reduce the amount of data generated to manageable proportions, only combined-cycle results were analysed for the light-duty vehicles.

Initial multiple regression analysis using a maximum of two variables (**Table 13**) revealed that cetane number and, possibly, total aromatics is the only consistent combination of variables which produces models for particulate (Pm) emissions with some degree of significance. However, inclusion of an aromatics term does little to improve the fit of the models to the measured data. In some instances there are improvements in R^2, but calculated F and T values show these to be of low significance. These observations hold for both measures of aromatics content investigated, i.e. there is no change in significance using total or di- + tri- aromatics. Aromatics content has even less impact on gaseous emissions, and the data have not been included in Table **13**.

In view of the results obtained above, the data were analysed by simple linear regression analysis using cetane number as the variable. This analysis, shown in Tables **14** - **17** for all emissions, demonstrated the following:-

1. Carbon Monoxide Emissions

All vehicles/engines, with the exception of engine No. 2, exhibit reducing CO emissions with increasing cetane number. The majority of the regressions are highly significant, whilst the correlation for engine No. 2 is, for all practical purposes, non-existent. The individual regressions for CO emissions from light-duty vehicles are shown in Figure 4.

2. Hydrocarbon Emissions

Five of the engines/vehicles gave reasonably significant correlations showing a trend to reducing HC emissions with increasing cetane number. Two models (vehicles 3 and 5) show an opposite trend but the correlation is so poor as to cast doubt on the validity of this observation.

3. Nitrogen Oxides Emissions

Here a slightly more complex picture emerges. The DI engines show a trend towards reducing NO_x emissions with increasing cetane number, with two engines showing reasonable correlations. The three IDI engines with Ricardo Comet-type combustion chambers show the opposite trend - this might be a feature of the timing plans for these models. It is not unusual for IDI power units to have retarded timing and this could explain their NO_x performance. The cetane number increase is, in effect, advancing the onset of combustion so that higher peak cylinder pressures are generated - this phenomenon has been reported in previous published work. [2]

4. Particulate Emissions

Although only a few of the engines/vehicles gave significant correlations, all the models show the same trend to reducing Pm emissions with increasing cetane number. The individual regressions for particulate emissions from light-duty vehicles are shown in **Figure 5**.

11. DATA ANALYSIS: LIGHT-DUTY VEHICLE POPULATION

As for the previous exercise, only combined-cycle data were analysed. The normalized data obtained for the light-duty population are included in **Tables 5 - 8**.

The results of multiple regression analysis using a maximum of two variables are shown in **Table 18**. It is again apparent that the most significant correlations are with cetane number. For CO emissions, aromatic content is significant at the 95% confidence level but ceases to be significant at the 99% confidence limit (see page 9). For hydrocarbon emissions there is a trend with cetane and aromatics, but no significant correlation. There is no overall influence of fuel quality on NO_x emissions, reflecting comments in the previous section.

For particulate emissions, cetane number is significant at both 95 and 99% confidence levels, whilst aromatic content is not significant.

The normalized regressions for gaseous and particulate emissions with cetane number are shown in **Figures 6** to **9**.

In view of the correlation of cetane number with density and viscosity (see **Appendix**), regression analysis was carried out using these variables, (**Table 19**). The degree of fit was not as good as that with cetane number, (**Table 18**) and no further analysis was undertaken using these variables.

As in the previous analysis, correlations with di- and tri- aromatic types and particulate emissions could not be demonstrated. The fuel matrix was not optimal for discriminating such an effect and correlations with (di- + tri-aromatics) show a similar fit to correlations with total aromatics. Both are less significant than correlations with cetane number.

12. INFLUENCE OF IGNITION IMPROVER ADDITIVES

The predominance of cetane number in influencing both carbon monoxide and particulate emissions, may be demonstrated using the normalized data on the light-duty vehicle population. For ease of reference, the relevant data for all emissions have been collected in **Table 20**, which compares data for two pairs of base and ignition improver additive-treated fuels. Reductions in CO and particulate emissions are obtained in line with measured cetane numbers.

Using these data, it is possible to predict a reduction in both CO and particulate emissions approaching 5% for each one number increase in cetane number. However, it must be stressed that this is a generalized relationship, based solely upon data from a seven vehicle population. **Figure 4** demonstrates that the influence of cetane number on CO emissions varies significantly between the vehicles over an approximate range of 2.1 to 5.4%. Similarily, **Figure 5** suggests that, for particulates, this influence lies in the approximate range 2.4 to 7.7%.

The data thus suggest that ignition improver additives may be used to reduce particulate and CO emissions. The above relationship would appear to hold for both natural and additive-treated cetane number, and to be largely independent of aromatics content.

13. COMPARISON OF CONCAWE AE/STF-7 DATA WITH PUBLISHED RESULTS

LIGHT-DUTY VEHICLES

Two cooperative European studies are relevant to the CONCAWE programme. These are the British Technical Council Diesel Particulate Project Group report[3] and the French Motor Industry UTAC report.[4] The former programme made use of a dearomatized fuel prepared in a similar manner to the fuels developed for the CONCAWE programme, whilst the latter used the fuels employed in the European VROM heavy-duty studies (see below). The BTC study found evidence of a relationship between cetane number and particulate emissions, whereas the UTAC report, although not including a statistical analysis, ascribed this relationship to a combination of cetane number and aromatics influences. In the UTAC programme, treatment with ignition improver additive gave reductions in CO and particulate emissions. Thus the conclusions of the two programmes broadly reflect the findings of the CONCAWE programme reported here for light-duty engines.

HEAVY-DUTY ENGINES

The Dutch Environment Ministry (VROM) commissioned a study[5] on a range of heavy-duty DI engines using a range of fuels supplied by CONCAWE. The findings of this study are discussed in a report by the Motor Vehicle Emissions Group (MVEG) of the EC[6], with the following conclusions:

"*No evidence could be found for an effect of aromatics over and above that of cetane number. The influence of cetane number on hydrocarbon and particulate emissions was such that, under ECE R49 13-mode conditions, from 5 to 20% increase was found for a six-number decrease in ignition quality.*"

These conclusions are broadly in line with the results of the limited assessment of heavy-duty engines carried out in this CONCAWE programme.

Work carried out in the US by the Southwest Research Institute on behalf of the Coordinating Research Council[7] concluded that aromatic content generally dominated US transient test emissions from DI engines, but that the differing effects of aromatics and cetane number could not be separated in this study. Regression analysis of fuel characteristics including both single and multi-ring aromatics did not resolve any significant difference in the influence of these aromatic types on emissions.

This work was followed by a programme designed specifically to investigate the cetane number and aromatic content effects.[8, 9] The conclusions of the report are: "*Cetane number, either natural or chemically induced, is a significant fuel property in predicting both HC and CO emissions*".

