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**Demonstration of Extremely Low NO_x Emissions with Partly
Close-Coupled Emission Control on a Heavy-duty Truck Application**

**Darstellung extrem niedriger NO_x-Emissionen an einem Heavy Duty
Truck durch Einsatz einer anteilig motornahen Abgasanlage und
optimierter Abgasnachbehandlungsstrategie**

Abstract

Based on the technologies required to comply with the Euro VI-D emission standards, this paper examines ways to improve these technologies to meet future regulatory requirements. Experimental results including PEMS measurements obtained while operating from a demonstrator vehicle on public roads will be shown, including a variety of local and regional delivery operations as well as current Euro VI in-service conformity trips. Special attention will be given to the robustness of the emission performance at cold and urban low load stop and go driving.

The paper discusses how NO_x emissions can be reduced to ultra-low levels in a broad range of operating conditions. This is achieved through an enhanced integration of proven emission control technologies with an advanced engine strategy on an existing Euro VI long-haul truck.

The innovative exhaust aftertreatment layout combines a close-coupled Diesel Oxidation Catalyst (ccDOC) with an adapted catalyst setup within the available space of the standard control emission box (EATS box). The technology package includes two sections of Selective Catalytic Reduction (SCR/ASC), a twin urea dosing system, a catalysed diesel particulate filter (cDPF) and Ammonia Slip Catalysts (ASCs). The location of the first SCR at the entry of the EATS box enables a very early start of the NO_x conversion due to fast warm-up. In addition, the close coupling of the first DOC to the turbocharger exit prevents poisoning of the SCR by HC/CO and increases the NO₂/NO_x ratio. Behind the first DOC a urea injector and mixer are included in the downpipe leading to a homogeneous urea feed to the ccSCR. This configuration will allow lowest NO_x emissions at low engine load and vehicle speed as well as during cold-start operation. A hydrocarbon injector is located downstream the SCR for thermal management of the DOC and cDPF in terms of passive and active regeneration. Finally, the second urea injector will feed the second SCR to govern the NO_x emissions when the SCR has reached sufficient temperature for dosing release at high engine load and vehicle speed operation. Both SCR catalysts include downstream ASC for ammonia slip reduction. A smart and advanced control strategy is implemented to ensure optimal interaction between all components. Additionally, the pollutants NH₃, N₂O and PN₁₀ will be investigated.

Finally, some limitations of the demonstrator system will be discussed as part of the outlook.

Kurzfassung

Ausgehend von den Technologien, die zur Einhaltung der Euro VI-D-Emissionsgrenzwerte erforderlich sind, werden in diesem Beitrag Möglichkeiten zur Verbesserung dieser Technologien untersucht, um die zukünftigen gesetzlichen Anforderungen zu erfüllen. Es werden experimentelle Ergebnisse einschließlich PEMS-Messungen gezeigt, die während des Betriebs eines Demonstratorfahrzeugs auf öffentlichen Straßen gewonnen wurden, einschließlich einer Vielzahl von Einsätzen im lokalen und regionalen Lieferverkehr sowie von aktuellen Euro VI-Konformitätsfahrten. Besonderes Augenmerk wird auf die Robustheit des Emissionsverhaltens bei kalten und städtischen Stop-and-Go-Fahrten mit geringer Last gelegt.

Es wird erörtert, wie die NO_x-Emissionen in einem breiten Spektrum von Betriebsbedingungen auf extrem niedrige Werte reduziert werden können. Erreicht wird dies durch eine verbesserte Integration bewährter Technologien zur Emissionsreduzierung in

Verbindung mit einer fortschrittlichen Motor- und Emissionskontrollstrategie an einem bestehenden Euro VI Fernverkehrs-LKW.

Das innovative Abgasnachbehandlungskonzept kombiniert einen motornah verbauten Dieseloxidationskatalysator (ccDOC) mit einer angepassten Katalysatoranordnung im Bauraum der Standard-Abgasnachbehandlungsbox (AGN-Box). Zu den verwendeten Technologien zählen zwei Einheiten zur selektiven katalytischen Reduktion (SCR), ein Doppel-Harnstoffdosiersystem, ein beschichteter Dieselpartikelfilter (cDPF) und Ammoniak-Schlupfkatalysatoren (ASC). Die Positionierung des ersten SCR direkt am Eintritt der AGN-Box vor DPF ermöglicht aufgrund des schnellen Aufheizens einen sehr frühen Start der NO_x-Konversion. Der direkt dem Turbolader nachgeschaltete ccDOC verhindert gleichzeitig eine Vergiftung dieses SCR durch HC/CO und erhöht das NO₂/NO_x-Verhältnis. Stromabwärts des ccDOC befindet sich der erste AdBlue-Injektor gefolgt von einem Mischer für optimale Gleichverteilung in der Rohrleitung zur AGN-Box. Dieser Injektor speist den ccSCR zur Reduzierung der NO_x-Emissionen primär im Kaltstartbetrieb sowie in Bereichen niedriger Motorlast und Fahrzeuggeschwindigkeit. Zwischen dem ccSCR und dem cDPF befindet sich ein Diesel-Injektor für die thermische Regulierung des DOC und des cDPF zur passiven und aktiven Regeneration. Der in typischer Position am Austritt der AGN-Box liegende zweite SCR wird durch einen zweiten Harnstoffinjektor unabhängig gesteuert, sobald die Temperaturschwelle für die Dosierfreigabe erreicht ist. Dieses zweite SCR-System ist vor allem für den Betrieb bei hoher Motorlast und Fahrzeuggeschwindigkeit ausgelegt. Beide SCR Systeme beinhalten nachgeschaltete ASC zur Ammoniakschlupfminderung. Eine fortschrittliche und gesamtheitliche Regelstrategie für beide SCR ist implementiert, um ein optimales Zusammenspiel aller Komponenten zu gewährleisten. Zusätzlich werden während der Fahrzeugversuche neben der Demonstration der Niedrigst-NO_x-Emissionen die wahrscheinlich künftig ebenfalls regulierten Schadstoffe NH₃, N₂O und PN₁₀ untersucht. Abschließend werden einige Einschränkungen des Demonstratorsystems im Rahmen des Ausblicks diskutiert.

Introduction

Clean air is essential to our health and to the environment. Despite a global strategy to improve air quality, the effects of poor air quality are still very visible throughout the world. One of the main areas for the improvement of local, regional, and global air quality is the transport sector. Within this sector, improvements in engine and Exhaust Aftertreatment System (EATS) efficiency have resulted in remarkable reductions in noxious and particulate emissions in recent years. The Euro VI regulation has been revised several times, helping to improve the on-road emissions of these vehicles. However, challenges remain, as it is explained below.

The Euro VI emission standards [1] for heavy-duty vehicles entered into force in January 2013. The type approval process for the engines of these vehicles includes two sets of emissions cycles: stationary engine operation using the World Harmonized Stationary Cycle (WHSC) and transient testing using the World Harmonized Transient Cycle (WHTC). As both cycles are conducted on an engine test bed and performed in a laboratory, they are not always representative of vehicle operating conditions, including the variations of vehicle size and weight. The introduction of a Portable Emission Measurement System (PEMS) demonstration test at type approval, combined with on-road in-service conformity testing allows for better analysis of the emission performance of these vehicles while driving on public roads. Furthermore, the recent introduction of Euro VI step E, applicable for new vehicles registered from the beginning of 2021, ensures that for the first time, the cold-start emissions are included in the calculations that determine if a vehicle is compliant to the Euro VI regulation. In addition, a limit has been introduced for the solid particulate number (PN) measured with PEMS.

Up until now regulations use post processing on the raw data which excludes some key data from the overall emissions assessment. This often results in significant amounts of data not being considered for the final emission calculation of the vehicle. When these areas of data, including a lot of peak and low power driving, are removed, a large contribution to emissions is no longer considered. The excluded data contains high emission levels, in particularly under urban driving conditions and low load operation [2] – [4].

