Commercial Vehicle Powertrain Technologies for achieving future low-emission regulations

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New emission regulations for heavy-duty Diesel engines will come into effect within the upcoming years. For Europe, the EUVII regulation framework is currently under development and a significant reduction of NO_x emissions will be required. Furthermore, this reduction needs to be achieved under any driving conditions classified as normal use. Especially cold start conditions are a challenge to the aftertreatment system as the light-off temperature of the Selective Catalytic Reaction (SCR) technology is not achieved in the first minutes of the driving cycle. To comply with such severe emission limits, new and improved technologies will be needed. Firstly, this requires the introduction of a twin-SCR aftertreatment system with advanced Urea mixing and control strategies. Secondly, SCR performance during the cold start needs to be improved by additional heating measures. Regarding the latter, an advanced fuel injection strategy supports the heat-up of the aftertreatment system. Even further reduction of the cold start duration requires additional heating components. Such heating devices have the drawback of increasing the CO_2 emissions of the engine. However, such drawbacks can be mitigated by employing a hybrid powertrain concept. The presented paper describes each of these technology solutions and uses a heavy-duty EUVI engine to demonstrate them through engine dynamometer measurements, as well as by validated simulation results.

Key words :

Diesel Aftertreatment System, EUVII, low-emission powertrain, NO_x reduction technologies, Aftertreatment Heating, Hybrid Heavy-Duty Vehicle, Advanced Fuel Injection Equipment

1. Introduction

Worldwide, strict new regulation frameworks for the emissions of heavy-duty Diesel engines are planned to come into effect over the course of this decade. The most severe regulations are planned to be adopted through the Californian Air Resources Board's (CARB) Stage 3 Low-NO_x program[1)], as well as by the European EUVII. Although EUVII is currently still under development, first proposals already have been published by the Consortium for ultra-low Vehicle Emissions (CLOVE). Judging from the most recent proposal [2)], the new EUVII will not only require a significant reduction of NO_x emissions but will also regulate emissions during any engine operation considered normal use. This specifically includes low load conditions and the cold start.

The presented paper summarizes the engine and aftertreatment technology solutions, that are necessary to comply with the current proposal. As a basis for the investigation, a 9l heavy-duty Diesel engine without exhaust gas recirculation (EGR) is used. Starting from a series EUVI aftertreatment configuration the different technologies are then introduced and evaluated by both, engine dyno testing, as well as by simulation studies. A detailed description and review of this activity has been published in [3)].

2. The System Approach towards low-NO_x Emission Powertrains

As a first step, the EUVII proposal shall be assessed against current EUVI engine and aftertreatment technology. The EUVII proposal on hand [2)] considers three separate limit definitions. Firstly, a so-called budget limit, which is to be triggered for trips accumulating to less total energy than the amount of three WHTCs. For the budget limit the vehicle must not exceed a defined threshold of accumulated NO_x emissions.

For longer engine operation, a limit during hot engine use (90-percentile limit), and a limit for the cold start (100-percentile limit) are defined. The underlying calculation method uses a moving-average window (MAW) to determine the NO_x-emissions during vehicle use. Each averaging window is as large as to include the accumulated energy of one World Harmonized Transient Cycle (WHTC). In evaluating all MAWs recorded during a trip, the 100-percentile represents the window with the highest amount of NO_x (i.e., the cold start).

For the 90-percentile, the 90 percent of all MAWs, which contain the lowest emissions are considered. From these windows, the one with the highest emissions represents the 90-percentile limit. This value is chosen to characterize the vehicle performance during normal hot use. For each of the three limits then in turn, two proposed values are given with different degrees of severity, which are denoted as HD2 (softer limits) and HD3 (stricter limits).

The underlying values of HD2 and HD3 are based on two different technology packages entailed within the proposal. HD2 assumes the aftertreatment to consist of a twin-SCR system. It further assumes engine-out NO_x emissions of less than 2g/kWh during cold start, facilitated through large rates of EGR. HD3 further adds a fuel burner for fast exhaust heating, which is assumed to contribute 60kW of heating power during the cold start.