A recent reappraisal of this work[10] suggests that density rather than aromatics is the predominant fuel property influencing particulate emissions under transient test conditions. However, the conclusion drawn by[8, 9] is broadly in line with the data reported in this CONCAWE programme, in which the heavy-duty engines were tested under steady-state conditions.

14. CONCLUSIONS

In emissions tests employing European procedures (light-duty, ECE15+EUDC cycles; heavy-duty, ECE R49) and using a fuel matrix in which cetane number and total aromatics were the main variables, this study has found that cetane number is the dominant fuel quality parameter influencing gaseous and particulate emissions.

For the light-duty vehicles investigated, strong correlations have been observed between cetane number and carbon monoxide emissions, and between cetane number and particulate emissions. These correlations appear to hold for both "natural" and additive-induced cetane numbers. A trend has been observed between hydrocarbon emissions and cetane number, but no strong correlation has emerged. No overall trend has been observed for nitrogen oxides emissions, which are strongly influenced by engine type.

Correlations of emissions species with aromatic content are less significant than correlations with cetane number. This applies for both total aromatics and condensed (di- and tri-) aromatics. Inclusion of aromatics terms in correlation equations with cetane number gives no improvement over correlations with cetane number alone.

For this matrix, which included both natural and additive-improved cetane number fuels, a reduction in both carbon monoxide and and particulate emissions was observed with increasing cetane number. This reduction was highly variable but approached 5% per unit increase in cetane number for the light-duty vehicle population tested. This relationship appears to be largely independent of aromatic content over the range examined.

For the heavy-duty engines, little correlation of fuel properties with gaseous emissions was apparent. Only one of the engines tested showed any correlation of fuel properties with particulate emissions. In view of the limited work carried out on heavy-duty engines, no conclusions can be drawn.

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17. TABLES

Table 1 Analytical data on test fuels used in the programme (mean values)

FUEL No.		1	2	3	4	5	6
PROPERTY	**UNIT**						
Sulphur content	% mass	0.19	0.19	0.20	0.19	019	0.19
Density @ 15°	kg/m³	866.8	843.5	854.8	867.0	855.7	837
KV @ 20°	mm²/sec	5.5	5.52	5.68	6.00	5.73	5.31
KV @ 40°	mm²/sec	3.57	3.41	3.47	3.61	3.49	3.27
Flash point	°C	86	72	77	87	80	86
Cloud point	°C	-3	-3	-3	-2	-3	-14
CFPP	°C	-10	-9	-10	-9	-10	-20
Water content	µg/kg	76	36	52	85	54	58
Copper corrosion		1A	1A	1A	1A	1A	1A
Carbon residue	% mass	0.02	0.01	0.01	0.02	0.02	0.01
AROMATICS AND IGNITION QUALITY							
FIA	% vol [+]	42.3	16.2	28.1	46.4	30.7	22.0
HPLC (a)	% mass [+]	44.3	17.1	29.9	45.4	31.8	24.3
HPLC (b)							
Mono- Aromatics	% vol	21.1	15.2	18.5	21.3	18.6	17.2
Di- Aromatics	% vol	12.0	0.1	5.7	11.5	6.2	3.3
Tri- Aromatics	% vol	2.7	-	1.0	2.7	1.2	0.5
Total Aromatics	% vol	35.8	15.3	25.2	35.5	26.0	21.0
Cetane number		47.0	56.7	52.8	50.3	53.6	54.9
Calculated Cetane Index (IP 380)		46.2	53.5	50.0	(46.4)*	(49.7)*	57.2
DISTILLATION DATA							
IBP	°C	190	176	185	194	183	200
10% vol	°C	243	234	240	244	240	250
20% vol	°C	258	249	254	259	254	259
30% vol	°C	269	261	265	270	266	266
40% vol	°C	279	271	275	280	276	272
50% vol	°C	288	281	284	289	285	278
60% vol	°C	297	291	294	299	295	285
70% vol	°C	307	301	305	309	305	294
80% vol	°C	321	314	318	322	318	304
90% vol	°C	339	332	336	340	336	318
95% vol	°C	354	347	352	356	352	330
FBP	°C	367	363	365	369	366	344
Recovery	% vol	98.5	98.4	98.3	98.4	98.4	98.5
Loss	% vol	0.4	0.4	0.4	0.3	0.1	0.3
Residue	% vol	1.1	1.2	1.3	1.3	1.5	1.2

(a) IP368/90 (b) IP391/90
[+] Data from one laboratory only
• Contain ignition improver additive

Table 2 Light-duty diesel vehicles - mean carbon monoxide data (g/test)

<table>
<tr><th colspan="8">A. ECE-15 CYCLE</th></tr>
<tr><th>FUEL</th><th>VEHICLE NO.1</th><th>VEHICLE NO.2</th><th>VEHICLE NO.3</th><th>VEHICLE NO.4</th><th>VEHICLE NO.5</th><th>VEHICLE NO.6</th><th>VEHICLE NO.7</th></tr>
<tr><td>1</td><td>3.23</td><td>8.58</td><td>4.09</td><td>9.19</td><td>6.70</td><td>11.91</td><td>10.91</td></tr>
<tr><td>2</td><td>2.05</td><td>3.99</td><td>3.16</td><td>5.47</td><td>3.66</td><td>7.30</td><td>8.55</td></tr>
<tr><td>3</td><td>2.66</td><td>4.89</td><td>3.78</td><td>6.93</td><td>5.06</td><td>8.83</td><td>9.48</td></tr>
<tr><td>4</td><td>2.96</td><td>6.55</td><td>3.93</td><td>8.02</td><td>5.98*</td><td>7.36</td><td>9.76</td></tr>
<tr><td>5</td><td>2.58</td><td>4.46</td><td>3.61</td><td>6.77</td><td>4.74*</td><td>8.11</td><td>9.46</td></tr>
<tr><td>6</td><td>2.16</td><td>3.98</td><td>3.30</td><td>6.18</td><td>5.78</td><td>7.74</td><td>9.03</td></tr>
<tr><th colspan="8">B. EUDC "HIGH SPEED" CYCLE</th></tr>
<tr><td>1</td><td>1.05</td><td>3.28</td><td>1.84</td><td>3.24</td><td>3.07</td><td>3.41</td><td>4.83</td></tr>
<tr><td>2</td><td>0.70</td><td>1.66</td><td>1.43</td><td>2.19</td><td>1.93</td><td>2.57</td><td>4.06</td></tr>
<tr><td>3</td><td>0.90</td><td>2.08</td><td>1.81</td><td>2.70</td><td>2.28</td><td>2.94</td><td>4.34</td></tr>
<tr><td>4</td><td>1.00</td><td>2.36</td><td>1.70</td><td>3.06</td><td>2.55*</td><td>2.98</td><td>4.50</td></tr>
<tr><td>5</td><td>0.83</td><td>1.80</td><td>1.57</td><td>2.52</td><td>2.55*</td><td>2.96</td><td>4.45</td></tr>
<tr><td>6</td><td>0.68</td><td>1.74</td><td>1.58</td><td>2.33</td><td>2.44</td><td>2.68</td><td>4.27</td></tr>
</table>

