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TNO report

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On-road NOx emissions of Euro-V trucks

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Samenvatting voor beleidsmakers

Het zware wegverkeer levert een grote bijdrage aan luchtkwaliteitsproblemen, met name in stedelijke gebieden. Het is daarom van groot belang dat de Europese emissiewetgeving ook de praktijk leidt tot minder uitstoot.
De moderne trucks, die aan de Euro-V normen voldoen, hebben in de meeste gevallen met name SCR nabehandelingssystemen om het uitlaatgas van stikstofoxides (NO_x) te ontdoen. Er was reeds twijfel of dergelijke systemen in de stad goed functioneren gezien de specifieke typegoedkeuringsprocedure. Recent, met nieuwe meettechnieken, is het mogelijk om dat in de praktijk te testen, zonder de beperkingen van een laboratoriumopstelling. De resultaten geven aan dat de uitstoot van NO_x in de stad drie keer hoger is dan voorheen aangenomen.
Omdat het wegverkeer, en daarin het zware wegtransport, een groot aandeel hebben in de lokale NO_2 concentraties, is de consequentie dat zeker tot 2015 de verbetering van de luchtkwaliteit veel minder zal zijn dan voorheen ingeschat. Ook de effecten van milieuzones voor vrachtverkeer zullen minder zijn dan voorheen verwacht. De daadwerkelijke verbetering van de luchtkwaliteit speelt zich vooral op de snelweg af, waar de emissiecontrole systemen met de huidige technologie beter functioneren.

Summary

With recent measurements better insight is gained in the real world emission performance of EURO V trucks, in particular in urban traffic conditions.

- The emission measurement programme using a portable emission measurement system yields a direct estimate of real-world NO_x emissions for modern, common Euro-V trucks.

- These new estimates of NO_x emissions from trucks in common urban situations are three times higher than the corresponding emission limit and much higher than real-world estimates based on laboratory tests as well.

- Only at high velocities, like occurring on the motorway, the NO_x emission control seems to function well.

- The recent Euro-III measurements under dynamic driving circumstances also show an increased NO_x emission with respect to older, static laboratory tests.

- The results implicate that that environmental zones, which enforce replacement of older trucks by EURO-V, are less effective than previously thought. However, there is still a substantial positive effect.

- The results, which correspond to other international results, highlight the need for including real-world emissions in the new EURO-VI legislation.

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1 Introduction

Road transport significantly contributes to the NO_2 air quality problems especially in cities both for the current situation and near future. In 2015 The Netherlands will have to satisfy the new European targets for NO_2 air quality. At that time Euro V vehicles will be the greater part of the vehicle fleet on the road, therefore the realworld NO_x emission performance of *modern Euro-V vehicles* is of utmost importance. Preliminary PEMS measurement programmes in Europe already indicated a limited emission control of modern heavy-duty trucks in urban traffic situations, in particular for Euro-V trucks with SCR aftertreatment systems. Within the measurement programme TNO performs for the Dutch ministry of Housing, Spatial planning and the Environment, TNO has set up an extensive programme to cover the most relevant vehicle types, usage, and payloads, as occurring on the Dutch roads. The results of this programme were recently analysed.

In this report, the new results are quantified, summarized, and compared with previous estimates. The portable emission measurement system (PEMS) used in the current study, yields a direct insight in real-world emission performance whereas previous estimations were based on indirect measurements enhanced with calculations. Furthermore, the current report also includes new information concerning realworld NO_x emissions of older Euro III trucks. This places the results in a historical trend.

2 Real world emission measurements of Euro-V trucks

2.1 Experimental procedure and measurement programme

PEMS

PEMS, or Portable Emission Measurement System, is a method to measure exhaust gas in a manner comparable to laboratory tests. The main difference is that the system can be mounted on a vehicle, and the measurement can take place on the road, in normal traffic. The system is meant to become part of the next emission legislation: Euro-VI.

