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# Diesel – Quo Vadis Diesel – The Road Ahead

## Abstract

Starting with the role that the diesel engine plays in achieving fleet CO<sub>2</sub> targets now and in the future, this paper discusses the subject of diesel engine emission compliance, which has lately fallen under heavy criticism. To this end, this paper will examine the following areas for their potential to achieve further reductions in CO<sub>2</sub> and emissions.

- o combustion and inner-engine temperature management
- o aftertreatment concepts
- base engine variability
- o further potential in combination with electrification

Based on those considerations, the future diesel engine should be defined with respect to technical features as well as size, additionally taking into account the whole drivetrain.

The diesel engine will remain a crucial element in achieving an affordable CO<sub>2</sub> fleet strategy in the future, especially in consideration of the market trend toward SUV and cross-over concepts. Particularly where the heavier vehicle classes are concerned, the diesel combustion concept does in fact make it possible to combine efficiency with environmental compatibility and driving pleasure – even under real-world operating conditions.

# Introduction – Why Diesel?

In order to fulfill global climate targets, many countries have introduced fleet  $CO_2$  targets and fleet fuel consumption targets in addition to their conventional emission legislation. Europe defined the fleet value of 95 g/km  $CO_2$  to be achieved by 2020/2021. Severe penalty payments are imposed for excess emissions. Already now the diesel engine plays an important role in achieving the current  $CO_2$  targets in a cost-efficient manner.

In <u>Figure 1</u> the NEDC-certified CO<sub>2</sub> values are plotted versus vehicle weight for different technologies. It is noticeable that a selection of currently available diesel models already meets the 2021 targets today, contributing significantly to the average CO<sub>2</sub> emissions of the fleet mix. This, along with the trend toward SUVs and cross-over models that already achieve a market share of around 20%, makes it evident that a significant reduction of the diesel share would pose an additional challenge in achieving future fleet targets.



Figure 1: CO<sub>2</sub> values vs. vehicle weight and technologies

For evaluating customer-relevant fuel consumption, real-driving consumption data are plotted in <u>Figure 2</u>. The values are based on around 160 test results from "auto motor und sport", a leading German automobile magazine [1]. The results plotted indicate that a shift from diesel toward gasoline increases customer-relevant volumetric fuel consumption in L/100km by 30% to 40%.



Figure 2:Volumetric fuel consumption gasoline & diesel in real-world operation

Not only the OEM focus on the achievable fleet CO<sub>2</sub> values but also the customer view on the volumetric consumption figures are good arguments for having a substantial share of diesel vehicles. This is especially true where the bigger and hence heavier vehicle classes are concerned, which typically also have a higher yearly mileage.

Taking the current status as starting point, the following section discusses the future potential with respect to RDE performance with a special focus on urban areas. Only by proving minimum-emissions performance across the entire use area will the diesel stand a chance to remain successful on the market and contribute to further CO<sub>2</sub> reduction. In an analysis of the conflicting area of load profile, driver influence and ambient conditions, we shall examine the challenging combination of aggressive driver and low ambient temperatures in urban as well as in extra-urban conditions.

# Status Quo Assessment – The Performance of a Modern Diesel

To provide a sound basis for further considerations, RDE measurements were recorded with moderate and aggressive driving styles. The dynamic/aggressive drive sequence reaches the limits legally defined for aggressive RDE driving. Tests were performed with a midsize passenger car with a curb weight of 1700 kg. The single-stage boosted 2.0L engine was equipped with an uncooled/cooled HP EGR system and an exhaust line consisting of an LNT (2.0L) as well as an SCR-coated DPF (2.7L) followed by a downstream SCR disk in the same canning (1.5L) and an ammonia slip catalyst in under-floor position (0.5L). The system, including the respective sensors, is shown schematically in <u>Figure 3</u>. Tests were conducted on a system representatively aged to full useful life.



Figure 3: Exhaust aftertreatment concept

For the test drives that were conducted at an ambient temperature of 0°C the urban part was evaluated separately in addition to the total trip result. For each part the following values were determined:

	CF total	CF city
RDE moderate	0.84	1.30
RDE dynamic	1.39	1.96

A moderate driving style delivers conformity factor (CF) values that are definitely attractive and clearly within the discussed limits. For the aggressive/dynamic driving style, the value of 1.39 for the total cycle is absolutely acceptable, whereas only the value for the city part shows a significant increase. Although even this value remains within the limit that takes effect in autumn 2017, it is obvious that there is need for further improvement.

<u>Figure 4 displays the measurements in detail.</u> Not only the tailpipe emissions, which are shown in table form as total value, but also the raw emissions are plotted over time. Especially the raw emission traces indicate the load-related impact on emission formation.

During inner-city operations the temperature profile generally remains below the critical threshold for the aftertreatment for a very long time, and even during extra-urban operation the temperature drops significantly after motoring, which, in the case of aggressive driving, is even followed by a standstill. This can be seen at around 5200 sec. The acceleration that follows the motoring/standstill phase causes a peak in the raw  $NO_x$  emissions that is also clearly reflected in the tailpipe emissions.