The ISC tests prescribed by the regulation today, also have very strict requirements and as such do not fully cover driving conditions trucks encounter frequently on the road. This includes heavy and static traffic or the transition from highway to urban operation. During these conditions, the exhaust gas aftertreatment system will potentially cool down and lose conversion efficiency.

To understand the impact of excluding data on the overall emissions performance, AECC conducted a study to demonstrate emissions performance without applying the current legislative processing rules [5]. The figure below shows the results from four Euro VI compliant heavy-duty vehicles. The data show speed binned tailpipe emission, without post processing. These vehicles represent different regulatory steps within Euro VI. A progression to lower emissions at urban operation can be seen from A to D, as the Euro VI regulatory evolution has focused on increased representation of urban vehicle operation. This has increased the need for technology innovation with improved emissions control at these conditions.

Despite improved technologies and performance, the data show emissions increase under specific conditions compared to when all data is considered, and above the Euro VI not-to-exceed threshold.

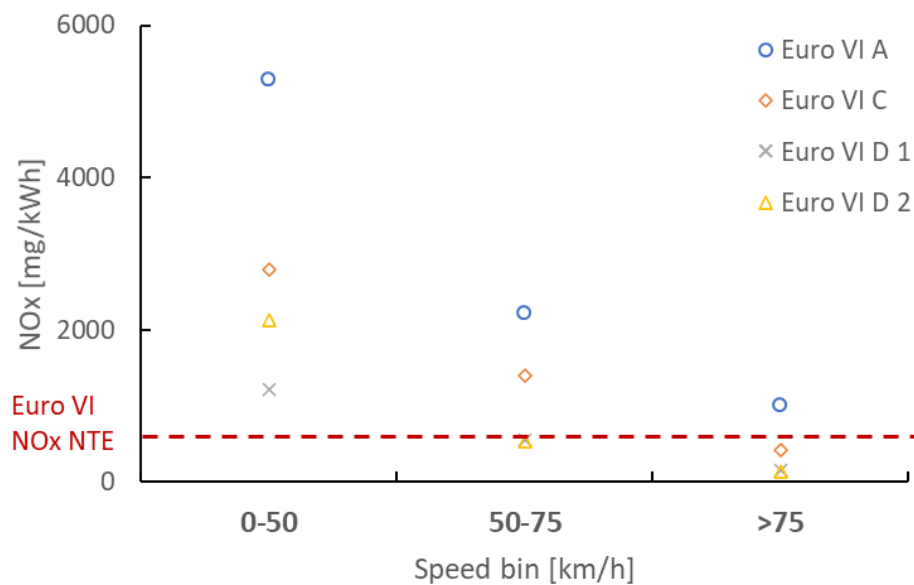


Figure 1: Euro VI vehicles NOx emission performance.

To develop legislation to achieve lower pollutant emissions in real-world driving conditions, the European Commission began the process of reviewing the emissions standards for cars, vans, trucks, and buses in 2019. The objective expressed by the European Commission is to ensure clean vehicles throughout their expected lifetime measured in real-world driving. The expected introduction of Euro VII standards is intended to further significantly reduce emissions from heavy-duty vehicles with internal combustion engines in order to improve air quality on the roads and especially in cities. Thereto, it is crucial that heavy-duty vehicles reduce their emissions over operation conditions where high emissions events are still found, like operation during cold-start and in stop and go traffic. Non-regulated pollutants need also to be considered: this means that NO_x conversion needs to be balanced against the emissions of ammonia (NH₃), nitrous oxide (N₂O) and ultrafine particulates (PN₁₀) even in the most challenging conditions.

A project was set up to investigate an improvement in emission control over the full operational window of a N3 heavy duty vehicle. A combination of a newly designed aftertreatment technology system layout and a NO_x emissions control system were implemented on a N3 heavy-duty vehicle. The objective was achieving ultra-low levels of emissions over a wide range of driving conditions while minimizing the impact on CO₂ emissions.

An initial simulation study was conducted to determine the optimal EATS sizing and layout to achieve lowest possible pollutant emissions. The system was calibrated for enhanced NO_x conversion finding a balanced optimized urea dosing to achieve lowest secondary emissions of NH₃ and N₂O. Finally, the vehicle was used to demonstrate improved emissions performance with a focus on the emissions at cold-start and in urban operation (e.g. city start and delivery) using PEMS measurement. Furthermore, currently non-regulated, "secondary" pollutant emissions (NH₃, N₂O and PN₁₀) have been measured to investigate an overall balanced overall emissions performance.

Technology strategy

Exhaust Aftertreatment System Layout

To ascertain the optimal system configuration and sizing, a simulation study was conducted using FEV's SimEx software [7]. The study evaluated the impact of different layout combinations, catalyst volumes and materials based on project engineering targets. The simulation study was conducted with 50% and 100% loading over established emissions cycles (WHVC) as well as compliant (In-Service Conformity) and non-compliant (urban and rural delivery) routes. The study also focused on worst case cold-start driving scenarios.

The engine behavior was simulated using FEV benchmark engine and emissions maps. Maps for both normal operation mode and "heating" mode were used to assess the potential impact of heating modes on both CO₂ and NO_x raw e and tailpipe emissions. The combined heating & low NO_x strategy was deployed at cold-start and the heat mode remained active until a desired gas temperature within the upstream SCR is reached.

The urea dosing for the SCR system was predicted using base urea dosing control algorithms, and the pipework was modelled to determine heat loss between components. An additional heat management strategy using HC dosing was considered. This is activated once the DOC average temperature reached 220°C. It remains active until the desired temperature within the DPF or SCR is achieved.

The simulated cycle and routes were: a standard WHVC cycle; a compliant ISC route with an average speed of 52km/h containing 9% idling conditions; a local delivery route with an average speed of 28km/h containing 52% idle and a regional delivery route with an average speed of 65km/h containing 12% idle conditions.

The main conclusions from the simulation study were that the integration of the close-coupled components significantly improve the NO_x reduction efficiency in all investigated cycle and routes, especially within the cold-start and long idling phases. Figure 2 shows the simulation results of the improvement on the heat up temperature of the close-coupled SCR vs the under-floor SCR from the base system.

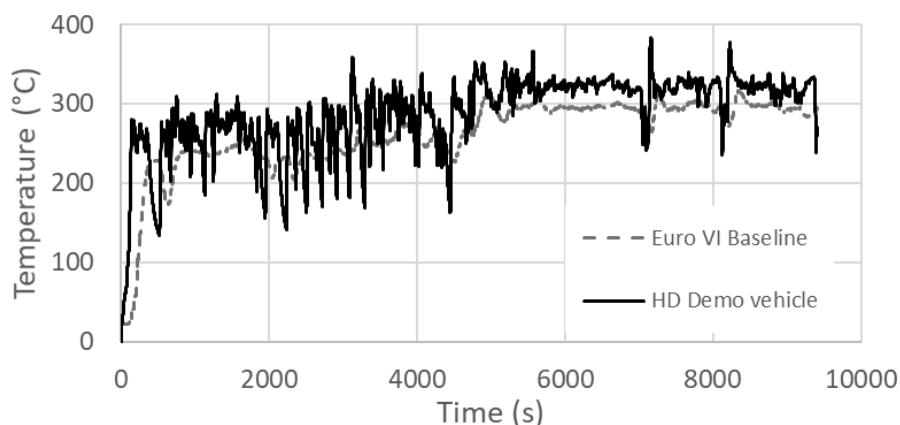


Figure 2: Simulation results showing the heat up temperature of the ccSCR improvement vs the baseline SCR system.

As pointed out, the simulation study determined that integrating a close-coupled SCR system significantly improves low temperature and urban driving NO_x reduction in comparison to the baseline EU-VI emissions control system. The original baseline EATS

box configuration contained a standard DOC, DPF, SCR and ASC layout and was simulated with all series application-based heating measures.