With the introduction of accurate on-road emission measurements (PEMS) it has become possible to monitor real-world emissions in common traffic situations. Before, real-world emissions were derived using engine tests and chassis dynamometer tests, in combination with extensive modelling. Such models are limited by the engine load and speed combinations and variations feasible in the tests. Hence, the link with real-world emission was tenuous, especially for trucks with modern exhaust aftertreatment. PEMS yields straightforwardly proper estimates for real-world emissions.

Test procedure

Using PEMS, recently a total of 7 common distribution and national long-haul trucks were tested on the same route and under similar circumstances. To match the typical Dutch circumstances, TNO has devised a reference trip with urban, rural, and motorway conditions. Furthermore, each truck was tested with at least two different payloads..

The test procedure consists of at least two days of testing on the road, driving the following trips;

- Representative trip; according the European PEMS documents for ISC testing a representative trip should be driven over which the emissions shall be evaluated. This trip and its results are also very useful for the development of representative driving cycles and emission factors.
- Standard Reference Test Trip; a predefined standard trip is applied to all vehicles. The trip includes different road types: urban, rural, highway and covers all relevant traffic situations. A cold start is included, as well as a coast down to determine the vehicles driving resistances, rolling resistance and drag.

The two types of trips were each driven for their specific purposes:

1. The representative trip was driven as this is required by the official EU technical procedure for PEMS, at the moment being developed for Euro V engines. The results are evaluated by means of a special pass-fail method.
2. The reference trip, which was driven to cover a wide range of relevant driving conditions and traffic situations (motorway, city-centre, constant speeds, sub-urban, etc). This trip, shown in Figure 1, is every time the same trip around Helmond and Eindhoven. The data from this trip is mainly used for modelling purposes. The results from these trips were used in this report.

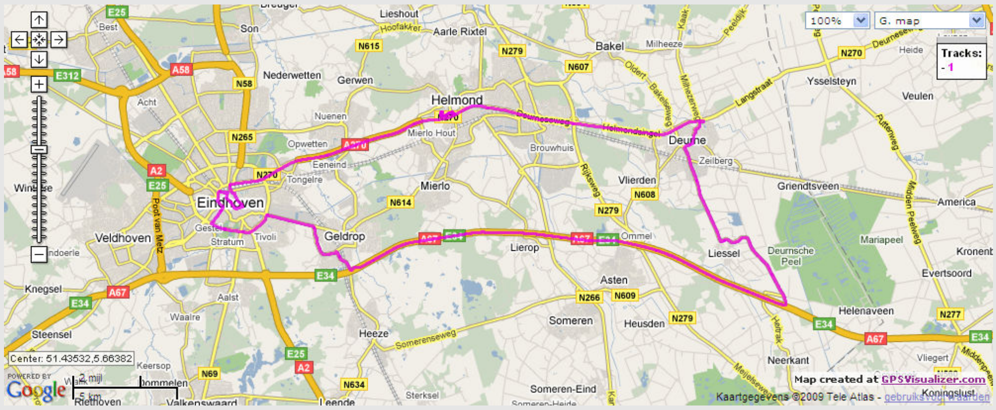

Figure 1; the reference trip starting at the TNO location in Helmond, driving the trip clockwise.

2.2 Trucks

All of the selected trucks satisfy the most modern emission standard: the Euro-V standard. One small distribution truck is labeled Environmentally Enhanced Vehicle or EEV, which implies however the same NO_x limit. From the 7 trucks all but one were equipped with an SCR (Selective Catalytic Reduction) system to reduce the NO_x, emissions. The one exception was equipped with an EGR (Exhaust Gas Recirculation) system serving the same purpose as the SCR system. This vehicle selection is considered to represent the Dutch fleet composition reasonably well. The kerb weight of the rigid trucks and truck-trailers ranged between 5.8 ton and 17.8 ton.

2.3 Data processing

The emission values of trucks vary greatly with velocity, work (kWh) and vehicle mass. For the Euro-VI legislation this is an open problem.To be able to compare the emissions of different trucks, and judge their performance against emission limits, a uniform analysis method is required.
To compare different trucks on the respective NO_x emissions, the grams of NO_x per kilogram CO_2 is suitable, as the NO_x per kilogram CO_2 is relatively invariant over a wide range of trucks and varies only slowly with ambient test conditions and driving circumstances. In this analysis, the total NO_x and total CO_2 emissions for particular velocity bins are summed, and the fraction NOx/CO_2 is determined per bin. These bins are velocities in a 5 km/h range, were both the average emission and the corresponding average velocity are determined.