Figure 4: RDE base measurements with moderate and aggressive driving style

The discussed driving cycles represent a worst-case scenario with respect to engine starting conditions. A fully NO<sub>x</sub>-loaded LNT is combined with SDPF and SCR catalysts without NH<sub>3</sub> load. Although this scenario may seem unusual, there are situations in real life, in which specific driving patterns and ambient conditions can lead to such an unfavorable constellation for the aftertreatment components.

In summary the assessment of the current status reveals that the analyzed baseline concept basically delivers attractive emission results. In view of more dynamic city operation and future requirements, however, there is still room for improvement.

As a next step, we shall turn our attention to the virtual development environment in order to gain more flexibility in our comparisons and evaluations of different approaches. For this purpose, we have transferred the entire system (consisting of drivetrain, exhaust aftertreatment and vehicle) to the model-based simulation environment [2]. Figure 5 shows the verification of the simulation quality by cross-plotting measured and simulated values during the test drive with dynamic driving behavior.



Figure 5: Comparison: simulation vs. measurement, dynamic driving, 0°C

The emissions as well as the decisive temperature traces are simulated with sufficient accuracy to enable comparison and evaluation of the different measures addressed below. The difference between simulation and measurement based on the cumulated NO<sub>x</sub> tailpipe emissions amounts to 4%, which proves the high simulation quality.

## Further Measures – Potential to Optimize Emissions and Efficiency

#### Conventional measures - high load and high dynamic range

In a first step we shall investigate emission challenges in the higher load range. In order to achieve a good trade-off between raw emission reduction and fuel economy, the base engine was supplemented by a low-pressure EGR with a water-cooled charge air cooler positioned close to the intake manifold. In combination with a temperature-controlled (coolable) high-pressure EGR, this allows EGR application over the entire engine map. The boundary condition for the reduction of the NO<sub>X</sub> raw emissions was the maintenance of the same DPF regeneration interval as with the exclusively high-pressure EGR system. Results are shown in Figure 6, in which the already simulated values served as basis (HP EGR only).



Figure 6: RDE drive with LP EGR and extended EGR range

A total CF below 1.0 is achieved – even with aggressive/dynamic driving. This means that even with this rather conventional approach, it is possible to meet the target values set for 2020 and beyond [3].

#### Conventional measures - cold start and low-load operating range

Nevertheless, there is further optimization potential regarding exhaust aftertreatment efficiency in the first 1000 seconds after cold start and, quite generally, in the case of the highly transient operating mode. Especially in the first 500 seconds of the cycle, the exhaust temperature is still too low for adequate NO<sub>x</sub> conversion. This means that aggressive catalyst heat-up measures are fundamental to ensuring faster catalyst light-off and hence minimum emissions, even with different driving profiles and ambient conditions. In Figure 7 the temperature increase via Early Exhaust Valve Opening (EEVO) is compared with an electrically heated catalyst (E-cat).

The advantage of using an electrically heated catalyst is that, regardless of the engine operating point, the energy goes straight to the exhaust aftertreatment system. In other words, the temperature increase is generated where it is needed. In addition, an engine operating point shift is caused by the higher load of the alternator, which, in turn, has a favorable impact on the combustion temperature. In order to further optimize the trade-off between emissions and consumption, the battery can be used to perform a balancing between the inner engine load and the corresponding raw emissions, the condition of the aftertreatment components and the battery's state of charge.

The applied EEVO strategy likewise leads to a significant increase in the exhaust temperature. Furthermore, lower HC emissions, resulting from the impact on the combustion itself, improve the performance of the exhaust aftertreatment system.



Figure 7: Comparison of heat-up measures – EEVO vs. e-cat

With regard to temperature increase, the EEVO as applied above reaches a temperature increase comparable to that of a 12V-e-cat with 1.5kW power. By comparison, a 48V e-cat with a power of 4kW exhibits a much better performance and the catalyst light-off is reached a lot faster. Further investigations were performed with the 4kW e-cat, since, in addition to the better performance, the modularity for a global product strategy can be represented more easily.

Another supporting measure regarding heating up and keeping warm not shown in this figure is cylinder deactivation. By suitable adjustment of the valve train, the temperature can be increased in a consumption-neutral way, based on the higher load for the remaining cylinders. This method also leads to a reduction of HC emissions. Moreover, the avoidance of the critical light-load range can also be achieved by a mild hybridization.

#### Support by mild hybridization

Generally speaking, the topic of the 48V vehicle power supply system is expected to gain importance in the near future, since it not only further increases the efficiency of the entire drive train but also addresses customer-relevant attributes such as driving pleasure and partial electric driving [4]. In the following section we shall assume an existing 48V architecture in P0 arrangement (BSG – belt integrated 10 kW electric motor), since this solution can be implemented without having to make major changes to the base engine, and focus on emission-related topics.

