Current experimental developments in 48 V-based CI-driven SUVs in response to expected future EU7 legislation

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Abstract

In this paper, we describe experimental developments in an Exhaust Aftertreatment System (EAS) used in a four-cylinder Compression Ignition (CI) engine. To meet the carbon dioxide (CO₂) fleet limit values and to demonstrate a clean emission concept, the CI engine needs to be further developed in a hybridized, modern form before it can be included in the future fleet. In this work, the existing EAS was replaced by an Electrically Heated Catalyst (EHC) and a Selective Catalytic Reduction (SCR) double-dosing system. We focused specifically on calibrating the heating modes in tandem with the electric exhaust heating, which enabled us to develop an ultra-fast light-off concept. The paper first outlines the development steps, which were subsequently validated using the Worldwide harmonized Light-duty vehicles Test Cycle (WLTC). Then, based on the defined calibration, a sensitivity analysis was conducted by performing various dynamic driving cycles. In particular, we identified emission species that may be limited in the future, such as laughing gas (N₂O), ammonia (NH₃), or formaldehyde (HCHO), and examined the effects of a general, additional decrease in the limit values, which may occur in the near future. This advanced emission concept can be applied when considering overall internal engine and external exhaust system measures. In our study, we demonstrate impressively low tailpipe (TP) emissions, but also clarify the system limits and the necessary framework conditions that ensure the applicability of this drivetrain concept in this sector.

Keywords Emission legislation · Exhaust gas aftertreatment · Electrically heated catalyst · CI · 48 V · EU7 · Hybrid drivetrain

Abbreviations

AGVES	Advisory Group on Vehicle Emission Standards
ASC	Ammonia slip catalyst
BEV	Battery electric vehicle
BMEP	Brake mean effective pressure
CC	Close-coupled
CF	Conformity factor
CH ₄	Methane
CI	Compression ignition
CLOVE	Consortium for ultra-low vehicle emissions
CO	Carbon monoxide

CO ₂	Carbon dioxide
CPSI	Cells per square inch
DOC	Diesel oxidation catalyst
EAS	Exhaust aftertreatment system
E _{BAT}	Battery energy
EHC	Electrically heated catalyst
EO	Engine-out
EOM	Engine operating mode
FSN	Filter smoke number
HC	Hydrocarbons
HCHO	Formaldehyde
HEV	Hybrid electric vehicle
HP-EGR	High-pressure exhaust gas recirculation
ICE	Internal combustion engine
LNT	Lean NO _x trap
LP-EGR	Low-pressure exhaust gas recirculation
LPS	Load point shift
MFB	Mass fraction burned
NEDC	New European Driving Cycle
NH ₃	Ammonia
NMOG	Non-methane organic gases

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NO _x	Nitrogen oxides
N ₂ O	Laughing gas
PHEV	Plug-in hybrid electric vehicle
SCR	Selective catalytic reaction
sDPF	Diesel particulate filter with SCR coating
SoC	State of charge
SUV	Sport utility vehicle
THC	Total hydrocarbons
TP	Tailpipe
UF	Underfloor
WLTC	Worldwide harmonized Light-duty vehicles Test Cycle
WtW	Well-to-wheel
w/	With

