the influence of gasoline benzene and aromatics content on benzene exhaust emissions from non-catalyst and catalyst equipped cars

a study of european data

Prepared for the CONCAWE Automotive Emissions Management Group, based on data available to the Special Task Force on emissions from gasoline powered vehicles (AE/STF-1):

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ABSTRACT

An analysis of data on the effect of gasoline benzene and aromatics contents on exhaust benzene emissions has been conducted. It was based on data from CONCAWE member companies and an Italian industry programme, and included the results of emission tests on 21 conventional non-catalyst and 34 catalyst cars. Although none of these programmes was specifically aimed at investigating the combined effects of gasoline benzene and aromatics content on benzene exhaust emissions, the combination of data from the individual programmes allowed some insight into these relationships.

Earlier programmes conducted with non-catalyst cars - using the ECE-15 test cycle - demonstrated that the main effect on benzene exhaust emissions derived from the benzene content of the gasoline employed. However, higher aromatics also influenced benzene exhaust emissions, albeit to a lesser extent. The effect of benzene in those earlier programmes was about twelve times higher than that of higher aromatics. Analysis of new emissions data over the combined ECE15+EUDC test cycle indicated that similar relationships existed for both non-catalyst and catalyst cars.

If benzene emissions are expressed as a percentage of total hydrocarbons emitted, then the effect of gasoline benzene content and other aromatics varies between vehicle type. More specifically, the influence of fuel benzene content was found to be over 18 times greater than that of non-benzene aromatics for non-catalyst cars. For catalyst equipped cars, the effect of benzene content was 10 times greater than that of other aromatics. Moreover, benzene exhaust emissions from catalyst cars were substantially lower. On average, emissions were reduced by around 85%, demonstrating the efficient control provided by the catalysts employed.

It has also been demonstrated that the regression equations developed predict the trends and magnitude of the benzene exhaust emissions observed over the modified ECE(11 s)+EUDC cycle, as used in the EPEFE programme and the 1994 CONCAWE gasoline study. This cycle employs a shorter idle period at the start of the test and collects exhaust emissions immediately from cranking the engine.

KEYWORDS

Gasoline, benzene, aromatics, composition, exhaust emissions

ACKNOWLEDGEMENTS

The Automotive Emissions Management Group and their Special Task Force, AE/STF-1 are indebted to Dr. R.F. Becker and Mr. P.J. Zemroch for their major contributions to this report.

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SUMMARY

An analysis of data on the effect of gasoline benzene and aromatics contents on exhaust benzene emissions has been conducted. It was based on data from CONCAWE member companies and an Italian industry programme. The data covered 21 non-catalyst and 34 catalyst cars.

- Over the combined ECE+EUDC driving cycle, the range of benzene exhaust emissions was as follows:
  - *non-catalyst cars* from 30.0 to 157.4 mg/km with an average of 67.5 mg/km,
  - *catalyst cars* from 1.4 to 33.3 mg/km with an average of 10.3 mg/km.
- For non-catalyst cars benzene exhaust emissions are reduced by about 23% during warm-up, as indicated by comparing ECE cycles 1+2 with cycles 3+4. However, the catalyst reduces emissions by more than 90% after light-off.

Benzene exhaust emissions from non-catalyst and catalyst car fleets have been modelled in terms of the content of benzene, (Bz) and Non-Benzene Aromatics, (NBA = total aromatics minus benzene) for the combined ECE+EUDC driving cycle. Equations for benzene exhaust emissions have been developed in terms of mg/km, % of total hydrocarbons (THC) emitted and mg/g of fuel consumed. Of these three types, the first gives actual emission values typical of current European vehicles, both with and without catalyst. However, this form of equation cannot be used to predict benzene emissions from a fleet of vehicles equipped with different emission control technology (e.g. European 1996 “Euro 2” cars). The second type of equation, which expresses emissions in terms of % THC, reduces the car-to-car variability in hydrocarbon emissions and is thus more widely applicable. The third type did not give a reliable estimate for catalyst cars of the relative effects of benzene and non-benzene aromatics as the only available results were on fuels of similar benzene content. Thus only the non-catalyst version can be employed, and is only applicable to current European non-catalyst vehicle fleets.

- For *non-catalyst cars* the relative effect of gasoline NBA content is lower than previously reported. The influence of benzene is between 16 and 19 times greater than the effect of non-benzene aromatics.
- For *catalyst cars* the relative effect of gasoline NBA content is higher than that observed for non-catalyst cars. The influence of benzene is between 8 and 10 times greater than the effect of non-benzene aromatics.

  Benzene emissions over the combined ECE+EUDC test cycle can be estimated by the equations, overleaf:

<u>In terms of mg Benzene/km:</u>

Non-catalyst cars:
Benzene = 15.74 + 11.711•Benzene + 0.7289•NBA
(Bz/NBA = 16.1)

Catalyst cars:
Benzene = 3.044 + 1.066•Benzene + 0.1370•NBA
(Bz/NBA = 7.8)

<u>In terms of % Benzene of Total HC Exhaust Emissions:</u>

Non-catalyst cars:
Benzene = 1.515 + 0.765•Benzene + 0.0414•NBA
(Bz/NBA = 18.5)

Catalyst cars:
Benzene = 1.237 + 0.599•Benzene + 0.0602•NBA
(Bz/NBA = 10.0)

Note: Gasoline benzene and NBA contents in % m/m.

The equations developed have been used to predict benzene emissions for the catalyst equipped fleet used in the EPEFE Project Group 4 work and the 1994 CONCAWE STF-1 project. Both programmes used the modified ECE+EUDC cycle, which stipulates a shorter (11 seconds) initial idle period and collects exhaust emissions from the time of cranking the engine. The data indicate that

- the equations describe the trend in actual benzene exhaust emissions;
- calculating the benzene exhaust emissions as per cent of total hydrocarbon emissions gives a reasonable correlation between the two programmes;
- as the total hydrocarbon emissions from the modern cars investigated in the EPEFE programme and the 1994 CONCAWE gasoline study are very low, benzene exhaust emissions in terms of mg/km from these tests - employing the modified ECE(11s)+EUDC cycle - are in general lower than estimated by these equations.

1. INTRODUCTION

Benzene emissions from motor vehicles have received growing interest in recent years and the concentration of benzene in the exhaust gases has been linked to the concentration of benzene in gasoline. In addition it has also been demonstrated that benzene exhaust emissions are related - but to a lesser extent - to the concentrations of higher aromatics in gasoline. In 1983 CONCAWE developed an equation linking benzene exhaust emissions from spark ignition engines with the benzene and aromatics content of gasoline[1]:

Benzene (Exhaust % m/m VOC) =
0.50 + 0.44•Benzene (Fuel) + 0.04•Non-Benzene Aromatics (Fuel)
(Bz/NBA ratio = 11)
Note: All concentrations in % m/m, NBA = Non-benzene aromatics

This equation was based on the ECE-15 cycle and the tests were conducted under fully warmed up conditions on four non-catalyst cars. The relative weighting of benzene and aromatics coefficients in the equation was 0.44 to 0.04, which indicates an eleven-fold greater influence of benzene compared with the non-benzene aromatics content:

A number of models have been developed in the United States, but these are for US cars over the FTP test cycle. Much of this work has been used to develop the so-called ‘simple’ and ‘complex’ models [3]:

<u>The US Simple Model</u>

$$EXHBEN = [1.844 + 0.949 \times FBEN + 0.113 \times (FAROM-FBEN)/100] \times 1000 \times EXHVOCS$$

Where:
EXHBEN is the exhaust benzene level in mg/mile
FBEN and FAROM are the fuel benzene and fuel total aromatics contents, respectively, expressed in % v/v.
EXHVOCS are the total exhaust volatile organic compounds (VOC - including aldehydes and ketones) in g/mile. EXHVOCS is taken to vary with season, according to further formulae, which include a term for fuel oxygen content in % m/m.

This is equivalent to the following model:

Benzene % m/m VOC =
1.884 + 0.949×Benzene (Fuel) + 0.113×NBA (Fuel)
(Bz/NBA ratio = 8.4)

The US Complex Model

$$EXHBEN = BENZ(b)\times[W_1(\exp\{b_1(t)\})/(\exp\{b_1(b)\}) + W_2(\exp\{b_2(t)\})/(\exp\{b_2(b)\})]$$

Where:
EXHBEN is the exhaust benzene level in mg/mile.
BENZ(b) is a baseline benzene emission. This is a constant, depending upon the year (so as take account of changes in the vehicle parc) and season.
W_1 and W_2 are weighting factors describing the fractions of emissions from the vehicle pool that are due to 'normal' and 'gross' emitters, respectively.
$b_i(x)$ are four expressions defining benzene emissions as a function of chemical and physical properties of the fuel for i = 1, 2 ('normal' and 'gross' emitters respectively) and x = b, t (b for the baseline fuel and t for the target fuel).

$b_1(x) = + 6.197 \times 10^{-4}$ *SUL*
$- 3.376 \times 10^{-3}$ *E200*
$+ 2.655 \times 10^{-2}$ *FAROM*
$+ 2.2239 \times 10^{-1}$ *FBEN*
(FBEN/FAROM = 8.376)

$b_2(x) = - 9.6047 \times 10^{-2}$ *OXY*
$+ 3.370 \times 10^{-4}$ *SUL*
$+ 1.1251 \times 10^{-2}$ *E300*
$+ 1.1882 \times 10^{-2}$ *FAROM*
$+ 2.22318 \times 10^{-1}$ *FBEN*
(FBEN/FAROM = 18.71)

Where: *OXY* is the % m/m oxygen content of the fuel
SUL is the ppm by mass sulphur content of the fuel
E200 and *E300* are the volume fraction distilled at these temperatures in °F
FAROM and *FBEN* are the % v/v aromatics (**including** benzene) and % v/v benzene respectively

However, little recent information is available for the European test procedure and European cars. The sole publication addressing this issue - but only for non-catalyst cars - is by Perry and Gee from Imperial College, London: [2]

Combined ECE-15 + EUDC Test:

Benzene (Exhaust) [mg/km] =
27.20 + 10.45•Benzene (Fuel) [%] + 0.81•NBA (Fuel) [%]
(Bz/NBA ratio = 12.9)
Note: NBA = Non-benzene aromatics

This equation shows a benzene effect which is 12.9-times higher than the aromatics effect.

Updated equations were required for the European ‘Auto/Oil Programme’ work on air quality modelling, both for catalyst and non-catalyst cars. CONCAWE was asked to develop such equations by March 1995. In addition, the relationship developed by CONCAWE in 1983 [1] had been recently questioned by the Toxicological Commission of the Italian Health Ministry, which placed a higher coefficient on aromatics content. This inferred that stricter control of gasoline aromatics content was required, in addition to the already existing EU benzene limit of 5.0% v/v max. This review was based on information developed within a joint oil and car industry programme in Italy. The project, which was planned in 1989 and completed in 1993, determined benzene exhaust emissions from conventional and catalyst cars using a series of representative unleaded and leaded gasolines. However, CONCAWE regression analysis of these data could not support the claim that there was a higher relative influence of aromatics content on benzene exhaust emissions. A closer examination of the data indicated that in this test fuel set benzene and aromatics content were highly inter-correlated which prohibited the separation of the two effects. This was not surprising as the fuels selected for this programme represented typical gasolines found in the market.

As a consequence, CONCAWE's AE/STF-1 was requested to develop new benzene emission equations based on published and in-house data from CONCAWE member companies.

2. EXPERIMENTAL DATA

A relatively large number of test data were made available by member companies for this investigation. In total, data on 21 non-catalyst and 34 catalyst equipped cars were submitted. Data were also available for a small number of these cars at various mileage accumulations. All vehicles were tested on at least 3 fuels (usually more) but not necessarily on the same fuel set. Where possible, the following information was provided on the test fuels used in the emissions tests:

Test fuel information:

- density at 15ºC
- benzene [% m/m]
- total aromatics [% m/m] by FIA or GC
- oxygenate content [% m/m]

Properties of the gasolines used at different laboratories are listed in **Appendix 1**. **Table 1** gives an overview on the mean and ranges of test fuel properties. Benzene contents range from 0.3 to 4.5% m/m, and total aromatics content from 21 to 55% m/m.

The following measurements of exhaust emissions and fuel consumption over the ECE 1-4, EUDC, and the ECE+EUDC combined cycle were provided:

- benzene exhaust emissions [mg/km]
- total hydrocarbon emissions [g/km]
- fuel consumption [g/km]

Averages and ranges for benzene exhaust emissions over the different parts of and the combined ECE+EUDC driving cycle are given in **Table 2**. Over the combined ECE+EUDC driving cycle benzene exhaust emissions ranged for:

- non-catalyst cars from 30 to 157.4 mg benzene/km, with an average of 67.5 mg benzene/km,
- catalyst cars from 1.4 to 33.3 mg benzene/km, with an average of 10.3 mg benzene/km. This represents a reduction of approximately 85% compared with the average benzene emissions from non-catalyst cars.

A complete set of the exhaust emissions and fuel consumption data used in this analysis is given in **Appendix 2**. As can be seen, full data were not available for all tests, especially for fuel consumption. In many cases only combined ECE+EUDC cycle emissions data were available.

For 91 non-catalyst and 162 catalyst tests, benzene emission data (in mg/km) were available split into three separate bags, i.e. ECE 1+2, ECE 3+4 and EUDC. This allowed examination of the way in which benzene emissions vary during warm-up, as shown below:

Cycle	Non-catalyst cars			Catalyst cars		
	mg/km	% ECE 1+2	% ECE+EUDC	mg/km	% ECE 1+2	% ECE+EUDC
ECE 1+2	109.3	100	31	45.5	100	73
ECE 3+4	83.8	77	24	3.2	7	5
EUDC	44.5	41	45	3.9	9	22
ECE+EUDC	63.4		100	11.3		100

Thus for non-catalyst cars, benzene emissions reduced by only 23% during initial warm-up (i.e. comparing ECE 1+2 and ECE 3+4), but by almost 60% when the engine was fully warmed up during the EUDC cycle. In contrast for the catalyst cars, emissions were reduced by over 90% after only the first two ECE cycles, i.e. once the catalyst had reached its operating temperature.