The final layout resulted in an exhaust line containing two separate Selective Catalytic Reduction (SCR) systems – one close-coupled, and another one in a regular underfloor position to be implemented to the truck. An example of the simulated cumulative NO_x tailpipe by the EU VI baseline vs. the demonstrator EATS for an ISC trip is shown in figure 3.

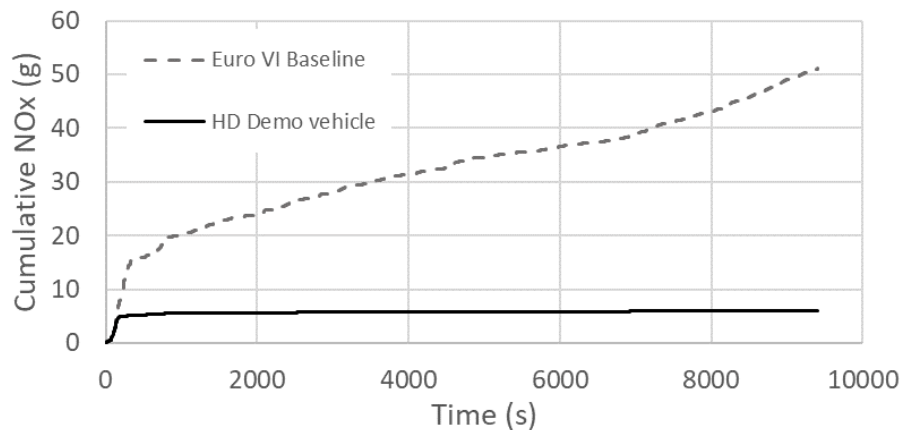


Figure 3: Simulated cumulative emissions results of the HD demo vehicle system vs the base Euro VI system performance during an ISC trip.

The initial complete configuration was specified as follows: a close-coupled 7L DOC, followed by a 14L SCR, a second 7.5L DOC, an 18L DPF and a 30L underfloor SCR/ASC. Modifications on the initial configuration were made based on the packaging constraints and the increased focus on worst case urban driving conditions, including 10% payload. It is important to have a good flow distribution and keep the exhaust back pressure within a reasonable range. Therefore, the ratio of the SCR components was altered so the close-coupled volume was larger on the demonstrator vehicle. The final configuration included a 25L ccSCR and a 25L ufSCR as shown in figure 6 below.

EATS Design and Integration

The design considered the OEM original system layout and packaging as well as the aerodynamics of the truck. Resulting in as much of the aftertreatment system as possible being installed within a box, equivalent to that of the baseline vehicle.

A close-coupled DOC was fitted directly behind the turbo for fast CO and HC control and to allow optimal heat transfer into the EATS system. The outlet cone of the DOC was modified to integrate a urea injector (figure 4a), allowing the use of the downpipe and compensator for optimal mixing of the injected urea before entering the close-coupled SCR contained directly within the box. The close-coupled SCR has a zone coated Ammonia Slip Catalyst to ensure minimized secondary emissions creation. This close-coupled system was integrated with the purpose of improving the cold-start, low temperature and city driving emission performance.

Downstream of the close-coupled SCR system, the component layout resembles that of a conventional truck EATS design (figure 4b), containing a DOC and DPF with integrated HC doser for DPF regeneration support. Downstream of the DPF is a second urea injector and mixing pipe before the second SCR with an integrated ASC to minimize ammonia slip. This

system is to support motorway driving and allow the potential for passive regeneration capability to be maintained to allow for a longer active regeneration interval allowing for potential cost and CO₂ saving potential. All integrated components were hydrothermally aged to represent full useful life aged conditions.

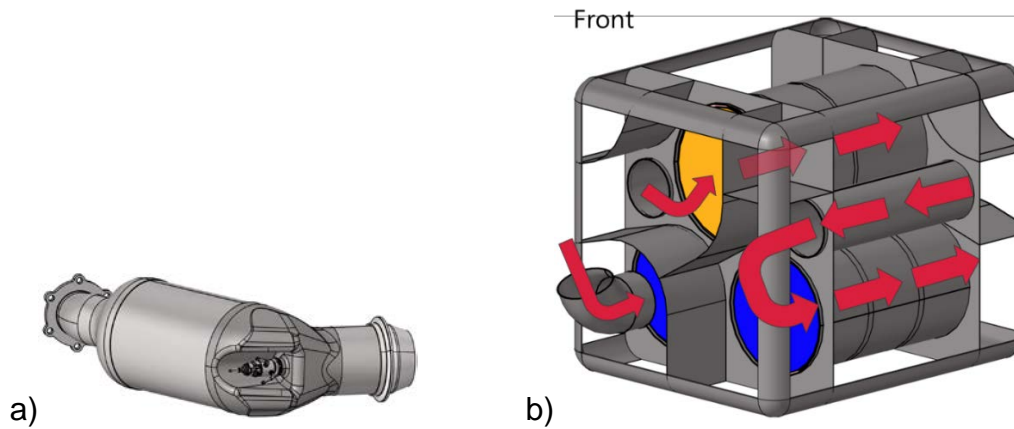


Figure 4: a) close-coupled DOC with integrated urea injector and b) EATS box containing the close-coupled SCR as well as the DOC/DPF and SCR/ASC system.

The pipework was modified as required to allow optimal flow, temperature and NH₃ uniformity throughout the full system. The design allows for a simple drop pipe to the exhaust line, ensuring easy instrumentation for PEMS measurements.

Urea Dosing

A twin dosing system was implemented to the demonstrator truck and controlled using FEV's in house developed twin dosing control software. The software controls both injection systems individually and coordinates the urea dosing based on desired conversion performance, the urea fill level, the NH₃ slip prediction and current driving conditions. Based on the derived input signals, the system determines if the front or rear system should be used to optimize conversion efficiency. As an example, it determines, based on the colder temperatures of cold-start operation that the conversion should be dominated by the first system. However, when driving on a motorway, switching the conversion to the second system allows the truck to passively regenerate the DPF.

Base Combustion

To optimize the low temperature performance, the vehicle base combustion settings were modified to create a low NO_x based heating mode. The Exhaust Gas Recirculation (EGR) and combustion settings were modified to drop the overall NO_x produced during regular operation by approximately 15%, depending on the chosen driving conditions. Drivability and torque requirements were prioritized where necessary. Additionally, the combustion settings were modified to create a more rapid heating of the exhaust line.

Experimental Setup

Vehicle and Powertrain Characteristics

The heavy-duty demonstrator vehicle was an N3 Daimler Actros 1845 LS 4x2 tractor equipped with a 12.8l engine with high pressure EGR and homologated to Euro VI-C. The rated power of the engine is 450hp at 1600rpm.



Figure 5: HD demo vehicle and the new ECT system installed.

Instrumentation Plan

To assure full system understanding, the EATS system was fitted with sensors as well as the previously described injectors. NO_x sensors were fitted at the turbine out position, downstream of the first SCR system and at the tailpipe to allow for full system conversion and individual system conversion calculation.

These sensors deliver a necessary input for the control of each of the SCR systems individually. NH₃ sensors were fitted downstream of both SCR systems to monitor the ammonia slip from each individual SCR and to assist in the calibration of both systems.

Temperature sensors were fitted upstream and downstream of all the EATS components as well as between the SCR substrates for in catalyst temperature monitoring. The OEM temperature sensors were fitted upstream and downstream of the box DOC, and at the tailpipe location.

Pressure sensors were also fitted throughout the system for backpressure determination and comparative analysis to check for potential blockages from HC/soot or urea. The OEM delta pressure sensors were fitted upstream and downstream of the DPF for regeneration control and monitoring. A schematic representation of the sensor layout can be seen in figure 6.