To highlight these different sets of limits in comparison to engine data, Fig. 1 shows an evaluation of the EUVI base engine and aftertreatment system against HD2 and HD3. The aftertreatment consists of a standard DOC-DPF-SCR configuration. The evaluation is carried out for three subsequent WHTCs and three Low Load Cycles (LLC) on an engine dyno. The LLC is specifically chosen to characterize the system behavior during long durations of low engine load, where the aftertreatment system is at risk of cooling down below the light-off temperature.

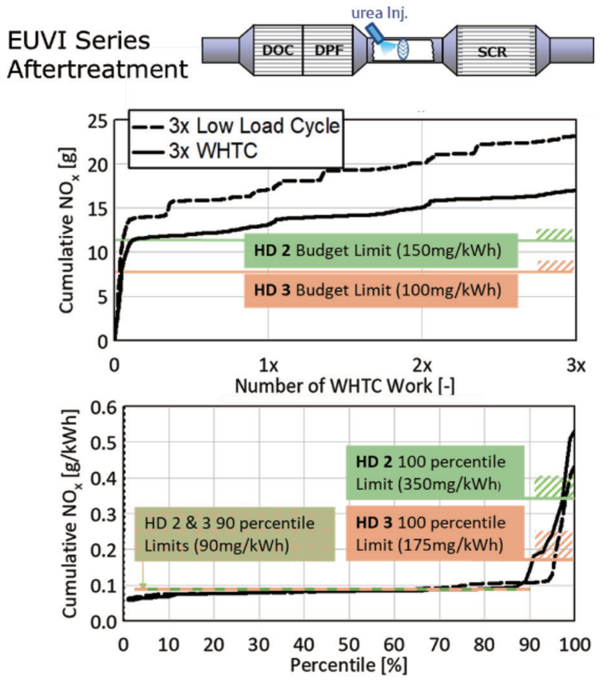

Fig. 1 Evaluation of the base EUVI aftertreatment system towards the proposed EUVII limits

Whereas Fig. 1 top shows the time-based accumulated NO_x, the bottom plot shows the emissions of each MAW, sorted from lowest to highest, thereby yielding the 90 and 100-percentile values. Considering the proposed limits both, the budget and the percentile limits are not achieved.

The regulation allows for a correction of the accumulated energy of the MAW. Thereby, windows that contain engine use under less than 10% of the rated power of the engine are changed to match that value. According to the published proposal, this is done to make windows with very low average power valid test. This inflates the accumulated energy and thus, reduces the specific NO_x emissions in g/kWh of the MAWs in question. As a result, this leads to a more favorable rating of the LLC as a benchmark cycle.

As neither the HD2, nor the HD3 limits are achievable with the current EUVI technology, additional measures need to be introduced to further reduce emissions. The first step consists of replacing the current EUVI aftertreatment with a twin-SCR system. Such system requires a highly accurate urea dosing and mixing, as well as dedicated controls. This approach is schematically illustrated in Fig. 2.