The current emission standard is based on the determination of specific emissions, or grammes per amount of work (g/kWh). In order to relate the emission results to emission limits, the emission limits must then also be expressed in terms of the NOx/CO2 fraction. For this, the efficiency of the engine (i.e. the amount of CO2 emitted per kWh) must be estimated. Under an assumption of an engine efficiency of 41% during the ETC (or ESC), the specific CO_2 is about 650 grams per kWh.
This value can be used to convert the emission limits to emission per kg CO_2. The Euro-V limit of 2.0 g/kWh, to which these trucks have to comply, then corresponds to a level

of 3.1 g NOx per kg CO_2. This value is not dependent on engine efficiency in practise. In practise engine efficiency can be lower than during the relatively high loaded ETC and ESC due to a relative increase of internal engine friction. This however does not affect the emissions per unit of fuel consumed or per kg of CO2.

2.4 Results

Figure 1 shows the the average NO_x emission per kg CO_2 emission for different velocities and different trucks:

- At lower velocities emissions are very high compared to the emission standard.
- Only on the motorway, at 80 km/h or higher, the emissions are comparable to the emission standard.
- The single truck with the EGR system seems to function better, however, these trucks are less common in The Netherlands.

Although the number of trucks is limited, straightforward statistical analysis showed a common trend of NO_x emissions appearing at more than three times the standard, especially at velocities below 60 km/h in the urban environment. The different traffic circumstances are roughly distinguished by their velocities.

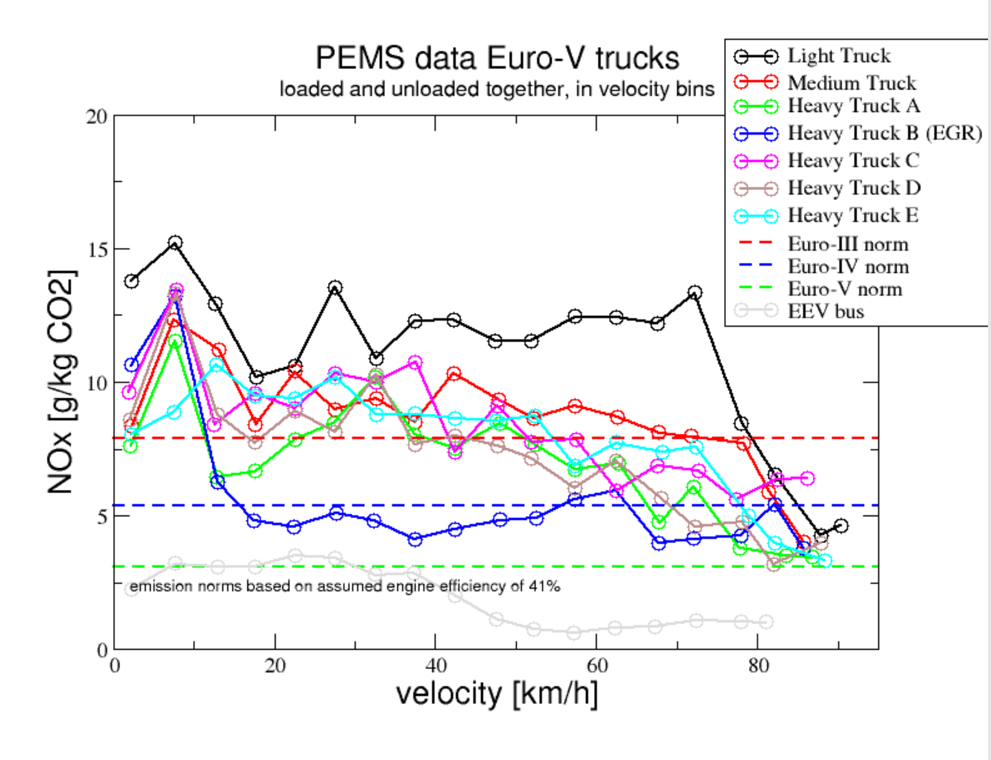

Figure 2: Results of the PEMS measurements on EURO V trucks.