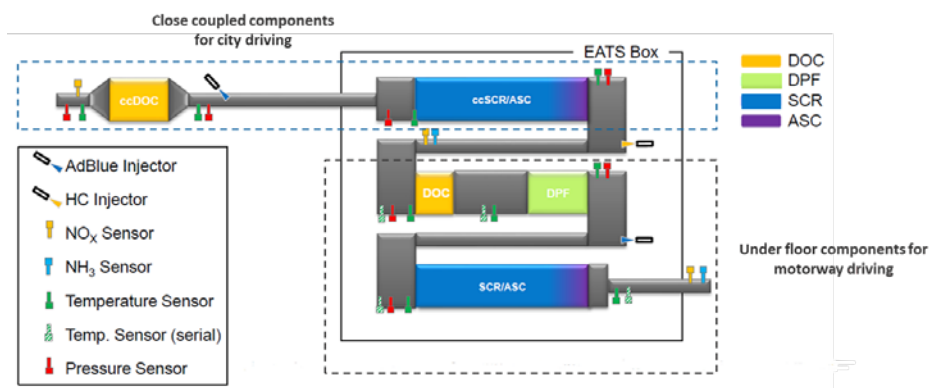


Figure 6: Instrumentation plan of the aftertreatment system.

PEMS Equipment Integration

To fully evaluate the accuracy of the sensor-based emissions control and to quantify cold-start NO_x emissions and secondary emissions compliance, an enhanced Portable Emissions Measurement System (PEMS) was fitted to the demonstrator vehicle as shown in Figure 7 below. The tailpipe was modified to contain the Exhaust Flow Meter (EFM) for the PEMS kit and the equipment itself was set up in the trailer bed.

The PEMS kit contained NO and NO_2 analysers to determine tailpipe NO_x speciation, as well as CO and CO_2 measurement devices. In addition to the gaseous measurements, PN_{10} measurement equipment was also fitted. NO is measured using chemiluminescence spectroscopy. NO_2 is measured using photo acoustic sensor technology. CO and CO_2 were measured using nondispersive infrared spectroscopy (NDIR) and the PN is measured using a condensing particle counter (CPC).

In addition to the standard equipment, the truck was additionally fitted with both NH_3 and N_2O measurement technology. N_2O was measured using a portable Interband Cascade Laser and the NH_3 was measured using a portable Quantum Cascade Laser setup.



Figure 7: PEMS installed in the vehicle.

Driving Conditions

The driving conditions covered in the project were chosen to be representative of the day-to-day missions of a variation of heavy-duty vehicle types, with a special focus on operations where the control of emissions currently remains challenging for similar vehicles.

Three test routes have been used during the calibration of the vehicle. The first one is an in-service conformity (ISC) route containing urban, rural and motorway driving shares. The second one is an Urban Delivery route which has a maximum speed of 50km/h. Finally, a slower Urban Delivery route with a maximum vehicle speed of 35km/h containing ten delivery stops. The three routes are represented in figure 8 below.

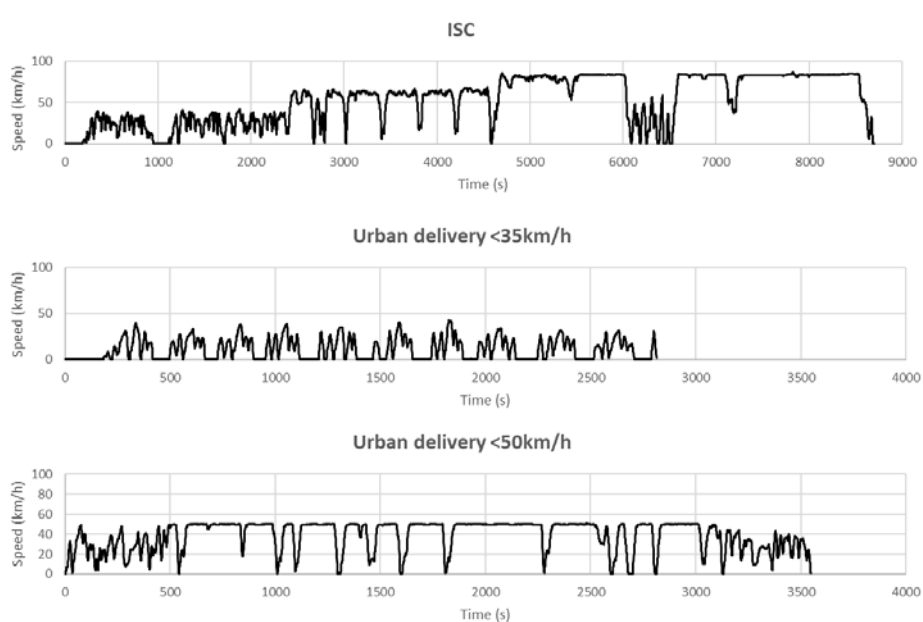


Figure 8: Driving routes.

The routes ensure a broad coverage of the engine operating map. The in-service conformity route ensures a complete operation of the engine torque, including full load operation. The U-50 Urban Delivery route covers lower load operation compared to the ISC and the Urban Delivery route with stops covers a very low speed and load profile as seen in figure 9.

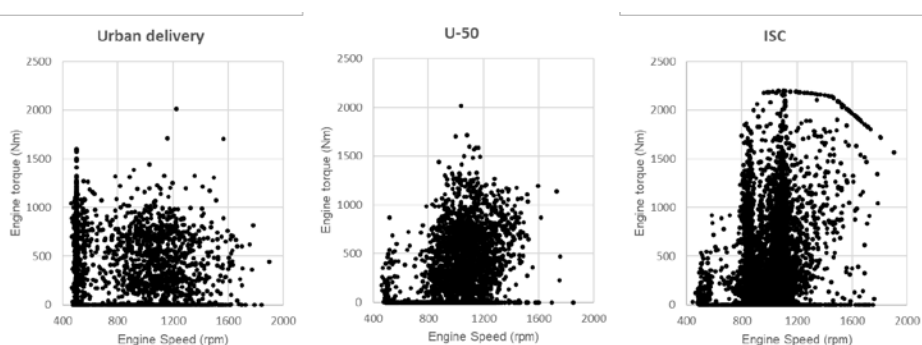


Figure 9: Engine operating map within the different test routes.

Further to these routes, some other tests were performed where heavy traffic impact could be also studied.

Results and Discussion

The combination of the close-coupled catalysts with the advanced controller was designed to achieve faster light-off (improved temperature profiles) and emissions. The results shown herein give insights into the capabilities of this novel system concept and show the impact for cold-start during urban and rural driving.

Cold-Start Light-off Behaviour

The novelty of this layout is the close-coupled position of the catalysts. The most notable improvement of the installation of such close-coupled aftertreatment system is the enhanced

light off temperature profile. The proximity of the front system allows a very rapid heat up of the ccDOC and ccSCR components. This allows the components to reach regime temperature very early within the drive route, under very low speed and load operating conditions. Figure 10 shows an example of a typical cold-start and pull away drive for a truck.

For this test, the ambient temperature was 8°C. It can be seen within the graph that after 40 seconds the engine is started, resulting in an immediate jump in the temperature before the close-coupled DOC – while the truck idles to allow the air pressure system to reach enough pressure for operating the breaks. After approximately 100 seconds of idling, the system is ready, and the truck begins to drive. At this stage, despite the low speed driving out of the parking lot, there is already a large increase in ccDOC inlet temperature. This ensures that CO light-off can be achieved prior to leaving the car park.

The proximity of the components allows optimal heat transfer to the DOC and the downstream close-coupled SCR component. As the ccDOC is positioned almost directly behind the turbine, it shows a transient profile based on the overall load of the engine.

