Independent Reassessment of EPEFE Equations in Respect of NO_X Emissions

Draft

Final Report

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Contents

1 Purpose of the contract

According to the TOR's the purpose of the study is to review within a time frame of five months the EPEFE prediction equations with regard to NO_X emissions particularly as they relate to gasoline aromatics content. The following steps have to be performed:

- identifying technical problems resp. gaps which need to be reviewed and/or substantiated,
- analysing of all data supplied and modifying data where necessary in the light of the state of the art.

2 Activities during the initial period

Based on Annex 05 of the EPEFE report the regression analysis for NO_X as a function of gasoline aromatics and E100 was derived. Basis of data processing was the data set LDGAS.XLS available on CD-ROM added to the EPEFE report. Minor differences in the results could be explained by slightly different pre-processing of the data set. The statistical group of EPEFE decided that tables of means would be generated by treating the data as if they were balanced whereas TÜV took each measuring result with the same weight. Despite of the smaller differences in the pre-processing procedure the trends of the NO_X prediction equation could be proved. More complicated forms of equations do not improve the correlation coefficient, so that the selected EPEFE model can be accepted.

A first meeting with the Commission was arranged in Brussels on 18.2.99. TÜV stated that the statistical procedure to derive the NO_X prediction equation of gasoline vehicles applied in EPEFE is acceptable and cannot be improved. The Commission informed about the main objective of the study and the controversial discussions between ACEA and CONCAWE.

In agreement with the Commission two separate meetings were arranged with CONCAWE (2.3.99) and ACEA (3.3.99) in Cologne in order to identify the different standpoints and gaps. The minutes of these meetings have been enclosed as annex 1.

All information provided by the Commission, CONCAWE, and ACEA has been compiled in Annex 2.

3 Main topics of the meetings with CONCAWE and ACEA

3.1 Gasoline

There is a common understanding between CONCAWE and ACEA with regard to the effect of NO_X/aromatics. It is in principle agreed that NO_X emission response can go in either direction depending on the base calibration of the engine. Whereas CONCAWE believe that the overall result of the EPEFE vehicle fleet reflects a real picture of the current three-way catalyst fleet, ACEA think that the results of the EPEFE fleet are biased due to the fact that all the fuels of the EPEFE matrix were blended to contain 10 % v/v MTBE in contrary to the reference fuel without MTBE according to EU regulation 94/12/EC, which was the basis for engine calibration of the EPEFE fleet. With other words ACEA argue that the superposition of a lean shift caused by MTBE and low aromatics content of the fuel may lead to a decrease in NO_X conversion which could be avoided by using a reference fuel for calibration with the respective content of MTBE.

Oxygenates are likely to be increasingly used in future commercial gasolines and therefore vehicles will be subjected to this lean shift in the market place.

To use the EPEFE NO_X prediction equation for future engine technologies would mean to transfer the mean calibration of the engine management of the EPEFE fleet to future vehicle types. Because of the fact that calibration philosophy is complex and lambda control techniques will be improved a prediction of NO_X response of future vehicle types cannot be solved by statistical means applied to measuring results of current vehicle technology.

Neither CONCAWE nor ACEA could provide information with regard to the effect of NO_X/aromatics for cycles with more dynamic driving behaviour.

3.2 Diesel

ACEA has proposed new NO_X prediction equations based on new parameters for both heavy duty and light duty vehicles. Whereas ACEA are convinced that total aromatics is the main fuel parameter which should be considered with regard to NO_X emissions CONCAWE think the influence of fuel aromatics is of minor importance. Both refer to literature results or own measurements.

The main statistical concerns of CONCAWE with regard to the new ACEA prediction equation refer to intercorrelation of the selected new parameters. Even if one assumes that total aromatics is a main fuel parameter it is not reflected in the EPEFE diesel fuel matrix which is based on a more or less stable mono-aromatic content.

ACEA has addressed these topics in (ACEA 1997). The following conclusions of this report are related to heavy duty engines and based on further investigations and re-evaluation of the EPEFE database:

- The influence of total aromatics on the NO_X emissions has been clearly identified. This statement is in line with other findings in the literature.
- No intercorrelation of the new parameters could be observed for the EPEFE fuel matrix.
- The different aromatics compounds have nearly the same influence on NO_X emissions.