1 Introduction

By introducing EU6d emission legislation, vehicle manufacturers have succeeded in producing what is probably the cleanest vehicle to date, not only in laboratory settings but also in real world. Numerous studies show that EU6d is effective, both TEMP [1] and especially FINAL [2], although the dynamic nature of the entire EU6 phase should not be disregarded. The first emission stage of EU6, EU6b, decreases the threshold value of nitrogen oxides (NO_x) from 180 to 80 mg per km in the New European Driving Cycle (NEDC); this stage is closely followed by the shift to the Worldwide harmonized Light-duty vehicles Test Cycle (WLTC) (EU6c). The transition to EU6d-TEMP (Conformity Factor (CF) = 2.1, which is equivalent to 210 % in Real Driving Emissions as compared to WLTC) was almost quicker. The final phase of this emission stage is EU6d (CF = 1.43), which essentially permits a CF = 1 plus any measurement tolerances [3]. All these changes were introduced over a period of less than 5.5 years; nevertheless, the next and even stricter emissions stage will be put in place soon. At the same time, the European Union has expressed its commitment to the Green Deal. This states that well-known carbon dioxide (CO₂) reductions in the currently valid 2021 limit value of 95 g/km must occur, i.e., of – 15 % must occur in the passenger car sector by 2025 and of – 37.5 % by 2030 [4]. Since a trade-off must be made between NO_x and CO₂, the development task to reduce both species at the same time is not an easy one. Technologies that are seen as particularly promising in the future include secondary air injection, electrically heated exhaust systems, large catalyst volumes and many more [5]. The following considerations were mainly made based on CO₂ aspects, assuming that the electricity mix is constant and additional electricity is not produced from fossil sources. Battery electric vehicles (BEV) present a great solution for future challenges, because these vehicles have the highest Well-to-Wheel (WtW) efficiency by far

[6]. Due to the higher CO₂ 'emissions backpack' incurred when producing a BEV and correlating to the battery size, the use of this technology to create small cars and vehicles that will travel short distances in urban areas is particularly reasonable [6, 7]. Ensuring good local air quality presents an equal challenge in urban areas, but this can be significantly improved using both BEVs and advanced zero-impact Internal Combustion Engines (ICE), as described later. Plug-in Hybrid Electric Vehicles (PHEV) as a bridge technology [8] present a great solution, as they enable the user to drive short distances with electric power without being dependent on charging infrastructures for long-distance use. Heavy vehicles, meanwhile, are mainly used to travel over long distances [6]. The installation of hybridized and clean ICE in these, often, premium vehicles provides a short- and middle-term solution [8]. For this reason, the developments described in this paper are assigned to this vehicle class (see Fig. 1), and are not representative of developments taking place in the average, overall vehicle fleet.

To comply with the Green Deal, politicians need to provide incentives for companies and scientists to consider WtW more strongly [9, 10]. Rather than supporting bans on certain technologies, politicians should provide leeway that allows highly qualified scientists to search for optimal, highly efficient solutions. Put differently, we need to support the development of a variety of drivetrains to provide a generally applicable sustainable mobility solution [10, 11]. The legislation process should continue to be based on aspects of air quality, rather than on the best available technology [10, 12, 13], as simulations have shown that NO₂ would not present a problem if an entire EU6d fleet were assumed [10]. From a macroeconomic perspective, however, it makes sense to work together to reduce CO₂ emissions, especially as the global supply and demand is expected to shift the use of fossil fuels mainly to developing countries with a low Gross Domestic Product.

Fig. 1 Technology landscape and investigated vehicle type

2 Experimental methodology

In this section, we provide an overview of the test vehicle and the methodology used for the investigation. At the end of the section, we discuss the engine calibration and different Engine Operating Modes (EOMs). These are required for two reasons: to ensure that thermal measures are applied and that strict emission control is practiced.

2.1 Test engine and exhaust aftertreatment

The research was conducted with a 2-l, Compression Ignition (CI), straight-four engine. In terms of hardware, the engine itself is not changed; however, significant interventions are made in the control unit. Since not all required functions are available in the engine control unit, and a classic bypass is not possible for cost reasons, the individual functions are outsourced to the test bench automation system AVL PUMATM. This primarily concerns the dynamic state machine used for diverse EOMs. An general overview of the basic engine characteristics is given in Table 1.

The basic configuration is engineered for Euro 6b emission level. To be able to present a low-emission concept, on the one hand higher Exhaust Gas Recirculation (EGR) rates are used as an internal engine measure [14], on the other hand, an extended Exhaust Aftertreatment System (EAS) is used as an external engine measure. Compared to a usual EU6 diesel catalyst configuration, the exhaust line is additionally equipped with an Electrically Heated Catalyst (EHC) as well as a double-dosing Selective Catalytic Reduction (SCR) system. Avoiding a possible ammonia

(NH₃) slip, an Ammonia Slip Catalyst (ASC) is placed as last catalyst brick. The whole final configuration including all associated measuring positions is shown in Fig. 2, based on future catalyst layouts.