* Single determination only

Table 3 Light-duty diesel vehicles - mean hydrocarbon data (g/test)

A. ECE-15 CYCLE							
FUEL	VEHICLE NO.1	VEHICLE NO.2	VEHICLE NO.3	VEHICLE NO.4	VEHICLE NO.5	VEHICLE NO.6	VEHICLE NO.7
1	0.93	1.36	0.71	1.42	0.80	6.17	6.28
2	0.37	0.40	0.90	0.53	0.71	4.39	5.48
3	0.33	0.33	1.08	0.60	0.75	3.52	6.48
4	0.50	0.27	1.04	0.92	0.76*	3.62	6.05
5	0.50	0.40	0.71	0.94	0.76*	4.66	5.68
6	0.47	0.37	0.84	0.79	0.68	4.49	5.24
B. EUDC "HIGH SPEED" CYCLE							
1	0.44	0.52	0.30	0.61	0.24	3.51	4.72
2	0.23	0.09	0.43	0.35	0.29	2.86	4.09
3	0.07	0.15	0.50	0.26	0.35	2.04	4.47
4	0.15	0.13	0.39	0.35	0.40*	2.18	4.51
5	0.21	0.13	0.38	0.36	0.40*	3.05	4.23
6	0.20	0.15	0.44	0.39	0.35	2.99	3.72

* Single determination only

Table 4 Light-duty diesel vehicles - mean nitrogen oxides data (g/test)

A. ECE-15 CYCLE							
FUEL	VEHICLE NO.1	VEHICLE NO.2	VEHICLE NO.3	VEHICLE NO.4	VEHICLE NO.5	VEHICLE NO.6	VEHICLE NO.7
1	2.80	2.55	3.38	1.85	5.56	6.03	23.88
2	3.00	2.96	3.49	2.00	4.50	5.93	21.04
3	3.20	2.91	3.35	1.96	5.04	5.94	21.80
4	2.70	2.95	3.49	1.89	4.81*	5.40	23.21
5	2.98	2.99	3.41	2.23	5.32*	6.76	21.52
6	2.81	2.82	3.25	2.00	5.14	5.51	21.33
B. EUDC "HIGH SPEED" CYCLE							
1	3.29	2.61	3.95	2.38	6.47	7.37	20.80
2	3.50	3.09	3.67	2.39	5.58	6.97	18.47
3	3.79	2.99	3.77	2.49	5.38	7.24	19.21
4	3.26	2.97	3.93	2.12	6.27*	7.00	20.79
5	3.48	3.08	3.87	2.74	5.69*	8.10	19.17
6	3.37	2.94	3.66	2.40	5.55	6.65	18.39

* Single determination only

Table 5 Light-duty diesel vehicles - mean carbon monoxide data (g/km) combined ECE-15/EUDC cycle

FUEL	VEHICLE NUMBER							NORMALIZED MEAN VALUE +
	1	2	3	4	5	6	7	
1	0.388	1.078	0.540	1.130	0.888	1.392	1.431	1.268
2	0.249	0.513	0.418	0.695	0.508	0.897	1.146	0.807
3	0.323	0.634	0.509	0.875	0.667	1.068	1.256	0.989
4	0.358	0.810	0.511	1.006	0.774*	1.121	1.296	1.096
5	0.309	0.578	0.471	0.844	0.662*	1.006	1.265	0.946
6	0.258	0.520	0.443	0.772	0.748	0.947	1.209	0.894

* Single determination only

\+ Dimensionless

Table 6 Light duty diesel vehicles - mean hydrocarbon data (g/km) combined ECE-15/EUDC cycle

FUEL	VEHICLE NUMBER							NORMALIZED MEAN VALUE +
	1	2	3	4	5	6	7	
1	0.124	0.170	0.092	0.184	0.094	0.879	1.000	1.473
2	0.054	0.044	0.121	0.080	0.090	0.659	0.871	0.873
3	0.036	0.044	0.143	0.078	0.100	0.505	0.995	0.857
4	0.060	0.036	0.135	0.114	0.105*	0.527	0.960	0.934
5	0.064	0.048	0.099	0.119	0.105*	0.700	0.901	0.939
6	0.060	0.048	0.116	0.107	0.094	0.679	0.814	0.925

* Single determination only

\+ Dimensionless

Table 7 Light-duty diesel vehicles - mean nitrogen oxides data (g/km) combined ECE-15/EUDC cycle

FUEL	VEHICLE NUMBER							NORMALIZED MEAN VALUE +
	1	2	3	4	5	6	7	
1	0.552	0.468	0.666	0.384	1.093	1.218	4.061	1.002
2	0.589	0.550	0.650	0.398	0.916	1.172	3.592	0.986
3	0.635	0.536	0.647	0.405	0.947	1.197	3.728	1.008
4	0.542	0.537	0.675	0.364	1.007•	1.162	4.000	0.991
5	0.587	0.552	0.662	0.452	1.000•	1.350	3.699	1.045
6	0.561	0.524	0.629	0.400	0.971	1.104	3.611	0.968

• Single determination only

+ Dimensionless

Table 8 Light-duty diesel vehicles - mean particulate data (g/km) combined ECE-15/EUDC cycle

FUEL	VEHICLE NUMBER							NORMALIZED MEAN VALUE +
	1	2	3	4	5	6	7	
1	0.075	0.248	0.146	0.129	0.264	0.299	0.567	1.353
2	0.046	0.069	0.103	0.090	0.142	0.163	0.434	0.755
3	0.059	0.097	0.130	0.107	0.177	0.232	0.523	0.968
4	0.068	0.140	0.147	0.133	0.243*	0.269	0.528	1.166
5	0.057	0.086	0.120	0.114	0.162*	0.198	0.545	0.920
6	0.051	0.062	0.098	0.094	0.233	0.176	0.464	0.838

* Single determination only

+ Dimensionless

Table 9 Heavy-duty diesel engines - mean carbon monoxide data (g/kWh) ECE R49 cycle

FUEL	ENGINE NO.1	ENGINE NO.2	NORMALISED MEAN VALUE +
1	2.41	1.25	1.066
2	2.10	1.28	1.001
3	1.96	1.38	1.005
4	2.23	1.31	1.044
5	1.82	1.29	0.937
6	1.87	1.28	0.947

