Meeting 2025 CAFE Standards for LDT with Fuel-Efficient Diesel Powertrains - Approaches and Solutions

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Abstract

In view of changing climatic conditions all over the world, Green House Gas (GHG) saving related initiatives such as reducing the CO_2 emissions from the mobility and transportation sectors have gained in importance. Therefore, with respect to the large U.S. market, the corresponding legal authorities have defined aggressive and challenging targets for the upcoming time frame. Due to several aspects and conditions, like hesitantly acting clients regarding electrically powered vehicles or low prices for fossil fuels, convincing and attractive products have to be developed to merge legal requirements with market constraints. This is especially valid for the market segment of Light-Duty vehicles, like SUV'S and Pick-Up trucks, which are in high demand. The modern DI Diesel engine has gained an increasing market share in the recent 25 years in the European market and has converted from a niche application to an established, highly appreciated propulsion system in the Light-Duty vehicle segment, covering passenger car as well as light commercial applications. In vehicle classes with high market penetration this low CO_2 concept offers a substantial contribution to minimized GHG emissions from the transportation sector. The current Diesel engine portfolio provides an average advantage of ≥20% reduction in CO_2 emissions in contrast to gasoline-powered applications, while best-in-class installations achieve already now the stringent CO_2 demands of 2020/21 for Europe. For the end consumer the fuel consumption behavior in real day usage is much more relevant, where Diesel powered vehicles typically offer even a further attractive attribute, due to the quite flat fuel consumption characteristics over the entire engine map. Therefore, modern and hence fuel efficient Diesel powertrains represent a promising technology to support also the U.S. market regarding compliance with tight upcoming CAFE standards, particularly for larger vehicle applications.

This paper provides an overview of core technologies which on one hand support meeting the ambitious fuel economy figures for SUV's and Pick-Up trucks in the weight range from 5,000 to 8,500 lbs considering a 6-cylinder design with ~3.3 L displacement, but also regarding compliance with the extremely challenging future CARB LEVIII / EPA Tier 3 emission standards. In addition, the question whether an in-line arrangement for 6-cylinder engines provides a substantial benefit for meeting low CO_2 numbers and simultaneously lowest tailpipe emissions versus the very compact and attractive Vee-type layout due to better charging conditions and easier realization of closed-coupled exhaust aftertreatment system positioning, will be analyzed and clarified.

The paper will conclude with an outlook on accompanying transmission and vehicle measures to meet the upcoming fuel economy targets.

Introduction

The worldwide efforts to improve local air quality have been strengthened continuously in the recent years, while simultaneously tightening the fuel consumption levels in order to limit the GHG emissions from the transportation sector. The Diesel powertrain represents the propulsion system with the highest thermodynamic efficiency and is therefore a prime candidate for low CO_2 powertrains. In addition, after nearly two decades of engineering, today's latest Diesel technology is also an ultra-low emission and clean mobility solution.

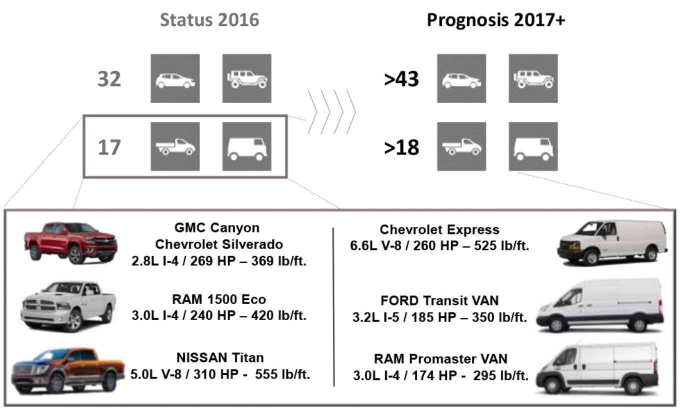


Figure 1. Representative overview of Diesel engine applications in the LDT/LCV market in the NAFTA market region and applications in market

Tomorrow's ultra-clean Diesel powertrain is referred to as the latest generation of diesel engine technology; a full-system concept, containing latest refinements in combustion performance, based on high fuel injection and charging pressures for highest efficiency and best EGR tolerance. Highly sophisticated exhaust aftertreatment systems and advanced engine management algorithms, all based on ultra-low sulfur diesel (ULSD) fuel, complete the technology package to achieve near zero emissions. Upcoming ultra-clean diesel engines feature the potential of highest energy efficiency, along with the ability to use a large range of alternative or renewable fuels, which further positions Diesel as a key technology to achieve overall cleaner air and reduced greenhouse gas emissions for individual mobility and growing prosperity, resulting in a sustainable environment around the world.

