A smart and robust NO_x emission evaluation tool for the environmental screening of heavy-duty vehicles.

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Abstract

At the request of the Dutch Ministry of Infrastructure and Environment a smart measurement system was developed to judge the real world NO_x emission of heavy-duty vehicles. The measurement system uses a NO_x - O_2 sensor for the measurement of the tail pipe concentration of NO_x and to estimate the tail pipe concentration of CO_2 for diesel engines. A GPS measures the time-based vehicle speed profile over the test trip. Furthermore, a special data-evaluation method helps to reveal emission performance over the speed ranges of a vehicle. The method is based on collecting (binning) emissions of NO_x and CO_2 in speed intervals and calculates the CO_2 specific NO_x emissions for each interval.

The measurement system proved to correlate well with PEMS, which can be seen as an accurate reference measurement. The method is less accurate than PEMS, but its merit to simply measure more and longer at lower costs increases the overall accuracy, because more of the often variable emission behaviour is captured.

The method can be extended with more exhaust gas compounds like NH_3 and CH_4 and particulate matter once accurate sensors become available.

The measurement system could fulfil several purposes, for instance as a screening tool for national emission surveillance programs, national approval schemes, in-service conformity checking and as tool to check emission requirements in the procurement of vehicle fleets.

Introduction

The Euro V/EEV requirements for diesel engines for trucks and buses have shown not to guarantee low NO_x emissions during urban driving conditions. A change in the Euro V test cycle or the development and introduction of specific off cycle provisions (Euro VI) to improve real-life urban emission behaviour would take too much time due to the EU legislative process to play a role in the remaining years of registration of new Euro V vehicles. Furthermore, it would take years before the fleet is refreshed with the cleaner Euro VI vehicles.

The Ministry of the Environment and Infrastructure of the Netherlands suggested that a label guaranteeing adequate urban emission behaviour might be a feasible alternative for vehicle operators and local authorities when purchasing trucks and buses intended for urban use. This labelling would not be used to prohibit the sale of vehicles without a favourable label, but serve as a means for operators of vehicles and (local) authorities to know whether vehicles have low NO_x and NO_2 emissions in urban operation and to subsequently for instance grant privileges to such vehicles.

For this labelling approach criteria are needed and a way to check vehicles against these criteria. This paper deals with the development of a procedure and requirements which could fulfil the need to evaluate the real world NO_x emission performance of HDV in a simple and robust way. As such this procedure might be considered for other formal test procedures, for instance for checking the conformity of the emissions of engines and vehicle in-service or checking the emissions of diesel engines retro-fitted with a dual-fuel system.

Simple Emission Measurement: principle, how does it work?

The method, in its most simple form, is based on measurement on a heavy-duty diesel vehicle with a combined automotive NO_x – oxygen sensor and a GPS under representative driving

conditions on the road. A dedicated method of data analyses is used to determine the NO_x emission performance: the measured oxygen is used to estimate the tail pipe CO_2 emissions. This can be used as the reference quantity in a unit expressing emissions as gram per kilogram CO_2 instead of the traditional unit which uses engine work (gram per kWh).

From work specific emissions to CO_2 specific emissions

To establish a result for the NO_x emission which is able to discriminate the real world NO_x emission performance of heavy-duty vehicles, the method uses CO_2 as a reference quantity. This means that the measured NO_x concentrations are related to the measured CO_2 concentrations to calculate a CO_2 specific NO_x emission.

The traditional method relates the measured tail pipe emission to net engine work (i.e. gram per kilowatt-hour) (ECE Regulation 49), (595/2009/EC). This method was chosen in the past to deal with the large differences in engine power of the heavy-duty engines and also non-road engines. In this way emission limits could be related to engine output. Another important reason for the calculation of work specific emissions is that the emission test procedures for heavy-duty and non-road are based on engine cycles where engines are tested on an engine test bed. For these tests engine work could be measured relatively easily by the engine dyno.

The method using CO_2 relates the measured emissions to a quantity which represents a certain engine performance as well, be it that work is a measure for the output of the engine while CO_2 is a measure for an engine's energy consumption. Below is described how the traditional emission per unit of work relates to emission per unit of CO_2.