\+ Dimensionless

Table 10 Heavy-duty diesel engines - mean hydrocarbon data (g/kWh) ECE R49 cycle

FUEL	ENGINE NO.1	ENGINE NO.2	NORMALIZED MEAN VALUE+
1	0.345	0.464	1.050
2	0.335	0.377	0.931
3	0.365	0.441	1.051
4	0.405	0.460	1.131
5	0.315	0.400	0.931
6	0.350	0.338	0.905

\+ Dimensionless

Table 11 Heavy-duty diesel engines - mean nitrogen oxides data (g/kWh) ECE R49 cycle

FUEL	ENGINE NO.1	ENGINE NO.2	NORMALIZED MEAN VALUE +
1	10.45	7.65	1.036
2	9.62	7.96	1.015
3	10.40	7.14	1.000
4	10.44	7.52	1.027
5	9.48	7.42	0.972
6	9.66	6.98	0.951

\+ Dimensionless

Table 12 Heavy-duty diesel engines - mean particulate data (g/kWh) ECE R49 cycle

FUEL	ENGINE NO.1	ENGINE NO.2	NORMALIZED MEAN VALUE +
1	0.60	0.38	1.290
2	0.55	0.24	0.966
3	0.50	0.29	1.018
4	0.59	0.29	1.110
5	0.49	0.20	0.828
6	0.48	0.18	0.788

\+ Dimensionless

Table 13 Regression analysis - particulate emissions, individual vehicles and engines (data analysis on mean of two tests)

CORRELATION PARAMETERS	COEFFICIENT		ADJUSTED R²	T-RATIO		F-RATIO OF MODEL
	CONSTANT	VARIABLE		CONSTANT	VARIABLE	
Vehicle No.1						
Cetane number	0.221	-0.0031	0.984	23.6	-17.3	299.4
Total Aromatics	0.025	0.0013	0.936	6.1	8.6	73.6
Di + Tri Aromatics	0.045	0.0018	0.944	24.4	9.3	86.0
(Cetane number) and	0.161	-0.0021	0.995	8.5	-7.2	523.0
(Total Aromatics)		0.0004			3.3	
(Cetane number) and	0.164	-0.0021	0.995	8.9	-6.5	500.3
(Di + Tri Aromatics)		0.006			3.2	
Vehicle No.2						
Cetane number	1.123	-0.0192	0.874	6.7	-6.0	35.7
Total Aromatics	-0.071	0.0071	0.589	-1.0	2.9	8.2
Di + Tri Aromatics	0.038	0.0101	0.621	1.2	3.0	9.2
(Cetane number) and	2.086	-0.0341	0.935	4.6	-4.7	37.1
(Total Aromatics)		-0.0068			-2.2	
(Cetane number) and	1.967	-0.0338	0.921	4.1	-4.0	29.9
(Di + Tri Aromatics)		0.0093			-1.8	
Vehicle No.3						
Cetane number	0.410	-0.0054	0.761	5.9	-4.1	16.9
Total Aromatics	0.060	0.0024	0.833	4.6	5.1	26.0
Di + Tri Aromatics	0.098	0.0034	0.836	15.7	5.1	26.5
(Cetane number) and	0.125	-0.0010	0.782	0.5	-0.3	10.0
(Total Aromatics)		0.0020			1.2	
(Cetane number) and	0.138	-0.007	0.784	0.6	-0.2	10.1
(Di + Tri Aromatics)		0.0030			1.2	
Vehicle No.4						
Cetane number	0.352	-0.0046	0.757	5.9	-4.1	16.6
Total Aromatics	0.054	0.0021	0.948	8.9	9.6	92.2
Di + Tri Aromatics	0.088	0.0030	0.950	30.2	9.8	95.9
(Cetane number) and	-0.042	0.0015	0.946	-0.4	0.9	44.5
(Total Aromatics)		0.0028			3.9	
(Cetane number) and	-0.029	0.0020	0.958	-0.3	1.3	57.5
(Di + Tri Aromatics)		0.0042			4.5	
Vehicle No.5 (single test run only)						
Cetane number	0.748	-0.0111	0.492	3.3	-2.4	5.9
Total Aromatics	0.081	0.0046	0.453	1.5	2.3	5.1
Di + Tri Aromatics	0.153	0.0065	0.456	5.7	2.3	5.2
(Cetane number) and	0.614	-0.0084	0.330	0.6	-0.5	2.2
(Total Aromatics)		0.0012			0.2	
(Cetane number) and	0.638	-0.0085	0.329	0.6	-0.5	2.2
(Di + Tri Aromatics)		0.0016			0.2	

Continued

Table 13 Regression analysis - particulate emissions, individual vehicles and engines (data analysis on mean of two tests)

CORRELATION PARAMETERS	COEFFICIENT		ADJUSTED R^2	T-RATIO		F-RATIO OF MODEL
	CONSTANT	VARIABLE		CONSTANT	VARIABLE	
(Continuation)						
Vehicle No.6						
Cetane number	1.022	-0.0152	0.949	12.3	-9.7	93.5
Total Aromatics	0.056	0.0063	0.874	1.9	6.0	35.6
Di + Tri Aromatics	0.153	0.0089	0.883	11.4	6.2	38.8
(Cetane number) and	0.834	-0.0123	0.938	2.4	-2.3	39.0
(Total Aromatics)		0.0013			0.6	
(Cetane number) and	0.849	-0.0122	0.938	2.6	-2.1	38.7
(Di + Tri Aromatics)		0.0019			0.5	
Vehicle No.7						
Cetane number	1.161	-0.0124	0.641	5.6	-3.2	9.9
Total Aromatics	0.367	0.0054	0.678	8.4	3.4	11.5
Di + Tri Aromatics	0.451	0.0076	0.668	21.1	3.3	11.1
(Cetane number) and	0.620	-0.0040	0.584	0.7	-0.3	4.5
(Total Aromatics)		0.0038			0.7	
(Cetane number) and	0.702	-0.0044	0.571	0.9	-0.3	4.3
(Di + Tri Aromatics)		0.0050			0.6	
Engine No.1						
Cetane number	1.069	-0.0102	0.311	3.6	-1.8	3.3
Total Aromatics	0.429	0.0040	0.224	6.1	1.6	2.4
Di + Tri Aromatics	0.490	0.0058	0.259	14.8	1.7	2.7
(Cetane number) and	1.245	-0.0129	0.088	1.0	-0.6	1.2
(Total Aromatics)		0.0012			-0.1	
(Cetane number) and	1.078	-0.0103	0.082	0.9	-0.5	1.2
(Di + Tri Aromatics)		0.0000			-0.0	
Engine No.2						
Cetane number	1.195	-0.0177	0.636	4.0	-3.1	9.7
Total Aromatics	0.097	0.0063	0.354	1.1	1.9	3.7
Di + Tri Aromatics	0.193	0.0090	0.379	4.6	2.0	4.0
(Cetane number) and	2.494	-0.0380	0.686	2.4	-2.3	6.5
(Total Aromatics)		0.0091			-1.3	
(Cetane number) and	2.378	-0.0383	0.674	2.3	-2.1	6.2
(Di + Tri Aromatics)		0.0130			-1.2	