It is worth noting that emissions from the catalyst cars, once the catalyst is operating, were over 90% less than emissions from the fully warmed-up non-catalyst cars. This demonstrates that a three-way catalyst, at its operating temperature, controls benzene exhaust emissions very efficiently.

For both non-catalyst and catalyst cars about 5% of total hydrocarbon exhaust emissions are benzene.

In relation to the amount of fuel consumed over the ECE and EUDC driving cycles, on average about one mg benzene is emitted for every g of gasoline consumed by non-catalyst cars. Catalyst cars emit only 0.14 mg benzene for every g of gasoline consumed over the combined ECE + EUDC cycle.

3. ANALYSIS OF RESULTS

Most of these data have been generated in programmes not specifically aimed at investigating the effect of benzene and aromatics content on benzene exhaust emissions. As a consequence, there are often strong inter-correlations between these two fuel parameters within individual data sets. In other data sets, the fuels have very similar benzene contents, so no effect of benzene variation on emissions can be seen. However, by combining the various programmes quite a range of properties is included in the overall data set. As can be seen in **Figures 1**, **2** and **3**, plotting benzene exhaust emissions for non-catalyst and catalyst cars, a wide range of benzene and NBA contents are used, and the inter-correlation between these properties is low. However these graphs also indicate that there are very few data in the high benzene/low aromatics range.

Regression equations relating exhaust benzene emissions to gasoline benzene and aromatics content were developed for the following cases:

(1) benzene exhaust emissions in mg/km,
(2) benzene exhaust emissions as % of total hydrocarbon (THC) emissions,
(3) benzene exhaust emissions in mg per g fuel consumed.

The second case has the advantage of reducing any variation in THC emissions related to the influence of different engine control and catalyst designs, plus other fuel properties.

The numbers of cars and test results available for each data set are shown in **Table 2**, which indicates that there are more emissions measurements expressed in mg benzene/km than in percentages of THC; whilst measurements of benzene emissions per gram of fuel consumed are fewest in number. Emissions in mg benzene/km also happen to be available for fuels with higher benzene contents than for the other cases. Considerably fewer results are available for the individual cycles than for the composite cycle. No EUDC results are available from fuels with more than 3.32% m/m benzene.

Differences in vehicles have much larger effects on emissions than differences in fuels and so no single equation can adequately describe the relationship between emissions and fuel properties for every vehicle. Separate equations are required relating emissions to fuel benzene and NBA for each car. Each vehicle was tested on a different set of fuels, but despite this, there was a good deal of commonality in the fitted equations. It was possible to model the emissions from car i as

$$\text{emissions} = c_i + a \bullet \text{benzene in fuel} + b \bullet \text{NBA in fuel}$$

as a first-order approximation, catalyst and non-catalyst vehicles being modelled separately. In addition, different coefficients c_i were fitted when a car was re-tested at several stages of its history. In this model, the emissions for the various vehicles lie on a set of parallel planes. The ratio of the coefficients a/b gives us a good indication of the relative importance of fuel benzene and fuel NBA on benzene exhaust emissions.

Figures 4 and **5** show the residuals about the above model plotted against predicted emissions. As in previous studies, the variability in emission measurements increases in absolute terms as the actual level of emissions increases. This non-homogeneity of variance renders conventional ordinary least-squares regression techniques invalid. To overcome this problem, the regression models discussed in this report were fitted using 'generalised linear modelling' techniques, the measurement errors being assumed to have a gamma rather than a normal distribution. Some of the results in **Appendix 2** are the averages of several emission tests. However, in the absence of complete, detailed information on the degrees of replication in the various experimental programmes, each result in **Appendix 2** had to be treated as if it was from a single test. Thus, whilst the regression analyses discussed in this report is exhaustive, its description of reality should be regarded as approximate.

A detailed description of the statistical procedures applied is found in **Appendix 3**.

4. REGRESSION EQUATIONS

Table 3 lists the equations developed for the combined ECE+EUDC test cycle. These were derived by fitting the parallel-plane model:

$$\text{emissions} = c_i + a \times \text{fuel benzene content} + b \times \text{fuel NBA content} \qquad (\mathbf{4.1})$$

with a different intercept c_i for each car i, assuming gamma measurement errors (see **Chapter 3** and **Appendix 3**). The mean intercepts in **Table 3** are the simple arithmetic averages of the values of c_i for those vehicles i for which test results were available. The physical significance of these intercepts is not known.

4.1. NON-CATALYST CARS

Figure 1(b) shows a three-dimensional (3D) plot of benzene exhaust emissions (mg/km) against fuel benzene and NBA for non-catalyst cars. Despite the large body of data, there are very few results from high-benzene low-NBA fuels. Nevertheless, there is a clear pattern in the data, perhaps surprisingly so given the many sources, with benzene emissions clearly increasing with both fuel benzene and fuel NBA. There is no evidence for a quadratic or a benzene × NBA interaction term in the model, so the simple planar model seems an adequate data summary. **Figure 6** shows the observed ECE+EUDC emissions plotted against the values predicted by the model. (Predicted emissions are calculated using the individual intercepts, c_i for each vehicle rather than the mean intercepts in **Table 3**).

Expressed in mg/km, the ratio of the benzene to NBA coefficients is 16.1 (S.E. = 2.2), indicating that fuel benzene has 16 times the influence of fuel NBA on benzene exhaust emissions over the combined ECE+EUDC cycle. This value is higher than those reported in previous studies. The coefficient ratios were 18.5 (2.9) and 18.8 (3.0) for benzene emissions expressed as percentages of THC and mg benzene/g of fuel consumption, the larger standard errors being due to the absence of results for high-benzene fuels.

The intercepts c_i were positive for many of the cars, irrespective of how the benzene emissions were expressed. This might suggest that some benzene is emitted from the exhaust even when the fuel contains neither benzene nor aromatics. However, such a suggestion is based on an extrapolation of the model (**Equation 4.1**, above) to fuels outside the range used in the fitting process.

4.2. CATALYST CARS

Figure 1(a) shows a 3D plot of benzene exhaust emissions (mg/km) against fuel benzene and NBA for catalyst cars. Again, despite the large body of data, there are very few results from high-benzene low-NBA fuels. The pattern in the data is directionally similar to that seen for non-catalyst cars with benzene emissions increasing with both fuel benzene and fuel NBA. Once more there is no evidence for a quadratic or a benzene × NBA interaction term in the model, so the simple planar model (4.1) seems an adequate data summary. **Figure 7** shows the observed ECE+EUDC emissions plotted against the values predicted by the model.

Expressed as mg/km, the ratio of the benzene to NBA coefficients is 7.8 (S.E. = 2.2), indicating that fuel benzene has 8 times the influence of fuel NBA on benzene exhaust emissions over the combined ECE+EUDC cycle. The coefficient ratios were 10.0 (2.5) and 3.3 (2.3) for benzene emissions expressed as percentages of THC and mg benzene/g fuel consumption respectively. The data used to derive these values are plotted in **Figures 2a** and **3a**. In the latter case, most of the test fuels had very similar benzene contents and the benzene coefficient *a* in equation (4.1) was not significantly different from zero. Therefore the ratio of 3.3 for benzene emissions in terms of fuel consumption is less than reliable.

The intercepts c_i were close to or just above zero for most cars, irrespective of how the benzene emissions were expressed.

4.3. CONVERSION TO % VOLUME (% v/v)

In the raw data, benzene and non-benzene aromatics (NBA) were generally expressed as % m/m, although some data were expressed in % v/v. For this analysis, all relevant fuel properties were converted into % m/m, using the following densities in kg/m^3 at 20°C:

Benzene	879
NBA	875

Thus all the equations developed are expressed in % m/m. For practical use however, both benzene and other aromatics contents are frequently expressed in volume terms. The equations can be converted for use with fuel properties in % v/v, provided the fuel density, D, is known:

Benzene emissions = c + a × (Fuel Bz % v/v) × 879/D + b × (Fuel NBA % v/v) × 875/D

where D = fuel density in kg/m^3 at 20°C. For a general equation, a figure of D = 750 may be used, (the average of the fuels tested in this work was 748).

5. COMPARISON WITH EPEFE RESULTS AND THE CONCAWE 1994 PROGRAMME

Although the correlations were all developed on test data employing the conventional ECE+EUDC driving cycle, a comparison with the data developed in the EPEFE Project Group 4 and the 1994 CONCAWE AE/STF-1 programme was considered worthwhile. **Figures 8** and **9** compare the emissions actually observed in these programmes over the modified ECE(11s)+EUDC driving cycle with the predicted emissions equations for catalyst cars from **Table 3**. It can be seen that:

- the equations describe the trend in actual benzene exhaust emissions over the modified ECE(11s)+EUDC driving cycle;

- calculating the benzene exhaust emissions as per cent of total hydrocarbon emissions gives an excellent correlation between the two programmes;

- as the THC exhaust emissions of the cars tested in the 1994 EPEFE and CONCAWE programmes are low compared with the older data, benzene exhaust emissions in mg benzene/km from the tests employing the modified ECE(11s)+EUDC cycle are in general lower than predicted by the regression equation.

6. CONCLUSIONS

An analysis of data on the effect of gasoline benzene and aromatics contents on exhaust benzene emissions has been conducted. It was based on data from CONCAWE member companies and an Italian industry programme, and included 21 conventional non-catalyst and 34 catalyst cars.

1. Over the combined ECE+EUDC driving cycle benzene exhaust emissions ranged for:

    - *non-catalyst cars* from 30.0 to 157.4 mg benzene/km, with an average of 67.5 mg benzene/km,

    - *catalyst cars* from 1.4 to 33.3 mg benzene/km, with an average of 10.3 mg benzene/km.

2. For non-catalyst cars benzene exhaust emissions changed only by about 25% during warm-up, as indicated by the ECE cycle 1+2 and cycle 3+4 exhaust emissions. However, for catalyst cars about 90% of the benzene exhaust emissions are observed during the first two ECE cycles, when engine and catalyst have not reached their optimum operating temperatures. As indicated in (1) above, catalysts reduced benzene emissions by an average of 85%, compared to emissions from non-catalyst cars.

3. Benzene exhaust emissions from non-catalyst and catalyst cars have been modelled in terms of the content of benzene and non-benzene aromatics, (NBA), in the fuel for the combined ECE+EUDC driving cycle.

4. For *non-catalyst cars* the relative effect of gasoline NBA content is lower than previously reported. The influence of benzene is between 16 and 19 times greater than the effect of non-benzene aromatics.

5. For *catalyst cars* the relative effect of gasoline NBA content is higher than that observed for non-catalyst cars. The influence of benzene is between 8 and 10 times greater than the effect of non-benzene aromatics.

6. Fleet average benzene emissions over the combined ECE+EUDC test cycle can be estimated by the equations:

    In terms of mg Benzene/km:

Non-catalyst cars:
Benzene = 15.74 + 11.711•Benzene + 0.7289•NBA (Bz/NBA = 16.1)

Catalyst cars:
Benzene = 3.044 + 1.066•Benzene + 0.1370•NBA (Bz/NBA = 7.8)

In terms of % Benzene of Total HC Exhaust Emissions:

Non-catalyst cars:
Benzene = 1.515 + 0.765•Benzene + 0.0414•NBA (Bz/NBA = 18.5)

Catalyst cars:
Benzene = 1.237 + 0.599•Benzene + 0.0602•NBA (Bz/NBA = 10.0)

Note: Gasoline benzene and NBA contents in % m/m.

7. Equations in terms of % benzene of THC are preferred. They reduce car-to-car variability in HC emissions and are more widely applicable than the relationships expressed as mg/km. The latter equations apply to the current car fleet and should not be used to predict benzene emissions from vehicles fitted with different emissions control technology.

8. The equations developed have been used to predict benzene emissions for the catalyst equipped fleets used in the EPEFE Project Group 4 work and a 1994 CONCAWE programme.

- calculating the benzene exhaust emissions as per cent of total hydrocarbon emissions gives a reasonable correlation between the two programmes;

- as total hydrocarbon emissions from the modern cars investigated in both the EPEFE programme and the 1994 CONCAWE work are very low, benzene exhaust emissions in mg benzene/km from these tests - employing the modified ECE(11s)+EUDC cycle - are in general lower than estimated by these equations.