Apart from the trucks, also an EEV bus has been measured with PEMS. The reason is that the bus was suspected to have elevated NO_2 emissions due to the diesel particulate filter mounted. Besides an observed high fraction of NO_2 this bus performs well on

NO_x with values on and below the EEV/Euro-V emission standard for NO_x. The results for the EEV bus are also shown in Figure 2. It has to be noted that the bus was not tested on the same reference trip, but on an urban bus route. However, it is not expected that this is a reason for the difference in NO_x emission performance.

2.5 Discussion

Previous estimates of realworld NO_x emission factors of modern heavy duty vehicles were based on engine tests and stationary-mode chassis tests which close to the ESC and ETC procedure. These measurement results where used as input for the PHEM emission model to estimate realworld emissions. Using this method, the real-world emissions of Euro V trucks were estimated only 10-15% higher than the emission standard. The results from this study shows a much higher difference between the emission standard and the realworld emissions.
This strongly indicates that the Euro-V emission standard did not bring the expected reduction of NO_x emissions. In all traffic situations but the motorway, the NO_x emission is about 10 grams per kilogram CO_2, which is about 3 times the applicable limit over a TA test like an ESC or ETC. The results of all vehicles measured, applying the method of analyses of NOx per CO2, are shown in the picture below.

Note that the results of the EEV bus indicate that it is possible to satisfy the Euro-V standard in circumstances not covered by the official ESC/ETC test.
Other research institutes in Europe confirm the NO_x results for urban and motorway. The results for the rural circumstances may vary from country to country due to the variation in speed limits and degrees of congestion.

3 Real world emissions of Euro-III trucks

3.1 Introduction

With, due to the PEMS programme, Euro-V emission factors close to the Euro-III emission factors, the question remains if from Euro-III to Euro-V some advances have been made. Additionally, one could argue the effects of stimulating new technology. Hence, an new analysis of Euro-III is warranted. Recently, Euro-III trucks were tested in dynamic tests, which mimic the real-world conditions better than earlier tests. These results were analysed for the NO_x emissions.

3.2 Dynamic chassis tests

For a previous programme on retrofit particulate filters trucks were tested at VTT in Finland. Besides particulate matter, NO_x and the other regulated gaseous emissions were measured in the laboratory. All of these trucks were older Euro-III trucks, and special care was taken together with the industry to match the usage to typical Dutch distribution trucks. The driving cycles used were the same as those applied for the calculation of national emission factors for urban and motorway. The payload was matched to the temperature profiles on the road. Four different trucks from three different manufacturers were tested. The tests were repeated for different particulate filters, which, however, would have little effect on the total NO_x emission. Hence all the tests can be used for appropriate statistics of the NO_x emission factors in urban situations and on the motorway. The driving behaviour and vehicle usage matched as well as possible the situation on the road. Hence, these measurements are a direct validation of the emission factors for Euro-III trucks.

3.3 Results

For all the motorway tests and for all the city-cycle tests the NO_x emission and the CO_2 emission were plotted together, and a line was fitted to the data. This line indicates over the whole range of vehicles and payloads the average NO_x emission per CO_2 emission, similar to the analysis performed on the PEMS results to yield a global result for all situations. See Figure 3 and 4.

