Exhaust Gas Aftertreatment of the Future

Exhaust gas from modern combustion engines is cleaner than ever before. Current projects of the Research Association for Combustion Engines (FVV) show that exhaust emissions can be reduced even further, especially in real operation. At the same time, electrification and the introduction of alternative fuels impose new requirements to exhaust gas aftertreatment.

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1 RESEARCH PRIORITY EXHAUST GAS AFTERTREATMENT

Developing exhaust gas aftertreatment systems is a major field of activity in modern engine design. Research as initiated by the FVV aims at understanding fundamental mechanisms during the generation or removal of individual pollutant components. This includes crucial research topics such as interactions with fuel composition and phenomena like catalyst aging. Additionally, exhaust gas purification needs to be carefully fine-tuned with the engine and its operating conditions to meet emission limits of air pollutant emissions, such as of nitrogen oxide (NO_X), sulfur dioxide (SO_2), volatile organic compounds without methane (NMVOC), ammonia (NH_3), dust, including the fine particle components PM_{10} and $PM_{2.5}$, carbon monoxide (CO), and climate-sensitive greenhouse gas emissions, such as carbon dioxide (CO_2), methane (CH_4) or dinitrogen monoxide (N_2O). Such interactions and their modeling are crucial topics in the research projects as initiated by the FVV engine emissions and immisions planning group, headed by Prof. Dr.-Ing. Uwe Gärtner.

VOICES OF THE FVV

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Prof. Dr.-Ing. Uwe Gärtner heads the advanced engineering performance & emissions/technical benchmark engines unit in the commercial vehicle development at Daimler AG. He is an honorary professor for combustion methods/thermodynamics at HTW Dresden and heads Engine Planning Group 6 "Emissions & Immissions".
"The research work coordinated within FVV brings together the knowledge of engineers, physicists and chemists."

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Prof. Dr.-Ing. Hans-Peter Rabl teaches combustion engine technology and automotive engineering at the Ostbayerische Technische Hochschule (OTH) Regensburg and heads its laboratory for combustion engines and exhaust gas aftertreatment.
"Less pollutant emissions from cold exhaust gas, that is an important focus of research."

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Dr.-Ing. Uwe Zink is the Technical Manager Regulatory Affairs at BASF Catalysts Germany GmbH and has been a member of FVV Engine Planning Group 6 "Emissions & Immissions" for many years.
"Ultimately, we want to achieve the lowest emission levels under real driving conditions."

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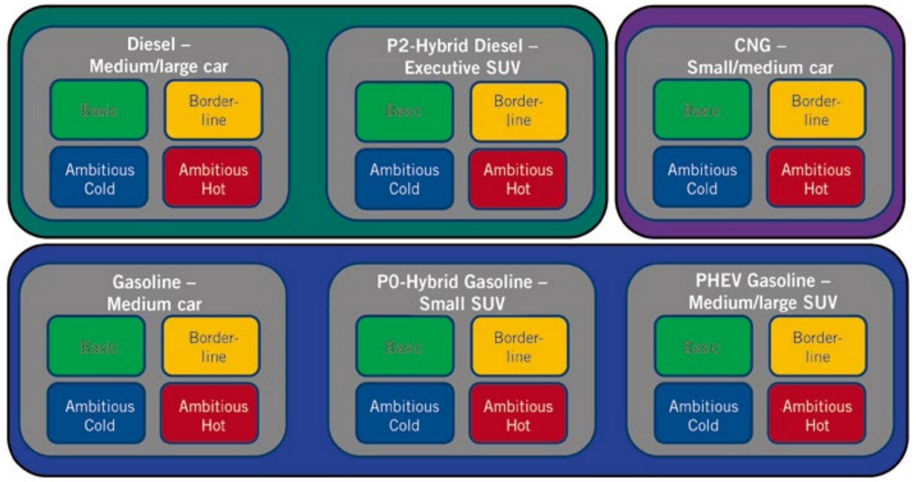


FIGURE 1: Analyzed vehicle-drive combinations and driving cycles in project "2025+ Requirements on Emission Control" (© VKM / TU Darmstadt)

The understanding of such basic principles as gained in FVV projects has greatly contributed to lowering exhaust emissions from combustion engines by several orders of magnitude in the past 25 years. One good example is the selective catalytic reduction of nitrogen oxides, researched as far back as the 1990s. Profound scientific investigations resulted in quickly establishing aqueous urea solution as reducing agent in SCR catalysis industrial standard.

Although emission values of modern combustion engines are very low, it is expected that ever-stricter limits and test conditions will eventually result in even more stringent requirements for exhaust gas composition. Since it is technically impossible to fulfil these requirements by just lowering engine-out emissions, research into exhaust gas aftertreatment will continue to play a significant role.

2 EXHAUST GAS AFTERTREATMENT OF THE FUTURE

To analyze the boundary conditions for future exhaust gas aftertreatment systems, FVV initiated two research projects using its own funds. They are to establish the development objectives for passenger car and commercial vehicle aftertreatment systems from 2025. This period was chosen for the pre-competitive character of such research.