7. REFERENCES

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3. US Federal Register, Vol. 59, No. 32, February 1994

8. TABLES AND FIGURES

Table 1 Test Fuel Properties: Ranges and Averages

	Density (g/ml)	Fuel Composition, % m/m			
		Benzene	**NBA**	**Total Ar.**	**MTBE**
Test Fuels for Programmes Using Catalyst Cars					
Minimum	0.7023	0.32	17.72	21.22	0.00
Maximum	0.7730	4.49	53.76	54.80	15.06
Average	0.7484	1.88	38.44	40.32	5.25
Test Fuels for Programmes Using Non-catalyst Cars					
Minimum	0.7023	0.32	17.72	21.22	0.00
Maximum	0.7730	4.49	51.38	54.30	15.06
Average	0.7485	2.23	36.99	39.22	5.46

Table 2 Exhaust Emission and Fuel Consumption Data: Ranges and Averages

Benzene Exhaust Emissions in Terms of		Minimum	Maximum	Average	N° of cars*	N° of test results
Catalyst Cars						
mg Benzene / km	ECE 1+2	8.13	117.10	45.47	21	162
	ECE 3+4	0.00	21.23	3.16	21	162
	ECE 1-4	4.31	61.35	24.93	25	175
	EUDC	0	35.80	4.05	23	169
	ECE + EUDC	**1.42**	**33.33**	**10.29**	**37**	**276**
% Benzene of THC	ECE 1-4	0.92	7.85	4.22	21	161
	EUDC	0	35.53	9.46	21	161
	ECE + EUDC	**1.61**	**18.37**	**4.59**	**34**	**260**
mg Benzene /g fuel	ECE 1-4	0.095	0.572	0.254	15	120
	EUDC	0.000	0.178	0.050	15	120
	ECE + EUDC	**0.023**	**0.502**	**0.143**	**26**	**204**
Non-Catalyst Cars						
mg Benzene / km	ECE 1+2	39.20	192.13	109.32	10	91
	ECE 3+4	35.00	141.45	83.79	10	91
	ECE 1-4	47.50	166.79	97.70	13	100
	EUDC	20.00	79.97	45.06	12	97
	ECE + EUDC	**30.00**	**157.43**	**67.48**	**23**	**210**
% Benzene of THC	ECE 1-4	2.26	6.13	4.24	10	91
	EUDC	3.19	6.98	4.83	10	91
	ECE + EUDC	**2.38**	**11.30**	**4.73**	**20**	**196**
mg Benzene / g fuel	ECE 1-4	0.522	1.924	1.137	4	49
	EUDC	0.375	1.317	0.786	4	49
	ECE + EUDC	**0.446**	**2.265**	**1.019**	**14**	**124**

* Cars which were tested at 3000, 4000, and sometimes 8000 km, are counted separately at each mileage accumulation.

Table 3 Regression Equations for ECE+EUDC Test Conditions

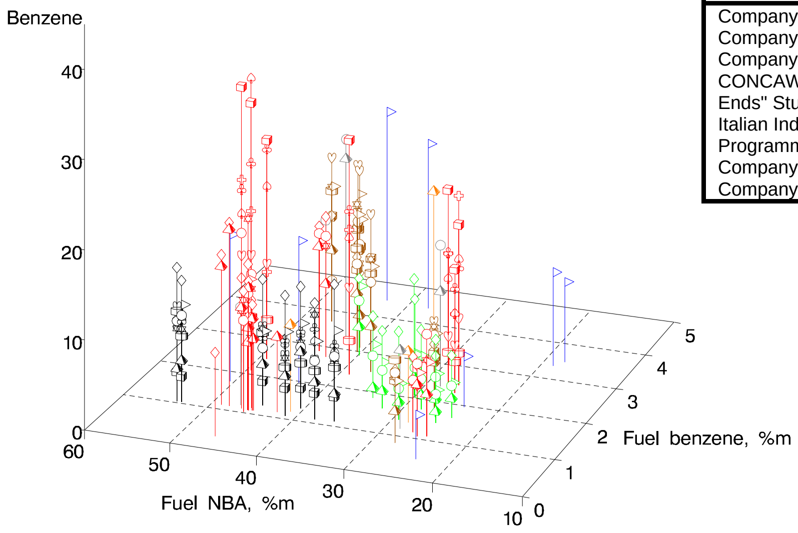
Exhaust Benzene = c_i + a•Benzene (Fuel) + b•NBA (Fuel)
Note: All fuel concentrations in % m/m

Dependent Variable	Mean Intercept c	Coefficients a [Benzene]	Coefficients b [NBA]	St.E. of Coefficients St.E. a [Benzene]	St.E. of Coefficients St.E. b [NBA]	Ratio of Coefficients a/b	St.E of ratio of Coefficients
Catalyst Cars							
mg Benzene / km	3.044	1.066	0.137	0.229	0.0169	7.8	2.2
% Benzene of THC	1.237	0.599	0.0602	0.107	0.0076	10.0	2.5
mg Benzene / g FC	0.0459	0.0072 *	0.0022	0.0048	0.0003	3.3	2.3
Non-catalyst Cars							
mg Benzene / km	15.74	11.711	0.7289	0.795	0.0668	16.1	2.2
% Benzene of THC	1.515	0.765	0.0414	0.057	0.0046	18.5	2.9
mg Benzene / g FC	0.276	0.201	0.0107	0.023	0.0010	18.8	3.0

* Not significant

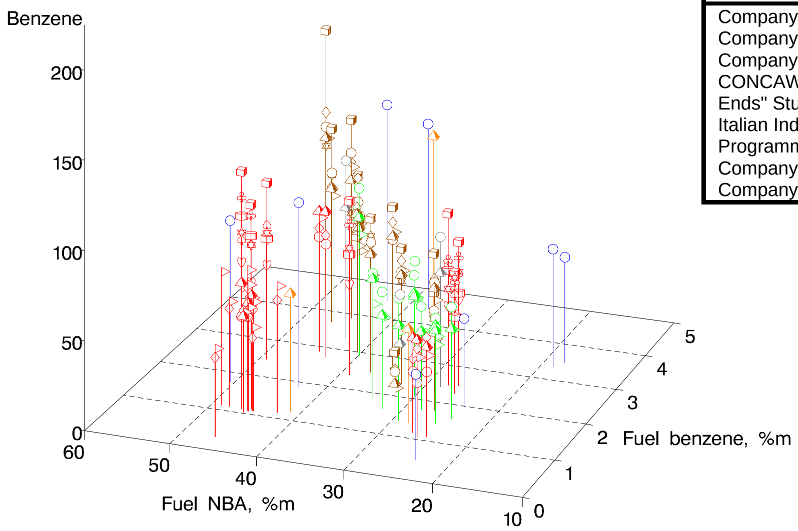
Figure 1 Benzene exhaust emissions (mg/km)

(a) Catalyst cars



SOURCE	COLOUR
Company A	Green
Company B	Blue
Company C	Red
CONCAWE "Heavy Ends" Study	Black
Italian Industry Programme	Brown
Company D	Grey
Company E	Orange

(b) Non-catalyst cars

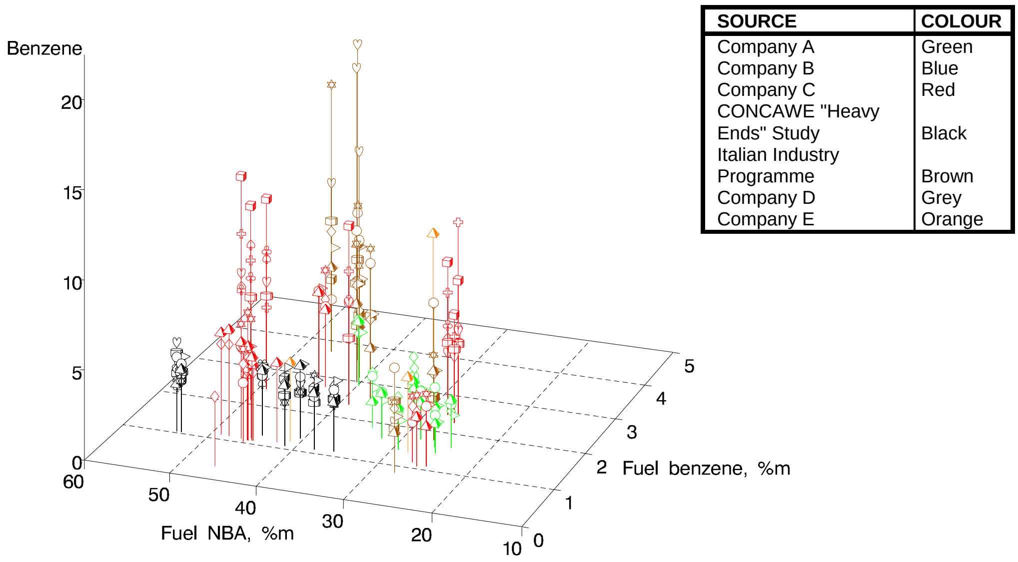


SOURCE	COLOUR
Company A	Green
Company B	Blue
Company C	Red
CONCAWE "Heavy Ends" Study	Black
Italian Industry Programme	Brown
Company D	Grey
Company E	Orange

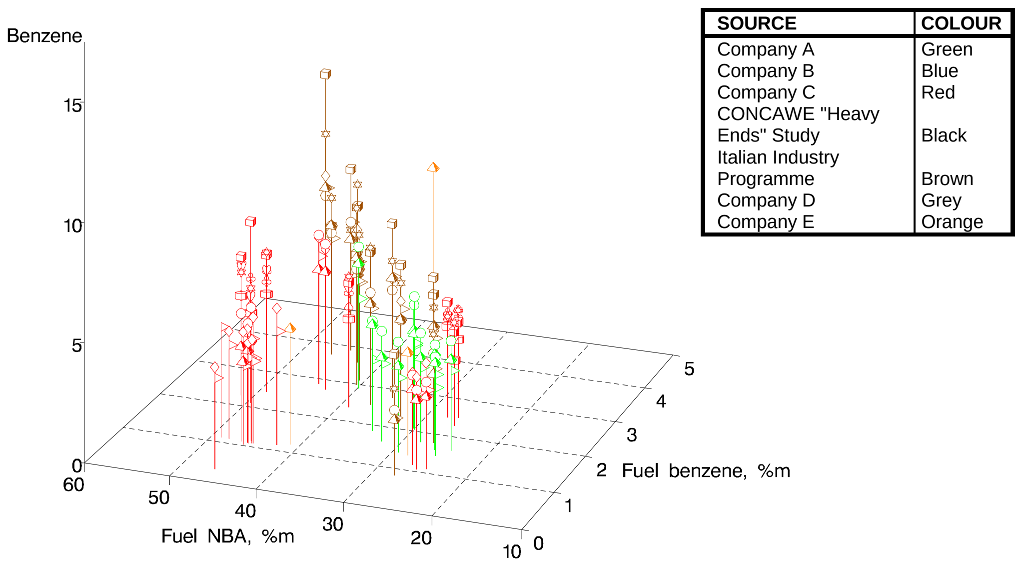
Note: Different symbols are used to identify the different cars

Figure 2 Benzene exhaust emissions (% benzene/total HC)

_(a)_ Catalyst cars



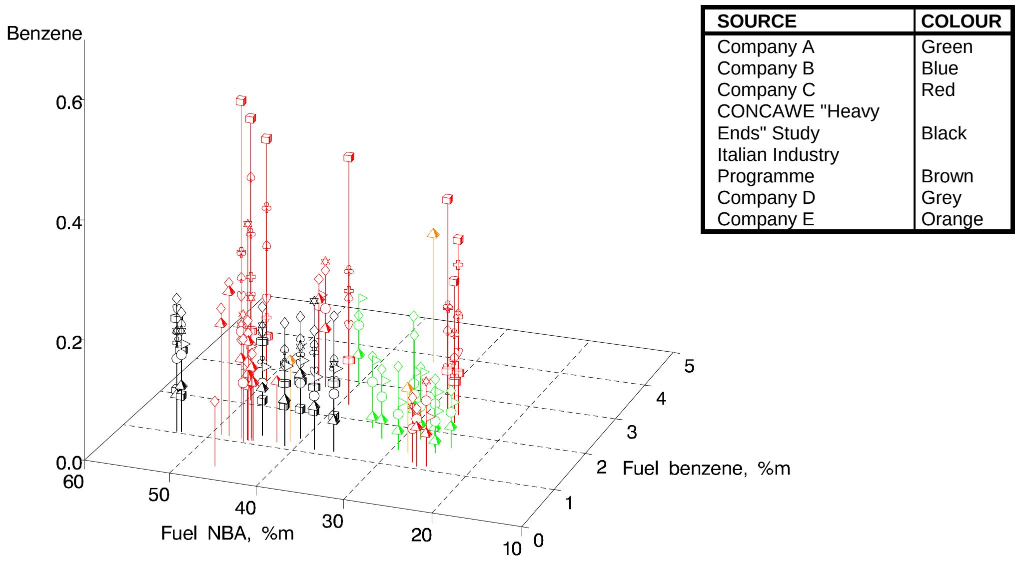
_(b)_ Non-catalyst cars



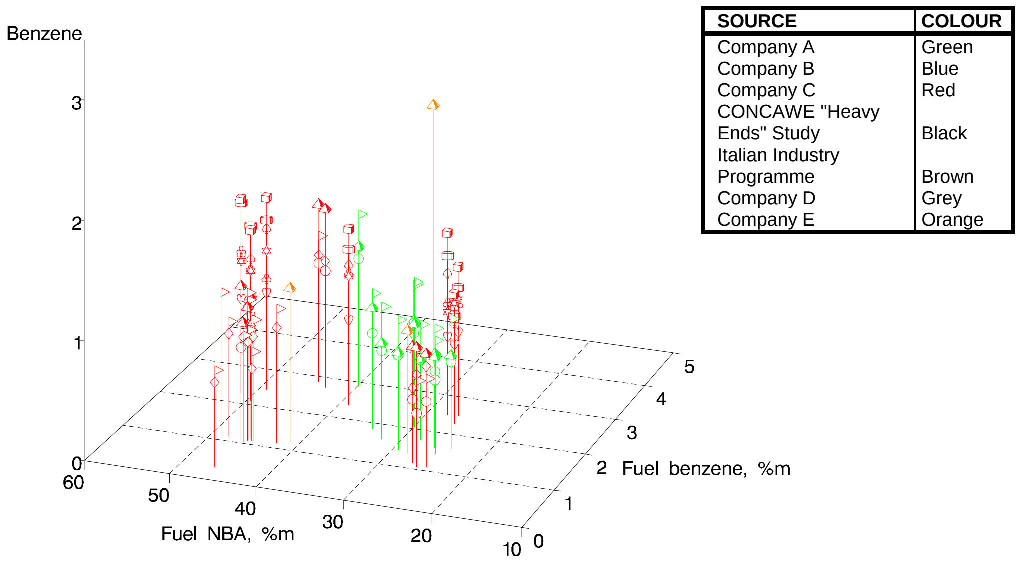
Note: Different symbols are used to identify the different cars

Figure 3 Benzene exhaust emissions (mg benzene/g fuel consumption)