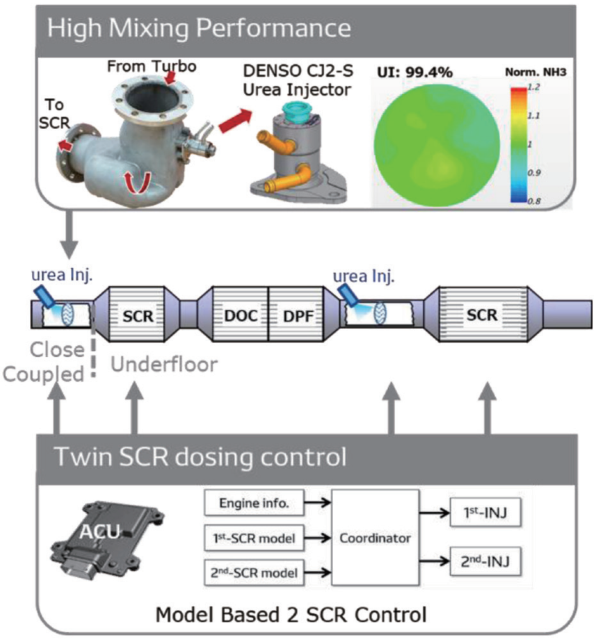

Fig. 2 DENSO technology for achieving ultra-low-NO_x emission requirements

The latest generation DENSO urea injector is coupled with a high-performance mixer, based on patented tumble flow technology [4)]. This mixer is installed in a close-coupled position directly behind the engine turbo. For excellent NO_x conversion efficiency of 99.5% the homogeneity of Urea within the exhaust gas needs to be as high as possible. For the used injector-mixer combination, a Uniformity Index of 99.4% is reached at the inlet of the SCR, according to validated CFD simulation [3)]. The Uniformity Index is a measure for the homogeneity of the Ammonia distribution in front of the catalyst and defined by:

$$\text{Eq. 1} \quad UI = 1 - \frac{1}{2n}\sum_{j=1}^{n}\frac{\sqrt{(X_j - X_{\mathrm{mean}})^2}}{X_{\mathrm{mean}}}$$

with X_j representing the molar fraction of ammonia along the cross-sectional area in front of the SCR and

X_{mean} the mean molar fraction of the ammonia.

In addition to optimizing the conversion efficiency during hot engine use, even lower emissions are achieved by targeting the NO_x during the cold start. For this, further improvements are demonstrated by use of a validated simulation environment. This is schematically illustrated in Fig. 3, where starting from the described twin-SCR configuration in underfloor position (*System 1*), two further aftertreatment topologies are evaluated. For *System 2*, the first SCR is moved upwards into a close-coupled position, reducing the piping length between engine and SCR to an absolute minimum. Whereas such configuration may not be feasible for all vehicle applications, it can be considered a theoretical best-case for twin-SCR systems, regarding its capabilities in reducing the cold start NO_x. *System 3* further introduces active heating components into the aftertreatment system. For the presented paper, an electrical heater is used as the example for active aftertreatment heating.

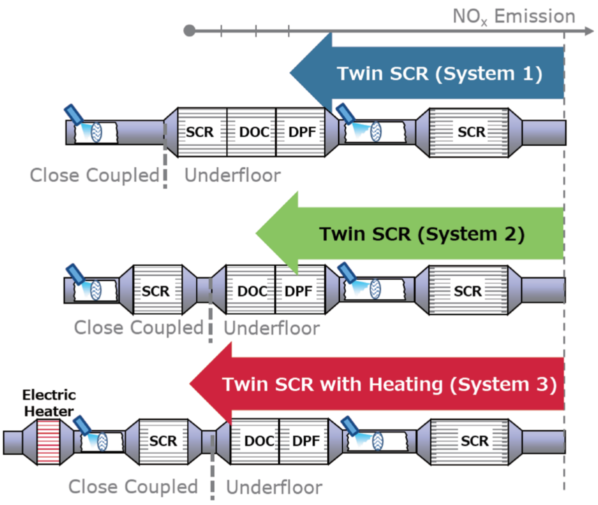

Fig. 3 Aftertreatment System configuration for EUVII

3. Twin-SCR System Performance in the Context of the Current EUVII Regulation Proposal

In a first step, the *System 1* configuration is tested on an engine dyno for different engine cycles. An exemplary result for NO_x emissions during three subsequent WHTCs in comparison to the EUVI stock system is presented in Fig. 4.

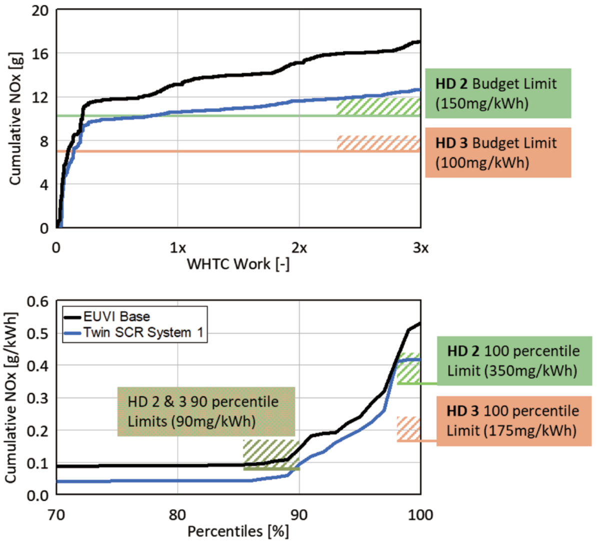

Fig. 4 Accumulated tailpipe NO_x emission of the EUVI base system and the System 1 configuration against the EUVII proposal emission limits