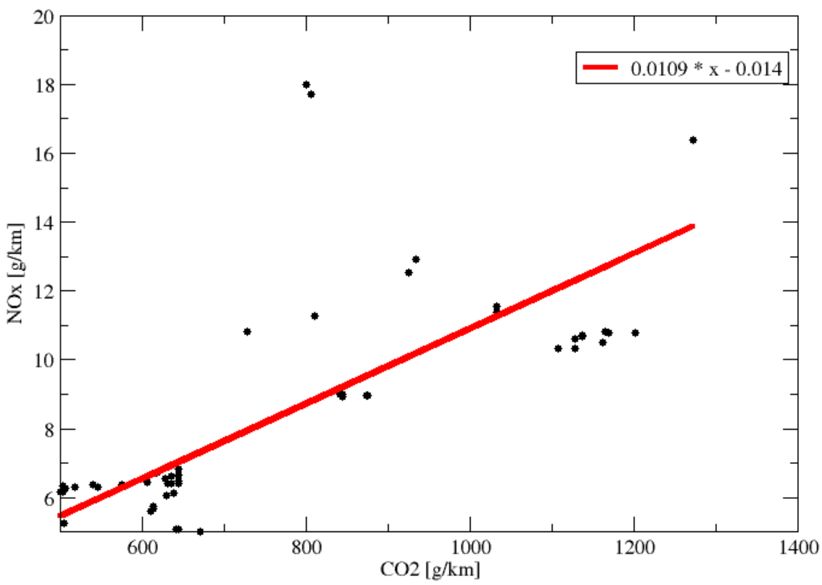

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Figure 3: The relation between NO_x and CO_2 for all the motorway measurements. The slope indicates a relation of about 11 g NO_x per kg CO_2. Originally the relation between NO_x and CO_2 was estimated at 8.5-9.0 g NO_x per kg CO_2.

The data shows a relatively consistent picture of 11 grams NO_x per kg CO_2, indicated by the line, over the whole range of vehicles mass and payloads, on the motorway. In urban driving circumstances the emission is 13 grams NO_x per kg CO_2.

3.4 Conclusions

From the new measurements performed in Finland it can be concluded that the previous Euro-III NO_x emission factors underestimated the on-road emissions, but not as much as the Euro-V emission factors. When converted in a manner similar to that used in chapter 2, the EURO III expressed in g NOx per kg CO2 is 11 (motorway) to 13 (city). Comparing this with the results presented here, it shows that the emissions of Euro-III trucks are 20% - 40% higher. For Euro-III the effect of dynamics has been underestimated, which yields a larger effect in uban situations than on the motorway. Applying the same method as for the Euro V on road results, determining the NOx performance by calculating NO_x over CO_2 the original emission factors were estimated at 8.5 to 9.0 g/kg CO_2

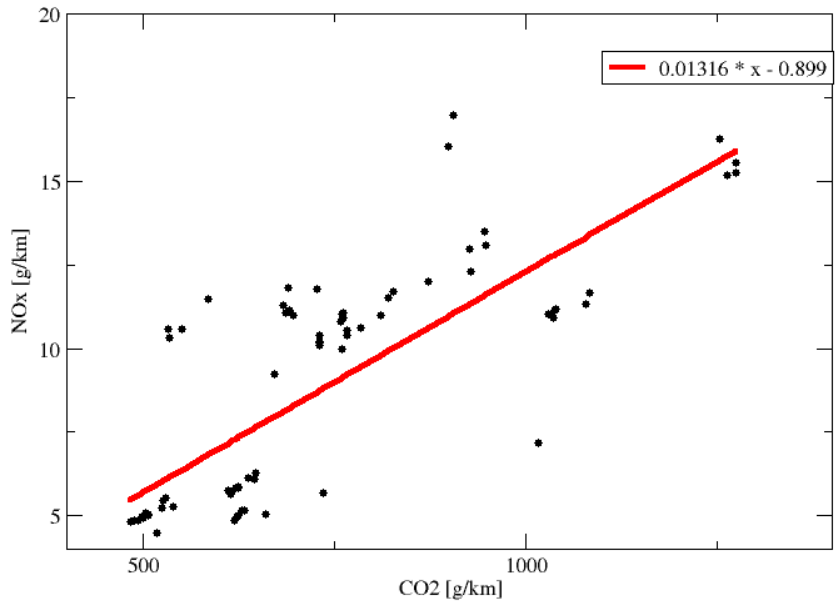

Figure 4: the relation between NO_x and CO_2 for all the city measurements. The slope indicates a relation of about 13 g NO_x per kg CO_2Originally the relation between NO_x and CO_2 was estimated at 8.5-9.0g NO_x per kg CO_2.