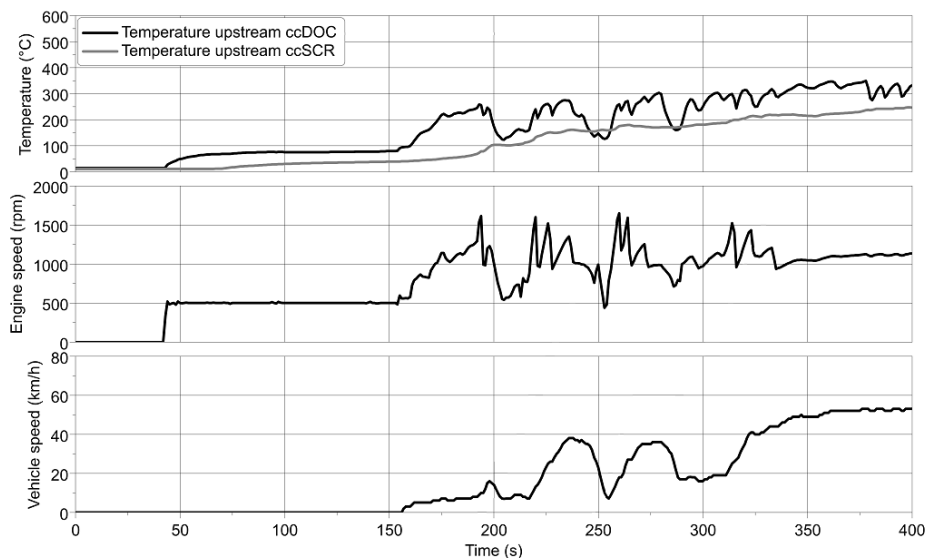


Figure 10: Close-coupled DOC and SCR temperatures, engine speed and vehicle speed during cold-start operation.

As soon as the vehicle departs and there is an increased exhaust mass flow improving heat transfer, the close-coupled SCR inlet starts to heat up. At around 330 seconds into the test (~200 seconds driving), the SCR has reached 200°C and urea injection will start, based on a conservative dosing strategy. This equates to approximately 750 metres of driving within a rural industrial estate. This means that the NO_x reduction begins very early and can be maintained throughout the duration of the driving. This results in a higher and sustained NO_x conversion performance at urban operation.

The benefit of the close-coupled system in driving conditions where the vehicle encounters heavy traffic during urban or rural conditions is shown in figure 11. The figure represents 20 minutes peak time traffic during the rural section of the ISC with an average speed of 24km/h. It can be seen that both the close-coupled and under floor SCR systems maintain temperatures above 200°C with the close-coupled system maintaining around 250°C in average during this time segment.

The layout allows the overall system to achieve show high NO_x conversion at such conditions, whereas the underfloor system does not contribute. The temperatures of both SCR components stay consistent and within operating temperature windows, as such only

minor drops in conversion performance are seen with average conversion values remaining above 95%.

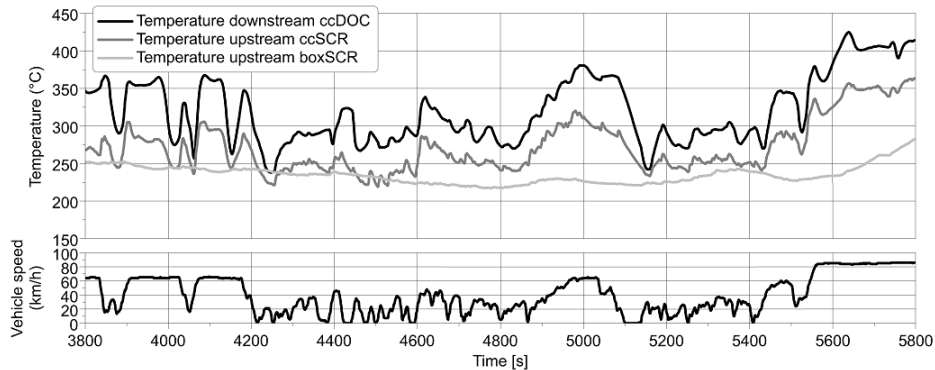


Figure 11: ccSCR and ufSCR temperature profiles during rural heavy traffic conditions.

The increased temperature is achieved for both closer positioned catalysts to the engine and the adaption of the base combustion calibration (the combustion settings were modified to create a more rapid heat of the exhaust line as indicated above).

Impact of Payload on Emissions and Performance.

Total NO_x conversion performance was investigated at 10% and 50% payload. Further testing at 100% payload will be completed at a later stage. To check the robustness of the system performance, 3 ISC-c test routes were conducted at each payload. The higher conversion performance is seen at 50% payload, with average conversion of the system of about 99.5%. The conversion efficiencies varied between 99.4 and 99.6% over these tests, including, driver, temperature, and slight route changes.

The fast light-off of the system means that there is only a 0.35% drop when operating the vehicle with only 10% payload. The average conversion seen was 99.3% with conversion efficiencies varying between 99.1 and 99.6%. This highlights how effective the system is over the full operational load of the vehicle and gives high confidence in the robustness of the calibration.

Overall NO_x Reduction over Studied Routes

An overview of NO_x emission results obtained during the ISC and urban delivery routes is provided in figure 12. The results are binned by the trip average speed.

The ISC trips are represented by the different shares of operation (urban, rural and motorway) average speed. These ISC tests have been conducted at ambient temperatures between 8 and 11 °C and most have started with a cold engine.

The highest emissions resulted from an urban delivery trip conducted at an ambient temperature of 4 °C at 50% payload.

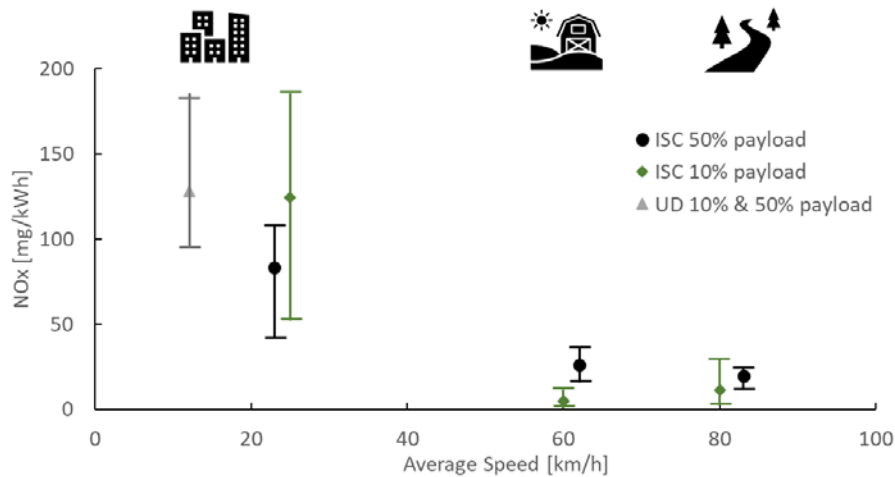


Figure 12: Speed binned NO_x emissions for ISC trips and urban delivery trips at 10% and 50% payload.

As it can be seen in figure 12, while the NO_x emissions are below 30mg for all tested conditions above 60km/h average speed, they are significantly higher (up to 187mg/kWh) at average speeds below 30km/h.

Fuel Consumption and Engine-out NO_x and PN Emissions

The fuel consumption is in general higher during the urban driving conditions. This is due to the overall lower efficiency of part load operation. The rural fuel consumption is lower than the motorway equivalent, this is caused by the more transient operation nature of the truck during the motorway section PEMS campaign. The impact of ambient temperature is also seen, albeit to a lesser extent.

This shift can also be perceived when looking at the engine-out NO_x emissions, less EGR operation in urban conditions pushes the overall NO_x higher in these conditions. The NO_x emissions decrease from urban to rural to motorway driving. This is caused by a combination of increased EGR rates and lower peak combustion temperatures in the higher load ranges of the engine map. These trends can be seen in figure 13. Test 1 and 2 were run at 8°C and 10°C ambient temperature respectively.