Work specific emissions

The traditional method for online measurement from raw exhaust gas over a test cycle according (ECE Regulation 49) and (ISO 16183). This calculation is also prescribed for calculating emission using a PEMS (Portable Emission Measurement System) (582/2011/EC). The work specific emissions are calculated according:

$$WSE_x \left[\frac{g}{kWh}\right] = \frac{\sum_{i=1}^{i=n}[(mgas_{x,i}])}{\sum_{i=1}^{i=n}[(Pn_i])} \quad \text{(Equation 1)}$$

where:

mgas is the mass of individual gas in g/h

Pn is the net power of the engine in kW

CO_2 specific emissions

For the calculation of the CO_2 specific emission the calculated net engine work in formula is replaced by the CO_2 mass:

$$CSE_x \left[\frac{g}{g}\right] = \frac{\sum_{i=1}^{i=n} mgas_{x,i}}{\sum_{i=1}^{i=n} mgas_{CO2,i}} \quad \text{(Equation 2)}$$

or:

$$CSE_x \left[\frac{g}{g}\right] = \frac{WSE_x \left[\frac{g}{kWh}\right]}{WSE_{CO2} \left[\frac{g}{kWh}\right]} \quad \text{(Equation 3)}$$

Example: a diesel engine with a brake specific fuel consumption of 210 g/kWh running on 100% EN590 diesel has a work specific CO_2 emission of 666 g/kWh over a test cycle. When the Euro V NO_x limit of 2,0 g/kWh for the ETC cycle is used for the example the equivalent CO_2 specific emission would be:

CSE_x=2,0/666=0,0030 [g/g] or 3,0 [g/kg]

However, the brake specific fuel consumption or the efficiency of a diesel engine is not constant. Figure 1 below depicts both the CO_2 as well as the work specific NO_x emission and shows that at lower speeds a lower average engine efficiency results in an decrease of the CO_2 specific NO_x emissions.

The engine efficiency not only varies during operation, the typical engine efficiency also varies from engine to engine, for different technologies and fuels. To understand the effect of a change in typical engine efficiency one can use an example:

Engine 1 has a NO_x emission of 2 g/kWh and has an average efficiency which corresponds to a work specific CO_2 emission of 630 g/kWh

Engine 2 has a NO_x emission of 2 g/kWh and has an lower average efficiency which corresponds to a work specific CO_2 emission of 660 g/kWh.

Because engine no. 1, which is more efficient, emitted less CO_2 to produce the same amount of work as engine 2 , the CO_2 specific NO_x emission of engine 1 will be higher compared to that of engine 2.

For diesel engines in heavy-duty vehicles the brake specific fuel consumption may vary roughly 20% between about 190 to 230 g/kWh. This margin however is still low compared to the large variation observed in NO_x emission performance of Euro V heavy-duty vehicles.

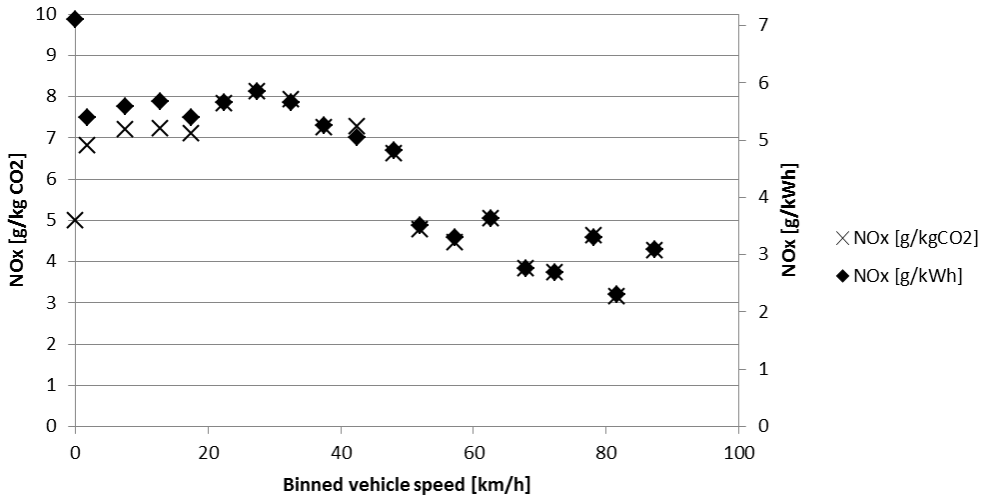


Figure 1: example of the measured work specific and CO_2 specific NO_x emissions over the speed range of a heavy-duty vehicle. At higher speeds both quantities correlate well, at lower vehicle speeds the average engine efficiency decreases and as a result the emission per kWh increase.

The use of CO_2 instead of work as reference quantity comes with some advantages (+), but also with some disadvantages (-):

+ when used for on-vehicle measurements the outcome of a pass-fail evaluation does not have to rely on the engine work which is calculated from signals broadcasted by the vehicles ECU via e.g. the CAN interface. Instead, a directly measured quantity CO_2 is used.

+ when the mass emissions are measured, possible errors of the flow meter are cancelled out because both the gas under evaluation as CO_2 are measured with the same flow meter.

