EMIS hearing of 24 May 2016

# Answers to questions from the EMIS committee to the Netherlands Organisation for Applied Scientific Research (TNO)

May 27, 2016

## Introduction

In a long sequence of projects since 1986, TNO has been carrying out emission measurements on passenger cars, vans and heavy duty vehicles for the Dutch government (currently the Ministry of Infrastructure and the Environment). The primary purpose of these projects is to gain an understanding of the emissions of road vehicles in real-world situations under varying operating conditions. The results provide input for the process of establishing emission factors which are used in the Netherlands for policies at the national, regional and municipal level relating to air quality and overall emissions of air-polluting substances.

The insights obtained in the projects furthermore serve as input for the activities of the Dutch government and the RDW (Dutch road vehicle authority) in the context of decision making processes in Brussels (European Commission) and Geneva (GRPE) to improve emission legislation and the associated test procedures for light and heavy duty vehicles, all with the aim to reduce real-world emissions and improve air quality.

In daily use Euro 5 and 6 diesel cars are found to emit much more $NO_x$ than during the type approval test on the roller bench. The detailed results have been published by TNO in a number of reports in recent years. On average the Euro 5 and 6 diesel passenger cars tested in real-world situations emit 3 to 5 times more $NO_x$ than in the type approval test. In extreme situations, such as strong acceleration or driving at high speed, this factor may be 10 to 20. The $NO_x$ emissions of Euro 5 Class III light commercial vehicles on the road are found to be a factor of 6 higher than the limits applicable to this vehicle category.

The tests performed by TNO are not intended nor suitable for enforcement purposes and are not suitable for identifying or claiming fraud or other vehicle-related irregularities in a technically and legally watertight way. The observed high $NO_x$ emissions under real-world test conditions, as reported by TNO, can and should therefore not be interpreted as an indication for the use of so-called “defeat devices”, “cycle beating” or other strategies that are prohibited by European vehicle emission legislation. Instead the test program has been designed to generate insight in the overall real-world emission behaviour of vehicles, required for environmental policy making and evaluation, as well as inputs for the activities of the Dutch government in the context of decision making processes for improving vehicle emission legislation and the associated test procedures.

Some recent reports by TNO on the real-world emissions of light duty diesel vehicles are:

- *On-road $NO_x$ and $CO_2$ investigations of Euro 5 Light Commercial Vehicles*, report number TNO 2015 R10192, 9 March 2015.
- *Detailed investigations and real-world emission performance of Euro 6 diesel passenger cars*, report number TNO 2015 R10702, 18 May 2015.

- *Emissions of nitrogen oxides and particulates of diesel vehicles*, report number TNO 2015 R10838, 11 June 2015.
- *$NO_x$ emissions of Euro 5 and Euro 6 diesel passenger cars – test results in the lab and on the road*, report number TNO 2016 R10083, 9 March 2016
- *$NO_x$ emissions of Euro 5 diesel vans – test results in the lab and on the road*, report number TNO 2016 R10356, 17 May 2016

These reports, as well as earlier publications, can be found on:

- https://www.tno.nl/nl/aandachtsgebieden/leefomgeving/mobility-logistics/schone-mobiliteit/overzicht-rapporten-emissiemetingen-aan-personen-en-bestelauto-s/

## Answers to specific questions from the EMIS committee

**Question 1**

*Please list the available technologies for mitigation of $NO_x$ emissions and their respective advantages, disadvantages and costs. Taking into account the latest technological developments, under which ambient conditions do they work? How do ambient temperatures affect emission control technologies? What is the range of temperatures in which these technologies are technically operable, and why? Would it be possible to have emission control systems that work well in the full range of temperatures experienced in Europe?*

The main technologies are EGR, LNT and SCR. A combination of technologies is needed to meet Euro 6 emission limits. This can be illustrated with a back-of-the-envelope calculation:

A traditional diesel engine (without emission control measures) typically produces 7-10 grams of $NO_x$ per kilogram of $CO_2$. For a vehicle that on average emits 95 g/km $CO_2$, this leads to engine-out emissions of 0.8 g/km $NO_x$. A 90% reduction is therefore needed to meet the Euro 6 limit of 80 mg/km. In many circumstances, especially at higher driving speeds and high constant engine load, this can be achieved with SCR only. The additional use of EGR has two main advantages: Firstly an initial reduction of engine-out $NO_x$, especially at low transient loads where SCR is less effective, of around 20% to 70% dependent on the driving conditions. Secondly the use of EGR leads to higher exhaust gas temperatures which helps to keep SCR and/or LNT aftertreatment systems at effective operating temperatures.