(a) Catalyst cars



(b) Non-catalyst cars



Note: Different symbols are used to identify the different cars

Figure 4 Residuals about the planar models (assuming normal errors) for non-catalyst cars

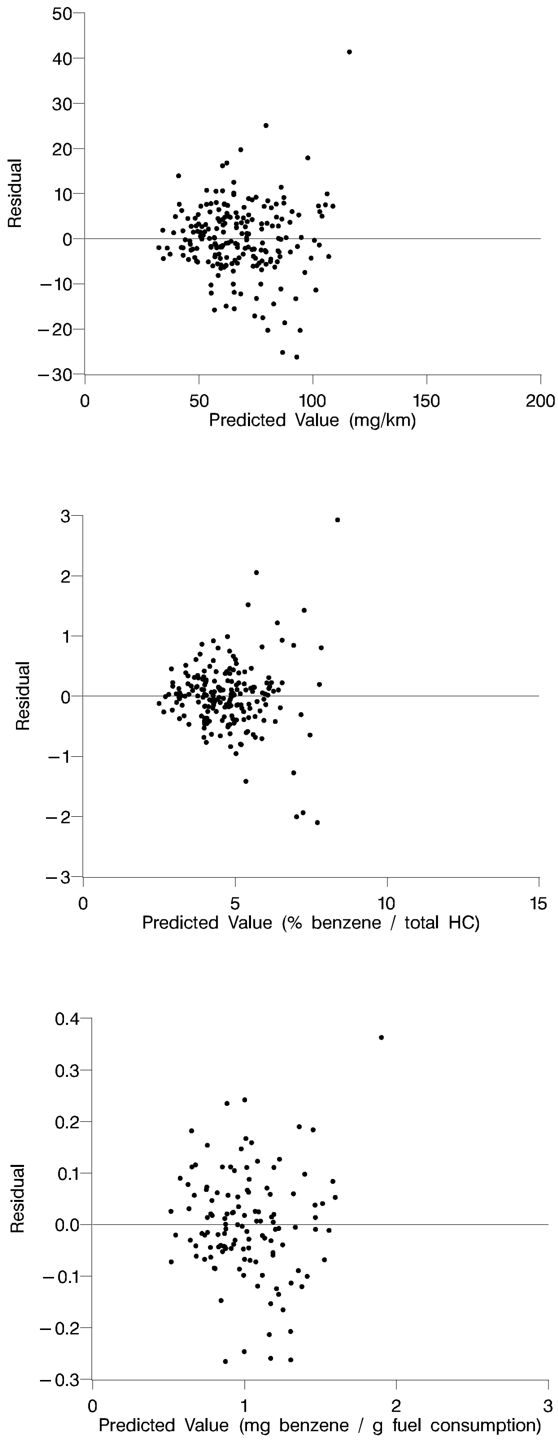


Figure 5 Residuals about the planar models (assuming normal errors) for catalyst cars

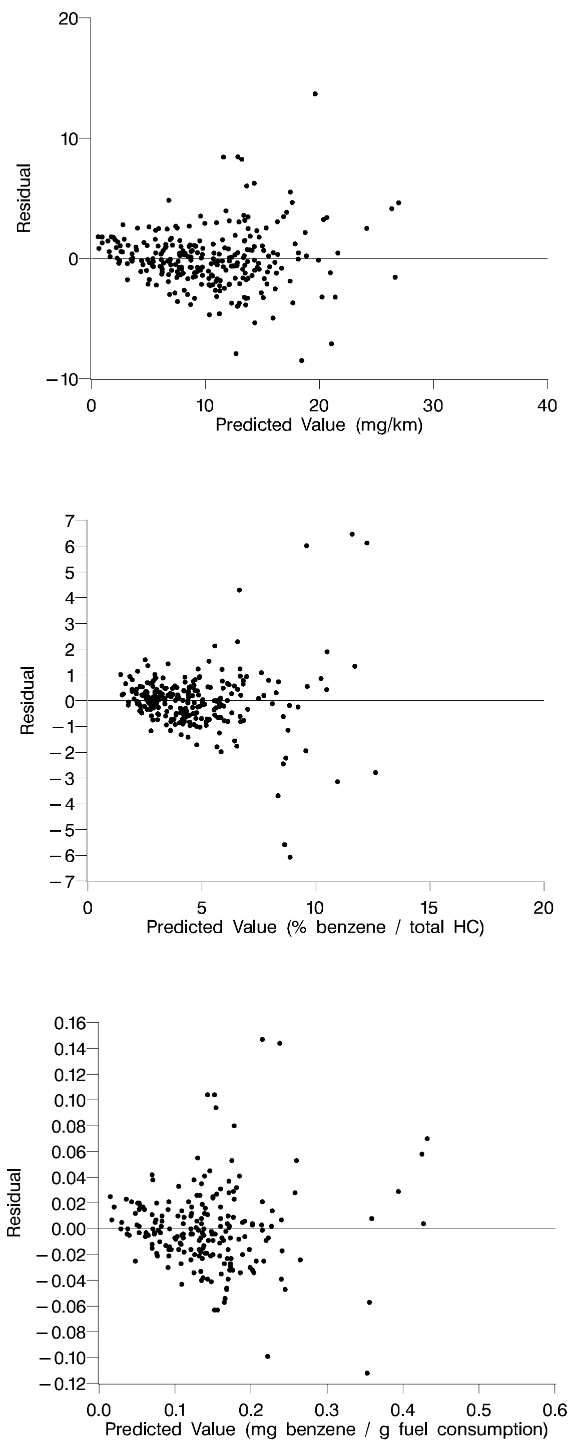


Figure 6 Observed vs. predicted model values (assuming gamma errors) for non-catalyst cars

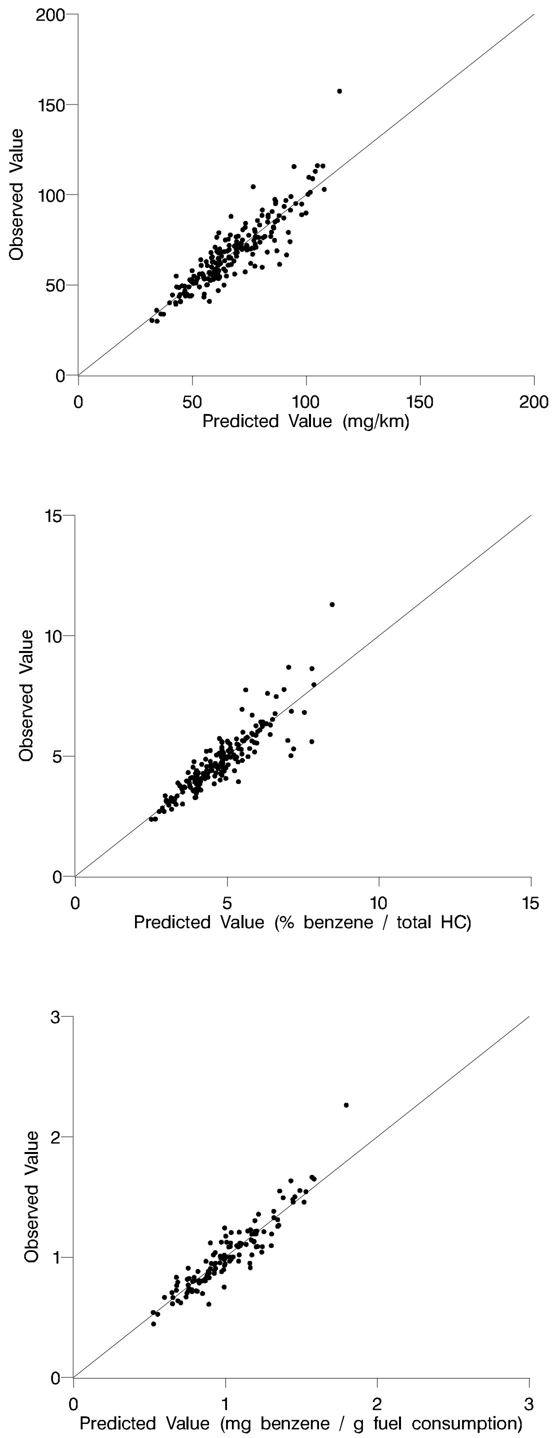


Figure 7 Observed vs. predicted model values (assuming gamma errors) for catalyst cars

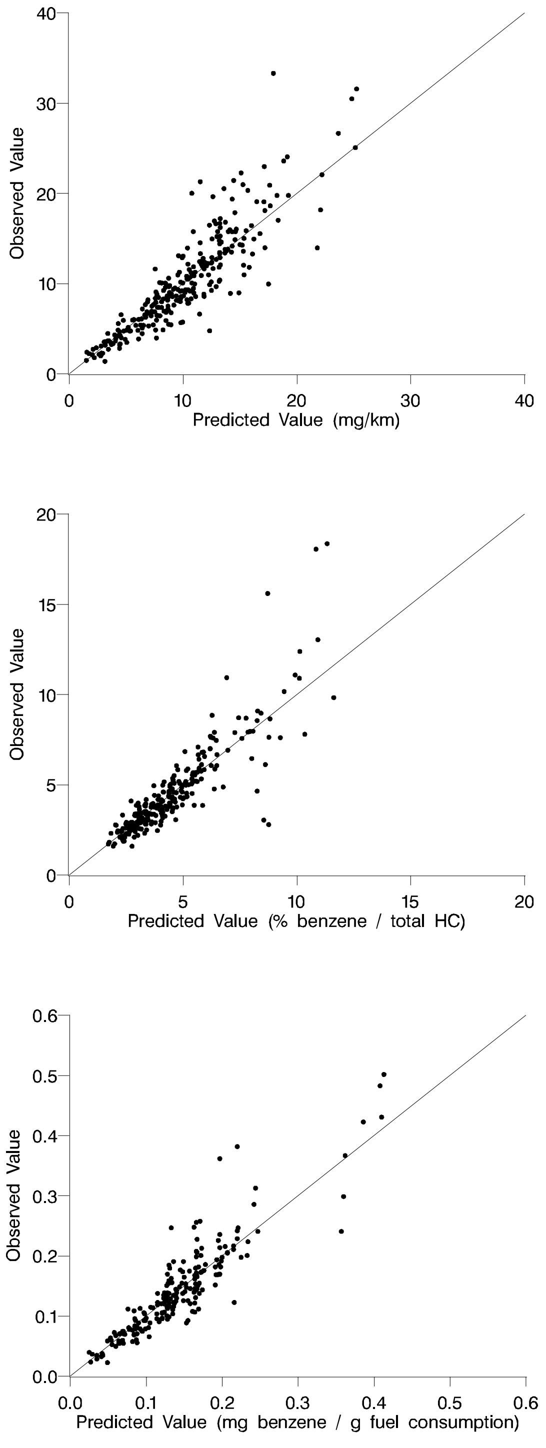


Figure 8 Prediction of benzene exhaust emissions in terms of % benzene of THC for EPEFE Project Group 4 and CONCAWE STF-1 test fleets

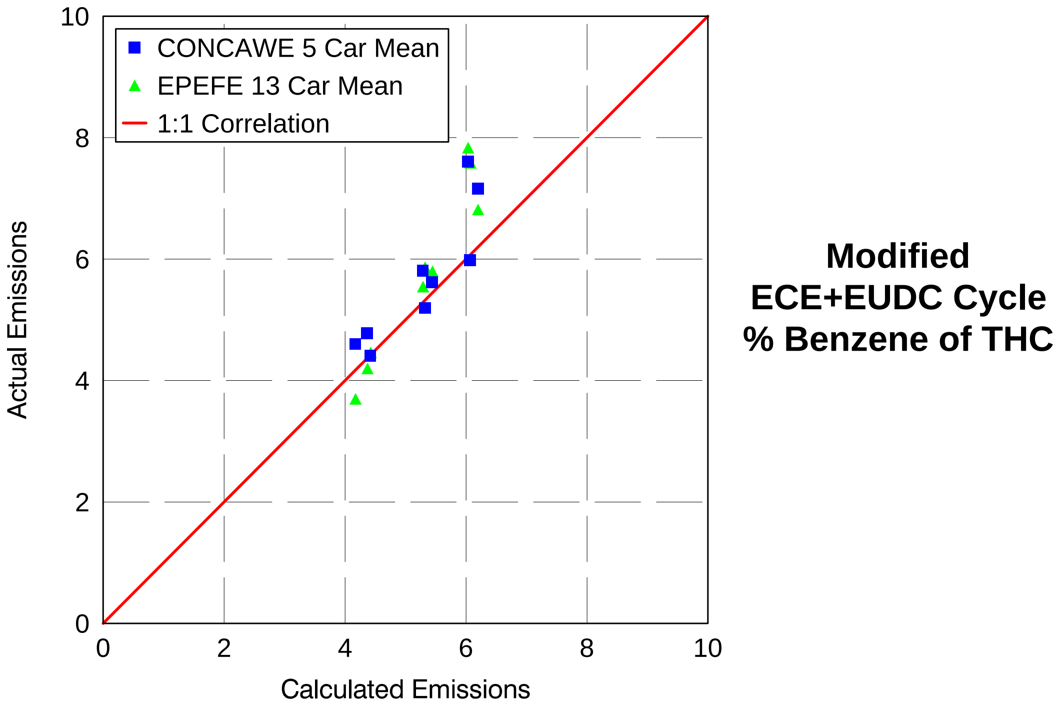
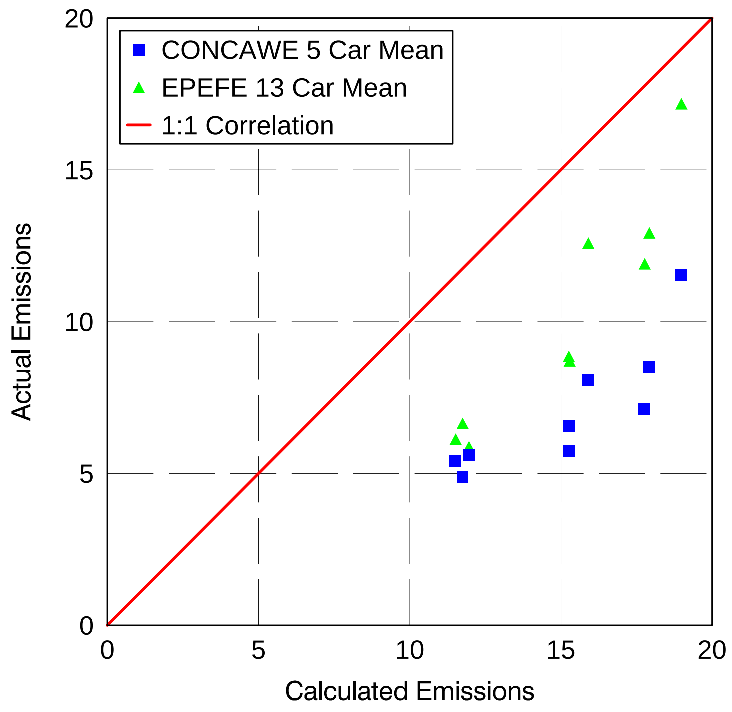