As the EAS is changed from the ground up, all catalyst bricks are defined on the basis of low-emission concepts and the prototypes are made by company partners. The total volume of all components is slightly below 12 l. The considerable effort required to effectively apply sustainable emission concepts is clearly evident here from both the perspective of packaging and that of cost. Estimates show that the cost of diesel passenger car powertrains will continue to rise in the future [15], and a similar picture is emerging in the heavy-duty vehicles sector [16].

The single volumes and crucial parameters are shown in Table 2. A worst-case analysis was conducted, so the catalytic converters must be aged. The DOC was subjected to a hydrothermal aging process for 20 h at 750 °C and the close-coupled (CC) SCR/sDPF bricks were subjected to this process for 20 h at 725 °C. The whole underfloor (UF) system was kept in a degreened state, as the aging behavior is also observed in a limited state in real terms. For thermal reasons, all catalytic converters were insulated with copper fleece. To be able to represent an ashed state, the backpressure p_{41} was raised from 550 to 850 mbar via the exhaust gas flap, with values defined as 4000 rpm and 14 bar Brake Mean Effective Pressure (BMEP).

Table 1 Engine characteristics

Engine	Straight-four engine
Ignition	Compression ignition
Fuel	Diesel oil
Displacement	2000 cm ³
Compression ratio	16.5
Injection system	Common-rail
Injection pressure	2000 bar
Turbocharger	Single stage
Number of valves	4
Max. cylinder pressure	150 bar
Rated speed	4400 min ⁻¹
Emission measures	Cooled HP-EGR (Bypass) 48 V EHC (4 kW peak power) Diesel oxidation catalyst (DOC) Diesel particulate filter (DPF) Double-dosing SCR system

Fig. 2 Schematics of the EAS

Table 2 Exhaust gas aftertreatment system

Catalyst	Volume	Ø	Coating	CPSI	Information
EHC	0.1 l	5.66 "	–	130	–
DOC	1.95 l	5.66 "	140 g/ft ³	600	Pt:Pd=4:1
SCR	2 l	7 "	200 g/l	400	EU6d final
sDPF	3 l	7 "	95 g/l	300	EU6d final
UF-SCR	4.8 l	Oval	–	–	incl. ASC

2.2 Test methodology

As already mentioned, a heavy Sport Utility Vehicle (SUV) was considered for the described investigations. The maximum test mass of the vehicle amounted to 2264 kg with driving resistance values of $R_0 = 240 \text{ N}$, $R_1 = 0.37 \text{ N/(km/h)}$ and $R_2 = 0.0471 \text{ N/(km/h)}^2$. The first progress steps are described in Sect. 2.3 and illustrated in Fig. 3. The initial development block consists of three steps. After setting up the test carrier, including the necessary peripheries, a calibration of diverse EOMs was carried out and various heating measures were applied to ensure a rapid catalyst light-off. This light-off showed a generally low tailpipe (TP) emission level. The next three steps taken were to validate the applied measures by making use of the cycle results, to determine the target calibration and to subsequently perform a sensitivity analysis with several driving cycles. These process steps and the obtained results enabled us to evaluate the emission concept as a whole.