No additional investigations have been performed for light duty diesel vehicles. The same statistical approach derived from results of HD engines was applied.

4 Gaps identified in EPEFE

4.1 Gasoline

The EPEFE NO_X prediction equations are based on emission measurements in the **N**ew **E**uropean **D**riving **C**ycle (NEDC) consisting of an urban part (UDC) and an extra urban part (EUDC). As many findings in the literature (Hassel et al., 1994; Joumard et al., 1990; Final Report of COST 319, 1998; MEET Deliverable 24, 1998) show the results of the EUDC or the UDC do not reflect real world emission behaviour of vehicles in cities or on highways. Therefore the results of the EPEFE prediction equations have to be corrected in order to take into account the influence of real world driving behaviour.

The calibration of the vehicle types of the EPEFE fleet was based on the reference fuel of EU regulation 94/12/EC which contains no MTBE. Nobody can answer the question what the response on NO_X emissions would have been when the reference fuel would have been adapted with regard to MTBE. The new EU regulation 98/69/EC prescribes the adoption of the reference fuel close to the mean quality of market fuels so that type approval calibration results in optimal emission behaviour in the field.

Future vehicle types (Euro 3 and 4) will be equipped with advanced lambda control techniques (second oxygen sensor behind the catalyst, adaptive control etc.). NO_X emission response on fuel aromatics for future vehicle technology cannot be predicted on the basis of EPEFE measurements representing Euro 2 plus technology.

4.2 Diesel

The EPEFE diesel fuel matrix was not designed to investigate the influence of total fuel aromatics on NO_X emissions. Therefore the measuring results based on the EPEFE fuel matrix cannot be used to prove that total aromatics is a key parameter to predict NO_X emission response. The literature results based on tests of single engines of different manufacturers are contradictory. Nevertheless the validation results of the NO_X prediction equations for light and heavy duty vehicles indicate that NO_X emissions cannot be predicted for low aromatics fuels like Swedish class 1 (SC1). Taking into account in addition the results of the comparison to California reference fuel (RFCAL) performed at Southwest Research Institute (SwRI) by order of the Commission, it can be assumed that the low levels of total aromatics content in the fuels are responsible for the lower NO_X emissions of SC1 and RFCAL (ACEA, 1997). To validate this assumption a new diesel fuel matrix has to be designed and investigated with total aromatics as a parameter.

Considering the results of actual studies recently performed it seems doubtful with regard to NO_X to select poly-aromatics as a parameter. Di-, tri-, poly- aromatics are reported to have different impact on NO_X emissions (Lange et al. 1997). A contrary conclusion (all aromatic compounds have nearly the same influence) is presented in ACEA, 1997.

The EPEFE data sets are based on Euro 2 technology. It can be assumed with high probability that future diesel engine technology will show different, perhaps less sensitivity to fuel composition, especially if engines with advanced exhaust aftertreatment are considered. Without additional investigations the impact of new engine technology with regard to NO_X emissions and total aromatic fuel content cannot be assessed.

As already has been mentioned in connection with the gasoline vehicles the emission results of the light duty diesel vehicles are based on the NEDC. Therefore the results of the prediction equations cannot be transferred without corrections to real traffic situations.

The heavy duty engines have been measured in the 13 mode cycle which covers two engine speeds. There are doubts that the results of the 13 mode test can be considered as representative for the whole engine map. The new EU regulation for Euro 3 and 4 has introduced an improved **E**uropean **S**teady State **C**ycle and in addition for advanced engine technology an **E**uropean **T**ransient **C**ycle similar to the US Transient Cycle for HD engines. The results of these improved test procedures may be more representative for the assessment of real world traffic situations.

5 Recommendations for the application of the NO_X prediction equations

5.1 Gasoline

The NO_X emission prediction equations are based on a vehicle fleet consisting of prototypes reflecting the emission level of Euro 2 vehicles and on measurements in the NEDC. Due to these frame conditions it is clear that the resulting mass emissions cannot be considered as representative for the current in-use three-way catalyst fleet. To quantify, however, the influence of fuel aromatics content on NO_X emissions the relative change in emissions can be applied to representative emission factors.