However, with respect to the NAFTA market, it can be observed that due to prevailing legal and market conditions, Diesel engines gain market acceptance mainly in the heavier vehicle classes, like LDT's and LCV's, which are very popular on the local market and gain increasing market shares. Figure 1 provides an overview of typical and representative applications, covering in-production and announced installations.

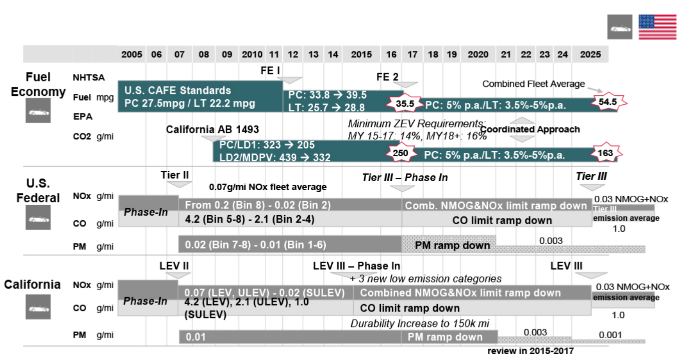


Figure 2. Overview of legal requirements for future vehicle powertrains (fuel consumption and tailpipe emissions)

Facing new and extremely tough emission regulations in the upcoming future leads consequently to the fundamental question, whether affordable technical solutions are available to comply with upcoming challenging CAFE standards while also meeting the very ambitious emission requirements of Tier 3 / LEV III for the above mentioned market segment.

With regard to the GHG emissions it has to be mentioned that not only CO_2 emissions have to be considered, but also all other impacting species of the exhaust gas composition with respect to the legislative norms, such as CH_4, N_2O, etc., are belonging to the so called CREE (Carbon Related Exhaust Emissions). These are converted into a combined CO_2 equivalent (CO_2e) and regulated in total. Figure 2 provides a summarized overview regarding upcoming legal requirements in the US market.

A more detailed look on the upcoming emission standards makes the extreme and ambitious characteristics of the Tier 3 / LEV 3 norms quiet obvious. Figure 3 displays the stepwise, but continuous tightening process from the ramp-in phase towards the final regulation in 2025, together with some additional legislative requirements.

For a detailed evaluation of the Diesel powertrain potential, and consideration of key enabler technologies, a typical LDT vehicle with virtual characteristics was selected as a representative application. In this context, especially when no constraints from predecessor engine are given, often the question regarding engine arrangement is heavily discussed and intensively evaluated. Especially when considering the strict simultaneous legislative demands concerning FE with highest mileage figures and ultra-low environmental impacts with lowest tailpipe emissions.

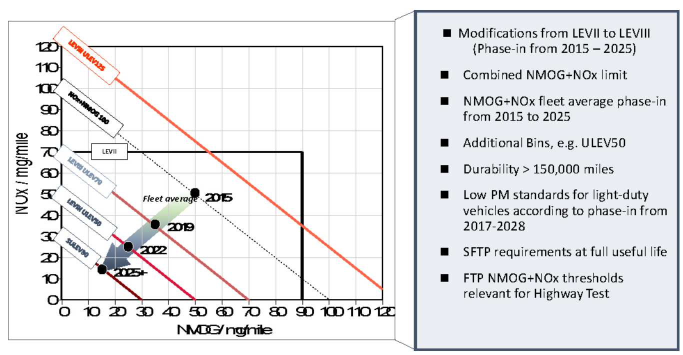
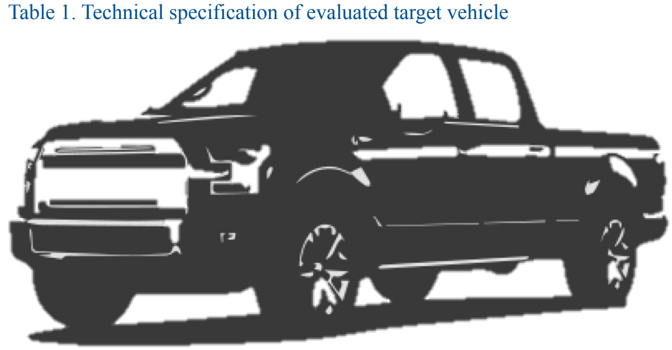


Figure 3. Overview of legal requirements for future vehicle powertrains (NOx and NMOG tailpipe emissions)

However, by scaling the ratio of vehicle weight and road resistance versus the engine capacity, the results can be easily transferred to other applications like SUV's or LCV's. The technical specifications for the target vehicle are summarized in Table 1.