2.3 Validation of a WLTC

To maintain the optimum injection pattern throughout the investigation, the appropriate operating mode was selected by considering the desired emissions and fuel consumption and using an external state control. In simple terms, three exhaust temperatures were selected to define the selection of the proper EOM. Starting with the cold temperature, the

setting “Heat Mode 1” was selected to ensure low NO_x emissions at the high exhaust enthalpy [17]. This enthalpy, in turn, was achieved with late injection timings [9, 18] and by bypassing the HP-EGR cooler [19]. As soon as the DOC converts the available hydrocarbons (HC), the quantity of the late post injection is raised, triggering exothermic reactions in the DOC (Heat Mode 2). This entire warming process is supported by an EHC with a maximal power of 4 kW. Once the temperature of the first SCR brick rose above 220°C , it was possible to select the engine calibration setting with the lowest NO_x levels (Low NO_x). Enhanced EGR rates were obtained by increasing the boost pressure and additionally late injection timings helped to reduce the formation of NO_x . By adapting the rail pressure and simultaneously optimizing the pilot injection timing, operating points could be calibrated with reasonable smoke production. Once the SCR/sDPF were fully warmed up, the ECO mode called “LowBSFC” was selected. This mode enables all efficiency measures to be exploited to reduce fuel consumption. At the same time, the NO_x level increases again, since the highest SCR conversion rates in the exhaust tract take place in this mode. When the temperature level drops, the state control switches back automatically. Overall, this mode selection process consists of four differently calibrated EOMs coupled with an EHC control strategy to ensure the lowest NO_x/CO_2 -ratio [20]. The adjustments made in the switching thresholds are verified in the WLTC using a diverse dynamic cycle validation method described in Sect. 3. The sequence of modes selected by the state machine are also referred as the “Master” in this paper.

As an example, we compared the Low NO_x and LowBSFC calibration for their fuel consumption and EO NO_x levels, as these are the two most important calibration parameters. In Fig. 4, a significant difference in the EO NO_x levels is apparent. This difference is recognizable but small at 14 bar BMEP and 2500 rpm, but the concentration area below 100 ppm NO_x can be extended tremendously at lower loads and Low NO_x calibration. The limit of calibration occurring at the top right-hand corner of this maps indicates the lack of two-stage charging due to higher pressure gradients required [21] as well as the absence of LP-EGR in this setup. Figure 5 shows consumption maps corresponding to the previously shown NO_x maps. As observed, the sweet-spot area appears significantly larger in the LowBSFC mode, particularly at lower loads. At the optimum point, the fuel consumption varies by 6.5 g/kWh, which corresponds to a difference of about 3 %.

At 2000 rpm and 2 bar BMEP, the calibration differences are shown in Fig. 6 starting from the EU6b base data. This calibration example was carried out without taking noise or comfort aspects into account; however, the example illustrates the full potential of this hardware. Compared to the basic system, calibration in the Low NO_x

Fig. 3 Development steps and section allocation

Fig. 4 Comparison of engine-out (EO) NO_x engine maps

mode leads to higher fuel consumption due to the later effects of gravity on combustion, increased boost pressure and EGR rate, but specific NO_x emissions can be reduced to a third of the original levels. The fuel consumption advantage obtained in the BSFC mode mainly occurs due to the lower boost pressure and the earlier effects of gravity on combustion. Nevertheless, the NO_x emissions can also be reduced. The two heat modes represent special operating modes, which are characterized by significantly higher fuel consumption levels. In this study, we observed a significant increase in T_{41} as well as an increase in the total hydrocarbons (THC) emissions in Heat Mode 2, resulting in a huge exothermic heat generation in the DOC. The higher exhaust gas temperatures also result, in a non-negligible quantity, due to attempts to open the HP-EGR cooler bypass during these two heating modes. The internal engine measures described in this section supported the development of a low-emission concept and allowed a stable investigation procedure.

3 Results

This section is split into two sub-sections. In the first part, results obtained from the methodology steps 4 and 5 shown in Fig. 3, and in the second part, the results from carrying out the final validation step 6 are presented. All

Fig. 5 Comparison of BSFC engine maps

driving cycles were conducted at a cold engine start and the usage of Master database unless separately noted. To compare results, all cycles were automatically conditioned and started. A complete DPF regeneration was performed while the NH₃ storage of the SCR catalysts was also empty at each cold starting point. The dosing strategy used for the reducing agent relies on a loading-based NH₃ model to operate the system continually at the optimal NO_x conversion rate. The EHC activation control was carried out in two stages, depending on the cooling water temperature. The light-off and low-load advantages of using an EHC system have been shown in simulations and experiments in several publications [22–26]. The NO_x cycle values were not corrected for humidity, as prescribed by EU legislation [27].