+ at low engine load, the engine hardly produces any net work. This leads to very high work specific emissions under these conditions. When the engine is idling, the work specific emission is infinite because there is no measureable net output at the flywheel. Under these circumstances CO_2 still is emitted. Therefore the use of CO_2 as reference quantity allows the evaluation of the emissions at low engine loads.

- engines which are less efficient are at an advantage because these engines emit more CO_2 to produce a certain amount of work. Hence, these engines would be allowed to emit more of the

noxious compound if this compound would be related to CO_2. This also accounts for e.g. SI engines running on natural gas.

Estimation of the CO_2 specific emissions based on measured tail pipe concentrations
A further simplification for the measurement procedure can be established by removing the measurement of the exhaust mass flow. In that case only the concentrations of the regulated noxious compound as well as the CO_2 concentration would need to be measured instantaneously. The rationale behind this approach is that the exhaust mass flow is cancelled out in the calculation.

Measurement of NO_x and CO_2 estimation

Measurement of NOx
The NO_x concentration is measured with an automotive NO_x sensor mounted in the tail pipe. The CO_2 concentration is estimated using the O_2 concentration which is measured by the same sensor.

In the past decade the automotive NO_x sensor became a mature, market ready product which typically fulfils the automotive requirements with regard to accuracy, stability and durability. The NO_x sensor was introduced in serial production in 2002 on passenger cars where the sensors were used to control the Lean NO_x Trap (LNT). The so-called smart NO_x sensor is a standalone unit which includes a data interface for easy integration in the engine or aftertreatment control. The NO_x sensor is mainly applied by OEMs for on-board diagnostics on heavy-duty vehicles equipped with a Selective Catalytic Reduction system (this OBD is mandatory as of Euro V, 2009) and as integral part of the (closed-loop) control of aftertreatment systems of both heavy- and light-duty vehicles.

In the past the ageing of the sensor was a problem but today the electro-chemical NO_x sensors have become more stable over time. Manufacturers declare typical accuracies of around 10ppm for fresh sensors and around 15 ppm for aged sensors, (Ochs, Wahl, Wendt, 2010), (Schmitt, Lemire 2010), (Sasaki, 2010).

The output of a NO_x sensor may be influenced by its cross sensitivity for other compounds. Known potentially problematic compounds are ammonia and water but pressure is also known to be of possible influence on the output. (Schmitt, Lemire, 2010). For the current sensors under normal operating temperatures mainly ammonia influences the output. A sensitivity to this compound of 100% is mentioned (Schmitt, Lemire, 2010). Because most modern heavy-duty vehicles have SCR systems with ammonia to reduce the NO_x emission, the risk for ammonia slip through the SCR catalyst is substantial. To deal with this sensitivity to ammonia slip, an additional ammonia sensor could be used for the measurement to distinguish the shares of NO_x and ammonia in the signals output. Another approach would be to accept the sensitivity to ammonia and include it implicitly as compound in the emission evaluation of NO_x. Another important aspect is the reported limited sensitivity for NO_2 of 80% (Schmitt, Lemire, 2010). This might influence the outcome when vehicles emit relatively large shares of their NO_x emission as NO_2, like for instance vehicles equipped with a passive soot filter.

Estimation of CO_2 concentration for diesel exhaust gas
The estimation of the CO_2 concentration is done based on the measured oxygen concentration. The rationale for this approach is that for a conventional diesel engine there is a linear relation between the measured oxygen and CO_2:

At fuel cut-off the tail pipe oxygen concentration is the same as the concentration of oxygen in the intake (-ambient air), say around 21%. Then the CO_2 concentration is 0%.

At the theoretical stoichiometric point of engine operation (lambda =1), which typically represents 0% oxygen concentration, the theoretical maximum CO_2 concentration is determined by the composition of the diesel fuel when full combustion is assumed. Mainly the ratio of hydrogen to carbon influences this theoretical maximum CO_2 concentration. For 100% regular diesel with a typical H/C ratio of 1,86 this concentration is 13,5%. Diesel fuel containing oxygen, like bio diesel, may influence the O_2 concentration and thus the calculated CO_2 concentration marginally. For B5 the effect on CO_2 is 0,25%.