Table 1. Technical specification of evaluated target vehicle



Conceptual Layout and Definition

The corresponding motorization in this segment of current in-production engine ranges from relatively compact 2.8/3.0L engines at the lower end of the scatter band up to large aggregates with 5.0 or even 6.6/6.7L displacement, covering the top end of the considered applications in the full-size truck segment. The selection of the main geometrical data for the future powertrain must ensure on one hand increasing performance demands from customer side, along with refined attributes concerning NVH and comfort, and on the other hand deliver the proper base to meet the ultra-low emission standards.

Under consideration of the available existing specifications but also anticipating future trends and tendencies, a 3.3L displacement was selected as core dimension of the new virtual engine within this study. The engine aligns with the well-proven 550 cm^3/cyl. combustion system, independent of the general engine arrangement. Further details of the evaluated engine specifications are shown in Table 2 below.

In order to support superior fuel economy of the targeted vehicle class, and while taking key customer attributes like superior drivability, excellent launch behavior and high towing capacity into account, the full load torque profile was set towards high torque figures at relatively low speeds, supporting downspeeding tendencies and favorable selection of gear settings of modern automatic transmissions. Details of the full load characteristics for both engine concepts - in-line and Vee-type - are depicted below in Figure 4.

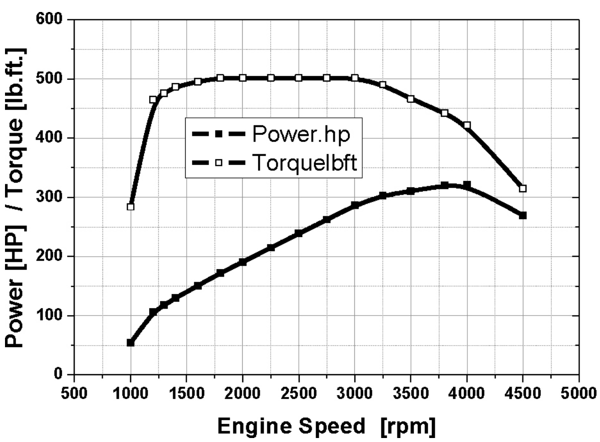


Figure 4. Full load target curve (Torque and Power) for conceptual design and hardware definition (incl. smoke limitation)

The key vehicle performance specifications considered in this study are:

- Fuel economy of ≥38 mpg
- Towing capacity of ≥10,000 lbs.

Base Engine Specification and Performance

To comply with the extremely stringent legislative requirements regarding pollutant and GHG emissions in the US market, a super ultra-low emission and highly efficient Diesel powertrain has to be designed. Despite meanwhile extremely capable exhaust aftertreatment systems like urea-based SCR systems are available, the fulfillment of the ultra-strict NOx emissions for EPA Tier 3 and CARB SULEV 30 emission norms (NMOG+NOx < 30 mg/mile) has to be met in a robust way. According to the prevailing certification procedures with the corresponding driving cycles, the robust achievement of the combined NMOG+NOx tailpipe emission in the FTP cycle is massively depending on the emission performance during the first 180…200 sec. Due to low exhaust gas temperature in the initial phase after engine start, it is necessary to achieve a best-balanced compromise between ultra-low engine-out emission performance regarding NOx emissions, heating strategies with lowest fuel consumption penalty and minimized HC emissions to lift the catalyst temperatures into the high conversion efficiency range. In addition, also the restarting phase after the hot soaking period characterizes a key hurdle for emission compliance. Many technologies have been explored in the recent past to overcome this issue. However, with the expected constrains of higher electrical voltage systems for the targeted vehicle segment, electrically heated catalysts with 48V supply are not considered within the case study.

With view on the relevance of emission performance in the first part of the certification cycle, the general engine arrangement - inline vs. Vee-type layout - represents already a key decision point. As Vee-type engine configurations represent typically a very compact design with beneficial boundaries for engine integration into the vehicle. Some shortcomings are identified regarding the realization of closed-coupled catalysts and the proper positioning and dimensioning of air system components, like turbochargers, charge air coolers and EGR system elements. Inline engine layouts provide more freedom to arrange the key subsystems, but often conflict with vehicle compartment proportions.