Moving from a single-dosing towards a twin-dosing aftertreatment system thereby leads to a significant reduction in NO_x emissions during hot use, as well as a moderate reduction during the cold start phase. However, this system does not yield the improvement that is necessary to comply with either HD2 or HD3. Especially the emissions during cold start, which not only negatively impact the 100-percentile, but also the 90-percentile values, need to be further reduced.

A similar result is exhibited for further evaluated engine and vehicle cycle tests. This is summarized in Fig. 5, which shows the results of the WHTC, as well as of the Federal Test Procedure (FTP) and the Low Load Cycle. Further included are also two vehicle cycles, the Long Haul (LH) and the Regional Delivery cycle (RD), each considering a 50% payload. For running vehicle cycles on an engine dyno, the cycle information (vehicle speed, inclination) needs to be transferred into an engine cycle trace, consisting of engine torque and engine speed. This was done by employing a vehicle model [3].

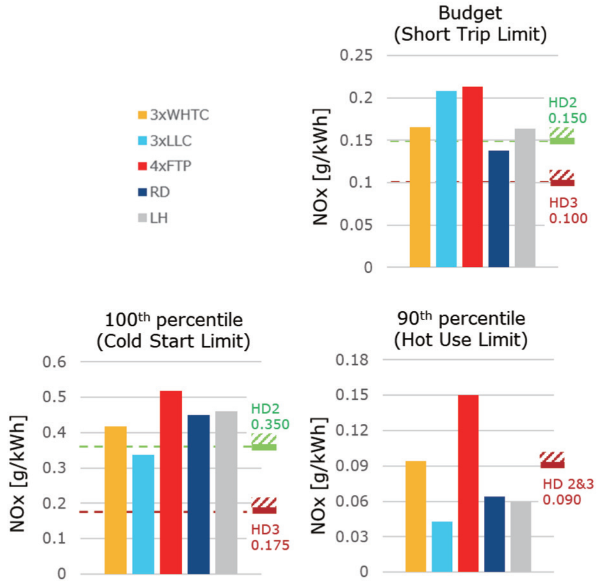

Fig. 5 Summary of NO_x emission results against proposed EUVII limits

For keeping with the EUVII regulation framework of distinguishing between trips below and above the energy of three WHTC, similar cycle repetitions have been carried out for the other cycles to ensure an accumulated energy of at least three WHTCs. The emission results for the different cycles further support the claim, that currently proposed limits will not be achievable by a twin-SCR upgrade to an existing powertrain topology.

To yield a more significant reduction of the cold start emissions, a faster light-off is needed. This requires less thermal inertia between the engine and the SCR, which enables a faster rise in temperatures at the aftertreatment system. Adding an electric exhaust gas heating device further reduces the time until the light-off is reached.

These improvements are incorporated into the *System 2* and *System 3* configurations established in Fig. 3 and further studied within a simulation environment.

Fig. 6 shows the resulting cumulative NO_x emissions and the percentiles of these two configurations for three WHTCs.

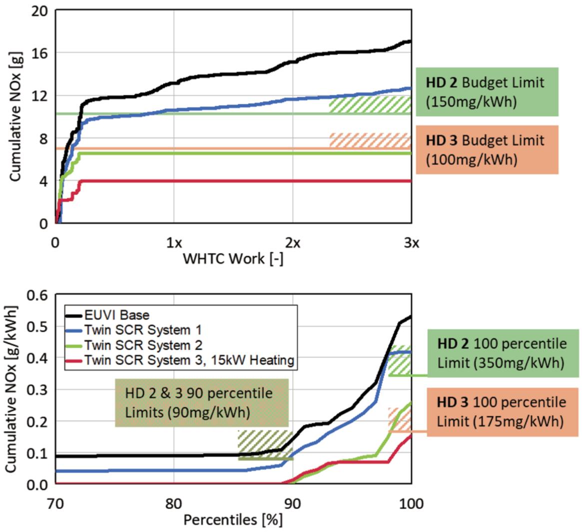

Fig. 6 Accumulated tailpipe NO_x emission of the investigated aftertreatment topologies against the EUVII proposal.