3.1 Validations based on WLTC

In our investigation, several variations of the experiments were performed to examine the influence of different EOMs and of using an EHC system, and specifically, to examine their influences on the emission levels and fuel consumption. Three WLTCs without and three cycles with EHC activation were run. In the second group, a Load Point Shift (LPS) was implemented via a battery model to ensure an equal State of Charge (SoC), which increased consumption (cf. [24, 28]) but made objective comparisons possible. Starting from the

Fig. 6 Operating point: $n = 2000$ rpm and BMEP = 2 bar

EU6b baseline shown at the left of Fig. 7, the experiment was repeated in the Low NO_x mode only.

The EO NO_x level correspondingly decreases (data not shown), but the TP level remains approximately the same. Slightly more incomplete combustion due to the higher EGR rates is reflected by the increased THC and carbon monoxide (CO) output. Investigation number three was a repetition carried out with the Master data set. Due to the faster light-off, the TP NO_x mass could be reduced by almost 40 %; however, due to the higher conversion rates, additional laughing gas (N_2O) is formed, as can be clearly seen at the middle of Fig. 7. Especially in Heat Modes 1 and 2, the THC levels also rise significantly and thus increase the methane (CH_4) emissions. The low temperatures in the entire exhaust tract caused that the CH_4 concentration level remained almost constant during the EAS. Activating the heat modes resulted in a moderate increase in fuel consumption, i.e., 2 gCO_2/km . By activating the EHC, a NO_x TP level of approximately 20 mg/km could be achieved. These three results indicate that the type of engine calibration used is almost irrelevant with regard to this pollutant. The NO_x , THC and CO conversion rates increased notably. The biggest difference seen at this calibration level is the NO_x - N_2O trade-off: Increasing

Fig. 7 Comparison of final values in different driven WLTCs

the EO NO_x level (cf. conversion rate of LowBSFC or Master over Low NO_x) leads to much higher N_2O levels. This effect is described in more detail below. The excess fuel consumption was measured at around 4.5 %, which resulted from the inefficient energy recovery to the battery.

Considering the WLTC run in the different calibration states shown previously, the EO NO_x emissions in all four phases (Low, Medium, High and Extra High) are presented in Fig. 8. The most relevant phase with respect to the TP NO_x cycle emissions is the first phase, due to the catalyst warm-up phase. Since extremely high EGR rates were used

throughout the investigation the difference seen in this phase is small. Nevertheless, every excess hundredth of a gram must be avoided before SCR light-off, but the effect of EHC activation is still essentially higher, in terms of minimizing total TP NO_x .

The other phases shown mainly affect the N_2O formation via the DOC and SCR catalysts. In these phases, the catalyst temperatures are far above those at light-off, resulting in excellent conversion rates. The low N_2O emissions are clearly evidence when examining the Low NO_x database, and especially the savings that occur in the last two phases due to engine calibration.

Basically, the N_2O emissions level from combustion is zero. The sources of formation are the DOC and the SCR catalysts. N_2O formation over DOC takes place at medium temperatures just above the temperature range within with the oxygen from the exhaust gas is used instead of NO_x to oxidize HC and CO. In the SCR catalytic converter, N_2O formation occurs depending on the temperature level and the NO_x conversion rate. These relationships are empirically determined and are shown in Fig. 9, where T_{52} and T_{71} are the representative SCR temperatures. The EO and TP NO_x emissions are shown in the same figure but below. N_2O formation is clearly apparent at particularly high EO NO_x emission or high conversion rates. The two cycles with extremely low EO NO_x emissions stand out in particular, as they also have low TP N_2O levels.