4 Implications for emission factors and low-emission zones

Emission factors for EURO-V and EURO-III trucks

The national emission factors, published by the Dutch ministry of Housing, Spatial planning and the Environment, have been largely determined from measurements in the laboratory. However, especially for future technology, emission measurements are not available and estimations have been based on calculations and expert knowledge. The desirable tendency is to link the emission factors as directly as possible to the measurements. Initially, improved driving cycles were developed, which represents the driving behaviour on the road better than the official test cycle. Also, an appropriate sample of vehicles, as seen on the road, was selected for testing. New measurement techniques, such as second-by-second measurements and PEMS have become available, allowing a more direct link between occurring emissions with the associated driving behaviour and vehicle state.
Within this trend, the experiences with PEMS over the last year were this autumn robust enough to warrant a transition from an engine-based emission model, to emission factors based on on-road PEMS measurements. Since only Euro-V trucks were measured, the emission factors were initially limited to Euro-V.
However, since the Euro-V trucks showed poor performance on NO_x, it became important to retrace history and use new insight for older vehicles. The Euro-III truck measurements for appropriate real-world driving were available, as described in Chapter 3. These trucks showed in the new results an inkling of the Euro-V performance: especially for urban circumstances the NO_x emissions were previously underestimated. Table 1 shows an overview of both the old and new NOx emission factors for Euro-III and Euro-V trucks. Note that these emission factors are expressed in gram NO_x per kilogram CO_2.

Table 1: The new and old emission factors expressed in terms of the CO2 emission.

g/kg CO2	standard	city	motorway	new city	new motorway
Euro-III	7.5	8-9	8-8.5	13	11
Euro-V	3.1	3.5	3-3.5	10	4

Implications for low emission zones

The NO_x emission factors do play a major role in the calculation of NO_2 air-quality along roads. From the current study it can be seen that in air quality calculations, the higher the NO_x emission factors will lead to an increased contribution of especially modern trucks. In addition it will also negatively affect earlier estimations of technology related measures, such as the effect of low-emission zones. However, other elements are important as well, such as the fraction direct NO_2 in the emission. Taking into account the decrease in direct NO_2 emissions, and the increase in NO_2 for retrofitted Euro-III trucks, the effect for low-emission zone after 2010 will decrease, but is expected to be a little better than follows from the reduction of NO_x. A preliminary estimate indicates about half of the previously expected effects of 4-6% reduction of the road-side NO_2 concentration in urban areas. In such zones a substantial fraction of

Euro-III trucks is replaced by Euro-V trucks, however, older Euro-I and Euro-II trucks are banned as well.

5 Euro-VI legislation

The results of this study illustrate a gap in the effectiveness of EURO-V legislation to reduce NO_x emissions under urban conditions. It is expected that the Euro-VI legislation will close the gap between the emission tests and the on-road, real-world emissions. The PEMS plays a key role in this development.
These new results on Euro-V trucks have become available as part of the programme to improve upcoming emission legislation for heavy-duty vehicles: the Euro-VI legislation. With this report, for the first time the consequences for air quality are part of this investigation. Before, the focus was to improve the legislation such that the problems seen in Euro-V and earlier will be banned in the future.
The Euro-V legislation was in greater part the same as Euro-III en Euro-IV with stricter standards. With Euro-VI the wish arose to steer legislation more towards the real-world emission control. The test procedure, the on-board diagnostics, and the in-use compliance tests are meant to be the three corners on this legislation.
The new test cycle, the WHDC, with the cold start, hot soak, and at lower engine load is meant to be closer to the real-world urban driving conditions. Furthermore, the recent PEMS testing brought to light possible emission control failure and tampering, which can be prevented by appropriate legislation for On-Board Diagnostic. In that case the truck will have to undergo maintenance if indicated by the engine control.
The last cornerstone of Euro-VI emission legislation is the PEMS measurement system, as used for this report, such that the compliance of heavy-duty trucks with emission legislation can be tested on-road, by interested parties. Moreover, the legislation can provide consequences to the failure to comply.