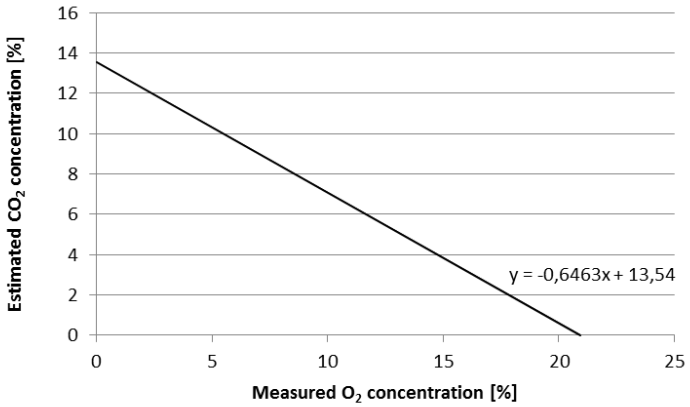


Figure 2: estimation of diesel tail pipe CO_2 concentration based on measured tail pipe oxygen concentration. The relation between CO_2 and O_2 is defined by the oxygen content in air and the oxygen, carbon and hydrogen content of the diesel fuel.

Data evaluation: binning in speed intervals

The primary purpose of the evaluation method is to facilitate the use of large amounts -hours of real-world data measured at 1Hz- as input to calculate the CO_2 specific NO_x emission for urban, rural and motorway conditions and to gain insight into the emission behaviour over the complete speed range of a vehicle. This evaluation method was developed in an earlier program (Verbeek et al., 2010) to facilitate the use of the larger quantities of data coming from a PEMS (Portable Emission Measurement System) system. Furthermore, the purpose of the method was to enable a fair comparison between individual vehicles all differing in engine output and gross vehicle mass. The data evaluation which fulfils these needs is a method which is based on the calculation of the CO_2 specific emissions in speed intervals. The method collects emission data belonging to a defined speed interval and determines the average CO_2 specific emissions for every interval over the complete speed range of a heavy-duty vehicle.

$$gNO_x \ per \ kgCO_2 = \frac{\sum_{v=vi}^{v=vi+5} NO_x[g/s]}{\sum_{v=vi}^{v=vi+5} CO_2[kg/s]} \qquad \text{(Equation 4)}$$

In principle the choice for the speed intervals is free. However, for use with a kind of labelling approach it is more feasible to use larger speed intervals. For the evaluation in this investigation the intervals 0-50, 50-75 and >75km/h are used. The intervals represent typical operating ranges of an heavy-duty vehicle of which it is important to distinguish the emission behaviour: test programs (Verbeek et al., 2010), (Vermeulen et al., 2012) have shown for instance that for Euro V heavy-duty vehicles on diesel, the NO_x emission may increase at lower vehicle speeds. To improve air-quality on the street level in urban areas however, it is especially important that the emissions are minimized at these lower (urban) driving speeds. On the other hand it is equally important that the emissions are controlled at higher driving speeds as well because for instance for long-haulage heavy-duty vehicles here the bulk of the kilometres is made.

To assure an agreeable emission performance under all conditions, a separate evaluation of critical driving conditions is necessary. This avoids that emissions under conditions which are relevant for local air-quality, like at urban driving speeds, are averaged with conditions where a good emission performance is easily obtained.

Furthermore, the use of larger intervals makes the method less sensitive for issues with alignment between the GPS speed signal and the sensors signals of the measured concentrations.

Validation exercise

Database with PEMS measurements

A database with Euro V and VI vehicles tested with PEMS is used to demonstrate the feasibility of the calculation method for the discrimination between vehicles with low and high NO_x emission. A small pilot program where the NO_x sensor and GPS are employed next to a PEMS (Portable Emission Measurement System) allows the validation of the tool and method against an accurate reference system.

A first exercise with available PEMS data shows the variance in emission behaviour and the discriminative power of the method to distinguish NO_x emission levels of modern heavy-duty vehicles under low, medium and high speed driving conditions (Figure 3). Especially, for Euro V and EEV the scatter in emissions is large, from about 3 to 14 g/kg . Also there is variation between the emission levels at low, medium and high driving speeds.