At the AGVES meeting held on 27.04.2021 [29], several possible future emission scenarios were presented. As compared to an earlier version [30], several aspects of these

scenarios seem more positive. Two scenarios are currently being discussed with regard to a new statement that an emission budget will apply up to 16 km (limit value times 16 km) and a limit value in mg/km will apply only beyond this distance. One great difficulty arises when legislators attempt to address individual events. To illustrate the current technical status, the different WLTCs discussed in this paper are plotted in an emission limit diagram (Fig. 10). The light gray

Fig. 9 N_2O formation via DOC and SCR catalysts

Fig. 8 Share of EO NO_x emissions in the WLTC's four phases

area (value in front of brackets) represents Scenario 1, which would be technically feasible, but which would involve an enormously high development and cost outlay due to the production effort required. Scenario 2, shown in dark gray (value in brackets), seems to be barely complied with, as many curves lay above the threshold. Nevertheless, also this scenario represents a proposal for the EU7 limits. However, as the investigation with this test setup shows, undercutting the limits is not an effortless process, even when considerable hardware and calibration effort is invested. The results

shown in this diagram indicate that the most reasonable variant appears to be to use the Master database along with the EHC system. In a series application, the heat mode calibration would have to be applied more moderately to further reduce the CH_4 and non-methane organic gas (NMOG) emissions.

The results of the sensitivity analysis are presented in the next part of this section, initially discussing the conversion of NO_x . The final calibration of the engine, i.e., with the Master database and EHC system activation, is shown in

Fig. 10 Limits described at the meeting of the “Advisory Group on Vehicle Emission Standards” (AGVES) on 27.04.2021

Fig. 11 Share of NO_x and N_2O through conversion

more detail here. Figure 11 shows the trade-off between NO_x conversion and N_2O formation for each of the four phases of the WLTC. In the first phase, the NO_x breakthrough obviously predominates due to the low conversion rates, the N_2O formation increases in the other phases.

In Fig. 12, the temperature curves at five different positions are shown. The NH_3 dosing quantities for CC and UF are shown directly below in light blue, while the dosing release is shown in dark blue. The constant mass flow at the dosing release results from the loading-based model, building up the NH_3 storage and ensuring high conversion rates. The energy required to heat the catalyst corresponds to 289 Wh in total. The process of shifting through all four modes, which is controlled by the state machine, is shown below as well as the speed track. Considering this driving cycle, Fig. 13 shows other time-dependent variables. The most important variables are the cumulative NO_x emissions, which are divided by the cumulative driving distance. Even before reaching 450 s cycle time, the limit value of 80 mg/km can be complied with. Below this limit value, the two emission tracks are shown before and after EAS, respectively. At the TP position, essentially only one large NO_x emission peak is identified before efficient conversion takes place. Due to the low temperatures, the UF system only contributes to the last phase (same as in [31]). Due to the energy required to energize the EHC, an LPS is performed. Taking the whole efficiency chain into account, a virtual battery level E_{BAT} is calculated. Starting at 80 % SoC (2000 Wh battery), the LPS is only active once the battery level has dropped below 20 % or the SCR catalyst light-off has been exceeded. At the bottom, the BMEP is shown over the entire cycle, whereby a mean pressure of 20 bar is only reached during the last phase. Within the box, the final cycle values are shown for completeness.

3.2 Sensitivity analysis

Once the calibration was performed, a sensitivity analysis was conducted on the basis of various dynamic driving cycles, and in particular, challenging short driving cycles were examined. In Fig. 14, the TP NO_x emissions are shown as the most important examination output. The increase on

Fig. 12 Temperatures and NH_3 dosing at final calib. point

the left side represents only the left part of the “bathtub curve” (cf. [32]). All cycle results are well below the 80 mg/km limit, but the Mumbai City Cycle and RTS95 clearly exceed the other cycle results. The former excess is due to the extremely low dynamics that occur over a short distance [32, 33], and the latter is due to the high dynamics that occur over a moderate driving distance. As will be shown later, a large proportion of the TP results from the cold engine start, and later on, from certain individual events as the SCR system is overloaded by huge NO_x concentration peaks.