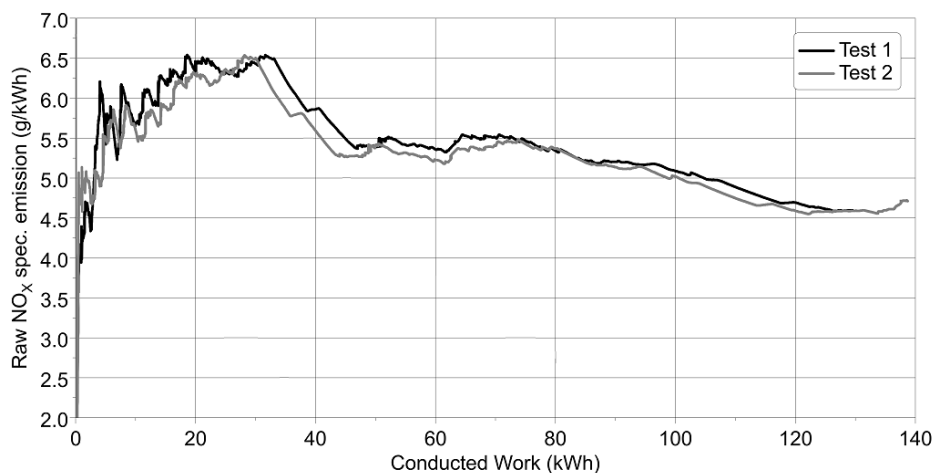


Figure 13: ISC NO_x emissions in g/kWh

Tailpipe NO_x Emissions and AdBlue Consumption

For both the sensor based and PEMS based measurements, it is the cold-start/urban NO_x performance that has the greatest impact on total tailpipe emissions.

As all tests shown include cold-start emissions, there is a notable increase in the urban proportion for tailpipe NO_x. As a result of the close-coupled system, the vast majority of rural and motorway NO_x are converted at extremely high efficiencies, again highlighting the importance of urban NO_x control.

Figure 14(a) shows the ISC work based specific NO_x emissions. As it can be seen, the temperature has a slight influence on the result. It is important to highlight that the specific NO_x emissions around 15kWh conducted work (about half of the reference WHTC work for this engine) are ~200mg/kWh. Figure 14(b) shows the efficiency of the system by comparing the cumulative engine-out (EO) emissions with the tailpipe(TP) NO_x emissions. The effect of the cold-start where most emissions are generated is clearly seen in this figure. Also, the efficiency of the system is such that the curve flattens out after these initial NO_x emissions as the system enters the regime temperature.

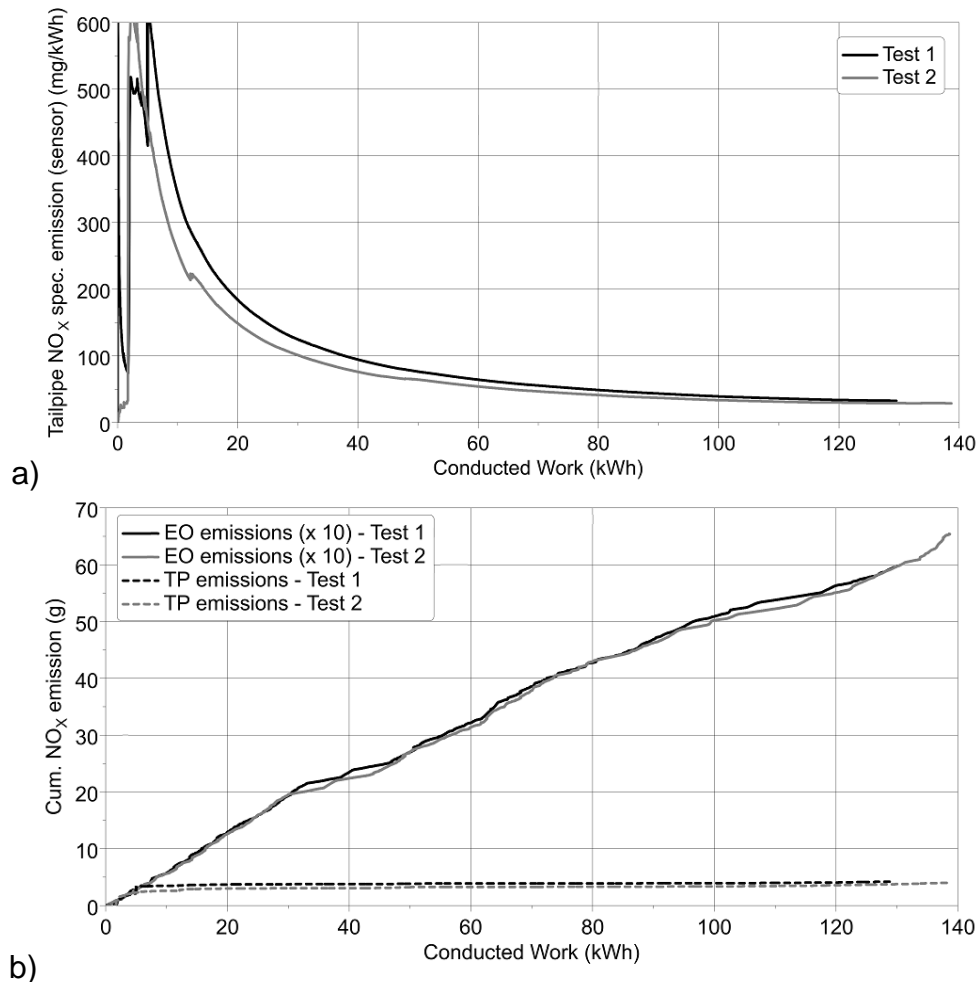


Figure 14: (a) Tailpipe NO_x emissions at ISC trip
(b) ISC cumulative EO NO_x and TP NO_x.

The overall cumulative emissions are showing differences between the PEMS and Sensor based measurements. It is assumed that cross contamination with NH₃ in the exhaust line is the main contributing factor to these differences. Despite these differences, the total

conversions recorded for the test at 10 °C ambient temperature were 99.3 % for the sensor based measurements and 99.4% for the PEMS based measurements and the overall trends and conversion performances are within a comparable range and within test by test variability for such low overall emissions values. Further improvements in PEMS measurement technologies would be required to accurately predict lower overall tailpipe emissions figures.

The low NO_x emissions could be further confirmed during the urban delivery tests. Figure 15 below shows the cumulative EO vs TP NO_x emissions during an urban delivery trip with long stops. Tests 3 and 4 were conducted at 6 and 10 °C of ambient temperature, respectively. These tests were run with an additional urban delivery route with increase stop lengths as shown below.