Figure 9 Prediction of benzene exhaust emissions in terms of mg benzene/km for EPEFE Project Group 4 and CONCAWE STF-1 test fleets



Modified ECE+EUDC Cycle mg Benzene/km

APPENDIX 1

TEST FUEL PROPERTIES

Test Fuel	Density	Fuel Composition, % m/m					
		Benzene	NBA	Total Ar.	Olefins	Par/Naph	MTBE
Test Fuels for Programmes Using Catalyst Cars							
Company A: Catalyst Cars 4-7							
A	0.7523	2.90	39.89	42.79			0.00
B	0.7455	1.85	34.07	35.92			4.96
C	0.7445	1.63	32.10	33.73			9.95
D	0.7378	1.46	25.25	26.71			15.04
E	0.7329	1.41	29.34	30.75			0.00
F	0.7362	2.07	30.09	32.16			0.00
G	0.7365	2.04	29.90	31.94			0.00
H	0.7368	1.64	24.11	25.75			15.06
I	0.7403	1.60	25.80	27.40			14.99
J	0.7432	1.75	28.06	29.81			14.95
Company B: Catalyst Cars 1 & 2							
95 UL	0.7523	4.43	37.33	41.76			
HB/HA	0.7584	3.13	45.57	48.70			
LB/LA	0.7203	2.08	21.32	23.40			
Company B: Catalyst Car A							
95 UL	0.7523	4.43	37.53	41.96			
A	0.7023	0.50	23.80	24.31			
B	0.7171	1.96	23.86	25.82			
C	0.7270	3.50	17.72	21.22			
D	0.7323	3.36	18.63	21.99			
E	0.7521	1.87	42.87	44.74			
F	0.7615	1.74	50.48	52.21			
G	0.7615	4.49	42.79	47.28			
Company C: Catalyst Cars A - F							
1A	0.7495	1.14	42.38	43.52	13.57	42.92	0.00
1B	0.7562	1.08	45.51	46.59	12.55	40.87	0.00
1C	0.7600	1.12	48.87	49.99	9.17	40.83	0.00
1D	0.7603	1.12	47.94	49.06	9.22	41.71	0.00
1S	0.7514	1.11	45.67	46.78	12.72	40.50	0.00
8A	0.7664	0.32	46.15	46.47	0.53	45.11	7.88
8C	0.7474	1.08	45.59	46.67	0.38	45.14	7.81
8D	0.7479	1.10	45.00	46.10	0.33	45.77	7.79
8F	0.7511	1.09	45.08	46.17	0.34	45.54	7.95
7B	0.7176	1.15	26.66	27.81	3.77	62.14	6.27
8B	0.7387	2.74	43.23	45.97	0.08	53.95	0.00

Test Fuel	Density	Fuel Composition, % m/m					
		Benzene	NBA	Total Ar.	Olefins	Par/Naph	MTBE
C1	0.7514	1.11	45.67	46.78	12.72	40.50	0.00
C2	0.7655	1.10	46.41	47.51	12.35	25.58	14.56
C3	0.7297	1.10	24.90	26.00	12.78	46.66	14.57
C4	0.7521	1.03	45.89	46.92	3.69	49.39	0.00
C5	0.7466	1.15	45.46	46.61	11.67	41.73	0.00
C7	0.7225	1.06	25.83	26.89	3.98	54.29	14.83
C8	0.7482	2.87	44.55	47.42	0.06	44.96	7.55
Company C: Catalyst Cars 1 - 6							
D-1	0.7280	2.28	26.15	28.43			7.60
D-2	0.7360	2.47	27.65	30.12			7.66
D-3	0.7400	2.50	26.53	29.03			7.31
D-4	0.7540	2.37	38.93	41.30			7.33
D-5	0.7620	2.46	49.14	51.60			7.33
D-6	0.7670	2.27	51.38	53.65			7.26
D-7	0.7730	2.11	49.56	51.67			6.88
CONCAWE STF-1 T90 Programme: 10 Catalyst Cars							
B140	0.7445	1.25	44.55	45.80	0.30	53.90	0.00
P160	0.7456	1.13	35.67	36.80	0.20	63.00	0.00
P180	0.7451	1.11	37.89	39.00	0.20	60.80	0.00
A160	0.7630	1.04	53.76	54.80	0.30	44.90	0.00
A180	0.7650	1.05	53.25	54.30	0.20	45.50	0.00
O160	0.7510	1.32	40.38	41.70	15.20	43.10	0.00
O180	0.7480	1.08	41.22	42.30	12.20	45.50	0.00
Italian Programme (1989): Catalyst Cars A - C							
B637	0.7712	3.58	42.74	46.32			9.63
B638	0.7647	3.70	46.40	50.10			0.00
B639	0.7553	3.11	40.67	43.78			9.82
B642	0.7512	2.99	40.50	43.49			0.00
B643	0.7499	2.52	36.97	39.49			0.00
B644	0.7350	1.77	26.63	28.40			10.06
B645	0.7381	0.83	27.50	28.33			10.02
Company D: Catalyst Cars A and P							
B658	0.7353	2.40	28.28	30.68			
B652	0.7643	3.32	43.16	46.48			
B660	0.7411	1.18	28.26	29.44			

Test Fuel	Density	Fuel Composition, % m/m					
		Benzene	NBA	Total Ar.	Olefins	Par/Naph	MTBE
Company E: Catalyst Car R							
1-A9212	0.7360	1.20	41.09	42.29			0.00
3-A9213	0.7430	1.37	28.07	29.44			11.66
5-A9216	0.7510	3.80	34.43	38.23			6.51

Test Fuels for Programmes Using Non-Catalyst Cars

Test Fuel	Density	Benzene	NBA	Total Ar.	Olefins	Par/Naph	MTBE
Company A: Non-Catalyst Cars 1 - 3							
A	0.7523	2.90	39.89	42.79			0.00
B	0.7455	1.85	34.07	35.92			4.96
C	0.7445	1.63	32.10	33.73			9.95
D	0.7378	1.46	25.25	26.71			15.04
E	0.7329	1.41	29.34	30.75			0.00
F	0.7362	2.07	30.09	32.16			0.00
G	0.7365	2.04	29.90	31.94			0.00
H	0.7368	1.64	24.11	25.75			15.06
I	0.7403	1.60	25.80	27.40			14.99
J	0.7432	1.75	28.06	29.81			14.95
Company B: Non-Catalyst Car 3							
95 UL	0.7523	4.43	37.33	41.76			
HB/HA	0.7584	3.13	45.57	48.70			
LB/LA	0.7203	2.08	21.32	23.40			
Company B: Non-Catalyst Car B							
95 UL	0.7523	4.43	37.53	41.96			
A	0.7023	0.50	23.80	24.31			
B	0.7171	1.96	23.86	25.82			
C	0.7270	3.50	17.72	21.22			
D	0.7323	3.36	18.63	21.99			
E	0.7521	1.87	42.87	44.74			
F	0.7615	1.74	50.48	52.21			
G	0.7615	4.49	42.79	47.28			

Test Fuel	Density	Fuel Composition, % m/m					
		Benzene	NBA	Total Ar.	Olefins	Par/Naph	MTBE
Company C: Non-Catalyst Cars P - S							
1A	0.7495	1.14	42.38	43.52	13.57	42.92	0.00
1B	0.7562	1.08	45.51	46.59	12.55	40.87	0.00
1C	0.7600	1.12	48.87	49.99	9.17	40.83	0.00
1D	0.7603	1.12	47.94	49.06	9.22	41.71	0.00
1S	0.7514	1.11	45.67	46.78	12.72	40.50	0.00
8A	0.7664	0.32	46.15	46.47	0.53	45.11	7.88
8C	0.7474	1.08	45.59	46.67	0.38	45.14	7.81
8D	0.7479	1.10	45.00	46.10	0.33	45.77	7.79
8F	0.7511	1.09	45.08	46.17	0.34	45.54	7.95
7B	0.7176	1.15	26.66	27.81	3.77	62.14	6.27
8B	0.7387	2.74	43.23	45.97	0.08	53.95	0.00
C1	0.7514	1.11	45.67	46.78	12.72	40.50	0.00
C2	0.7655	1.10	46.41	47.51	12.35	25.58	14.56
C3	0.7297	1.10	24.90	26.00	12.78	46.66	14.57
C4	0.7521	1.03	45.89	46.92	3.69	49.39	0.00
C5	0.7466	1.15	45.46	46.61	11.67	41.73	0.00
C7	0.7225	1.06	25.83	26.89	3.98	54.29	14.83
C8	0.7482	2.87	44.55	47.42	0.06	44.96	7.55
Company C: Non Catalyst Cars 1-6							
D-1	0.7280	2.28	26.15	28.43			7.60
D-2	0.7360	2.47	27.65	30.12			7.66
D-3	0.7400	2.50	26.53	29.03			7.31
D-4	0.7540	2.37	38.93	41.30			7.33
D-5	0.7620	2.46	49.14	51.60			7.33
D-6	0.7670	2.27	51.38	53.65			7.26
D-7	0.7730	2.11	49.56	51.67			6.88
Italian Programme (1989): Catalyst Cars D - F							
B632/2	0.7543	2.77	35.35	38.12			0.00
B635	0.7700	3.88	44.76	48.64			0.00
B636	0.7700	4.39	49.91	54.30			0.00
B637	0.7712	3.58	42.74	46.32			9.63
B638	0.7647	3.70	46.40	50.10			0.00
B639	0.7553	3.11	40.67	43.78			9.82
B640	0.7437	2.20	28.24	30.44			0.00
B641	0.7467	2.34	32.64	34.98			0.00

Test Fuel	Density	Fuel Composition, % m/m					
		Benzene	NBA	Total Ar.	Olefins	Par/Naph	MTBE
B642	0.7512	2.99	40.50	43.49			0.00
B643	0.7499	2.52	36.97	39.49			0.00
B644	0.7350	1.77	26.63	28.40			10.06
B645	0.7381	0.83	27.50	28.33			10.02
Company D: Non-Catalyst Cars B and F							
B658	0.7353	2.40	28.28	30.68			
B652	0.7643	3.32	43.16	46.48			
B660	0.7411	1.18	28.26	29.44			
Company D: Non-Catalyst Car A							
B652	0.7600	3.15	44.89	48.04			
B710	0.7600	1.18	46.86	48.04			
Company E: Non-Catalyst Car 1							
1-A9212	0.7360	1.20	41.09	42.29			0.00
3-A9213	0.7430	1.37	28.07	29.44			11.66
5-A9216	0.7510	3.80	34.43	38.23			6.51

APPENDIX 2

EXHAUST EMISSION AND FUEL CONSUMPTION DATA

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	ECE 1-4	EUDC	ECE+EUDC	ECE 1-4	EUDC	ECE+EUDC	ECE 1-4	EUDC	ECE+EUDC

Catalyst Cars

Company A: Catalyst Car 4

A			3.516			0.093			61.880
B			1.417			0.088			61.630
C			2.188			0.083			61.656
D			1.518			0.087			62.425
E			2.161			0.089			61.263
F			2.322			0.089			60.663
G			2.030			0.089			60.702
H			2.429			0.087			61.250
I			2.269			0.095			61.721
J			1.821			0.084			61.793

Company A: Catalyst Car 5

A			6.295			0.167			60.624
B			4.770			0.163			61.493
C			4.249			0.164			60.453
D			3.201			0.152			60.747
E			3.452			0.163			58.801
F			4.267			0.154			59.894
G			3.274			0.155			59.749
H			3.607			0.147			59.707
I			4.503			0.135			61.304
J			3.385			0.126			61.154

Company A: Catalyst Car 6

A			7.960			0.260			52.827
B			6.050			0.266			52.655
C			5.183			0.243			53.191
D			3.680			0.212			52.594
E			4.036			0.250			51.098
F			4.787			0.253			51.744
G			4.769			0.242			51.341
H			3.970			0.217			51.488
I			4.883			0.210			52.394
J			5.956			0.215			52.723

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**
Company A: Catalyst Car 7									
A			8.855			0.296			73.030
B			9.229			0.293			75.993
C			8.669			0.344			74.852
D			9.271			0.383			75.300
E			9.799			0.334			70.263
F			13.123			0.339			70.988
G			10.989			0.333			71.061
H			6.982			0.338			72.678
I			6.844			0.362			72.598
J			8.877			0.338			73.172
Company B: Catalyst Car 1									
95 UL	50.000								
HB/HA	48.600								
LB/LA	28.000								
Company B: Catalyst Car 2									
95 UL	47.000								
HB/HA	41.000								
LB/LA	21.000								
Company B: Catalyst Car A									
95 UL			19.400						
A			4.900						
B			5.700						
C			9.200						
D			10.700						
E			16.500						
F			16.700						
G			22.300						
Company C: Catalyst Car A									
1A	20.525	1.760	8.670	0.480	0.020	0.190	112.200	63.782	81.696
1B	29.395	4.980	13.970	0.625	0.040	0.260	113.770	63.294	82.199
1C	27.181	9.150	15.790	0.615	0.060	0.270	113.886	64.144	82.764
1D	35.514	11.010	20.040	0.780	0.060	0.330	113.589	61.888	81.200
1S	21.586	4.080	10.530	0.490	0.030	0.200	108.051	61.615	79.047
8C	16.701	2.690	7.850	0.470	0.030	0.190	114.016	63.977	82.662