OEMs currently seem to favour application of LNT over SCR in many Euro 6 vehicles. Our measurements indicate that the applied strategies are not (yet) sufficiently robust for controlling $NO_x$ emissions under real-world conditions. In particular high emissions are observed in rural driving where engine loads are favourably high but insufficiently constant to allow effective buffering and controlled regeneration of the LNT.

All vehicles meet the emission limits on the type approval test. This proves that the applied technologies are in principle able to achieve the required low $NO_x$ emission levels. There are only a few possible reasons why this would not be the case under all driving circumstances:

- Higher engine loads than those experienced on the type approval test and for which the systems have been designed, leading to higher $NO_x$ emissions. Higher loads may be the result of higher speeds (e.g. >130 km/h) or accelerations than on the NEDC, but also result from the fact that the vehicle's road load in reality is higher than the values simulated on the roller bench. This, however, is not the core of the current problems as strongly elevated $NO_x$ emissions are currently also observed under real-world driving conditions that have (low) engine loads similar to those required on the NEDC (e.g. city traffic).

- Applying high levels of EGR may lead to reduced engine cooling. This may cause problems in situations with prolonged high engine loads, such as driving at high speeds on highways. The trend towards smaller engines, as a means to reduce $CO_2$ emissions, may increase this problem. However, engine cooling can be improved with existing technologies. Furthermore the problem can be solved by relying less on EGR operation by combining EGR with SCR.
- Specific optimisation of the control strategy of engine and aftertreatment towards the NEDC test. If this is the case it is a choice made by OEMs. The NEDC in principle covers a reasonable part of the speeds and accelerations occurring on the road, but due to its stylized nature the NEDC lends itself to specific optimisation.
- Protection of the engine, in particular the EGR's intercooler. Manufacturers claim that EGR systems may suffer from intercooler clogging (deposition of a "lacquer") at low inlet air temperatures. This is said to lead to increased vehicle maintenance. The need to avoid this may be enhanced by durability demands in the emission legislation.
  - TNO regards the information provided by manufacturers on this issue as technically plausible, but has not verified the statements. Also TNO does not give any judgement on the extent to which explanations provided are acceptable in the light of the emission regulation.
  - We believe that EGR problems related to low air inlet temperatures can be solved, as there is plenty of waste heat available in the engine to heat up the intake air.
  - We do not believe that switching-off of the LNT or SCR can be justified for reasons related to protection of the engine.

TNO is convinced that it is technically feasible to reduce $NO_x$ emissions in practice over the full range of normal driving conditions experienced in Europe using existing technologies. Available test results from different labs on a number of vehicles show that a good combination of the various reduction methods that exist can produce a real-world emission performance that does come close to the type approval value. So no new technology has to be developed to achieve lower real-world $NO_x$ emissions. However, the existing components and control strategy must be adapted to be functioning in a wide range of common ambient and vehicle operation conditions. This may require some hardware changes, especially for proper thermal management and dimensioning of the systems for extended high engine loads, uncommon on the type-approval tests.

**Question 2**

*Is it technically possible to reduce fuel consumption (and hence $CO_2$ emissions) and $NO_x$ emissions at the same time or, given the physical nature of combustion, focusing on reducing consumption entails higher $NO_x$ emissions and vice-versa? What would be the best technical solution to reconcile these goals? Is it possible for car manufacturers to comply with $CO_2$ limits for the fleet average and respect $NO_x$ thresholds with current diesel technology?*

Yes, it is technically possible to reduce fuel consumption (and hence $CO_2$ emissions) and $NO_x$ emissions at the same time. At the engine level there is a trade-off between energy efficiency and

$NO_x$ emissions, but since emission aftertreatment systems are required to meet Euro 6 emission limits, fuel consumption (and hence $CO_2$ emissions) and $NO_x$ emissions are essentially decoupled.