The *System 2* configuration achieves the HD2-limits for cold start, budget, and hot use. Further adding a heater with 15kW of electric power to the aftertreatment (*System 3*) even yields tailpipe NO_x emissions with sufficient remaining engineering margins to comply with HD2. HD3 emissions limits are also achieved by this configuration, however, without remaining margins.

4. The fuel injection system for the future low-NO_x powertrain

The fuel injection system needs to play a decisive role to support with an ultra-low-NO_x strategy. Lowering the engine-out NO_x levels will require higher EGR-rates, while at the same time further efficiency improvement is still necessary to comply with stricter CO_2 regulation. Resulting from an increased use of EGR, higher soot emissions also need to be considered.

Such trade-offs can be resolved by an advanced fuel injector concept, which employs a faster injector opening to reduce soot emissions. This is especially critical during the cold start before the SCR light-off, where lowest engine-out NO_x emissions are needed. To meet higher efficiency demands, higher compression ratios coupled with larger nozzle flows offer further improvement potential. Up to 4.5% better fuel consumption was found in a previous study published in [5)].

In addition to this, the injector can be directly used to support aftertreatment heating. A highly accurate and stable injection behavior over lifetime is a prerequisite for this, which is achieved by the DENSO 4th Generation fuel injection system [6-7)]. This enables the use of multiple post-injections within a dedicated cold-start engine mode. To highlight the advantages of such strategy, an investigation was carried out, which is summarized in Fig. 7 for one exemplary steady-state point of the engine map. A detailed explanation of this study has been published in [3)].

A current state-of-the-art injection pattern for best fuel consumption and a regular engine heating strategy are used as a baseline (see Fig. 7, black and blue data points). From this, a novel Split-Post strategy has been defined, which uses up to five separate injection events, three of which are located after the main injection with small injection quantities of 5 mm^3/str. The exact timings, as well as the rail pressure are optimized under the constraints of keeping HC and CO emissions at the same or lower levels than observed by the baseline injection patterns. Furthermore, soot emissions are decreased compared to the baseline engine calibration.

This Split-Post strategy offers benefit during the cold start by on the one hand reducing the engine-out NO_x emissions and on the other hand increasing the thermal heat to the aftertreatment. In the given example of Fig. 7, a 22% reduction of NO_x and an additional heating power of 4.9kW to the aftertreatment via increased exhaust gas enthalpy are achieved.