For the current fleet the equations and relative changes respectively are applicable provided the following points are noted:

- The content of oxygenates in future fuels will increase. As there will be no recalibration of the engines the in-use vehicles will be subjected to a certain extent to a lean shift in the market place.
- Real world driving behaviour may be significantly different compared to the NEDC. The influence with regard to the effect of NO_X/aromatics is not considered by the equations. Especially for cycles with more dynamic driving behaviour or high engine load (i.e. highway) it can be assumed, that the influence of low aromatics fuel will decrease under conditions with rich mixture (partial compensation of lean shift).

Using the equation for future engine technologies would mean to transfer the mean calibration of the engine management of the EPEFE fleet to future vehicle types. Future vehicle types, however, will be equipped with advanced lambda control techniques, so that lean shift can be compensated and thus the increase of NO_X emissions can be

avoided. Compared to the overall NO_X reduction of future vehicles the influence of a low aromatics content in the fuel can be neglected.

In principle a decrease of NO_X emissions is possible in the whole speed range for fuels with low aromatics content. The impact on NO_X emissions can be quantified only on the basis of respective measurements. A compilation of the proposed application of the EPEFE NO_X prediction equations is depicted in Table 5.1.

Table 5.1: Application of the EPEFE prediction equations for NO_X emissions of gasoline vehicles

Vehicle technology	Euro 1	Euro 2	Euro 3	Euro 4
ECE	A	A	N	N
EUDC	A 1)	A 1)	N	N

1) Real world driving behaviour on highways is significantly different to the EUDC.

TÜV assessment for speed range above 100 km/h: no increase of NO_x emissions for low aromtics fuels.

A = EPEFE equation acceptable

N = EPEFE equation not acceptable, TÜV assessment: fuel neutral

5.2 Diesel

The NO_X emission prediction equations for light duty vehicles are based on a vehicle fleet with Euro 2 emission level and on measurements in the NEDC. For heavy duty engines the measurements were conducted on the basis of the 13 mode cycle. As already mentioned in connection with the gasoline vehicles only the relative change in emissions can be applied to representative emission factors.

The EPEFE equations do not take into account total aromatics of the fuel as a parameter. According to the actual literature in Annex 2 it can be assumed that total aromatics of the fuel have a strong correlation to NO_X emissions, even if the relative changes of NO_X emissions are small for large changes in aromatics content. Therefore the EPEFE equations cannot predict NO_X emissions for fuels with significantly different aromatics content for current and future engine technology.

In priciple one can agree with the ACEA proposal to introduce total aromatics as a parameter. But there are doubts if data processing based on the EPEFE results will lead to emission predictions close to reality. There exists only poor information about the influence of different aromatics composition with regard to NOx emissions (Langer, 1997). Because of this difficult situation TÜV proposes to perform a new measuring programme based on an adequate fuel matrix design harmonised between ACEA and CONCAWE.

In addition the new measuring programme should avoid the gaps with regard to driving behaviour. That means for light duty vehicles that the test programme should be based on cycles which cover a larger range of real world driving behaviour. For heavy duty vehicles it would be favourable to perform the measuring programme on a dynamic engine test bench. The transient cycles should cover as far as necessary the complete range of the engine map so that changes in emissions can be calculated for different speed/load distributions reflecting driving behaviour in different traffic situations. As far as possible advanced engine technology in connection with exhaust aftertreatment should be taken into account.

Annex 1

Independent Reassessment of EPEFE Equations in Respect of NO_X Emissions

Meeting with CONCAWE in Cologne on 2.3.99

Participants:

Dr. Peter Heinze, CONCAWE
Steve McArragher, Shell
Dr. Heinrich Waldeyer, TÜV Rheinland
Franz - Josef Weber, TÜV Rheinland
Dieter Hassel, TÜV Rheinland

1 Gasoline

1.1 Differences between LDGAS.XLS and final data set

There are no differences between these data sets. TÜV did not take into account that tables of mean values would be generated by treating the data as if it were balanced. Thus for each emission of each vehicle * fuel combination the mean of each set of back - to - back results was calculated.
Because of illness Mr. Sonnborn could not attend the meeting. TÜV has duplicated the regression analysis for NO_X. The trends correspond to those calculated by EPEFE. The regression coefficients are slightly different because of the different calculation of the means per vehicle. If however some additional information is needed with regard to detailed recalculation TÜV will contact CONCAWE via Dr. Heinze.