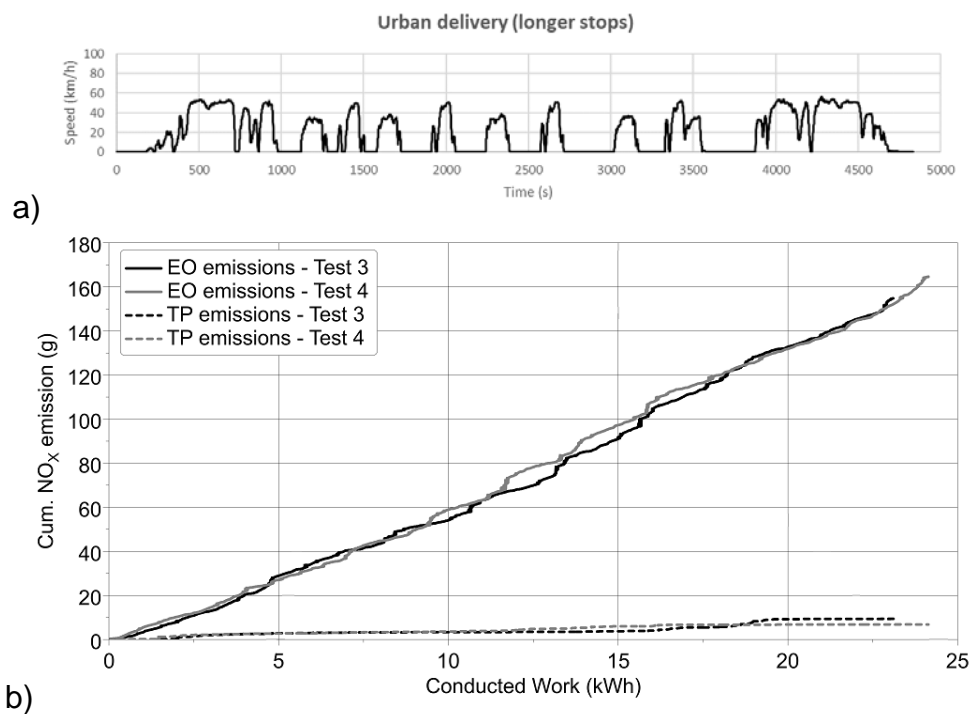


Figure 15: a) Urban delivery speed profile and
b) Urban delivery cumulative EO NO_x and TP NO_x.

Further testing is planned at lower ambient condition temperatures. In addition, the AdBlue consumption has been monitored and it has been found that is consistent at higher temperatures and showing an increase in overall consumption for colder conditions. This correlates to the corresponding increase in EO NO_x emissions at colder ambient conditions. The urban Adblue® consumption is higher owing to the need to both convert NO_x and to establish an ammonia storage level within the SCR components. As both the close-coupled and the underfloor SCR systems are activated within the urban driving conditions, this difference is magnified because of building an ammonia storage within both systems.

Particulate Number Emissions (PN₁₀)

Results of PN PEMS measurements during ISC and urban delivery tests confirm overall very low emissions. The higher PN emissions are seen in urban conditions and can be attributed to the cold-start heat up behaviour in combination with possible overnight effects which disrupt the soot cake.

After cold-start, the PN behaviour is consistent resulting in lower absolute PN emissions. Figure 16 shows the cumulative particulate number emissions for an ISC trip conducted at 10 °C. In this trip the specific PN emissions are 3.1×10^{10} #/kWh. It is important to mention that these values are quoted as measured, and do not consider error margins of the measurement equipment.

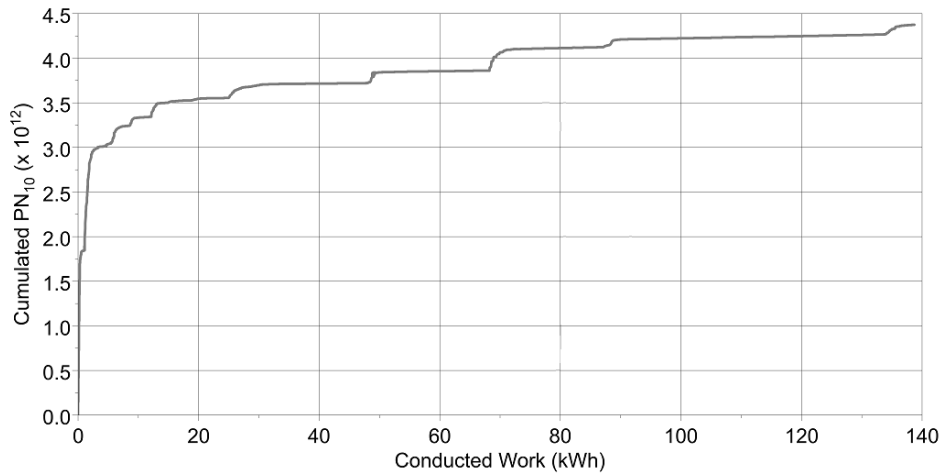


Figure 16: Cumulative PN emissions for an ISC trip.

Low PN emissions are also confirmed during the urban delivery trip. In this case, the trip is much shorter than the ISC. This trip was conducted at 10°C ambient temperature. The PN emissions seen at the beginning of the trip have a greater effect on PN work specific emissions. In the urban delivery trip shown on Figure 17, the specific emissions are 5.8×10^{10} #/kWh.

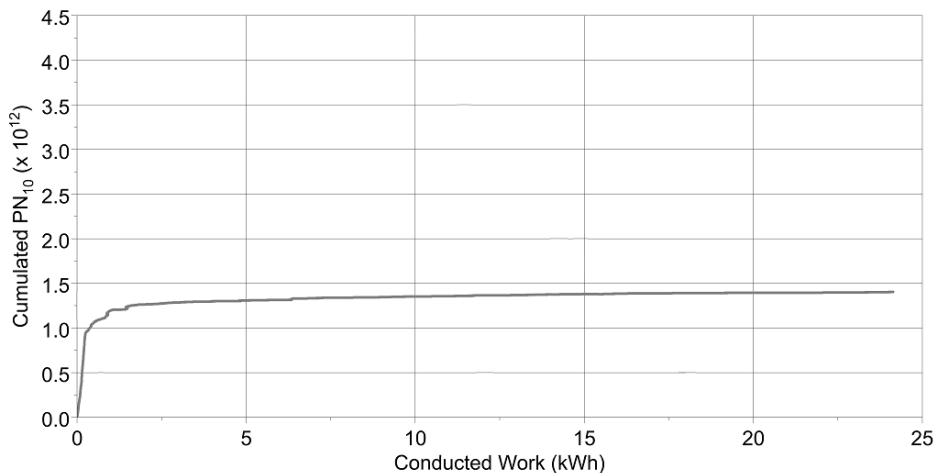


Figure 17: Cumulative PN emissions for an urban delivery trip.

NH₃ and N₂O Emissions

The NH₃ and N₂O emissions must be balanced against the overall NO_x conversion. Higher ammonia injection requested for increased conversion efficiency can often result in ammonia slip during transient operation.

This NH₃ slip will oxidise over an ASC, and the side reactions over the SCR result in the production of NO_x and N₂O. As not all N₂O formation can be avoided, it is essential to minimise the absolute amount of N₂O generated during operation. This is typically done by

robust and balanced ammonia dosing and storage combined with optimised slip calibration. The NH_3 and N_2O traces are shown in figure 18 and 19 respectively for an ISC trip conducted at 10°C ambient temperature. The specific emissions achieved during the trip are 6.9 mg/kWh for NH_3 and 45.3 mg/kWh for N_2O . Both figures are reported as measured and do not consider error margins at this point.

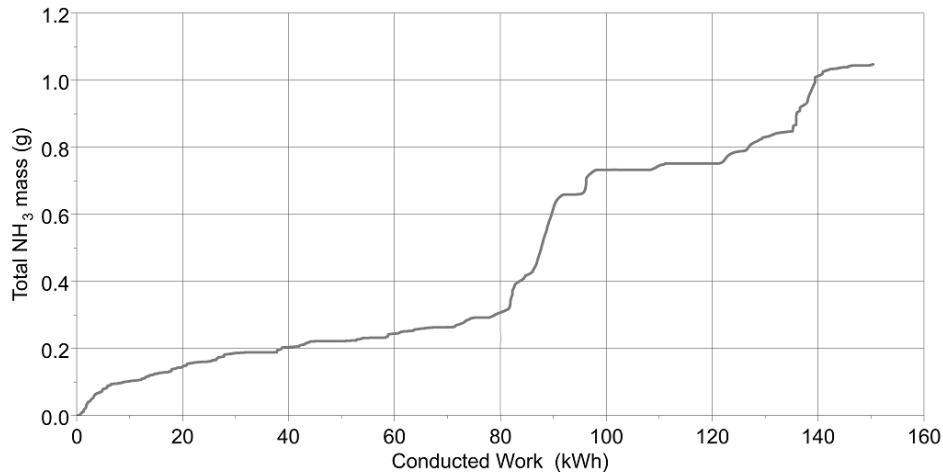


Figure 18: Cumulative NH_3 emissions for an ISC trip.