2.1 EXHAUST GAS AFTERTREATMENT IN PASSENGER CARS

The investigation began with the "2025+ Requirements on Emission Control" project. It was run at the Institute for Internal Combustion Engines and Powertrain Systems of Technische Universität Darmstadt and was completed at the end of 2017. Although the project had been planned even before the approval of RDE legislation, one major focus was to keep within emission limits under real driving conditions. Researchers successfully set up a simulation environment for installing virtual RDE tracks and spotting emission-critical driving maneuvers. For this, it was necessary to model engine-out emissions, exhaust gas mass flows and temperature gradients for various vehicle-drive combinations in detail. The combinations were defined in advance, taking account of the strict 75g/km CO_2 fleet limit and the continuing trend towards relatively heavy and large "Sports Utility Vehicles", **FIGURE 1**. Consequently, two of the vehicle models were equipped with a 48-V hybrid system and one with a plug-in hybrid drive.

The results [1] rendered with the simulation environment include:

- In a conventional gasoline engine, 50 % of nitrogen oxide emissions are produced during a few peak performance phases. A 48-V hybrid system in a P0 arrangement is not a suitable countermeasure.
- In a Diesel engine, the 48-V hybrid system contributes to avoiding emission peaks in urban traffic. Outside of cities, however, very high conversion rates are required to achieve the emission targets. The exhaust system's rapid cooling during long downhill stretches has a counteracting effect.
- It was demonstrated that a gasoline engine operated with CNG produces considerably less emissions under all operating conditions than conventional gasoline engines.
- With an adequate operating strategy, emission behavior of a plug-in hybrid drive can be completely decoupled from the RDE route.

These are exemplary results based on realistic but abstract vehicle-drive combinations. By using the established methodology, it will be possible in the future to assess the emission behavior of real drives without the need for elaborate road tests.

2.2 EXHAUST GAS AFTERTREATMENT IN COMMERCIAL VEHICLES AND MOBILE MACHINERY

Since the methodology developed for passenger cars has proven to be effective, plans are to transfer it to commercial vehicles and working machines within the project on "2030+ Requirements on Emission Control" at the Institute for Combustion Engines of RWTH Aachen University. One challenge is the fact that the variance of vehicle drive-combinations is much higher than in passenger cars, as the spectrum under consideration ranges from vans and public service buses to long-distance trucks, industrial trucks and harvesters. Moreover, load cycles during operation as well as emission legislation for the vehicles and machines vary. All of these aspects should be considered when setting up a simulation environment, which also encompasses the models for different emission control technologies. Once completed in early 2020, this project, too, will make available a comprehensive tool that can provide the boundary conditions and requirements necessary to target the development of emission reduction initiatives at an early development stage [2].

3 REDUCTION OF PRIORITY POLLUTANT EMISSIONS

Most FVV projects initiated in the Planning Group "Emissions & Immissions" deal with the reduction of individual pollutants. The following chapter provides examples of important results of recent years.

3.1 METHANE CATALYSIS

When natural gas is used to fuel combustion engines, the low carbon content leads to a substantial reduction of CO_2 emissions per km. However, since methane released into the environment causes a much higher greenhouse effect than carbon dioxide, it is important for the overall balance to catalytically convert unburned methane in the exhaust system. Due to the high reaction temperatures required, methane catalysis is challenging as it is. The first "Methane catalytic I" project, completed in 2013, showed that conversion rates of a palladium-platinum catalyst dropped rapidly under typical operating conditions, especially when the exhaust gas also contained sulfur dioxide. The subsequent project "Methane catalytic II" [3] carried out at the Institute for Chemical Technology and Polymer Chemistry at the Karlsruhe Institute of Technology analyzed the mechanisms of deactivation as well as the various ways of reactivation, **FIGURE 2**. Palladium oxidation turned out to be the essential cause for deactivation. A five-minute exposure of the catalyst to rich exhaust gas without residual oxygen can completely reverse palladium oxidation. However, this reaction, too, is highly temperature-dependent. Other factors that influence catalyst contamination, such as material composition of the carrier or boost pressure of the turbocharger, were identified and partly quantified.