Table 14 Linear regression analysis - carbon monoxide emissions vs cetane number. Individual vehicles and engines (data analysis on mean of two tests)

Vehicle Engine	Intercept	Slope	Adjusted R^2	T-Ratio		F-Ratio of Model
				Intercept	Slope	
Vehicle No.1	0.865	-0.0106	0.635	4.8	-3.1	9.7
Vehicle No.2	3.932	-0.0617	0.932	10.1	-8.3	69.1
Vehicle No.3	1.141	-0.0125	0.850	9.4	-5.4	29.3
Vehicle No.4	3.288	-0.0457	0.995	44.9	-32.8	1077.9
Vehicle No.5	2.415	-0.0325	0.710	5.1	-3.6	13.2
Vehicle No.6	3.689	-0.0498	0.942	12.8	-9.1	82.3
Vehicle No.7	2.691	-0.0271	0.945	17.5	-9.3	86.4
Engine No.1	4.599	-0.0482	0.427	3.9	-2.2	4.7
Engine No.2	1.180	-0.0023	0.000	3.5	0.4	0.1

Table 15 Linear regression analysis - hydrocarbon emissions vs cetane number. Individual vehicles and engines (data analyis on mean of two tests)

Vehicle Engine	Intercept	Slope	Adjusted R^2	T-Ratio		F-Ratio of Model
				Intercept	Slope	
Vehicle No.1	0.402	-0.0064	0.430	2.6	-2.2	4.8
Vehicle No.2	0.652	-0.0112	0.450	2.5	-2.3	5.1
Vehicle No.3	0.030	0.0017	0.000	0.2	0.6	0.4
Vehicle No.4	0.597	-0.0092	0.601	3.6	-2.9	8.5
Vehicle No.5	0.123	-0.0005	0.000	2.7	-0.5	0.3
Vehicle No.6	1.425	-0.0146	0.000	1.5	-0.8	0.6
Vehicle No.7	1.792	-0.0165	0.490	5.0	-2.4	5.8
Engine No.1	0.521	-0.0032	0.000	2.4	-0.8	0.6
Engine No.2	1.047	-0.0121	0.607	4.8	-3.0	8.7

Table 16 Linear regression analysis - nitrogen oxides emissions vs cetane number. Individual vehicles and engines (data analysis on mean of two tests)

Vehicle Engine	Intercept	Slope	Adjusted R^2	T-Ratio		F-Ratio of Model
				Intercept	Slope	
Vehicle No.1	0.354	0.0043	0.000	1.5	1.0	0.9
Vehicle No.2	0.157	0.0071	0.522	1.1	2.5	6.5
Vehicle No.3	0.815	-0.0031	0.272	8.6	-1.7	2.9
Vehicle No.4	0.209	0.0036	0.000	1.0	1.0	0.9
Vehicle No.5	1.835	-0.0161	0.786	9.5	-4.4	19.4
Vehicle No.6	1.376	-0.0033	0.000	2.2	-0.3	0.1
Vehicle No.7	6.709	-0.0557	0.907	16.1	-7.0	49.4
Engine No.1	15.560	-0.1056	0.517	7.0	-2.5	6.3
Engine No.2	7.765	-0.0061	0.000	2.9	-0.1	0.0

Table 17 Linear regression analysis - particulate emissions vs cetane number. Individual vehicles and engines (data analysis on mean of two tests)

Vehicle Engine	Intercept	Slope	Adjusted R^2	T-Ratio		F-Ratio of Model
				Intercept	Slope	
Vehicle No.1	0.221	-0.0031	0.984	23.6	-17.3	299.4
Vehicle No.2	1.123	-0.0192	0.874	6.7	-6.0	35.7
Vehicle No.3	0.410	-0.0054	0.761	5.9	-4.1	16.9
Vehicle No.4	0.352	-0.0046	0.757	5.9	-4.1	16.6
Vehicle No.5	0.784	-0.0111	0.492	3.3	-2.4	5.9
Vehicle No.6	1.022	-0.0152	0.949	12.3	-9.7	93.5
Vehicle No.7	1.161	-0.0124	0.641	5.6	-3.2	9.9
Engine No.1	1.069	-0.0102	0.311	3.6	-1.8	3.3
Engine No.2	1.195	-0.0177	0.636	4.0	-3.1	9.7

Table 18 Regression analysis, normalized light-duty emissions (combined cycle, vehicle population basis) regression with cetane and aromatics.

CORRELATION PARAMETERS	COEFFICIENT		ADJUSTED R^2	T-RATIO		F-RATIO OF MODEL
	CONSTANT	VARIABLE		CONSTANT	VARIABLE	
Carbon Monoxide						
Cetane number	3.473	-0.0471	0.998	73.6	-52.5	2755.2
Total Aromatics	0.500	0.0189	0.844	5.1	5.3	28.1
Di + Tri Aromatics	0.791	0.0268	0.859	17.6	5.6	31.4
(Cetane number) and		-0.0521	1.000	54.4	-47.3	9000.8
(Total Aromatics)	3.796	-0.0023			-4.8	
(Cetane number) and	3.782	-0.0524	1.000	62.2	-49.2	10705.4
(Di + Tri Aromatics		-0.0034			-5.3	
Hydrocarbons						
Cetane number	3.883	-0.0549	0.571	3.7	-2.8	7.7
Total Aromatics	0.523	0.0180	0.231	1.7	1.6	2.5
Di + Tri Aromatics	0.797	0.0260	0.261	5.4	1.7	2.8
(Cetane number) and	9.887	-0.1479	0.785	3.5	-3.4	10.1
(Total Aromatics)		-0.0421			-2.2	
(Cetane number) and	9.316	-0.1494	0.753	3.3	-3.0	8.6
(Di + Tri Aromatics)		-0.0596			-2.0	
Nitrogen Oxides						
Cetane number	-2.416	0.0682	0.179	-1.0	1.4	2.1
Total Aromatics	2.056	-0.0336	0.318	4.1	-1.8	3.3
Di + Tri Aromatics	1.524	-0.0457	0.283	6.1	-1.7	3.0
(Cetane number) and	5.87	-0.0602	0.136	0.6	-0.4	1.4
(Total Aromatics)		-0.0581			-0.9	
(Cetane number) and	4.195	-0.0468	0.069	0.4	-0.3	1.2
(Di + Tri Aromatics)		0.0726			-0.7	
Particulate						
Catane number	4.360	-0.0639	0.993	33.4	-25.8	666.2
Total Aromatics	0.309	0.0261	0.878	2.6	6.1	37.0
Di + Tri Aromatics	0.711	0.0369	0.895	13.5	6.6	43.6
(Catane number) and		-0.0609	0.991	7.5	-6.9	261.0
(Total Aromatics)	4.164	0.0014				
(Catane number) and	4.108	-0.0596	0.991	7.9	-6.5	271.3
(Di + Tri Aromatics)		0.0028			0.5	

Table 19 Regression analysis, normalized light-duty emisisons (combined cycle, vehicle population basis). Regression with density and viscosity.