Figure 15 illustrates the time shares of the respective active operating modes. Engine stop phases are not counted, as no species are emitted at these time steps. The share of active heating modes is significantly higher in the low-load and short-distance cycles. This share increase results first in higher fuel consumption and second in a generally high emissions level. In the Mumbai City cycle in particular, the distribution clearly shows that, despite the internal engine heating measures taken and the use of the activated EHC system, the whole EAS does not really overcome the light-off threshold. In comparison, the Artemis cycle is predominantly driven in the consumption-optimized engine mode, meaning that SCR catalysts rapidly operate within the optimal temperature range. Astonishingly, the behavior in this cycle is quite similar to that seen in a WLTC.

Fig. 13 NO_x concentrations at the EO and TP positions

A general overview of these results is depicted in Fig. 16. The emission trends displayed by the different species shown are similar to one another. Mainly due to incomplete HC and CO conversion over the DOC, the TP emissions of these two pollutants increase. Nevertheless, even in the Mumbai City cycle, the combined (HC + NO_x) limit of 170 mg/km can be met; in this case 167 mg/km. The energy required for EHC operation is mainly determined by the thermal mass and target temperature of the catalysts, whereby at RTS95 the energy is notably less due to the high exhaust enthalpy at the cycle start. The increasing CO₂ value shown on the left-hand side of Fig. 16 results from two aspects: first, due to its tendency to operate at low loads (i.e., inefficient operating points), and second, due to increasing LPS.

Altogether, the study results show that the engine and dosing control unit calibration is of high quality. To gain

Fig. 14 NO_x sensitivity analysis of driving cycles

more insight into the cycles investigated, all driving cycles were examined in more detail. Figure 17 is split into two individual parts. The top three cycles represent low-load cycles, while the bottom three cycles tend to be higher load cycles. This is particularly evident when examining the cloud of operating points. Few points above 12 bar BMEP can be seen at the top of this figure, but a trend towards high loads is clearly visible at the bottom of this figure. From an idle status to an engine speed of approximately 1500 rpm, the range is essentially only covered up to 6 bar BMEP. When using an 8-speed automatic transmission, speeds above 2500 rpm are hardly ever reached, resulting in appropriate emission values. In this paper, the cycles shown are SoC neutral, meaning that the cloud of operating

Fig. 15 Time share of EOMs in driving cycles

Fig. 16 Sensitivity analysis of important key parameters

points is influenced by the LPS, tending to cover higher loads. The speed traces in the middle of the graph give the reader a sense of dynamic motion. The Mumbai City cycle and WLTC 3xCity (i.e., three times the City part of the WLTC) fall within the extremely low speed range. Even in low-load NEDC, all other investigated cycles included overland, respectively, highway periods. On the right-hand of Fig. 17, we show a temperature histogram for each cycle which refers to T_{41} . Here, the influence of the dynamics is also clear. As the acceleration and speed increase, the distribution of temperature becomes more homogeneous. The increase in the trend towards higher temperatures is viewed positively, since this also increases the exhaust gas enthalpy, and consequently, the emission conversion behavior. Since the heat modes released many HC species, and so additional energy, the full impact of the heating measures cannot be

demonstrated with this bar chart. Regarding the EAS, however, these measures affect the most dynamic temperature point in the exhaust system, as this is located directly beyond the turbine.