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	ECE 1-4	EUDC	ECE+EUDC	ECE 1-4	EUDC	ECE+EUDC	ECE 1-4	EUDC	ECE+EUDC
Company C: Catalyst Car A (cont.)									
8D	17.481	2.870	8.250	0.490	0.020	0.190	113.868	62.599	81.820
8F	22.191	3.760	10.550	0.535	0.030	0.220	115.106	63.994	83.072
8B	19.829	2.070	8.610	0.485	0.020	0.190	114.905	63.824	82.808
C1	20.695	2.740	9.350	0.620	0.030	0.250	117.181	62.216	82.804
C2	23.621	4.580	11.590	0.520	0.030	0.210	116.318	64.072	83.746
C3	11.146	1.250	4.890	0.520	0.030	0.210	116.898	63.922	83.624
C7	13.752	1.460	5.980	0.520	0.030	0.210	118.273	68.710	87.278
C8	26.974	3.670	12.250	0.585	0.025	0.235	116.139	65.954	84.734
Company C: Catalyst Car B									
7B	15.227	0.250	5.760	0.645	0.030	0.260	134.765	84.462	103.119
8B	35.376	1.290	13.840	0.745	0.030	0.300	138.506	81.257	102.532
C1	32.540	1.480	12.920	0.690	0.040	0.280	136.905	87.839	106.173
C2	50.633	1.610	19.670	0.953	0.035	0.380	142.861	89.449	109.313
C3	29.488	0.690	11.300	0.843	0.045	0.340	139.373	83.259	104.128
C4	26.441	0.770	10.220	0.785	0.030	0.310	135.228	84.386	103.414
C5	39.067	0.940	14.980	0.823	0.030	0.325	127.034	78.244	96.349
C7	21.508	0.190	8.040	0.735	0.030	0.290	139.009	80.631	102.306
C8	35.111	0.930	13.520	0.660	0.030	0.260	138.829	82.601	103.626
Company C: Catalyst Car C									
C1	36.235	1.920	14.560	0.675	0.060	0.280	136.379	67.776	93.098
C2	30.485	1.550	12.210	0.555	0.050	0.240	144.488	72.876	99.438
C3	20.740	0.880	8.190	0.570	0.050	0.240	138.570	76.108	99.312
C7	17.665	0.870	7.050						
C8	34.390	1.100	13.360	0.615	0.030	0.250	131.421	65.393	89.784
Company C: Catalyst Car D									
1B	34.559	2.710	14.440	0.740	0.060	0.310	104.431	66.016	80.233
1C	39.688	3.510	16.830	0.770	0.080	0.330	104.652	63.688	78.888
1D	44.997	6.310	20.560	0.870	0.120	0.400	103.819	65.690	79.832
1S	38.463	4.850	17.230	0.800	0.100	0.350	106.924	69.054	82.955
8A	24.280	0.540	9.280	0.610	0.020	0.240	114.960	68.976	85.990
8C	27.197	0.630	10.420	0.680	0.030	0.270	104.412	64.575	79.449
8D	27.338	0.340	10.280	0.690	0.020	0.270	115.476	66.114	84.438
8F	28.326	2.240	11.850	0.670	0.040	0.270	106.168	66.097	80.969
7B	21.970	0.390	8.340	0.685	0.020	0.270	101.827	64.010	78.290
8B	42.350	0.750	16.070	0.805	0.030	0.320	105.893	64.710	80.075

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**

Company C: Catalyst Car D (cont.)

C1	39.764	2.540	16.250	0.785	0.057	0.327	107.475	66.349	81.702
C2	36.620	1.800	14.630	0.700	0.050	0.290	114.481	72.187	87.956
C4	33.475	1.810	13.480	0.755	0.050	0.310	107.701	61.296	78.519
C5	30.223	1.550	12.110	0.755	0.050	0.310	106.950	61.818	78.542
C7	20.955	0.240	7.870	0.655	0.020	0.260	107.472	67.120	82.076
C8	37.795	0.670	14.350	0.705	0.030	0.280	107.816	65.916	81.479

Company C: Catalyst Car F

7B	10.840	2.330	5.470	0.330	0.050	0.150	78.470	47.075	58.700
8B	29.770	2.770	12.710	0.450	0.040	0.190	78.561	47.203	58.874
C1	44.540	7.790	21.320	0.690	0.080	0.300	77.807	47.864	58.835
C2	21.070	5.020	10.930	0.365	0.050	0.170	75.325	46.160	56.953
C3	18.480	2.540	8.410	0.480	0.050	0.210	78.917	48.160	59.544
C4	26.450	4.320	12.470	0.520	0.070	0.240	78.143	46.630	58.363
C5	26.300	5.790	13.350	0.430	0.060	0.200	75.108	45.543	56.518
C7	11.020	2.310	5.520	0.320	0.040	0.140	81.823	50.142	61.918

Company C: Catalyst Car 1

D-1	18.190	11.550	13.990	0.396	0.132	0.228			58.080
D-2	16.985	25.050	22.100	0.385	0.178	0.255			60.205
D-3	15.860	19.570	18.200	0.387	0.152	0.238			60.850
D-4	24.660	27.810	26.680	0.420	0.169	0.262			63.034
D-5	21.370	27.250	25.100	0.375	0.144	0.230			58.240
D-6	24.420	35.795	31.600	0.386	0.179	0.255			62.936
D-7	36.845	26.800	30.510	0.474	0.160	0.275			63.162

Company C: Catalyst Car 2

D-1	8.150	0.910	3.570	0.201	0.018	0.085			50.516
D-2	9.055	0.580	3.700	0.224	0.013	0.090			49.430
D-3	9.240	0.430	3.660	0.231	0.010	0.090			50.831
D-4	9.670	0.480	3.860	0.253	0.015	0.102			50.887
D-5	12.225	0.000	4.490	0.209	0.012	0.084			49.233
D-7	14.425	1.230	6.070	0.259	0.014	0.103			50.979

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**

Company C: Catalyst Car 3

D-1	13.795	0.430	5.340	0.349	0.020	0.142			71.395
D-2	14.855	0.000	5.460	0.389	0.019	0.155			69.449
D-3	19.140	0.800	7.540	0.395	0.020	0.158			71.358
D-4	23.600	1.770	9.810	0.404	0.033	0.169			72.610
D-5	23.160	3.670	10.850	0.403	0.047	0.177			69.959
D-6	28.820	2.530	12.190	0.426	0.036	0.179			73.908
D-7	29.685	3.460	13.080	0.540	0.050	0.229			73.922

Company C: Catalyst Car 4

D-1	30.550	0.900	11.840	0.713	0.019	0.274			78.085
D-2	38.120	1.500	14.970	0.769	0.019	0.294			80.518
D-3	33.355	1.650	13.310	0.795	0.031	0.310			78.928
D-4	45.888	2.760	18.650	0.788	0.040	0.314			81.594
D-5	61.345	2.420	24.080	0.782	0.027	0.304			77.000
D-6	49.033	2.720	19.800	0.858	0.033	0.337			81.942
D-7	56.790	4.190	23.620	0.842	0.041	0.337			82.525

Company C: Catalyst Car 5

D-1	21.845	1.560	9.010	0.601	0.017	0.231			80.415
D-2	28.245	2.650	12.070	0.716	0.022	0.277			83.830
D-3	33.120	3.320	14.290	0.720	0.033	0.286			82.488
D-4	34.500	4.560	15.570	0.693	0.026	0.270			85.504
D-5	43.820	5.700	19.800	0.675	0.023	0.265			80.178
D-6	36.160	5.895	17.050	0.719	0.024	0.280			85.965
D-7	56.895	19.540	33.330	0.925	0.055	0.376			87.140

Company C: Catalyst Car 6

D-1	16.960	4.260	8.950	0.381	0.068	0.183			83.771
D-2	28.675	6.890	14.900	0.466	0.070	0.215			81.932
D-3	23.390	17.530	21.460	0.430	0.059	0.196			83.960
D-4	29.540	8.780	16.460	0.458	0.075	0.217			84.689
D-5	4.305	13.290	9.980	0.469	0.066	0.214			81.420
D-6	37.145	11.430	20.930	0.493	0.077	0.230			86.410
D-7	33.425	9.240	18.120	0.513	0.061	0.227			85.942

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**

CONCAWE STF-1 (T90): Catalyst Car 2

B140	12.348	2.000	4.871	0.323	0.015	0.129	79.077	46.070	58.324
P160	8.348	2.600	3.293	0.288	0.015	0.116	81.412	47.264	59.872
P180	11.006	2.400	4.342	0.327	0.019	0.134	79.245	45.839	58.244
A160	9.879	0.000	3.897	0.349	0.016	0.140	80.321	46.909	59.293
A180	12.295	2.900	4.850	0.326	0.020	0.134	81.258	46.910	59.678
O160	16.697	1.700	6.587	0.400	0.016	0.157	79.805	46.442	58.758
O180	11.892	1.100	4.691	0.331	0.018	0.134	78.723	45.912	58.105

CONCAWE STF-1 (T90): Catalyst Car 9

B140	16.455	2.900	6.491	0.435	0.049	0.192	97.794	58.905	73.311
P160	18.308	2.800	7.222	0.493	0.045	0.211	99.817	60.207	74.910
P180	16.482	2.400	6.502	0.518	0.049	0.223	97.213	58.699	72.960
A160	22.925	5.700	9.043	0.512	0.041	0.216	97.859	59.361	73.614
A180	24.589	6.300	9.700	0.585	0.059	0.254	99.741	59.907	74.649
O160	17.449	5.200	6.883	0.475	0.037	0.199	98.531	59.134	73.733

CONCAWE STF-1 (T90): Catalyst Car 5

B140	21.207	2.200	8.366	0.529	0.034	0.218	100.277	55.629	72.187
P160	25.582	3.200	10.092	0.622	0.041	0.257	101.223	56.330	72.987
P180	22.012	2.100	8.683	0.559	0.030	0.226	99.177	55.249	71.545
A160	23.354	3.600	9.213	0.548	0.037	0.227	101.563	56.233	73.042
A180	27.622	6.700	10.897	0.613	0.049	0.258	102.877	56.220	73.524
O160	24.160	2.500	9.531	0.552	0.036	0.228	100.596	55.904	72.479
O180	23.837	3.600	9.403	0.524	0.031	0.214	96.615	54.200	69.960

CONCAWE STF-1 (T90): Catalyst Car 1

B140	35.971	2.000	14.190	0.983	0.012	0.372	91.231	50.194	65.419
P160	38.655	1.000	15.249	1.112	0.012	0.417	95.165	51.290	67.477
P180	32.750	3.800	12.919	1.070	0.015	0.406	91.275	50.026	65.345
A160	38.118	2.200	15.037	1.139	0.012	0.429	94.231	51.037	67.030
A180	34.521	1.200	13.618	1.042	0.013	0.395	95.174	51.507	67.718
O160	34.629	1.100	13.660	1.053	0.012	0.397	93.691	50.895	66.734
O180	34.038	0.800	13.427	1.004	0.013	0.381	91.409	49.914	65.285

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**
CONCAWE STF-1 (T90): Catalyst Car 10									
B140	21.985	2.862	8.673	0.628	0.017	0.251	62.787	36.488	46.524
P160	17.663	2.300	6.968	0.667	0.021	0.268	64.465	37.287	47.651
P180	29.528	3.845	11.648	0.704	0.024	0.283	63.170	36.875	46.889
A160	20.777	2.705	8.196	0.682	0.027	0.277	65.118	37.601	48.107
A180	20.670	2.691	8.154	0.702	0.030	0.287	64.673	37.531	47.881
O160	18.737	2.440	7.391	0.707	0.022	0.284	64.597	37.265	47.696
O180	16.375	2.132	6.460	0.664	0.023	0.267	63.580	36.555	46.847
CONCAWE STF-1 (T90): Catalyst Car 6									
B140	6.979	0.909	2.753	0.206	0.005	0.081	57.181	39.116	45.980
P160	6.979	0.909	2.753	0.238	0.006	0.094	58.000	39.159	46.309
P180	7.409	0.965	2.923	0.218	0.006	0.086	57.190	39.185	46.025
A160	8.483	1.104	3.346	0.254	0.007	0.101	58.755	39.821	47.016
A180	7.248	0.944	2.859	0.243	0.009	0.098	58.174	39.696	46.726
O160	5.852	0.762	2.309	0.225	0.007	0.090	57.756	39.225	46.277
O180	7.892	1.028	3.113	0.206	0.006	0.082	57.233	38.851	45.837
CONCAWE STF-1 (T90): Catalyst Car 3									
B140	20.885	2.719	8.239	0.512	0.037	0.213	71.666	40.129	51.780
P160	15.194	1.978	5.994	0.497	0.033	0.205	72.185	41.008	52.520
P180	13.690	1.782	5.401	0.501	0.034	0.207	71.671	40.265	51.866
A160	25.717	3.348	10.145	0.555	0.038	0.229	73.748	41.103	53.166
A180	18.737	2.440	7.391	0.513	0.044	0.218	73.933	41.440	53.458
O160	12.939	1.685	5.104	0.480	0.034	0.198	72.607	41.012	52.698
O180	13.798	1.796	5.443	0.464	0.033	0.192	72.085	40.362	52.083
CONCAWE STF-1 (T90): Catalyst Car 7									
B140	22.495	2.929	8.874	0.515	0.051	0.223	69.138	40.434	51.021
P160	15.516	2.020	6.121	0.462	0.043	0.197	71.033	41.358	52.304
P180	16.643	2.167	6.565	0.483	0.047	0.208	68.423	40.682	50.920
A160	26.951	3.509	10.632	0.494	0.049	0.213	70.207	40.798	51.647
A180	19.113	2.488	7.540	0.485	0.065	0.220	69.772	41.914	52.196
O160	16.375	2.132	6.460	0.494	0.044	0.211	69.471	41.110	51.571
O180	17.073	2.223	6.735	0.467	0.041	0.198	68.801	40.242	50.789