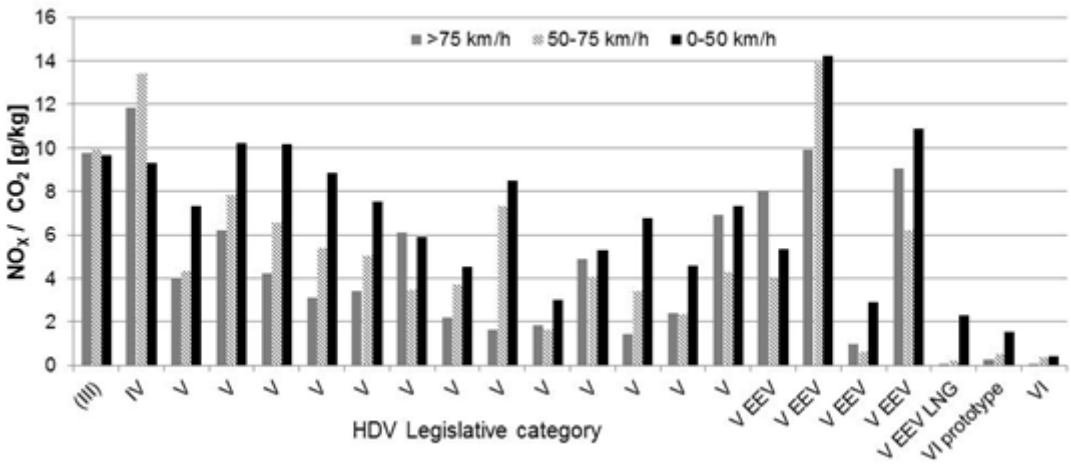


Figure 3: CO_2 specific NO_x emissions for large speed intervals (bins) of 0-50, 50-75 and >75 km/h show that Euro III to Euro VI vehicles show a large scatter in emissions. The emissions are determined with PEMS. All vehicles are tested over the same test trip and with the same payload percentage (55% of the difference between the maximum technically permissible laden mass or Gross Vehicle Mass of the combination, whichever is smaller, and the empty vehicle mass in running order).

Correlation mass based vs. concentration based PEMS emission results

The simple measurement procedure is solely based on the measurement of tail pipe concentrations. This principle is compared with a measurement where exhaust gas flow is used to calculate mass emissions (PEMS). To achieve this, PEMS data was used of a few vehicles which differ in NO_x emission behaviour. The CO_2 specific NO_x emission was calculated in two ways, applying the speed binning method for data evaluation:

1) based on the tail pipe mass emissions of NO_x and CO_2 and

2) based on the tail pipe concentrations of NO_x and CO_2. A correction was applied for the difference in molar mass of the NO_2 and the CO_2 molecule.

As can be observed from the graphs in figures 4, 5 and 6 both methods correlate well for diesel vehicles. Only for the spark-ignition LNG (Liquefied Natural Gas) vehicle (figure 7) the relation between the two methods is not proportional. This may caused by the effect of throttling the engine. For a conventional spark-ignition engine which runs a stoichiometric air-fuel mixture the engines the load control is quantitative which means that the tail-pipe CO_2 concentration is more or less constant. This is also true when the engine is throttled and as such CO_2 concentration on its own is not a good indicator for the engines exhaust mass flow.

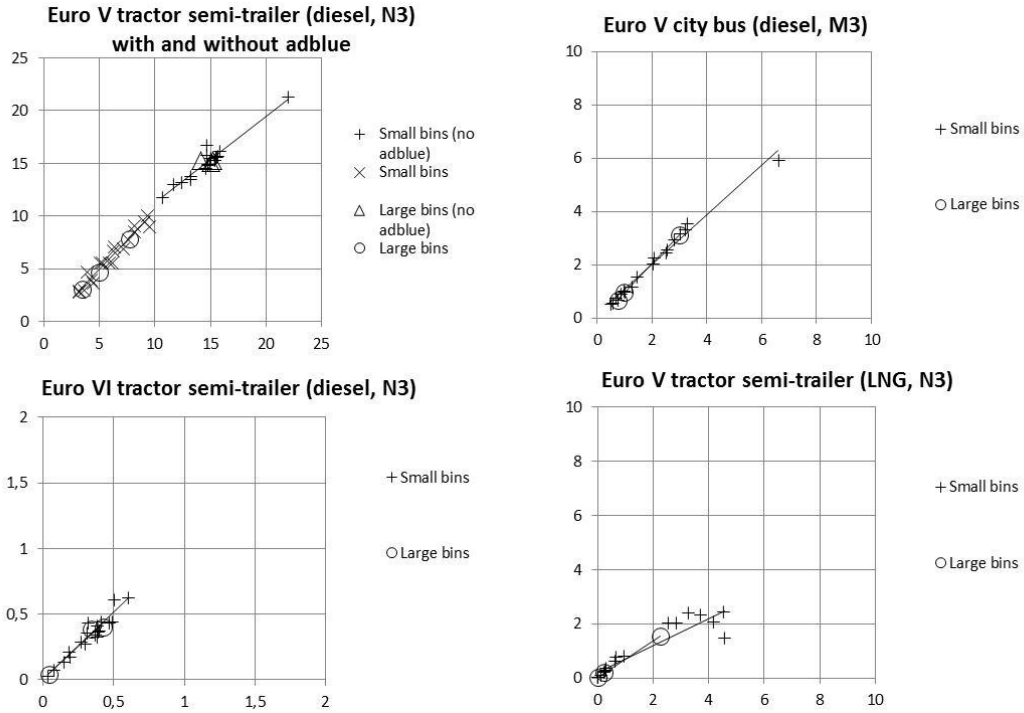


Figure 4, 5, 6, 7: correlation between mass based (g/kg, x-axis) and concentration based CO_2 specific NO_x emission (ppm/%/10*density factor, y-axis) as both measured with PEMS. Small speed bins of 5km/h are used for the data evaluation, as well as large speed bins (0-50, 50-75 and >75 km/h). For diesel engines the relation is proportional, for the vehicle with spark-ignition LNG engine the relation is not proportional.