CORRELATION PARAMETERS	COEFFICIENT		ADJUSTED R^2	T-RATIO		F-RATIO OF MODEL
	CONSTANT	VARIABLE		CONSTANT	VARIABLE	
Carbon Monoxide						
Density	-8.930	11.625	0.667	-3.0	3.3	11.0
(Density) and	-20.988	35.682	0.867	-4.3	3.8	17.3
(Viscosity)		-2.447			-2.7	
Hydrocarbons						
Density	-7.974	10.505	0.112	-1.1	1.3	1.6
(Density) and	-25.452	45.377	0.134	-1.4	1.3	1.4
(Viscosity)		-3.547			-1.1	
Nitrogen oxides						
Density	13.114	-13.986	0.000	1.0	-0.9	0.8
(Density) and	64.476	-122.445	0.666	3.5	-3.4	6.0
(Viscoity)		11.033			3.1	
Particulate						
Density	-12.980	16.366	0.729	-3.5	3.8	14.4
(Density) and	-26.688	43.715	0.856	-3.8	3.3	15.9
(Viscosity)		-2.782			-2.1	

Table 20 Influence of ignition improver additive on normalized combined cycle emissions (light-duty vehicles)

Fuel Cetane number	1 47	4* 50	3 53	5* 54
CO	1.268	1.096	0.989	0.946
HC	1.473	0.934	0.857	0.939
NO_x	1.002	0.991	1.008	1.045
Particulate	1.353	1.166	0.968	0.920

Fuels 1 and 4: 36% aromatics

Fuels 3 and 5: 26% aromatics

* With ignition improver additive

APPENDIX

Fuel matrix correlations for individual properties - STF-7 aromatics programme

	Total Aromatics	Cetane number	Density 15°C	Viscosity 40°C
Total Aromatics	1.000 0.0000	-0.9477 0.0040	0.9156 0.0104	0.8079 0.0518
Cetane number	-0.9477 0.0040	1.0000 0.0000	-0.8717 0.0236	-0.7476 0.0876
Density at 15°C	0.9156 0.0104	-0.8717 0.0236	1.0000 0.0000	0.9713 0.0012
Viscosity at 40°C	0.8079 0.0518	-0.7476 0.0875	0.9713 0.0012	1.0000 0.0000