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	ECE 1-4	EUDC	ECE+EUDC	ECE 1-4	EUDC	ECE+EUDC	ECE 1-4	EUDC	ECE+EUDC

CONCAWE STF-1 (T90): Catalyst Car 4

B140	19.381	2.523	7.646	0.518	0.015	0.200	79.989	49.226	60.580
P160	21.529	2.803	8.493	0.723	0.023	0.282	81.192	49.560	61.251
P180	25.609	3.334	10.102	0.734	0.025	0.292	81.916	50.220	61.933
A160	23.730	3.090	9.361	0.653	0.020	0.254	82.145	50.373	62.108
A180	22.952	2.988	9.054	0.676	0.023	0.264	81.438	50.482	61.911
O160	21.958	2.859	8.662	0.681	0.023	0.265	80.124	49.115	60.561
O180	21.475	2.796	8.472	0.572	0.016	0.221	80.204	49.727	60.977

CONCAWE STF-1 (T90): Catalyst Car 8

B140	21.851	2.845	8.620	0.743	0.016	0.293	64.448	40.397	49.554
P160	19.542	2.544	7.709	0.746	0.020	0.297	65.788	40.188	49.940
P180	22.119	2.880	8.726	0.766	0.021	0.306	64.831	40.407	49.721
A160	21.529	2.803	8.493	0.846	0.025	0.338	65.847	40.813	50.350
A180	23.301	3.034	9.192	0.806	0.028	0.325	66.218	41.027	50.620
O160	21.099	2.747	8.323	0.744	0.020	0.296	64.954	40.261	49.664
O180	20.348	2.649	8.027	0.710	0.019	0.282	65.031	40.198	49.637

Italian Programme : Catalyst Car A at 3,000km

B637			9.600			0.140			
B638			8.600			0.170			
B639			4.000			0.130			
B642			6.900			0.150			
B643			5.400			0.170			
B644			5.600			0.140			
B645			3.700			0.160			

Italian Programme : Catalyst Car A at 40,000km

B637			12.600			0.147			
B638			4.800			0.157			
B639			11.900			0.150			
B642			10.100			0.116			
B643			10.200			0.129			
B644			8.400			0.109			
B645			7.700			0.133			

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**

Italian Programme : Catalyst Car A 80,000km

B637			15.800			0.240			
B638			15.800			0.260			
B639			14.800			0.260			
B642			15.800			0.280			
B643			12.000			0.240			
B644			8.600			0.220			
B645			6.800			0.220			

Italian Programme : Catalyst Car B at 3,000km

B637			12.400			0.182			
B638			12.400			0.177			
B639			8.600			0.222			
B642			10.900			0.196			
B643			10.100			0.215			
B644			7.400			0.199			
B645			8.000			0.226			

Italian Programme : Catalyst Car B at 40,000km

B637			13.830			0.154			
B638			15.770			0.101			
B639			9.700			0.150			
B642			16.970			0.213			
B643			12.830			0.147			
B644			9.370			0.196			
B645			7.200			0.186			

Italian Programme : Catalyst Car C at 3,000km

B637			11.900			0.260			
B638			12.300			0.290			
B639			11.300			0.310			
B642			9.500			0.290			
B643			12.900			0.260			
B644			6.500			0.270			
B645			6.900			0.280			

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**
Italian Programme : Catalyst Car C at 40,000km									
B637			11.700			0.200			
B638			15.300			0.200			
B639			11.670			0.210			
B642			11.930			0.210			
B643			11.230			0.230			
B644			5.940			0.240			
B645			9.110			0.230			
Italian Programme : Catalyst Car C at 80,000 km									
B637			19.107			0.104			
B638			19.096			0.194			
B639			20.360			0.156			
B642			15.898			0.088			
B643			17.893			0.229			
B644			9.913			0.130			
B645			6.650			0.237			
Company D: Catalyst Car P									
B658	23.000	4.000	11.000						
B652	40.000	11.000	21.000						
B660	17.000	4.300	9.000						
Company D: Catalyst Car A									
B658	25.000	11.000	16.000						
B652	28.000	20.000	23.000						
B652	31.000	3.700	14.000						
B710	24.000	3.300	11.000						
Company E: Average for Catalyst Car R									
1-A9212			9.994			0.220	95.114	57.709	71.479
3-A9213			8.177			0.190	97.927	59.626	73.726
5-A9216			16.656			0.219	97.518	58.982	73.169

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	ECE 1-4	EUDC	ECE+EUDC	ECE 1-4	EUDC	ECE+EUDC	ECE 1-4	EUDC	ECE+EUDC

Non-Catalyst Cars

Company A: Non-Catalyst Car 1

A			80.805			1.480			66.281
B			68.723			1.503			66.137
C			53.537			1.478			65.032
D			53.112			1.338			64.373
E			54.010			1.461			64.854
F			59.010			1.396			65.003
G			58.150			1.404			65.261
H			51.390			1.315			64.345
I			52.595			1.285			65.241
J			45.046			1.240			64.487

Company A: Non-Catalyst Car 2

A			96.387			1.582			87.854
B			70.640			1.520			87.544
C			65.580			1.420			88.324
D			53.048			1.286			86.415
E			67.873			1.472			85.533
F			68.119			1.303			86.610
G			76.728			1.365			86.881
H			62.209			1.352			85.627
I			55.539			1.261			86.968
J			57.892			1.265			86.308

Company A: Non-Catalyst Car 3

A			69.790			1.812			47.113
B			53.390			1.773			46.653
C			51.180			1.579			45.969
D			43.735			1.537			46.208
E			49.366			1.585			45.279
F			54.689			1.559			45.806
G			56.278			1.541			45.799
H			49.577			1.477			45.648
I			45.456			1.434			45.411
J			44.270			1.413			45.748

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**
Company B: Non-Catalyst Car 3									
95 UL	127.000								
HB/HA	99.000								
LB/LA	58.000								
Company B: Non-Catalyst Car B									
95 UL			109.000						
A			46.900						
B			50.000						
C			60.500						
D			67.100						
E			104.500						
F			91.600						
G			116.000						
Company C: Non-Catalyst Car P									
7B	75.000	42.000	54.000	2.482	1.198	1.671	63.723	49.730	54.968
8B	119.000	65.000	85.000	2.493	1.148	1.643	63.750	49.345	54.664
C1	84.500	47.000	61.000	2.423	1.048	1.554	60.976	49.893	54.026
C2	98.000	57.000	72.000	2.678	1.238	1.768	61.355	51.595	55.193
C3	70.500	40.000	51.000	2.408	1.198	1.643	58.960	50.203	53.414
C4	74.000	43.000	55.000	2.363	1.068	1.545	60.770	49.864	53.926
C5	93.000	48.000	65.000	2.338	1.039	1.517	60.960	49.201	53.531
C7	76.500	43.000	55.000	2.718	1.347	1.852	60.257	51.081	54.477
C8	113.500	63.000	82.000	2.433	1.169	1.634	58.996	49.531	53.047
Company C: Non-Catalyst Car Q									
7B	55.000	22.000	34.000	1.533	0.548	0.910	87.081	51.308	64.512
8B	107.500	41.000	65.000	1.758	0.618	1.038	89.974	50.010	64.784
C1	82.000	34.000	52.000	1.748	0.638	1.046	86.937	49.893	63.644
C2	83.500	34.000	52.000	1.618	0.588	0.967	92.855	52.666	67.517
C3	56.000	24.000	36.000	1.668	0.608	0.998	91.687	51.736	66.476
C5	92.500	38.000	58.000	1.748	0.620	1.035	88.397	49.126	63.760
C7	47.500	20.000	30.000	1.508	0.568	0.914	90.963	53.393	67.265
C8	104.000	43.000	66.000	1.697	0.638	1.028	88.699	50.578	64.719

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	ECE 1-4	EUDC	ECE+EUDC	ECE 1-4	EUDC	ECE+EUDC	ECE 1-4	EUDC	ECE+EUDC

Company C: Non-Catalyst Car R

1A	101.000	53.000	71.000	2.348	0.988	1.488	74.725	56.063	63.033
1B	84.000	43.000	58.000	2.493	1.108	1.618	73.654	55.203	62.084
1C	107.500	56.000	75.000	2.607	1.028	1.609	74.366	54.948	62.168
1D	85.000	43.000	59.000	2.378	0.978	1.493	72.875	53.981	60.976
8A	78.000	32.000	49.000	2.108	0.821	1.294	74.379	53.035	60.929
8C	124.000	54.000	79.000	3.960	1.228	2.234	77.356	55.233	63.529
8D	86.000	46.000	61.000	2.692	1.138	1.710	72.845	52.129	59.907
8F	69.500	34.000	47.000	2.237	0.850	1.361	74.885	55.056	62.416
7B	67.500	31.000	44.000	2.287	0.908	1.416	76.424	51.739	60.924
C1	103.000	52.000	70.000	2.608	1.088	1.648	75.779	49.968	59.511
C2	100.000	49.000	68.000	2.547	1.008	1.575	76.933	50.676	60.398
C3	68.000	31.000	45.000	2.192	0.898	1.375	77.275	52.028	61.441
C4	70.500	48.000	56.000	2.691	1.128	1.703	78.294	52.948	62.424
C5	95.000	43.000	62.000	2.328	0.928	1.443	77.086	52.859	61.818
C7	65.000	32.000	44.000	2.172	0.928	1.386	77.271	52.237	61.557
C8	115.500	55.000	77.000	2.242	0.908	1.399	74.708	53.197	61.203

Company C: Non-Catalyst Car S

1A	104.000	39.000	63.000	2.003	0.570	1.098	82.820	54.714	65.132
1B	84.000	35.000	53.000	2.137	0.748	1.259	83.031	52.405	63.748
1D	85.500	37.000	55.000	2.073	0.718	1.217	83.291	51.776	63.409
1S	90.000	36.000	56.000	1.998	0.719	1.190	82.015	49.893	61.840
8A	66.500	31.000	44.000	1.743	0.631	1.040	81.737	51.272	62.615
8C	91.000	36.000	56.000	2.010	0.683	1.171	83.223	53.140	64.351
8D	97.000	33.000	57.000	1.972	0.558	1.078	84.475	53.400	64.993
8F	67.000	26.000	41.000	1.718	0.491	0.942	89.681	54.004	67.223
7B	68.500	25.000	41.000	1.818	0.630	1.067	89.305	52.026	65.947
8B	121.000	40.000	70.000	2.058	0.640	1.162	89.826	49.419	64.415
C1	96.000	51.000	68.000	2.126	0.986	1.405	81.038	48.766	60.713
C3	85.500	37.000	55.000	2.093	0.758	1.249	85.922	54.144	65.965
C4	91.000	37.000	57.000	2.082	0.698	1.208	88.221	50.391	64.530
C5	102.000	35.000	60.000	2.032	0.668	1.170	85.560	49.948	63.237
C7	60.000	43.000	49.000	1.633	1.076	1.281	84.496	51.731	63.941
C8	115.500	45.000	71.000	1.905	0.674	1.127	87.914	51.775	65.168

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**

Company C: Non-Catalyst Car 1

D-1	101.985	40.280	65.640	2.439	0.959	1.497			64.282
D-2	92.195	32.650	54.580	2.201	0.730	1.270			61.971
D-3	110.285	38.130	64.650	2.415	0.834	1.412			64.913
D-4	124.520	41.770	72.200	2.250	0.745	1.294			65.824
D-5	123.980	42.960	72.740	2.075	0.720	1.213			60.876
D-6	120.228	48.290	74.765	2.324	0.898	1.416			65.950
D-7	116.900	45.590	71.800	2.359	0.955	1.466			64.847

Company C: Non-Catalyst Car 2

D-1	104.905	47.040	68.310	2.714	1.117	1.703			62.273
D-2	149.940	66.960	97.490	3.306	1.217	1.988			62.854
D-3	126.960	55.080	81.570	3.248	1.272	2.001			64.447
D-4	150.475	69.010	99.060	2.992	1.201	1.862			65.900
D-5	142.800	77.310	101.430	2.774	1.108	1.720			61.417
D-6	166.785	76.480	109.715	2.941	1.201	1.843			65.858
D-7	146.975	64.610	94.920	3.252	1.048	1.224			65.079

Company C: Non-Catalyst Car 3

D-1	57.095	35.290	43.330	2.523	0.994	1.550			47.400
D-2	100.603	44.580	65.150	2.754	1.077	1.686			47.917
D-3	89.390	31.220	52.590	2.624	0.964	1.570			48.233
D-4	100.525	50.540	68.880	2.910	1.202	1.825			51.777
D-5	93.875	55.360	69.470	2.637	1.089	1.652			47.617
D-6	130.390	57.580	84.250	3.221	1.259	1.968			51.496
D-7	119.835	52.430	77.110	3.468	1.169	2.000			51.582

Company C: Non-Catalyst Car 4

D-1	73.763	27.515	44.545	2.110	0.677	1.203			66.710
D-2	73.715	27.820	44.720	1.872	0.561	1.043			67.197
D-3	83.200	28.540	48.660	2.070	0.643	1.168			68.872
D-4	84.505	31.850	51.210	1.815	0.549	1.014			71.178
D-5	89.095	33.380	53.880	1.777	0.605	1.034			64.983
D-6	95.230	35.495	57.485	1.870	0.564	1.044			71.530
D-7	80.390	32.470	50.070	1.999	0.581	1.101			69.817