<u>Direct comparison between PEMS and the simple emission measurement systems (SEMS)</u>
To validate the measurement principle and the evaluation procedure, tests have been performed where the emissions are simultaneously measured with PEMS and with the simple emission measurement system (SEMS). Three heavy-duty vehicles were tested this way, see table 1.

Table 1: test vehicles used to perform simultaneous measurements with PEMS and SEMS.

	Legislative category (2007/46/EC)	Gross Vehicle Mass [tonne]	Emission class	Emission red. techn.
Vehicle A	N3 tractor semi-trailer	50	Euro VI	EGR, SCR, DPF
Vehicle B	N2 distribution truck	10	Euro V (B2I)	SCR
Vehicle C	N2 distribution truck	3,5 (N2->N1)	Euro V (B2G)	EGR

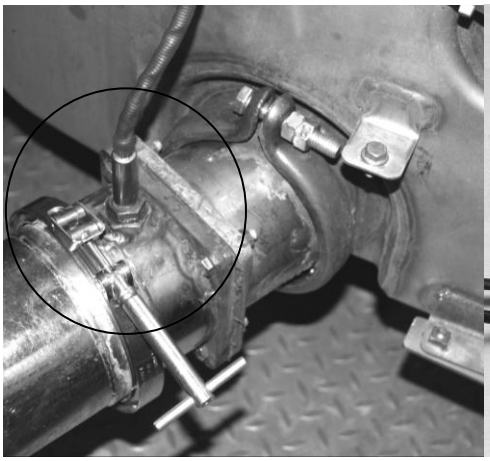


Figure 8, 9: left the NO_x - O_2 sensor installed at the tailpipe of a Euro VI heavy-duty vehicle. Right, the sensor and data acquisition unit which logs the sensor data, GPS data and optionally the CAN data.

The measured 1Hz oxygen signal of the sensor was converted to an estimated CO_2 concentration. The raw NO_x concentration signal and the signal of the estimated CO_2 were compared with the online NO_x and the CO_2 signals from the PEMS. Figures 10 and 11 show a short part of the signals. For both components the general correlation is good. The sensor however, seems to have a somewhat longer response time than the PEMS signals. This results in momentary mismatches in correlation. For the CO_2 signal also some offset is noticed at moments where the concentrations are stable.