Upper number - correlation coefficient

Lower number - significance level

Figure 1 Aromatics distribution in European diesel fuels

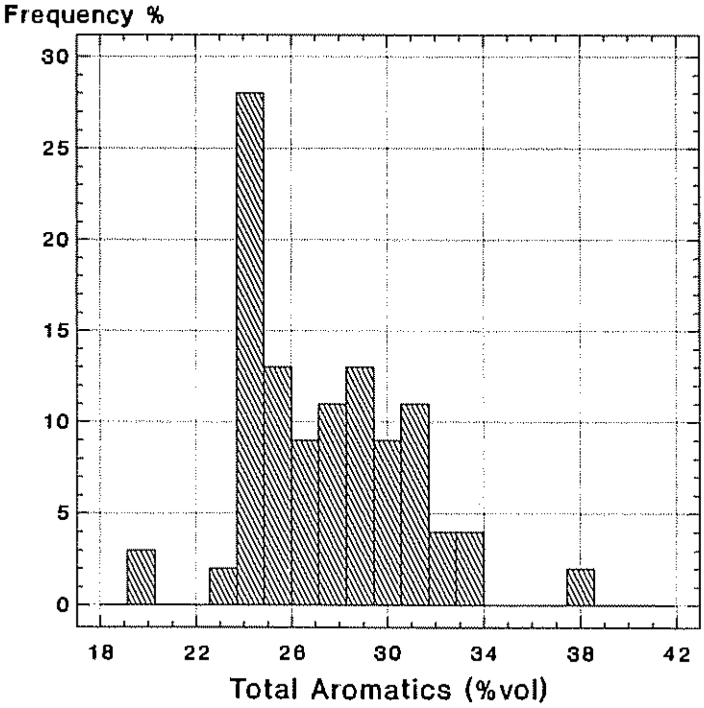


Figure 2 Test fuel matrix

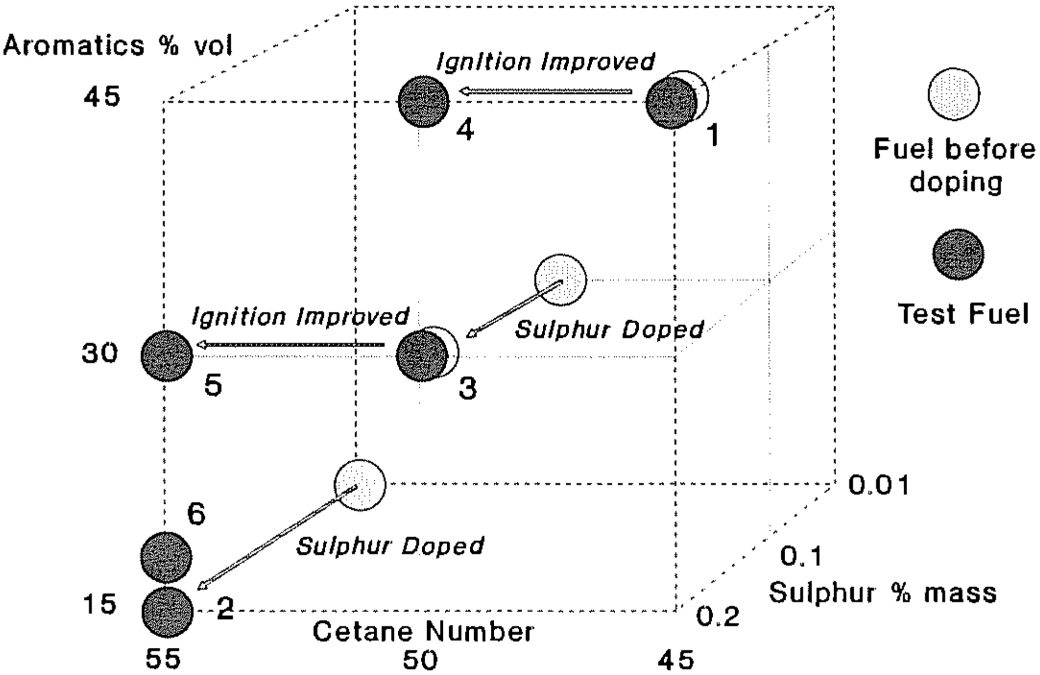
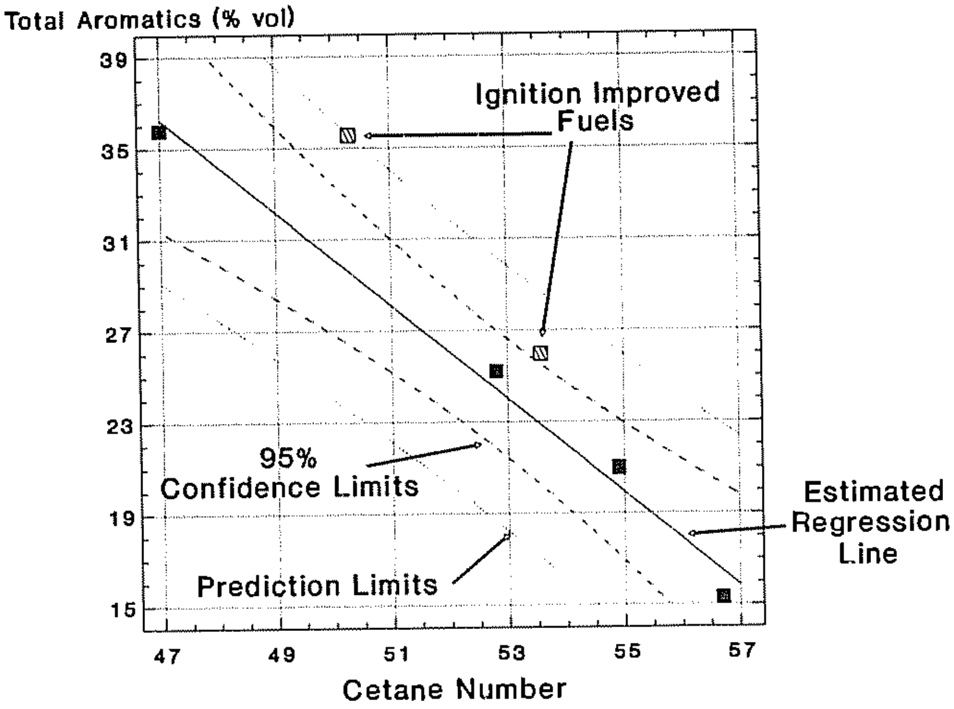


Figure 3 Regression of total aromatics on cetane number



Graphical Analysis Explanatory Notes

The estimated straight line regression, boundary curves and symbols shown in *Figure 3*, above, are also applicable in *Figures 6 - 9*; that is:

———— Estimated Regression Line
- - - - - - - 95% Confidence Limits
··········· Prediction Limits for the Model
▨ Ignition Improved Fuels

The *NORMALIZED* emission rates depicted in *Figures 6 - 9* are non-dimensional and apply to the light duty vehicles *only*. See the main body of the text for a description of the normalization procedure

Figure 4 Light-duty vehicle CO emissions
Individual regressions on cetane number

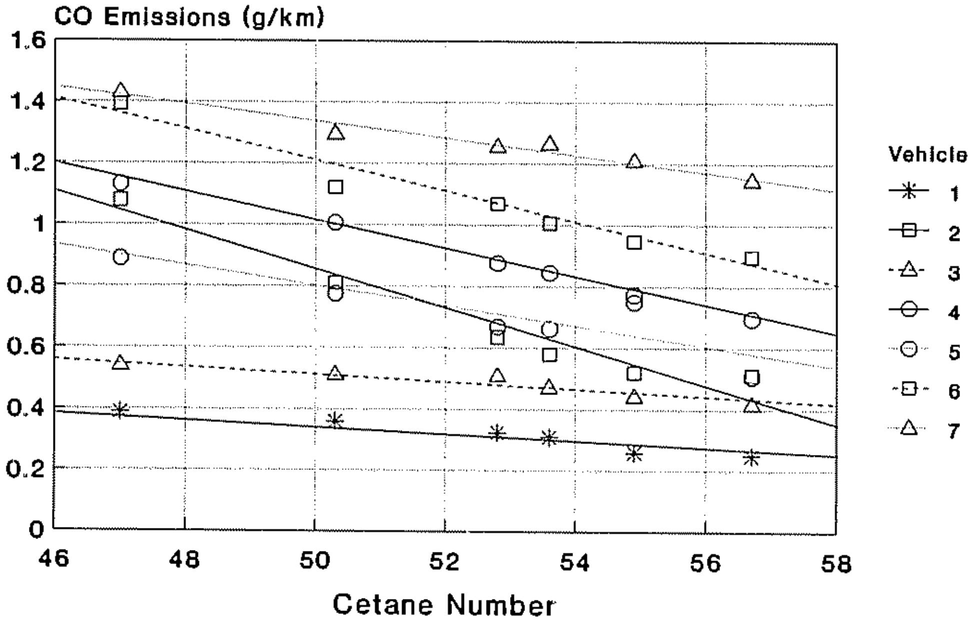


Figure 5 Light-duty vehicle particulate emissions
Individual regressions on cetane number

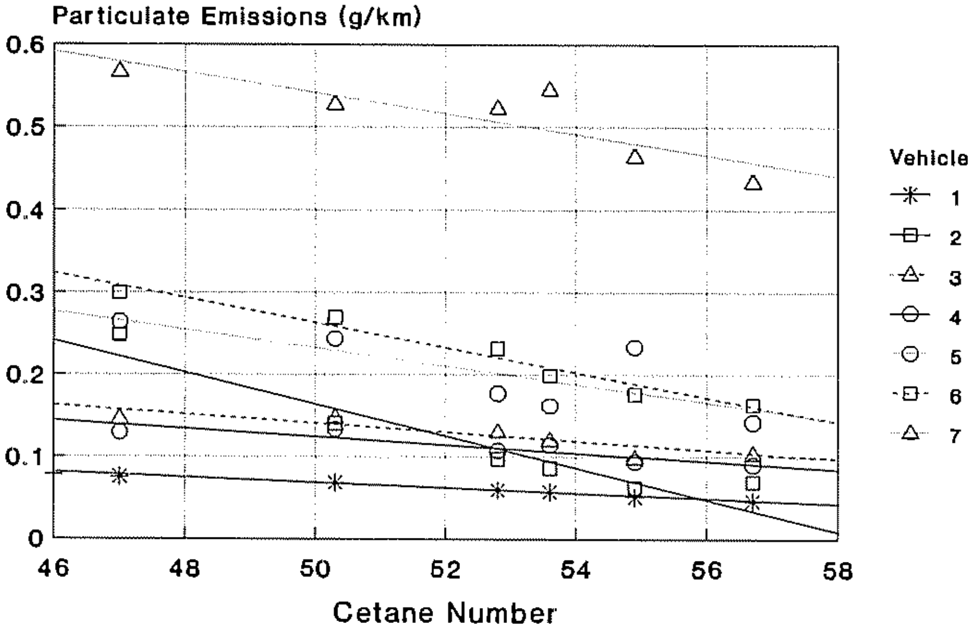


Figure 6 Normalized light-duty vehicle emissions
Regression of CO on cetane number