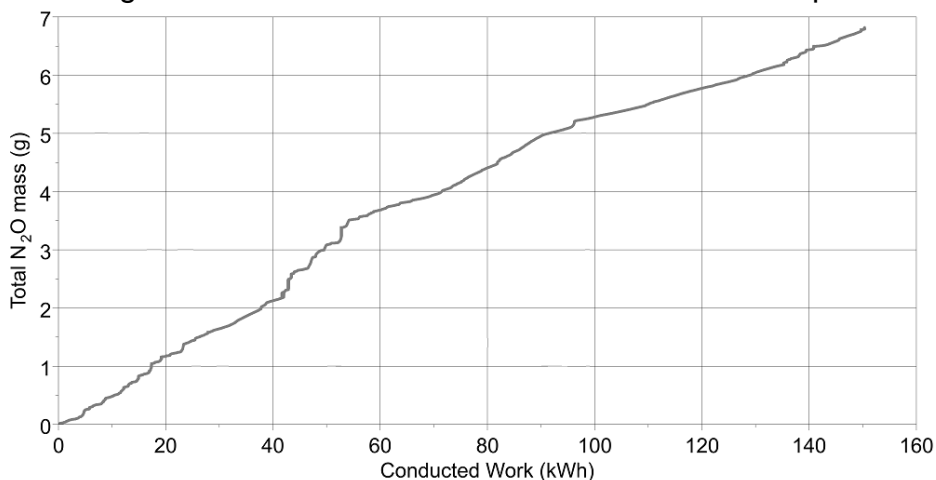


Figure 19: Cumulative N_2O emissions for an ISC trip.

Summary and Conclusions

A novel close-coupled EATS layout, containing current catalyst technologies was evaluated and specified using FEV's SimEx software. The system was then designed, optimised, and integrated into an N3 heavy-duty vehicle. The combustion calibration was adapted to reduce overall NO_x emissions and to allow for rapid heat up and good thermal management in urban conditions. The dual dosing SCR software was calibrated to a robust demonstrator level to produce reproducible results over key emissions driving routes. Robustness testing was conducted to show the maturity of the emissions calibration, and a PEMS measurement campaign was conducted to determine the impact of secondary pollutant emissions such as NH_3 , N_2O and PN_{10} as it is expected that these will be considered for future emissions legislation.

The key benefit of the system has been shown as the improved overall thermal transfer from the engine to the EATS. The proximity of the EATS components allows the system to reach 200°C , required for robust NH_3 dosing conditions, significantly quicker than can be seen on

a standard Euro VI emission control technologies layout. Additionally, the splitting of the SCR into 2 systems and the optimized volumes facilitate reducing NO_x emissions to ultra-low levels.

The integration of close-coupled catalysts combined with the advanced controller have achieved high deNO_x efficiencies with a minimum ammonia slip and results show good control of the N₂O under the conditions tested.

The results show that remaining emissions are mainly generated during the cold-start operation.

Different emission tests were conducted within the project to check the robustness of the NO_x control over a wide range of driving conditions, focussing on urban, rural and motorway driving. It is to be noted that such a program cannot cover all possible combinations of driving conditions and boundary conditions.

The truck demonstrates that diesel NO_x emissions can be consistently kept at very low levels over a wide range of driving conditions by combining existing catalyst technologies with improved engine and aftertreatment control functions. The design of the EATS layout shows that significantly improved NO_x emissions can be achieved within the constraints of a typical truck application.

Outlook

Heavy duty vehicles have achieved great pollutant emissions reductions in the past two decades thanks to the implementation of advanced emissions control systems. This project demonstrates that further significant improvements can be obtained with an innovative use of current proven emissions control technologies. The implementation of close-coupled catalysts significantly contributes to the reduction of high NO_x emissions in challenging conditions like cold start and urban operation. The results shown are valid for the chosen routes tested and as specified. The non-regulated emissions shown do not consider error margins from the instrumentation used.

As it can be seen, cold start remains the area for future improvements. Furthermore, key technologies will be required to robustly and comprehensively fulfil possible Euro 7/VII requirements.

A non-exhaustive list of technologies under assessment is:

- SCR catalysts are and will continue increasing their efficiency through continuous innovation of substrates and catalyst formulations. Same applies for filtration efficiency of particulate filters.
- Electrically heated catalysts which can help to more quickly increase EAT system temperatures. Challenges remain for the integration, which would increase the engine load owing to the need for electric power supply, with an effect on vehicle's fuel consumption. This option is being intensively studied for heavy-duty applications.
- Advanced HC dosers can help on supporting the fast heat up of the system. This is generally a well-known technology for heavy-duty applications. Its integration into the exhaust system is sometimes challenging (depending on the desired position) apart from the associated undesired increase on fuel consumption.
- Fuel burners in the exhaust system are also used for heating support. This solution has almost no limitation in heating power. Challenges remain when integrating these burners into heavy-duty applications. This is a complex technology that needs careful implementation. Also since this is not a standard component, it's not readily available.
- Hybridisation of the heavy-duty powertrains as well as advanced sensor and control technologies will further contribute to operate heavy-duty vehicles in a more efficient and clean manner.

In parallel to new pollutant emissions standards, the European Union is discussing the revision of the greenhouse gas reduction target for 2030 from 40% to 55% compared with 1990 levels. The current CO₂ reduction targets for the heavy-duty vehicles fleet sold from 2025 and 2030 onwards are -15% and -30% respectively, compared to the EU average in the reference period July 2019 to June 2020.

To achieve these ambitious targets, all available paths to reduce the carbon footprint of these vehicles will be needed. As a result, the vehicle mix of the future will be more diverse than it is today, comprising hybrid and plug-in hybrid trucks as well as fuel cell and fully electric vehicles [6].

One important element to consider is the use of low carbon and 100% renewable liquid fuels. This will guarantee lower greenhouse gas emissions from new vehicles as well as from the existing vehicle fleet. Renewable liquid fuels, like e-fuels or carbon-neutral fuels, are particularly fit for purpose; this is because they can use the same fueling infrastructure already in place allowing a swift implementation in the market.

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References

1. Commission Regulation (EU) No 582/2011 of 25 May 2011 implementing and amending Regulation (EC) No 595/2009 of the European Parliament and of the Council with respect to emissions from heavy duty vehicles (Euro VI) and amending Annexes I and III to Directive 2007/46/EC of the European Parliament and of the Council
2. Perujo Mateos Del Parque, A., Mendoza Villafuerte, P., PEMS emissions testing of heavy-duty vehicles/ engines : assessment of PEMS procedures in fulfilment of Article 14(3) to Regulation (EU) 582/2011, 2015
3. Posada, F., Badshah, H., Rodriguez, F., In-use NO_x emissions and compliance evaluation for modern heavy-duty vehicles in Europe and the United States. White Paper, International Council on Clean Transportation, 2020
4. AECC Presentation AGVES, July 2020
5. Blanco-Rodriguez, David, Holderbaum, Bastian and Vagnoni, Giovanni. EU6 C-Segment Diesel vehicles, a challenging segment to meet RDE and WLTP requirements. IFAC-PapersOnLine. 2016, 49-11, pp. 649-656
6. Stefan Pischinger, Ferenc Aubeck, Dr. Peter Heuser, Dieter van der Put, Bernd Lindemann, Dr. Martin Müther, Dr. Markus Schönen, Markus Ehrly, Dr. Joschka, Schaub, Dr. Marius Walters, Dr. Lukas Virnich, Giuseppe Sammito, Luping Bi, Thomas Lüdiger, Efficient commercial powertrains – How to achieve a 30% GHG reduction in 2030. 41th International Vienna Motor Symposium 2020, 2020.