Table 2. Main geometrical data and features of considered 6-cylinder variants

Engine Arrangement	6 cyl. / In-line	6 cyl. / Vee-type
Engine capacity	183.07 in^3 / 3300 cm^3	
Bore	3,386 in / 86 mm	
Stroke	3,72 in / 94,5 mm	
Stroke-to-Bore	1,1	
Compression Ratio	16,2 :1	
Peak Firing Pressure	2,900 psi ± 72,5 psi / 200 bar ± 5 bar	
Power	323 HP / 241 kW @ 4000 rpm	
Max. Torque	501.5 lb.ft / 680 Nm @ 1800 rpm	
Low End Torque	475.73 lb.ft. / 645 Nm @ 1300 rpm	
Boosting	1 x VTG	1 x VTG per bank
EATS	cc LNT + UF DPF + UF SCR	2 x cc LNT + UF DPF + UF SCR
Max. Inj. Pressure	2,500 – 2,700 bar / 36,260 – 39,160 psi	
Glow Plug Sensor	1 per engine (@coldest cylinder)	

In addition, the expected output of future engines with the associated high peak firing pressures for ~73 kW/l engines impacts the selection of the crank case material, as the mechanical stresses for the Vee-type engine are more challenging as for the inline configuration.

In order to depict the substantial upgradation of the required engine technology, a compressed, but representative overview of the in-production vehicles are displayed subsequently in Figure 5. The chart in the left half indicates the engine-out emission status of available applications, whereas the graph on the right documents the tailpipe emission status, showing only one application on the market, which seems to meet the SULEV 30 norms. However, as SULEV 30 demands 160,000 miles emission compliance, the actual available car ensures only the emission performance up to 120,000 miles, therefore no full coverage of SULEV 30 is given, besides the also intensified OBD requirements for that upcoming standard.

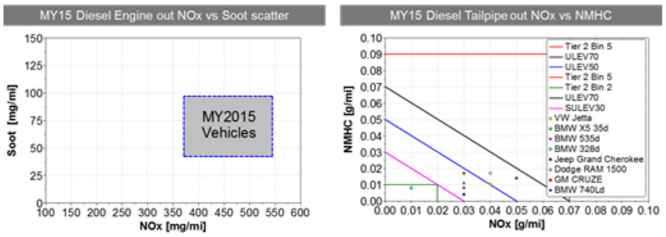


Figure 5. Representative overview of emission status of in-production Diesel vehicles on the US market

The layout of the bottom end structure and the definition of bore pitch for a Vee-type crankcase depends on the bank angle and the design of the crankshaft. Considering a 90° bank angle, a stroke-to-bore ratio of >1 and a split-pin crankshaft design, a Vee-type engine becomes very short and compact as illustrated in Figure 6. Due to a complex structure and the high loads with additional cross forces on the main bearings this engine block type generally is made of compacted graphite iron (CGI). In contrast to this, developments of modern in-line Diesel engine consider aluminum as block material in combination with bearing caps made of ductile iron.

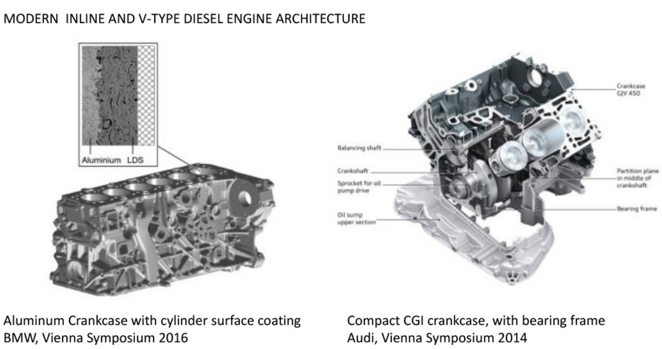


Figure 6. Different in-production bottom end designs [3], [4]