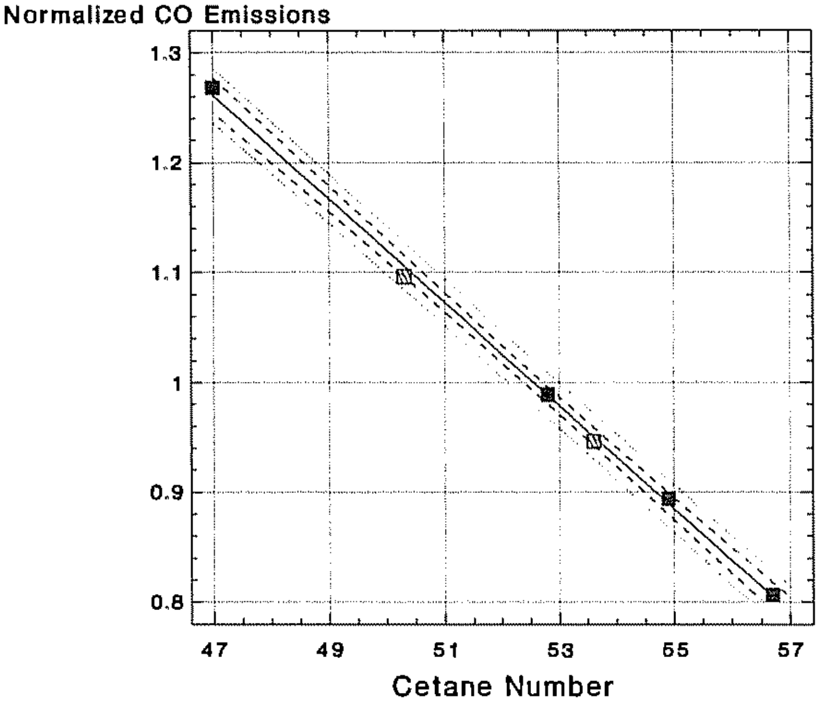


Figure 7 Normalized light-duty vehicle emissions
Regression of HC on cetane number

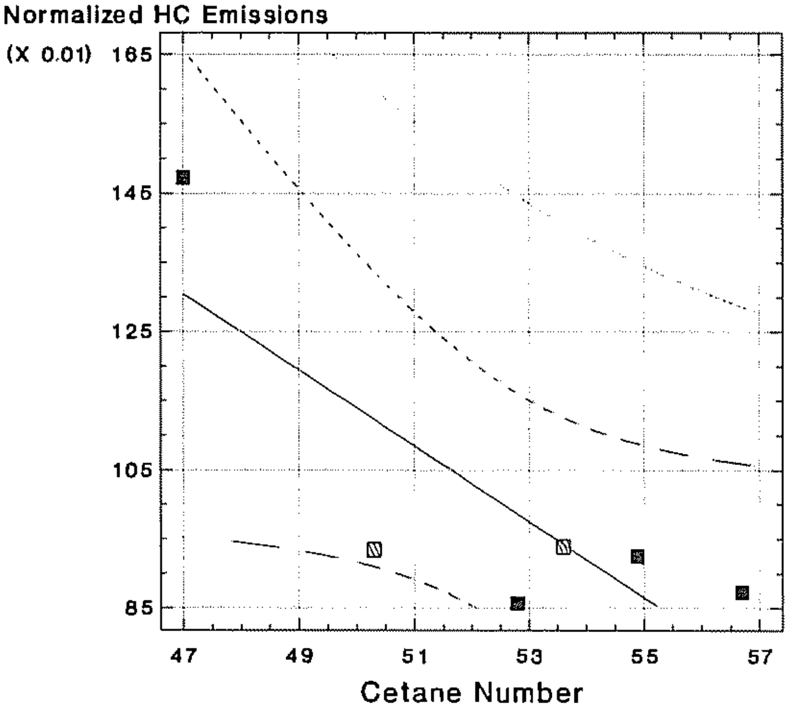


Figure 8 Normalized light-duty vehicle emissions
Regression of NO_x on cetane number

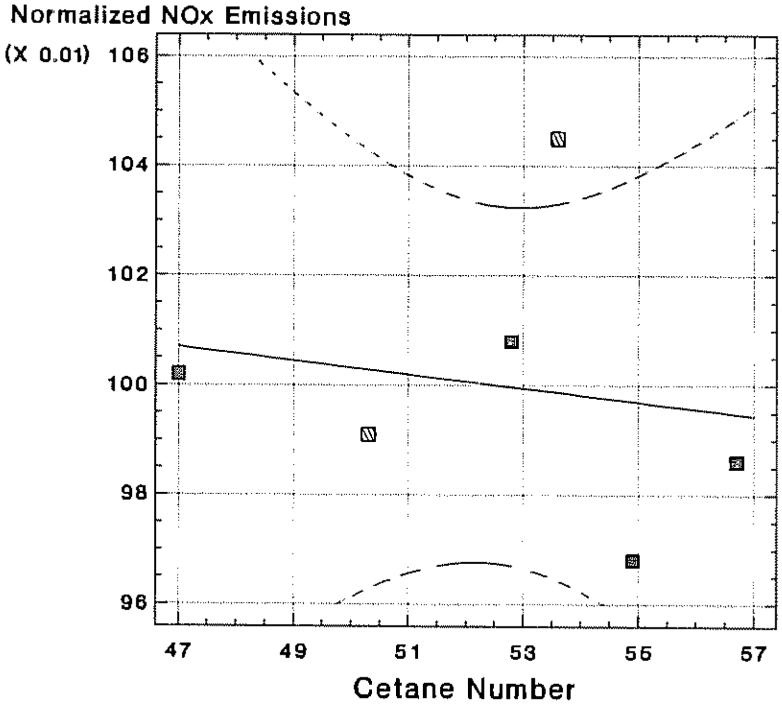


Figure 9 Normalized light-duty vehicle emissions
Regression of particulates on cetane number