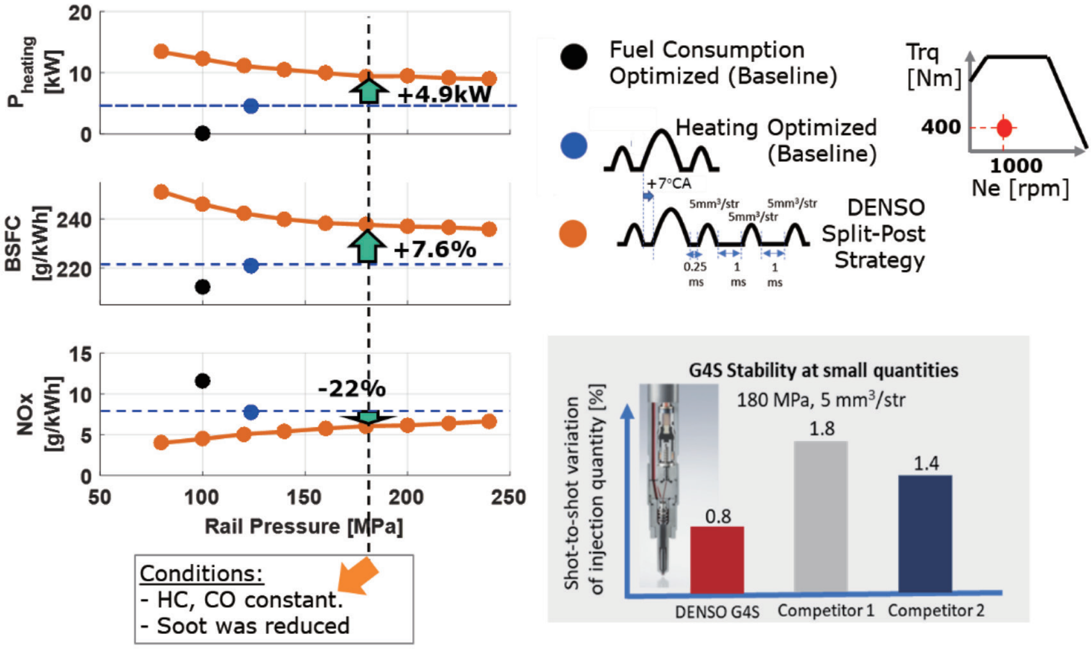

Fig. 7 Advantage of the DENSO Split-Post Strategy for cold-start heating

This process is carried out for multiple steady-state points within the entire low-load area of engine map and evaluated within vehicle model simulation, using the *System 2* aftertreatment configuration. Whereas the brake-specific fuel consumption (BSFC) is increased by this strategy (7.6% for the exemplary load point), this increase is significantly smaller than observed for the e-heater. This is further highlighted in Fig. 8, which shows the trade-off between a low NO_x tailpipe and the CO_2 emissions for one cold started WHTC.

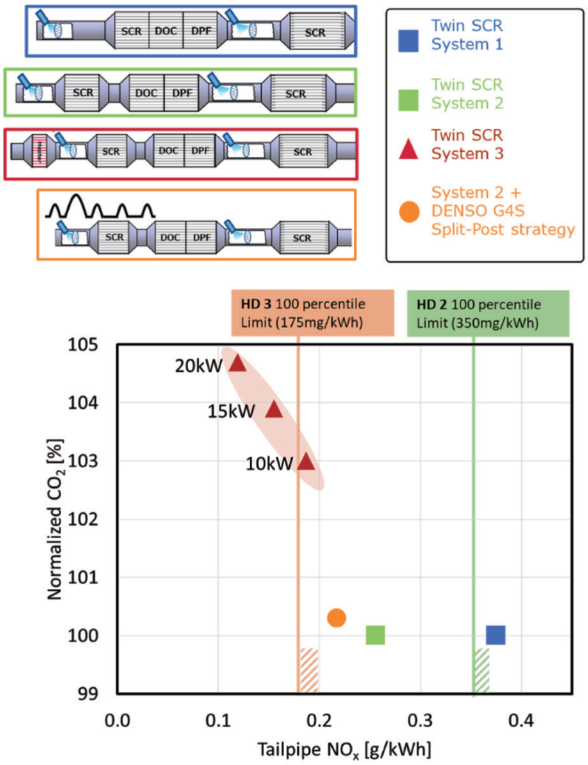

Fig. 8 CO_2-NO_x trade-off for a cold-start WHTC

The electric heater enables the reduction of tailpipe NO_x during the cold start, complying with HD3 limits at heating power values above 15kW. The Split-Post strategy on the other hand yields a smaller NO_x benefit in comparison, however, this reduction is achievable without a significant CO_2 penalty. By this, such strategy offers a strong benefit for reducing the amount of additional heat to a minimum.

5. Hybridization as a low-NO_x Technology

The drawbacks in CO_2, which arise from adding electric heating to the aftertreatment system can be in part mitigated by a hybridized powertrain. This has been studied by a vehicle model, based on the same 9l Diesel engine and the *System 3* aftertreatment topology, which was introduced in the previous chapters. A P0 hybrid configuration is chosen as it has low integration effort and comparatively low system cost while offering the potential to offset the increase of CO_2 from electrical heating methods. To obtain the best NO_x-CO_2 trade-off a dedicated control strategy is utilized, which is described in detail in [3].