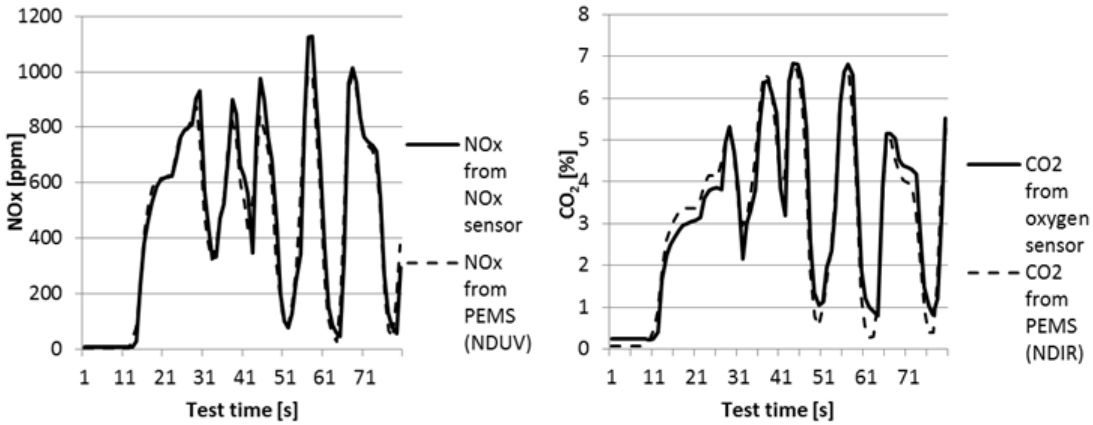
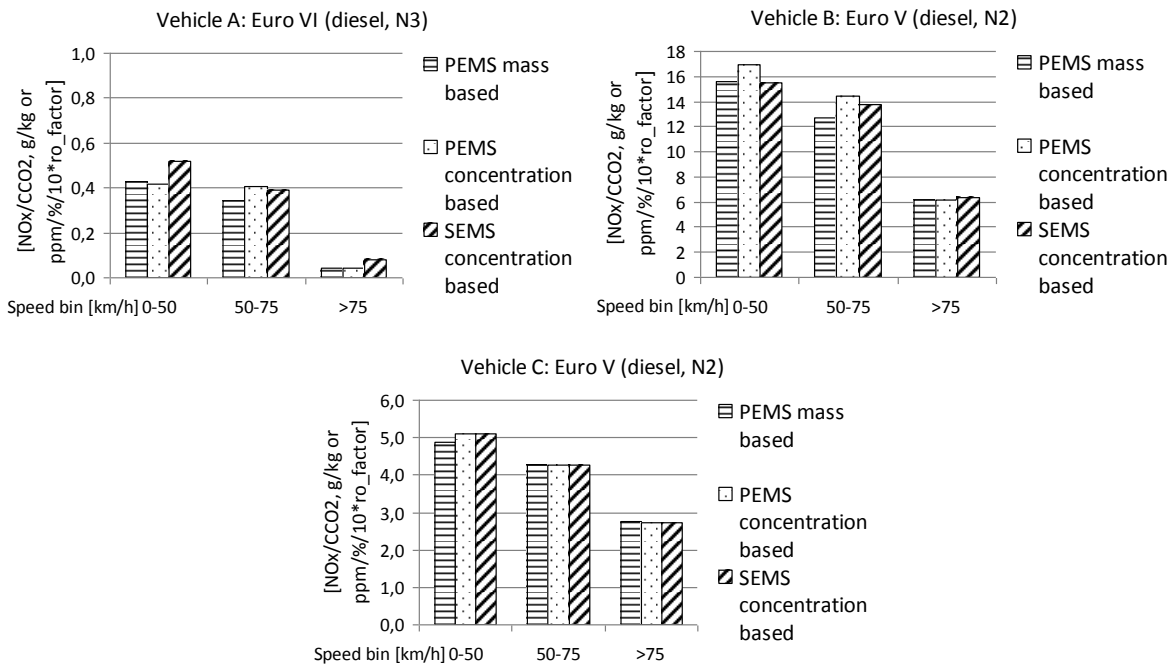


Figure 10, 11: left, the 1Hz signal of the estimated NO_x signal (from the NO_x – O_2 sensor), compared to the NO_x signal of PEMS (measurement principle non-dispersive ultraviolet). The signals correlate well. The NO_x sensor seeems to have a somewhat higher response time.Right, the 1Hz signal of the estimated CO_2 (from the NO_x – O_2 sensor), compared to CO_2 signal of PEMS (measurement principle non-dispersive infrared). The signals correlate well. The NO_x-O_2 sensor seems to have a higher response time and has a minor offset compared to PEMS.



Figures 12, 13 and 14: the PEMS and SEMS are compared and the data-evaluation method is applied, based on large speed bins. For PEMS both the mass emissions and the concentration of the emissions were used for the evaluation. For SEMS the evaluation is purely based on the raw sensor output (and a separate GPS system). The outcome of the data-evaluation with PEMS and SEMS differs from a few to a maximum of about 20%. In general, the trends over the large speed bins are very well comparable.

In figure 15 below the results of the data evaluation is plotted for the same vehicles for the mass based PEMS results and the concentration based SEMS results. The correlation is good and the method clearly distinguishes the NO_x emission levels at the different speeds. As a reference also the equivalent NO_x limit including the conformity factor are included in the figure. The equivalent limits are calculated for three engine efficiencies (190, 210 and 230 g/kWh) to demonstrate their effect.