Due to the support of the electric machine, most of the interruptions in LNT regeneration can be avoided. With dynamic driving behavior, these events are typically interrupted by requested torque changes, which not only leads to emission peaks but also to an increase in consumption. In the described configuration, the internal combustion engine's torque can be kept constant until the end of the regeneration event. The dynamics are thus intercepted in a certain range by the electric machine. This is indicated in Figure 8 by the uniform course of the LNT charge state exhibiting complete regenerations.



Figure 8: RDE test with support of 48V

Furthermore, the applied e-cat strategy can be seen in the lower part of the diagram. This leads to very attractive aftertreatment efficiency values shortly after the start. Overall, a CF of 0.5 with aggressive/dynamic driving was achieved across the entire cycle, as well as in the city part.

In addition, at the beginning of the cycle the engine could be motored by belt of the electrical motor, which allows the heating of the exhaust gas aftertreatment with simultaneous activation of the e-cat before the engine starts outputting emissions. Accordingly, a further reduction of emissions in cold start would be possible.

In the case of hybrid architecture with extended electric driving options, as is typical for P2 or P4 configurations, the temperature-critical light load range is almost entirely avoided [5]. On the one hand, this area can be completely covered in electrical mode with a full battery, on the other hand, when the battery is low, the load for the internal combustion engine can be correspondingly increased to charge the battery in parallel.

# Summary & Outlook

<u>Figure 9</u> gives a summary of the collected simulation results. Starting out from quite an acceptable basis, the conformity factor (CF) for the total RDE test trip as well as for the NO<sub>x</sub> emissions during pure city operation was reduced significantly.



Figure 9: CF and fuel consumption, aggressive driver, 0°C ambient temperature

Already in the first step, the EGR system adaptation and a corresponding calibration strategy set the conformity factor to the range of 1. Especially due to the implementation of a low pressure EGR system, fuel consumption was reduced by 2.4% at the same time. In a next step, aggressive catalyst heating by means of an electrically heated catalyst reduced the CF further by 30%. Although linked to a certain increase in fuel consumption, the consumption value remained below the initial level. By switching to the 48V mild hybrid configuration, an excellent CF in the range of 0.5 for the total driving cycle as well as for city operation was achieved in combination with significantly reduced fuel consumption. For those results we must bear in mind that we are talking about a dynamic/aggressive driver at an ambient temperature of 0°C combined with worst-case starting conditions (full LNT, NH<sub>3</sub> empty SDPF/SCR). Considering moderate driving behavior, even the baseline configuration is within the range of CF 1.

Those results indicate that there are no objectively reasonable grounds for banning diesels from urban areas as is currently being discussed. Considering the whole picture of fuel economy and CO<sub>2</sub> emissions, the diesel drivetrain continues to be an attractive package. For extended high-speed driving in very specific vehicle segments we have the option of moving the 2<sup>nd</sup> SCR brick to an under-floor position and adding a 2<sup>nd</sup> urea dosing unit. The additional cost is moderate since the whole urea infrastructure already exists. This specific additional under-floor configuration ensures the safe handling of long high-speed sessions due to the temperature reduction which this arrangement achieves. This can be of particular importance for extra heavy vehicles traveling on German highways at speeds higher than 180 km/h for long periods of time.

Furthermore, the upcoming electrification improves emissions stability and complements the package for customers by adding attractive functionalities and increased agility. Especially in the segment for heavier vehicles and for the booming SUV trend, the market demand will remain strong, allowing a continued cost-efficient reduction in the fleet average CO<sub>2</sub> emissions, also enabled by diesel technology.

This fact-based status quo assessment and the description of further measures highlight the significance of the described drivetrain concept. The current emotional bias in reports focusing on non RDE-compliant applications has led to some uncertainty on the consumer side, which in turn places future market acceptance somewhat at risk. We must not forget that there are some examples already on the market today, which comply with the future more stringent emission requirements and prove that the diesel can be clean and efficient at the same time.

The investigations show that a modern diesel engine is fully capable of reaching minimum emission values, while ensuring and even improving customer relevant fuel efficiency levels and the associated attractive range advantage at moderately raised system costs, and will continue to do so in the future. Especially in combination with electrification, the vehicle's efficiency and driving pleasure will be further optimized. This ensures that the diesel drivetrain will remain an attractive option.

## **Abbreviations**

SUV	Sport Utility Vehicle
NEDC	New European Driving Cycle
RDE	Real Driving Emissions
CF	Conformity Factor
HEV	Hybrid Electric Vehicle
LNT	Lean NOx Trap
SDPF	SCR on DPF
ASC	Ammonia Slip Catalyst
EO	Engine Out – raw emissions
TP	Tailpipe – downstream aftertreatment
Temp.	Temperature
EGR	Exhaust gas recirculation
E-Cat	Electrically heated catalyst (here as uncoated heating element)
EEVO	Early Exhaust Valve Opening
P0	Hybrid architecture – here: e-motor integrated in belt
P2	Hybrid architecture - here: e-motor between engine & transmission
P4	Hybrid architecture – here: electric axle (in combination with P0)

## Literature

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