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**

Company C: Non-Catalyst Car 5

D-1	82.665	52.130	63.340	1.866	1.384	1.557			74.336
D-2	93.863	57.835	71.080	1.993	1.388	1.605			74.667
D-3	87.980	64.320	72.990	1.965	1.376	1.587			77.308
D-4	108.985	72.310	85.780	2.145	1.526	1.750			76.674
D-5	97.965	52.180	69.000	1.705	1.310	1.450			72.565
D-6	121.260	79.970	95.140	2.060	1.444	1.663			78.065
D-7	116.405	72.840	88.810	2.177	1.375	1.663			79.449

Company C: Non-Catalyst Car 6

D-1	87.810	37.240	55.820	2.275	0.965	1.440			56.806
D-2	107.443	46.470	68.865	2.663	1.062	1.643			56.988
D-3	101.400	41.720	63.630	2.590	1.007	1.583			58.519
D-4	109.950	46.780	69.990	2.589	1.095	1.639			58.571
D-5	123.320	50.020	76.940	2.351	0.984	1.480			55.641
D-6	112.555	46.230	70.620	2.653	1.067	1.645			59.151
D-7	107.950	51.220	71.970	2.898	1.057	1.724			59.335

Italian Programme : Non-Catalyst Car D at 3,000km

B632/2			75.400			1.440			
B635			82.200			1.650			
B636			95.200			1.500			
B637			59.900			1.520			
B638			79.300			1.380			
B639			70.900			1.440			
B640			60.900			1.410			
B641			62.800			1.500			
B642			80.700			1.450			
B643			68.500			1.560			
B644			44.900			1.500			
B645			33.900			1.420			

Italian Programme : Non-Catalyst Car D at 40,000km

B632/2			72.200			1.560			
B635			96.900			1.720			
B636			100.300			1.700			
B637			74.800			1.550			
B638			87.200			1.640			
B639			76.400			1.530			

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	ECE 1-4	EUDC	ECE+EUDC	ECE 1-4	EUDC	ECE+EUDC	ECE 1-4	EUDC	ECE+EUDC

Italian Programme : Non-Catalyst Car D at 40,000km (cont.)

B640			62.900			1.530			
B641			63.500			1.560			
B642			79.700			1.600			
B643			74.100			1.550			
B644			56.100			1.490			
B645			39.400			1.460			

Italian Programme : Non-Catalyst Car E at 3,000km

B632/2			76.500			1.470			
B635			88.600			1.570			
B636			93.600			1.500			
B637			62.000			1.410			
B638			73.800			1.450			
B639			56.100			1.320			
B640			52.900			1.420			
B641			64.100			1.410			
B642			61.400			1.370			
B643			55.400			1.350			
B644			40.300			1.290			
B645			30.400			1.280			

Italian Programme : Non-Catalyst Car E at 40,000km

B632/2			82.000			1.600			
B635			91.500			1.650			
B636			109.000			1.610			
B637			88.500			1.530			
B638			79.200			1.530			
B639			76.300			1.510			
B640			64.800			1.610			
B641			69.700			1.430			
B642			83.300			1.680			
B643			72.900			1.550			
B644			53.600			1.450			
B645			40.800			1.510			

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**

Italian Programme : Non-Catalyst Car F at 3,000km

B632/2			71.600			1.220			
B635			61.500			1.160			
B636			89.000			1.030			
B637			88.600			1.140			
B638			85.800			1.250			
B639			70.500			1.120			
B640			60.800			1.210			
B641			58.200			1.030			
B642			77.600			1.020			
B643			77.800			1.160			
B644			51.600			1.130			
B645			40.200			1.120			

Italian Programme : Non-Catalyst Car F at 40,000km

B632/2			90.767			1.214			
B635			116.200			1.458			
B636			157.430			1.393			
B637			89.939			1.319			
B638			113.040			2.016			
B639			74.093			1.476			
B640			57.309			1.028			
B641			76.553			1.193			
B642			66.707			1.180			
B643			87.676			1.343			
B644			88.050			1.267			
B645			50.299			1.003			

Company D: Non-Catalyst Car F

B658	102.000	45.000	66.000						
B652	116.000	55.000	77.000						
B660	80.000	32.000	49.000						

Company D: Non-Catalyst Car B

B658	132.000	59.000	85.000						
B652	150.000	76.000	103.000						
B660	120.000	50.000	75.000						

	Benzene Exhaust Emissions (mg/km)			HC Exhaust Emissions (g/km)			Fuel Consumption (g/km)		
Test Fuel	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**	**ECE 1-4**	**EUDC**	**ECE+EUDC**

Company E: Average for Non-Catalyst Car 1

1-A9212			67.684			1.365	71.570	39.856	51.531
3-A9213			53.602			1.223	71.948	39.444	51.410
5-A9216			115.684			1.330	70.599	39.817	51.066

APPENDIX 3

STATISTICAL ANALYSIS:

MODELS FOR DATA WITH CONSTANT COEFFICIENT OF VARIATION

Appendix 3 Models for data with constant coefficient of variation

In several recent studies (CONCAWE, EPEFE, US AQIRP), measurements of emissions have been made across a range of fuels and vehicles. In most of these studies, the variability of the emission measurements has been found to increase as the actual level of emissions increases. Typically, the standard deviation has been found to be proportional to the mean. This non-homogeneity of variance means that conventional least-squares regression methods cannot be used to model the data. Least-squares regression assumes that the errors in each observations are independently and identically distributed as normal with mean zero and constant variance σ^2. Most emissions data do not have constant variance but coefficient of variation (C.V. = S.D./mean).

The simplest way of overcoming this problem is to assume that the emission measurements Y_i have the lognormal distribution. Thus we assume that $X_i = \log_e(Y_i)$ has the normal distribution with mean μ_i, which varies from car to car and fuel to fuel, and constant variance σ^2. Y_i then has mean:

$$\exp\left(\mu_i + \sigma^2/2\right)$$

and variance:

$$\exp\left(2\mu_i + \sigma^2\right)(\exp(\sigma^2) - 1)$$

Thus the standard deviation of Y_i is:

$$\exp\left(\mu_i + \sigma^2/2\right)\sqrt{\exp(\sigma^2) - 1}$$

and the coefficient of variation is:

$$\sqrt{\exp(\sigma^2) - 1}\,.$$

The coefficient of variation is thus constant for all data points Y_i as it depends only on σ^2, the variance of $\log(Y_i)$, which is constant.

It is very simple to fit models to lognormal data. We simply take logarithms, i.e. calculate:

$$X_i = \log\left(Y_i\right)$$

and then fit ordinary least squares models to the X_is, e.g.

$$X_i = a + b.F_i + c.C_i + \ldots$$

This gives an exponential model in Y_i, i.e.

$$Y_i = \exp(a + b.F_i + c.C_i + \ldots).$$

This works well in some cases, but in others, an exponential model will not provide a satisfactory fit and a linear model is required in the original units of Y, e.g.

$$Y_i = a + b.F_i + c.C_i + \ldots \quad \text{... (1)}$$

Such a model can be fitted by assuming the Y_is to have the gamma distribution. The gamma distribution has two parameters κ and θ and probability density function (p.d.f.)

$$f(y) = \frac{y^{\kappa-1}\exp(-y/\theta)}{\theta^{\kappa}\Gamma(\kappa)}$$

where $\Gamma(\kappa)$ is the gamma function. The mean of the gamma distribution is $\kappa\theta$ and the variance is $\kappa\theta^2$. Thus the standard deviation is $\sqrt{\kappa\theta}$ and the coefficient of variation is $1/\sqrt{\kappa}$.

Figure 1 shows the gamma p.d.f. for four pairs of values of κ and θ, the mean $\kappa\theta$ being equal to 1 in all cases. When $\kappa = 1$, we have the exponential distribution. The parameter κ will typically exceed 1 for emission measurements. When the Y_is have the gamma distribution, models such as (1) above can be fitted using the generalized linear modelling routines in statistical packages such as GENSTAT or GLIM, specifying a "gamma" error distribution and an "identity" link function. In generalized linear modelling, the fitted value η_i under model (1) corresponding to each data point Y_i is

$$\eta_i = \hat{a} + \hat{b}.F_i + \hat{c}.C_i + \ldots$$

where the parameters $\hat{a}$, $\hat{b}$ and $\hat{c}$ are the values which minimise the "deviance"

$$\text{deviance} = 2\sum_i \left[\frac{y_i - \eta_i}{\eta_i} - \log\left(\frac{y_i}{\eta_i}\right) \right]$$

For each data point *i*, the fitted value η_i is an estimate of the product of gamma-distribution parameters $\kappa\theta_i$. The mean deviance, i.e. the deviance divided by the number of degrees of freedom, provides an estimate of the "dispersion parameter" $\phi = 1/\kappa$. The parameter κ and thus the coefficient of variation $1/\sqrt{\kappa}$ are constant while the parameter $\theta_i = \eta_i/\kappa$ varies from point to point under the model. The variance of Y_i is $\phi\eta_i^2$ and the standard deviation $\sqrt{\phi}\eta_i$.

Figure 2 illustrates the above process for a simple linear model. The observations Y_i at the various values of X_i are assumed to have gamma distributions with the same shape parameter κ. However, the mean and standard deviation of these distributions increase in step with one another as the value of *X* increases.

The scatter in the observed data increases as X and Y get larger and this increases the chances of generating measurements which deviate quite substantially from the values expected under our model. These measurements would have a large influence on the residual sum of squares were conventional least-squares to be used and thus would have a disproportionately large influence on the fitted model. However, such points have much less influence on the gamma deviance and so have less leverage on the fitted model when this error distribution is assumed.

The lognormal and gamma distributions perform very similarly in most practical regression problems. The choice thus depends on whether an exponential or a linear/polynomial model is required. Difficulties can arise, however, if observed or fitted values go negative. These problems will not be discussed here.

Figure 1 Probability density function for the gamma distribution

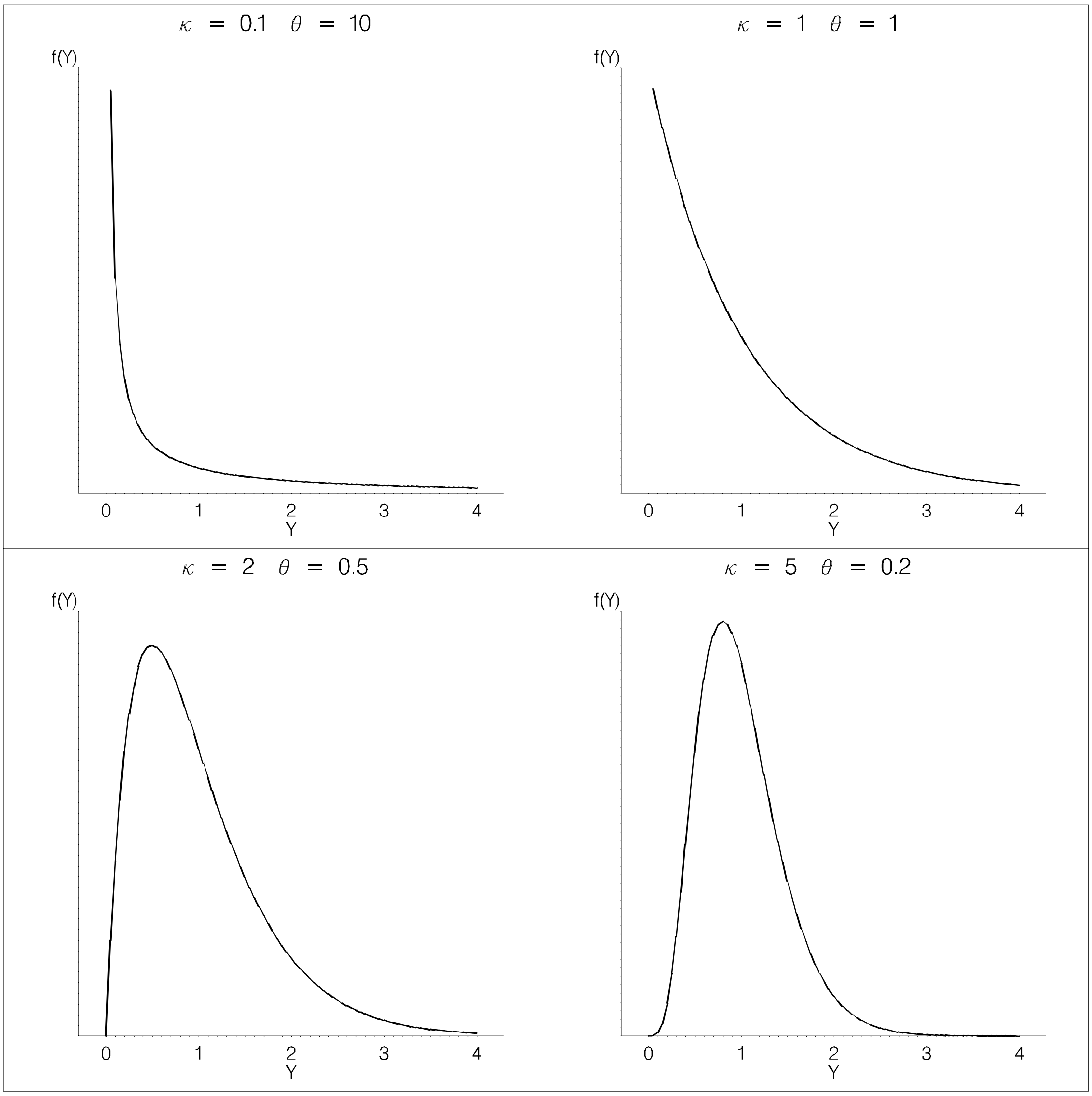


Figure 2. Linear regression for data with gamma errors.