The base vehicle model consists of different subsystems that model the behavior and interactions between components such as the engine, the motor generator, battery, and gearbox. It is enhanced by a P0 hybrid, which consists of a 400V motor generator with peak power of 50kW and peak torque of 60Nm. Detailed description of the motor generator has been published in [8]. The battery is modeled with a capacity of 5kWh. Additional electrical components other than the E-heater are not considered for this study. The system has been evaluated, using vehicle cycles with and without payload. The simulation has further been

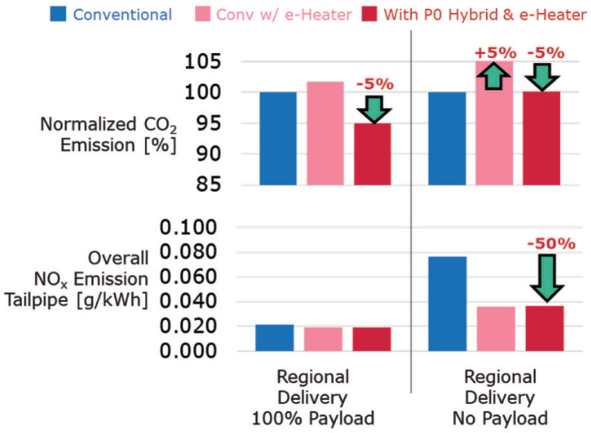

Fig. 9 Impact of P0 hybridization for overcoming the CO_2-NO_x trade-off

validated by comparing its results to engine testing. The results of this investigation are summarized in Fig. 9 for an exemplary Regional Delivery cycle.

Here, the normalized CO_2 and the specific NO_x emissions at the tailpipe are compared for the non-heated base engine, the base engine with 15kW of added electric heating and the P0 hybrid with the same electric heating. The results indicate, that a P0 concept reduces the CO_2 emissions by 5% compared to the conventional, non-heated baseline engine. For the cycle with no payload, the amount of recuperable energy is lower in comparison, however, here the P0 still is able to mitigate the CO_2 penalty that arises from the electrical heater.

For future low-NO_x emission regulations like the HD3 scenario where additional heating is required, a P0 thereby changes the cost-benefit calculation for electric heating. At the same time, a significant reduction in the NO_x emissions is achieved.

6. Conclusions

Different technology solutions for achieving the future low-NO_x powertrain have been studied by means of both, experimental measurements on an engine bench, as well as through simulation studies. Given the current EUVII emission limit proposal, the results indicate, that no single one, but a mix of different technologies will need to be added to the aftertreatment system, as well as to the engine itself.

As a first step, the series EUVI-D aftertreatment configuration is replaced with a twin-dosing SCR system, employing a highly accurate Urea injector-mixer combination and optimized controls (*System 1*). As especially cold start NO_x emissions are not satisfactorily reduced by this system alone, further improvement is considered by moving the SCR into a close coupled position (*System 2*) and then adding electric heating of the aftertreatment (*System 3*).

The twin-dosing SCR configurations demonstrate significant emission reductions during hot engine use. For the cold start, however, additional measures need to be established. Active electric heating of the aftertreatment has the potential to reduce light-off time significantly, while at the same time resulting in a substantial increase in CO_2 emissions.

Here, the fuel injection system plays a major role, as it can be employed for improving the light-off time by adding several kilowatts of additional heat to the aftertreatment system, using a Split-Post injection strategy. Such measure results in a NO_x reduction with significantly lower CO_2 penalty when compared to electric heating.

To achieve a more favorable trade-off between NO_x and CO_2 emissions, a P0 hybrid concept was further studied by means of a vehicle model. Results show a strong potential for reducing CO_2 emissions below the baseline values even with an additional 15kW of electric heat being used during cold start.

Even in an aftertreatment configuration with twin dosing and active heating, the most severe emission limits are barely reached, therefore, even further improvement points will be necessary in such circumstance. Here, increased rates of exhaust gas recirculation need to be considered to reduce the engine-out NO_x, especially during cold start. This aspect will further be highlighted in future work.

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