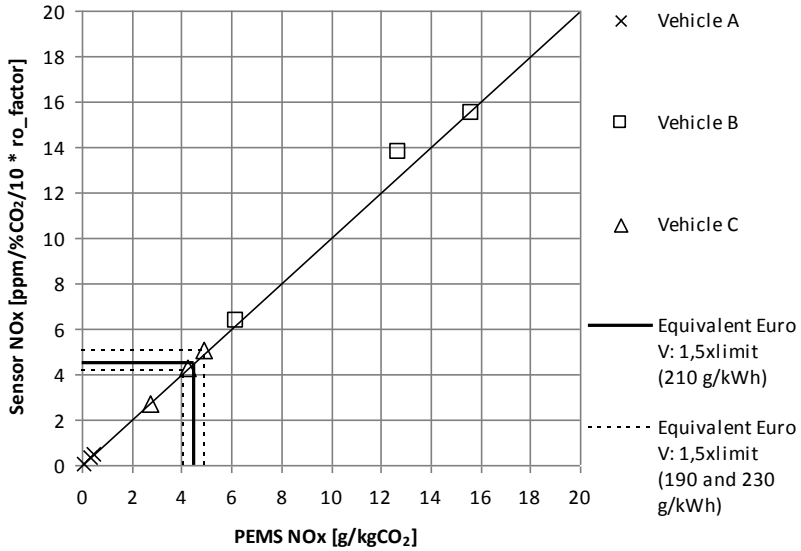


Figure 15: the CO_2 specific emissions as measured by the SEMS and based on measured concentrations, compared to the mass based emissions as measured by PEMS. Each point represents a speed interval of either 0-50, 50-75 or >75 km/h. Equivalent NO_x limits are calculated for three engine efficiencies (190, 210 and 230 g/kWh) including a conformity factor of 1,5. The inner square represents an equivalent limit based on a lower engine efficiency (230 g/kWh), the outer square represents a higher engine efficiency (190 g/kWh).

Discussion

The method based on a sensor and data-binning in speed intervals is a simplified method. This means that it is less accurate than the conventional PEMS or lab based measurements. However, measurements on recent generations of heavy-duty vehicles have shown that variations may occur from test to test (Riemersma et al., 2009), (Vermeulen et al., 2012). For the NO_x tail-pipe emissions this is caused by thermal and chemical history effects of the aftertreatment. The mentioned effects are largely caused by how a vehicle is used (payload, docking, loading/unloading situations, route and drive style). Therefore, not only the accuracy of the test is important, it may be more important to test under a wider scope of real-world driving conditions, because the variations occurring in the real-world may be larger than the accuracy of the measurement system itself.

Important criteria for a test are that the test is reproducible and that the test checks emission under representative and relevant conditions. Due to the simplicity and the low costs of operation, the SEMS tool enables to check the NO_x emissions under a wide scope of these conditions. To implement the procedure for local incentive programs or for conformity checking of vehicles in-service, the procedure should be completed with requirements for:

- the driving route, including minimum requirements for test time (per speed interval) and average speed.
- payload. Several options are at hand: a representative payload can be chosen, as well as a fixed percentage of the loading capacity. Furthermore, the choice for a range of payloads is optional. But this extends the test matrix with one dimension i.e. the number of payload variants.
- sensor and GPS accuracy and a way to check this.

So far, the procedure only proved feasible for diesel heavy-duty vehicles. Due to differences in the principle of engine operation spark-ignition engines, with a quantitative control of air-fuel mixture, need a correction for the exhaust flow. This complicates the procedure. Optionally, an empirical formula could be developed which corrects for the given effects. As a backup a PEMS measurement could be requested once the accuracy becomes doubtful or if relevant parameters are lacking. It has not yet been investigated if a correction based on an empirical formula improves the accuracy enough.

Given the principle of operation the method could be extended with more emission compounds. Important compound to judge for heavy-duty engines are for instance:

- NH_3. A sensor which can detect NH_3 slip with sufficient accuracy is already available.
- Particulate Matter. Sensors which can detect PM levels, like the OBD threshold limits, are under development.
- CH_4. For vehicles fuelled with natural gas (e.g. dual-fuel vehicles). To check methane slip, the method could be complemented with a simple methane or hydrocarbon measurement. It still needs to be investigated if this is feasible.

Conclusion

A smart emission measurement system (SEMS) was developed which is able to screen the emission performance of heavy-duty vehicles in a relative easy way, while driving a real-world trip on the road. The method is able to evaluate large quantities of data and to cover a wide scope of real-world driving conditions. The accuracy of the method is somewhat lower compared to conventional on-road measuring techniques, but this is traded for the merit to include more data under a wider scope of driving conditions at relatively low costs and a reduced complexity of the test. The rationale for such an approach is that shorter tests for the current generation of heavy-duty vehicles may not be reproducible due to the large variability in mainly emission behaviour of NO_x, which largely depends on the trip and the trip composition.

The method is based on an automotive NO_x - O_2 sensor and is combined with a GPS and data-acquisition to gather useful data about the speed profile of the vehicle during the test trip. A special data-evaluation method is used to calculate the emission performance. This method uses CO_2 as reference quantity instead of the conventional engine work. The benefit is that the on-board measurement is based on directly measurable quantities. The method still needs to be completed on some points to be able to include it in an operational emission checking procedure. For instance, a method is required to check the accuracy of the sensor. Furthermore, the method is not directly suitable for testing spark-ignition engines.

A factor which reduces the absolute accuracy somewhat is the exclusion of a dedicated exhaust flow measurement. For diesel engines this proved to be of minor influence on the final result because the data-evaluation method based on CO_2 and binning of emissions in speed intervals cancels out most of the variations caused by exhaust flow. As such, the method proved to be a tool to check the NO_x emissions in a effective, robust, relatively cheap and simple way.

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