To complete the investigation and finalize the last step (i.e., number 6 shown in Fig. 3), the cycle results needed to be validated for each possible future scenario. As in Fig. 10, all driving cycles were entered into the existing emission grid and evaluated. Figure 18 displays the results. The NO_x and N_2O emissions exceed the limits in the RTS95 and Artemis cycles. The adsorption capacity of the SCR is not sufficient in these cycles; thus, the NO_x emissions are released before the SCR system exceeds the light-off temperature. Regarding NO_x , the emission line always shows a strong increase when it approaches zero; thereafter, this line flattens. All further increases indicate an overload of the EAS,

Fig. 17 Operating points, vehicle speed profile and temperature histogram of the investigated cycles

and most of these overloads are related to large peaks that occur at moderate system temperatures. All other limits seem feasible in the light gray scenario. These hardware components do not seem to allow compliance with the stricter regulations; therefore, in Scenario 2, indirect banning of the ICE from passenger car powertrains occurs. The HC species, and specifically CH_4 and NMOG, were usually found exactly at or above the limit set in the stricter scenario in this investigation. These species primarily resulted from the application

of targeted heat modes and only resulted to a small extent from unavoidable, incomplete combustion. CO poses almost no threat, and especially in diesel engine combustion. The newly considered species formaldehyde (HCHO) was mainly formed during cold start phases [34], and a crucial share was subsequently oxidized by the DOC, allowing the low limit value of 5 mg/km to be met. NH_3 is deliberately not shown, since the TP level is negligible (< 0.1 mg/km) due to the appropriately calibrated urea double-dosing and the use of

Fig. 18 Sensitivity analysis considerations regarding the limit values, discussed at the AGVES meeting on 27.04.2021

an ASC. This low NH_3 level represents one major advantage compared to gasoline applications.

4 Conclusions and outlook

Ongoing investigations by researchers allow the efficiency of a modern EAS to be impressively demonstrated. In the current investigation, various calibration steps were performed to represent NO_x TP emissions of 18 mg/km in a WLTC at a total conversion rate of 96.5 %. The THC emissions of 25 mg/km and CO emissions of 64 mg/km at TP also remained at a moderate level throughout the study. Our evidence indicates that, although a modern overall system calibration effectively reduces NO_x , non-negligible amounts of N_2O (18.5 mg/km) are formed in the EAS. The global warming potential of these emitted species cannot be ignored, since CH_4 is 25 and N_2O is 298 times more harmful than CO_2 [35].

In all cycles studied, the current emission legislation requirements could be met. These results are not surprising, considering the giant catalyst volume of almost 12 l. Despite the enormous hardware and calibration effort required, we could demonstrate the system performance, but predict that it will not be easy to comply with emission limits in the future should these become stricter. High-load cycles do not really cause problems, since the EAS must be designed for maximum space velocities, including a consideration of aging effects. However, low-load cycles show the limits of such a system due to the lack of EAS readiness. Using hybrid layouts enables engineers to reduce catalyst aging under real operation conditions [36], and the use of such layouts will additionally be mandatory for thermal stabilization purposes, if a Lean NO_x Trap (LNT) with a SCR double-dosing emission concept will be applied as an emission measure in the future [9, 18]. Some challenges remain, however, as different LNT loadings with the application of such concepts have yielded different NO_x TP results [33].

To prepare to meet future challenges, the influence of a hybrid drive system will have to be considered much more carefully, and the EAS will have to be improved still further. Primarily, this statement refers to the use of mainly passively operated LNTs with a minimum number of purges [37], since this use increases both CO_2 and CH_4 emissions. Secondarily, it also refers to, e.g., external air pumps that are used to condition the EAS before starting the engine. To further optimize the system as a whole, simulations should be run to examine the potential of using parallel hybrid structures and LNT-based layouts with a heating disc to reduce emissions still further in the future. The best technical solution considering climate change is not to ban the respective technologies. Instead, an overall consideration should

be made of the CO_2 equivalent emissions during the entire vehicle cycle, but such work goes beyond the scope of the current study.

Appendix

See Table 3

Table 3 Fuel data

Parameter	Value
Fuel type	Diesel B7
H_u	42321 kJ/kg
Density ρ	0.833 kg/dm ³
μ_C	85.0 %(m/m)
μ_H	13.8 %(m/m)
μ_O	1.2 %(m/m)

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