Applying EGR has a direct - though limited - $CO_2$ penalty through reduced engine efficiency. SCR, LNT and DPF increase the exhaust back pressure and/or require regeneration which leads to higher fuel consumption and $CO_2$ emissions (most prominent for DPF). Overall, however, the fuel consumption penalty of $NO_x$ aftertreatment technology is a few percent. Assessments in support of the EU LDV $CO_2$ legislation have shown that the full potential of technical measures available for reducing $CO_2$ emissions, which includes many more options besides measures to improve engine efficiency, is more than sufficient to meet the short and longer term $CO_2$ targets (130 g/km in 2015 and 95 g/km in 2021 for passenger cars). In addition the utilisation of test flexibilities allows manufacturers to meet the $CO_2$ targets with less technology and at lower costs than foreseen (at the expense of the legislation's effectiveness for reducing real-world $CO_2$ emissions). Applying some additional $CO_2$ reduction technology to compensate for the modest fuel penalty caused by $NO_x$ emission control measures therefore does not involve prohibitively high costs.

The fact that both $NO_x$ limits and $CO_2$ standards can be met is furthermore proven by the current generation of Euro 6 vehicles, which meet both standards simultaneously on the type-approval test in the lab.

High $NO_x$ emissions in real-world operation of vehicles is in our view to a large extent not caused by insufficient reduction capacity of the available technologies, but by insufficient levels of application of these technologies and insufficient operation of the applied technologies resulting from the control strategy implemented by the OEM. The latter is proven by the fact that strongly elevated $NO_x$ emissions are also observed under real-world driving conditions that have (low) engine loads similar to those required on the NEDC (e.g. city traffic).

**Question 3**

*The $NO_x$ emission control techniques available at the time of adoption of the Euro5/6 legislation, and the ones that have shown best results in tests, are exhaust gas recirculation (EGR), lean $NO_x$ trap (LNT) and selective catalytic reduction - AdBlue (SCR). Is it technically possible to meet $NO_x$ emission limits of 80 mg/km in normal driving conditions with a combination of these technologies? If so, since when has it been possible? Is it possible without using all three at the same time? With LNT alone? Can a $NO_x$ limit of 200 mg/km be met without the need for after-treatment? According to a TNO report from 2005, with which technologies would it be possible to meet a $NO_x$ limit value of 75 mg/km in addition to a PM limit of 2.5 mg/km, and at what additional cost? What about the US $NO_x$ limit of 43.5 mg/km?*

As stated above it is technically possible to meet $NO_x$ emission limits of 80 mg/km in normal driving conditions with a combination of EGR, LNT and/or SCR. Based on available information TNO believes that a combination of at least EGR and LNT or EGR and SCR is necessary. Under the full range of normal driving conditions a $NO_x$ emission level of 200 mg/km cannot be met without one or more of these technologies.

Due to the application of closed DPF Euro 6 diesel cars have real-world PM emissions well below 2.5 mg/km. As a $NO_x$ limit of 75 g/km is close to the existing Euro 6 limit, it is concluded that a $NO_x$ limit value of 75 mg/km combined with a PM limit of 2.5 mg/km can be achieved with a combination of EGR, LNT and/or SCR and a DPF. TNO has not made any assessments of the feasibility and costs or meeting the US $NO_x$ limit of 43.5 mg/km for diesel cars.

It should be noted that g/km-based limits can by definition not be met under all driving circumstances. Emissions are generally higher at very high speeds or engine loads as well in situations which involve a large share of idle running of the engine (stop & go). Running idle at standstill leads to infinite emissions per kilometre driven.

**Question 4**

*Have there been any recent developments in $NO_x$ emission reduction techniques? For instance, in order to contribute to closing the gap between emission measured during type-approval tests and real world emissions, do catalyst systems need better calibration, or to advance their technical development?*

As stated above no new technology has to be developed to achieve lower real-life world $NO_x$ emissions. Also further technical development of existing options does not appear crucial. The existing technology must be better accommodated in the development of new and or modification of existing models and diesel engines. This involves proper dimensioning of the systems to provide sufficient reduction capacity, appropriate calibration (in the case of SCR application of sufficient amounts of AdBlue needs to be administered under all driving circumstances) and possibly better thermal management to avoid EGR problems related to low air inlet temperatures, and ensuring warm and functioning SCR and LNT.