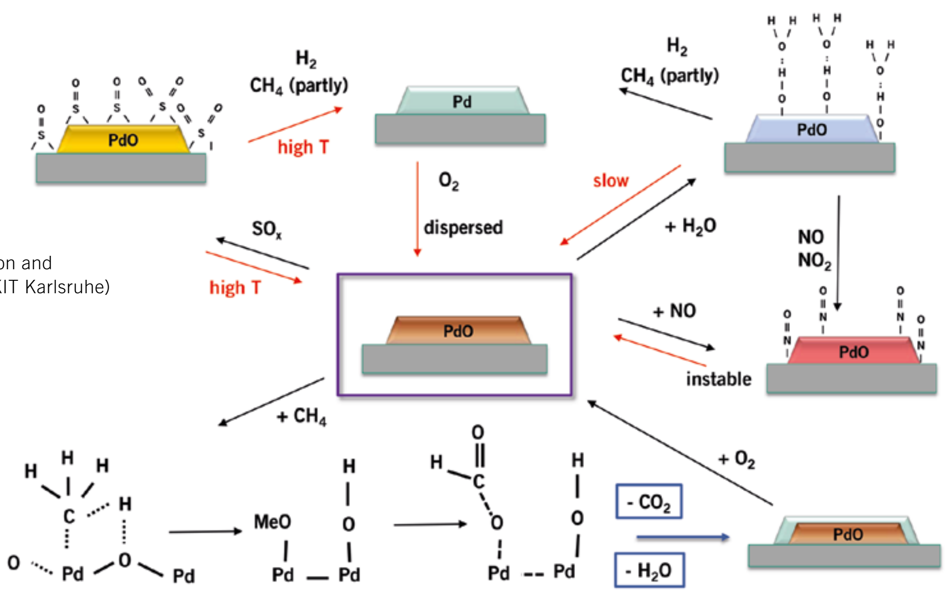
3.2 FORMALDEHYDE

Stationary gas engines play an increasingly important role in decentralized electricity supply. They reach very high efficiency levels in lean cycle mode, although their high levels of excess air account for higher emissions of unburnt hydrocarbons such as formaldehyde (CH_2O). The fact that oxomethane, the correct chemical name for the aldehyde, can indeed be reduced without affecting the gas engines' excellent CO_2 balance, is demonstrated by the project "Formaldehyde" [4] which was completed in early 2017. In this project, the Institute of Internal Combustion Engines of the Technische Universität München cooperated closely with the Institute for Chemical Technology and Polymer Chemistry at the Karlsruhe Institute of Technology. The researchers in Munich analyzed which engine parameters could be changed to lower engine-out emissions. The results reveal that the improvement of CH_2O engine-out emissions either compromises efficiency or leads to higher nitrogen oxide emissions, **TABLE 1**. Although ideal valve timing adjustment and catalyst technology optimization make it possible to reach raw emission values which allow for very low formaldehyde as well as nitrogen oxide limits and to obtain an efficiency level of about 45 %. Meanwhile, chemists in Karlsruhe analyzed the performance of platinum-oxidation catalysts. They demonstrated that under standard conditions, commercially available catalysts show CH_2O conversion rates of 87 to 97 %, and that engines equipped with them meet the standards of TA Luft (Technical Instructions on Air Quality Control). They also showed, however, that even low sulfur dioxide concentrations lead to a quick catalysts deactivation, thus jeopardizing limit compliance.

3.3 NITROGEN OXIDE REDUCTION AT LOW TEMPERATURES

The high efficiency of Diesel engines and lean-mixture-operated gasoline engines go hand in hand with higher nitrogen oxide formation. This may be compensated by state-of-the-art exhaust gas aftertreatment technology, consisting of a NO_x storage catalyst and an SCR system. They are subject to certain restrictions which occur at low temperatures, for example when cold-starting an engine. This is why the FVV project "Low-Temperature $DeNO_x$" [5] looked for specific alternatives to currently com-

FIGURE 2: Factors that influence the deactivation and reactivation of palladium catalysts (© ITCP / KIT Karlsruhe)



–	HCHO	ηi	NO_x
Higher engine load	+	+	-
Higher charge air temperature	+	--	-
Higher cooling water temperature	+	+	-
Lower exhaust back pressure	+	++	-
Higher compression ratio	-	+	-
Beyond EU50	+	--	++
Inhomogenous mixture	0	-	0
Miller inlet valve timing (λ constant)	--	++	+
Higher valve overlapping	-	-	0
Optimized combustion chamber geometry	+	+	0

++ improvement of more than 20 % in HCHO (reduction)/increase of more than 0.5 % in ηi
+ improvement of 5-20 % in HCHO (reduction)/increase of less than 0.5 % in ηi
0 no significant influence
- increase of 5-20 % in HCHO emissions/deteriration of less than 0.5 % in ηi
-- increase of more than 20 % in HCHO emissions/deterioration of more than 0.5 % in ηi

TABLE 1 Change of engine-out emissions of CH_2O and NO_x as well as change of efficiency because of engine parameter variation (© LVK / TU München)

mercially available systems. The 26 systems found in comprehensive literature and patent research were then described in detail, clustered and assessed while the assessment matrix also considered the carbon footprint. The study carried out at the Laboratory for Combustion Engines and Exhaust Gas Aftertreatment at the Eastern Bavarian Technical University Regensburg reveals that none of the systems can replace current standard technology. Some of the systems, however, have the potential to be used as complementary systems for specifically reducing nitrogen oxide emissions at low temperatures.

4 OUTLOOK

Not only does scientific research provide answers to questions, it also keeps raising new ones. It is evident that overall, exhaust gas characteristics in real operation become more and more important for all dynamically operated combustion engines. Converting pollutants in cold exhaust gas is a key challenge, whereas it is insignificant whether the low heat and thus energy input in the exhaust system is caused by higher electrical driving proportions or by cold starts. Catalyst aging definitely remains an essential research topic, also in view of the new fuels that are discussed. FVV is therefore drawing up more research projects specifically dedicated to related topics.

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