CONCAWE cannot provide information with regard to NO_X prediction for cycles with more dynamic driving behaviour not covered in EPEFE.

1.2 NO_X/Aromatics effect

The effects of gasoline aromatic content have been explained in a common paper of Shell and VW (Graupner et al., 1997) and in a Shell paper (McArragher et al.). The first paper identifies a leaning of metered A/F ratio on low-aromatic fuels, due to increased engine out exhaust hydrogen and reduced heavy hydrocarbons causing the lambda sensor to give a false rich reading. This can be sufficient to move the A/F ratio slightly lean of stoichiometry into an area of low NO_X conversion efficiency. McArragher mentions a second mechanism, which is an increase in exhaust methane content from non-aromatic fuels. Methane has a very low reactivity for NO_X reduction and therefore contributes little to it‘s conversion. Probably both mechanisms play a role. It is clear that both effects are synergistic.

The sensitivity of the lambda sensor to hydrogen is well known and explains why different vehicles respond to changes in fuel aromatics to a different extent. Vehicles which are calibrated lean or very close to stoichiometric will move into an area of low NO_X conversion efficiency. Vehicles calibrated slightly richer however will show little effect.

CONCAWE is convinced that the EPEFE NO_X prediction equation is valid for EURO 2 technology. The increase of NO_X tail pipe emissions in connection with the introduction of low aromatic fuels may be compensated by EURO 3 and 4 technology due to respective calibration.

The fuels of the EPEFE fuel matrix contain a constant level of 10 vol.-% MTBE. Therefore MTBE cannot be introduce into the prediction equation as a parameter. The lean shift caused by MTBE will be compensated by the lambda sensor, provided that the shift does not exceed the control range of the sensor.

2 Diesel

2.1 ACEA proposal of revised NO_X prediction equations

The revised ACEA equations are based on new parameters:
a total aromatics term instead of a total poly-aromatics term and an additional cetane index term, so that the equations are extented to five parameter equations.

There are two arguments of CONCAWE against an application of the revised ACEA equations:

From a statistical point of view the regression analysis should be based on independent parameters. This is not the case for the new ACEA equations, which are over-parametrized since it includes density and T95 twice (once as themselves, and again because they are included in the cetane index).

The other argument addressed the fact that the diesel fuel matrix has been designed for the parameters density, T95, cetane number, and poly-aromatics. The mono-aromatics are more or less stable in the EPEFE diesel test fuels so that the new parameter „total aromatics„ reflects the variability caused by the poly-aromatics.

In addition CONCAWE is not convinced that total aromatics is a parameter that affects NO_X emissions. CONCAWE will provide TÜV with additional information with regard to this topic. According to the available literature the correlation seems to be very weak. From a technical point of view the only acceptable solution would be a new measuring programme with the respective design of the fuel matrix reflecting all relevant parameters and avoiding overparameterising.

The arguments of CONCAWE against the reviewed ACEA equations are serious from a technical point of view. The excellent fit of the new equations are not convincing since they are not derived from a sound scientific basis. It is only a mathematical solution which can be achieved with other parameters, too, as CONCAWE has proved.

3 Check of completeness of information

All references made available to TÜV have been compiled in Annex 2 of the Interim Report.

4 Relationship between fuel sulphur and NO_X emissions

This topic was discussed, but will not be addressed in the TÜV report.