**Question 5**

*Would after-treatment systems effective for $NO_x$ abatement substantially increase the fuel consumption of vehicles and result in high production costs, in particular in the case of small engines, as claimed by some manufacturers? Would they influence engine performance, and how? Could more efficient emission control technology used in large engines be used in small engines?*

As stated above the fuel penalty of $NO_x$ abatement technologies is limited to a few percent and can be easily compensated by applying additional $CO_2$ reduction measures.

Over the last years the share of diesels has particularly increased in the A and B segment. It is plausible that applying combinations of EGR, LNT and SCR at levels needed to meet Euro 6 $NO_x$ standards for diesels under all (normal) driving conditions leads to a relative cost increase for diesels in these segments that would make them unattractive compared to petrol vehicles. Full application of these $NO_x$ reductions technologies may also be challenging in view of the extremely small profit margins that OEMs have for vehicles in these segments. Here it should be noted, however, that increasing the share of diesels in the new vehicle sales was not included in the range of compliance mechanisms assessed for the 95 g/km $CO_2$ target. Costs for meeting the target have been assessed under the assumption of constant shares of petrol and diesel vehicles relative to the 2009 situation, and have been considered acceptable both from a societal as well as an end-user perspective. Reduced sales of diesel vehicles in the A and B segments is therefore not considered to reduce the attainability of the 95 g/km $CO_2$ target.

**Question 6**

*Can you describe the differences, if any, of the drivetrain and emissions mitigation technology of same model vehicles, destined for the US and the EU markets?*

In diesel vehicles destined for the US and EU markets the same main technologies are applied. The first series of Euro 6 (compatible) diesel passenger cars tested by TNO, back in 2010, were actually models designed for the US market which contained the same technologies – EGR, SCR and LNT – that are currently applied in EU models.

TNO does not have insight in possible differences in dimensioning of system components or calibration and control strategies of vehicles for the US and EU markets.

**Question 7**

*Are all $NO_x$ abatement techniques vulnerable to manipulation by software defeat devices, and why? What is the reason why $NO_x$ control techniques are not operated in full, at all speeds and ambient temperatures? What is the reason why reduction technologies are active and effective during type approval tests, but can be partly switched off during real world operation?*

Yes, all systems are software controlled and can therefore be manipulated.

TNO does not have first-hand insight in the motivations of OEMs to apply control strategies that lead to the observed high real-world emissions. Also TNO does not give any judgement on the extent to which explanations provided by OEMs are acceptable in the light of the emission regulation. As stated in the answer to question 1, TNO is not aware of any fundamental technical reasons why the $NO_x$ emission limits could not be reached under a wide range of normal operating conditions.

As far as AdBlue dosing is concerned possible reasons for OEMs to limit the AdBlue consumption could be weight reduction (smaller AdBlue tank), avoiding the need to refill in between service events or reduction of costs for the end-user.

**Question 8**

*Regulation 715/2007 prohibits the use of defeat devices, but there are derogations that permit the use of defeat devices under certain conditions such as protection of the engine against damage or accident and for safe operation of the vehicle. How can reduced effectiveness or the complete deactivation of emission control systems prevent accidents or engine damage? What kind of everyday situations would make it necessary to deactivate or reduce the effectiveness of emission control systems, and how likely are those situations?*

As mentioned under question 1 manufacturers claim that EGR systems may suffer from intercooler clogging at low inlet air temperatures. Reduced operation of the EGR could be a strategy to avoid engine damage. We believe, however, that EGR problems related to low air inlet temperatures can be solved, as there is plenty of heat available in the engine to heat up the intake air.

We see no reasons to reduce the use of LNT or SCR to prevent engine damage.

**Question 9**

*You have tested Euro 5 and Euro 6 vehicles available on the market as regards the performance of $NO_x$ emission control techniques. Have you acquired direct or indirect knowledge of cars fitted with defeat devices? Did you share your results for the concerned vehicle models/engines with the relevant national type approval authorities and the Commission? If yes, which national authorities and Commission DGs were informed, and when? If not, why not?*

First of all it should be pointed out that the current legislation is quite unclear with regard to the definition of what is a “defeat device”. This makes it difficult to judge which observations could be considered as possible direct or indirect evidence of the use of a “defeat device”.