6 General conclusions

In this study, the real-world emissions of 7 EURO-V trucks have been measured using PEMS, and the results have been compared to EURO-V emission limits. The following conclusions are drawn:

1) Under urban conditions, the EURO-V trucks consistently show NO_x emissions of about 3 times higher than previously estimated. At higher velocities, the discrepancy between measured emissions and the limit value is strongly reduced.

2) Analysis of recent data on EURO-III trucks shows a similar trend, although the deviation of the limit value is of smaller magnitude.

3) The data imply that the effect on NO_2 concentration of replacing older trucks by EURO-V trucks in environmental zones is about half of what was previously thought. Nevertheless, a positive effect for air quality remains.

4) The data highlight the need for incorporating real-world emission behaviour into the new EURO-VI legislation for trucks.

7 Signature

Delft, December 7th 2009

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A Background on the PEMS measurement programme

To adapt legislation for checking the real world emissions, In-Service Conformity or Off-Cycle emission performance a method is being developed which can measure these emissions under real world circumstances in a vehicle. The method which is currently examined by the EC for integration in EU emission legislation is the PEMS method. PEMS stands for Portable Emission Measurement System. PEMS is already applied in the U.S. In-Use Compliance legislation with the NTE (Not To Exceed) approach. This NTE approach was not found effective for the special situation in the EU.
In the EU a special PEMS working group has been set up, which examines the method for its suitability for integration in EU legislation in a PEMS Pilot Programme. Additionally, the EC looks at covering a broader spectrum of the practical circumstances, so that PEMS can be used in the EU with increased effectiveness.

Truck manufacturers, engine manufacturers, Technical Services, Type Approval Authorities, Member States, equipment manufacturers as well as a group of consultants contribute to the PEMS Pilot Programme. In the programme the test procedure is conducted as laid down in the PEMS Pilot Programme Project Plan [DG ENTR, 2007]. In this plan all test conditions are written down to be able to conduct the testing for the Pilot.

The EU Pems Pilot Programme has several goals:

- To validate the use of PEMS for in-service conformity;
- To evaluate the PEMS test protocol and its implementation;
- To provide further information on incorporating the PEMS approach in the European type-approval legislation;
- To develop and share ‘best practice’ approach for the use of PEMS in ISC testing to all relevant stakeholders;
- To benchmark the dialogue between manufacturers and type-approval bodies (reporting format);
- To address open technical issues of the PEMS Project (in particular use of after-treatment systems, cold start and PM measurement).

Because of the developments in the field of EU emission legislation the current PEMS systems have considerably improved over the previous years in the field of exactitude, robustness and user friendliness. The systems seem a relative simple and cost-efficient means to measure emissions under real world conditions in a vehicle. The systems are however not entirely mature. Thereby findings from the practice indicate that working with PEMS systems is not always simple and that the application of these systems in practice sometimes appears more cumbersome than expected. Because all developments of the emission legislation seem to go in the direction of using PEMS for In-Service testing, it is important to gain experience with such systems, testing emissions in a vehicle on the road under real world driving conditions. Therefore, PEMS has been introduced in the Dutch In-Service Testing programme. The goals are:

- to determine the performance of a PEMS in terms of absolute accuracy
- to gain experience with evaluating and interpreting results obtained with a PEMS

- collecting HD real world emission data and driving data for the purpose of emission modeling
- to gain insight into real world emission behavior of HD vehicles
- to contribute to the EU Pilot programme for determination of a pass fail method with pass fail criteria
- to determine the robustness of the EU PEMS procedure with regard to detecting malfunctioning of emission control devices of HD vehicles In-Use.
- to collect emission data for use by the TAA

By developing such knowledge VROM and TNO can:

- value PEMS system and its results
- gain insight in real world emission performance of HD vehicles with respect to durability, malfunctions, inspections and maintenance, real world emission levels, other factors of influence
- discuss on national and international level on HD emissions and legislation
- develop and share a vision on how HD emission testing should look like
- deliver real world emission data for national en international emission modeling
- develop real world driving cycles, for use on engine test beds and vehicle test beds