Annex 1

Independent Reassessment of EPEFE Equations in Respect of NO_X Emissions

Meeting with ACEA in Cologne on 3.3.99

Participants:

Nancy Homeister, Ford Motor AG
Meinrad Signer, Iveco Motorenforschung AG
Anders Röj, Volvo
Dr. Heinrich Waldeyer, TÜV Rheinland
Franz - Josef Weber, TÜV Rheinland
Dieter Hassel, TÜV Rheinland

1 Gasoline

1.1 Differences between LDGAS.XLS and final data set

See minutes of the meeting with CONCAWE

1.2 NO_X/Aromatics effect

There is no doubt that ACEA and CONCAWE have the same technical understanding with regard to the NO_X/aromatics effect, but there is one important argument of ACEA which underlines the different standpoint:

ACEA is not convinced that the EPEFE NO_X prediction equation reflects reality, due to the calibration of the EPEFE test vehicles. In the frame of type approval testing the calibration of the vehicles is based on the reference fuel of the current exhaust legislation. This fuel does not contain MTBE in contrary to the EPEFE fuels containing 10 vol.-% MTBE. Therefore the lambda control of the EPEFE gasoline vehicles had to compensate the lean shift of the A/F mixture when tested on the basis of the EPEFE fuel matrix with the

consequence that the control range of the sensor is reduced. According to ACEA the lean shift caused by MTBE and additional leaning by paraffinic produced hydrogen may result in a lean shift out of the tolerance band of the sensor and could be one explanation why the majority of the EPEFE test vehicle fleet show especially in the EUDC reduced NO_X emissions with increasing gasoline aromatics.

ACEA is convinced that vehicles, which are base calibrated rich react by a decrease of NO_X emissions when aromatics content in the fuel is lowered (at least two of 16 EPEFE vehicles show even in the EUDC a significant increase of NO_X emissions with increasing fuel aromatics).

2 Diesel

The technical arguments of CONCAWE are in principle accepted by ACEA, that means the parameters of the regression analysis should be independent and the diesel fuel matrix was not designed to reflect total aromatic content as a parameter. Despite of these weak points ACEA is convinced, that the revised NO_X prediction equations for light and heavy duty vehicles are a better basis to assess the impact of fuel quality on NO_X emission behaviour. For the HD engine the additional investigations performed by the manufacturers are described in detail in (ACEA, 1997). According to the findings of this report the fuel parameter „ poly-aromatic content„ has to be exchanged by „total aromatic content„. In addition several investigations published in 1995 to 1997, which will be sent to TÜV for evaluation, prove a good correlation between NO_X emissions and total aromatic content of the fuel underlining that total aromatics are the key parameter with regard to NO_X emissions. The decision of the introduction of poly-aromatics as parameter for the EPEFE fuel matrix was based on results of Lange et al., 1993. In comparison to the recently published results it can be understood that ACEA requires a revision of the parameters.

While additional investigations have been performed for the HD engines this was not the case for LD vehicles. The good validation result in the EPEFE report was due to an incorrect calculation of the mean NO_X emissions when using Swedish Class 1 fuel. After

correction the need of review of the NO_X prediction equation became obvious. The EPEFE data set of LD diesel vehicles was used to derive a new NO_X prediction equation based on the same parameters used for the HD engines.

The parameter selection of ACEA was discussed in detail. According to current knowledge total aromatics are the key fuel parameter with regard to NO_X. It has been shown (ACEA, 1997) that mono-aromatics and poly-aromatics have a very similar influence on NO_X emissions, i.e. that the EPEFE diesel fuel matrix reflects the parameter „total aromatics„ with the disadvantage that range of variability is small. As already has been mentioned there should be no intercorrelation of the fuel parameters used in the regression analysis. The intercorrelation of the fuel parameters has been investigated with the result that there is no or only weak correlation between the respective parameters.
Within the EPEFE diesel fuel matrix the variation of cetane number has been achieved mainly by cetane improver (additives). That is the reason why CI and CN are not correlated for the EPEFE diesel fuel matrix. From a technical point of view the CONCAWE comment is correct that the ACEA equation predicts a NO_X increase for high natural CN and a decrease for additive related CN increase.

3 Check of completeness of information

All references made available to TÜV have been compiled in Annex 2 of the Interim Report .

4 Relationship between fuel sulphur and NO_X emissions

This topic was discussed, but will not be addressed in the TÜV report.

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