The tests performed by TNO are not intended nor suitable for enforcement purposes and are not suitable for identifying or claiming fraud or other vehicle-related irregularities in a technically and legally watertight way. The observed high $NO_x$ emissions under real-world test conditions can and should therefore not be interpreted as an indication for the use of so-called “defeat devices”, “cycle beating” or other strategies that are prohibited by European vehicle emission legislation.

An observation that, with the knowledge of today, could be interpreted as a possible indirect indication is the fact that in our tests many vehicles showed higher $NO_x$-emissions on an NEDC-test started with a warm engine than on the official NEDC-test started with a cold engine (preconditioned between 20 – 30 °C). Similar behaviour is seen in tests on the road starting with a cold or warm engine. This counter-intuitive effect has been described in previous TNO-reports, and is also mentioned in our recent report *$NO_x$ emissions of Euro 5 and Euro 6 diesel passenger cars – test results in the lab and on the road* (report number TNO 2016 R10083).

The test program, carried out by TNO for the Dutch Ministry of Infrastructure and the Environment, has been designed to generate insight in the overall real-world emission behaviour of vehicles, required for environmental policy making and evaluation, as well as inputs for the activities of the Dutch government in the context of decision making processes for improving vehicle emission legislation and the associated test procedures. Regardless of the technical origin, the high real-world NOx emissions of modern diesel cars, as observed in our tests, significantly contribute to the difficulties European cities have in meeting the EU air quality standards. Over the last 5 years the Dutch Ministry of Infrastructure and the Environment and TNO have frequently asked attention for this problem, both at the national and the European level. This has been done through publications, the organisation of public stakeholder meetings on the subject and by providing technical input in various committees and working groups. In Brussels the Dutch Ministry of Infrastructure and the Environment together with the Dutch road vehicle authority RDW, with technical support from TNO, have actively contributed to the development and implementation of regulatory measures intended to solve this problem.

Upon request of our client, the Dutch Ministry of Infrastructure and Environment, TNO has over the last years regularly shared test results or overall insights obtained from the test programme with the European Commission (DG Enterprise/DG Growth, DG Environment, JRC).

Results of our tests have been shared with, and in many cases also discussed with the respective importers and manufacturers.

Until recently TNO did not share results for the concerned vehicle models/engines with the relevant national type approval authorities. Upon request of the Dutch Ministry of Infrastructure and the Environment TNO now shares detailed test results with reference to make and model with the Dutch road vehicle authority RDW, which can inform the relevant Type Approval Authorities if appropriate. This is done since February 2016, and includes results of tests carried out since 2010.

Reports with results from TNO's test programme for the Dutch Ministry of Infrastructure and Environment are public. Until recently test results were always anonymized, i.e. presented without reference to make or model. As from 2016 TNO will publish all test results with reference to make and model. Detailed results from the tests carried out in the 2010-2015 period have recently also been published with reference to make and model (See TNO 2016 R10083 - *$NO_x$ emissions of Euro 5 and Euro 6 diesel passenger cars – test results in the lab and on the road* and TNO 2016 R10356 - *$NO_x$ emissions of Euro 5 diesel vans – test results in the lab and on the road*).

**Question 10**

*How reliable are portable emissions measurement systems (PEMS)? What technical limitations do PEMS have on the road? Do you think the accuracy of PEMS within the next five years would be sufficient to evaluate on-road emission precisely? Would research on PEMS need additional funding to ensure the development of viable and reliable measurement systems?*

PEMS equipment is well suited for performing on the road real-world emission tests, not only for assessment purposes but also in a legislative context such as RDE. The overall inaccuracy of $NO_x$-measurements with current generation PEMS equipment is around [plus or minus] 30%. This results from a combination of variations in reproducibility of 20% and a direct measurement inaccuracy of 20%. JRC came to a similar uncertainty in an assessment of their test program.

Rules in the legislation for establishing (non)compliance with the RDE requirements can be designed in such a way that proper account is taken of the measurement inaccuracies related to using PEMS and testing on the road.

Second generation PEMS systems could be more accurate. The three main sources of inaccuracy are: First, the flow measurement used to translate measured concentrations to absolute emissions. Second, inaccuracy in span and offset of the concentration measurement, which has improved with the second generation PEMS equipment. This inaccuracy is important especially at low concentrations observed in well-performing vehicles. Third, poor operation practice and mounting of PEMS equipment in harsh and vibrating conditions.

The largest measurement errors are caused by inaccuracies in the exhaust flow measurement. We see a tendency of PEMS manufacturers to apply cheaper and less accurate flow meters. In addition exhaust systems with multiple tailpipes increase this inaccuracy further.

Furthermore the reliability of PEMS measurements is affected by (variations in) the ambient conditions to which the PEMS unit is subjected. Proper system conditioning is essential. Mounting the PEMs inside the vehicle (e.g. in the trunk) provides more constant operating conditions than mounting outside the vehicle and also increases reliability of the measurements.

Setting absolute demands on PEMS accuracy could help to make sure that systems are further improved.

**Question 11**

*What is your opinion of the current and future state of the diesel vehicle technology? Has the diesel engine reached its technical potential, or can it improve in terms of fuel efficiency and emissions, and how? Would future improvements rather come from the combustion technology itself (such as advance combustion modes or Exhaust Gas Recirculation), from after-treatment such as SCR, or from working on the diesel fuel itself? Would retrofitting certain diesel-engine passenger cars with additional emission-mitigation technology be viable, and what would be the cost?*

As mentioned above TNO believes that it is technically feasible for diesel vehicles to achieve real-world emissions close to the Euro 6 limits by appropriate application of existing emission reduction technologies. Implementation of such improvements can be effectively enforced by adding an effective Real Driving Emissions (RDE) test to the type approval, as proven by the developments in Euro VI heavy duty vehicles.

It should be emphasized that the effectiveness of RDE legislation does not only depend on the stringency of the Conformity Factors. Details of the test procedure and the evaluation method, used for translating the measurement results to a number to which the Conformity Factor is applied, are equally important for the effective stringency of the legislation. This includes a broad window of acceptable test conditions (related to e.g. driving behaviour and ambient temperature), appropriate methods for evaluation of test results, and the possibility of independent validation tests. Essential for RDE's effectiveness with respect to improving urban air quality is also the introduction of a separate evaluation of emissions in urban traffic conditions.

Diesel engines have limited potential for further efficiency improvements, but significant improvements of vehicle fuel consumption and $CO_2$ emissions are possible by application of a wide range of other technical measures (e.g. related to transmissions, powertrain hybridisation, weight reduction and reduced air drag and rolling resistance). Extreme levels of engine downsizing (as a measure to improve engine efficiency) could be less compatible with meeting Euro 6 emission limits than previously considered.

Measures related to fuel quality or composition have negligible impact on the direct emissions and fuel efficiency of modern diesel cars. However a good fuel quality is needed to assure proper functioning of fuel injection equipment over the lifetime of the vehicle.

Retrofitting existing diesel-engine passenger cars with additional emission-mitigation technology does not seem viable due to the required integration of these technologies in the engine control systems, and required hardware changes in the vehicle. Updating control software could provide a means to improve the real-world emission performance of existing vehicles, but technical feasibility (and impacts on durability) need to be assessed.

**Question 12**

*Do you have access to software, source code or technical documentation for Emission Control Units (ECU) in car engines? Can you list any contractual obligations such as non-disclosure agreements, grant agreements, non-compete clauses in work contracts the TNO has or individual employees at the TNO have that prevent, restrict or otherwise influence their ability to conduct research of or publish about ECUs and its components?*

The Sustainable Transport & Logistics department of TNO does not have access to software, source codes or technical documentation for Emission Control Units (ECU) in car engines of the vehicles which it tests for the assessment of real-world emission performance as part of the contract for the Dutch Ministry of Infrastructure and the Environment.

In R&D projects carried out by other TNO departments for clients in the automotive industry TNO may have access to software, source codes or technical documentation for ECUs. If that is the case, the availability of such information to TNO is subject to confidentiality agreements.