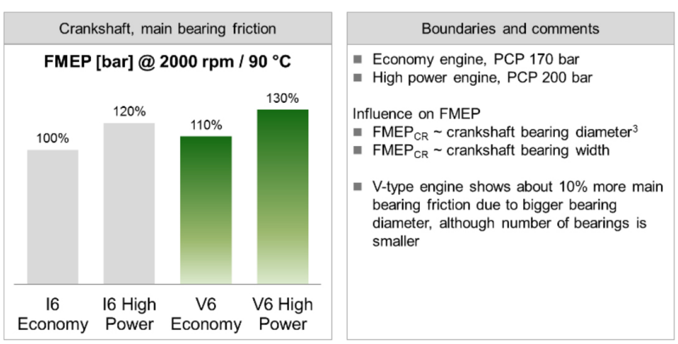


Figure 7. Friction losses of In-line and Vee-type engine architectures

With respect to best performance and lowest fuel consumption, the concept and layout of the base engine also needs to consider a favorable friction behavior of the powertrain. In this context, FEV developed specific software to simulate the fillet rolling process in order to optimize the crankshaft design and the crank pin and main bearing dimensions to enable lowest friction losses. Considering similar optimization level, the inline engine architecture is beneficial over Vee-type engine architecture. High output variants with higher peak firing pressure (PFP) capability in this comparison show about 20…30 % higher friction losses, Figure 7.

In order to minimize total engine weight increase, driven by the demand for complex and therefore heavy close coupled aftertreatment systems, each base engine component has to be optimized for a lightweight design. Special attention has to be applied to the cylinder head, the engine block and the components of the crank train, which can account for ~50 % of the total engine weight. Recently this has become a challenging task as the thermal and mechanical loads have been constantly rising over the last years. For this purpose, FEV developed an integrated product development process, which is based on the extensive usage of state of the art CAE tools. This methodology, which is following the philosophy of virtual front-loading, can achieve on the one hand a robust cutting-edge engine design and on the other hand significantly reduced development times and costs. Figure 8 provides an overview on the comprehensive process chain on the example of a modern Diesel engine cylinder head.

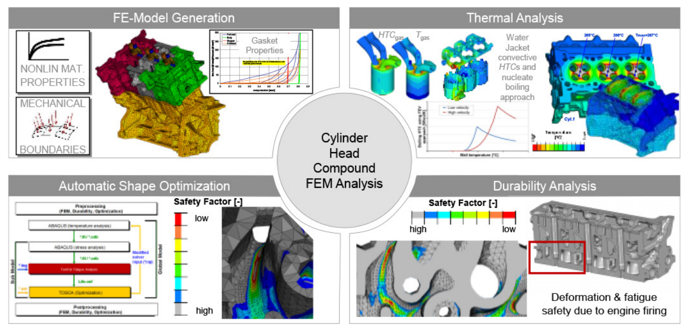


Figure 8. Integrated, CAE based product development process for a robust, lightweight engine design

Besides the proper dimensioning of the engine base architecture for the tough market requirements with a high expectation level concerning robustness and reliability, meeting emission compliance describes a core challenge in the development process. As the number of possible technical options is quite large and interacting, an advanced development process has to be utilized in order to define the best and dedicated system definition. Figure 9 summarizes the main modules of the full development tool kit for precise and advantageous definition of the system specifications.

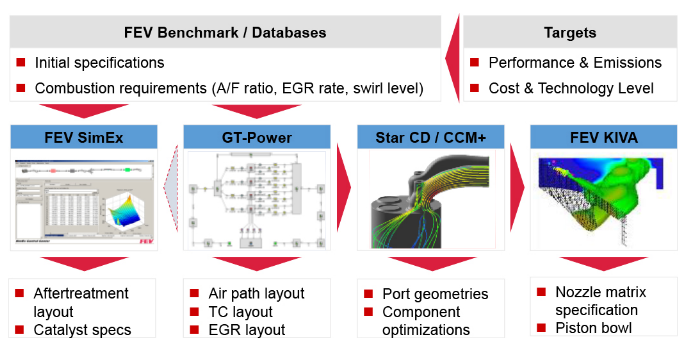


Figure 9. Integrated development methodology for emission control system layout and combustion system definition

Considering the ultra-low tailpipe emissions and with respect to the furthermore tightened OBD norms and the extended durability demands it appears obvious to lower the nominal exhaust aftertreatment requirements in order to gain some additional safety margin.

To achieve low engine-out NOx emissions, intensive usage of EGR under nearly all load conditions is mandatory. Besides the merits of increased injection pressures, considered already from the beginning with the selection of a ≥2500 bar FIE system, also the good mixing and air utilization of air/EGR with the injected fuel is required. As cylinder head flow performance and swirl characteristics tend to depend on each other, specific measures had to be introduced to allow superior flow performance for the targeted high power density with mono-TC layout. As a first measure, swirl generation was shifted from the port geometry to a new feature, known as seat swirl chamfer. This mechanical machining of tailored eccentric chamfers close to the intake valve seats at the cylinder head fire deck ensures on one hand very favorable flow performance with good nominal swirl levels and in addition, a very homogenous in-cylinder charge motion, Figure 10.

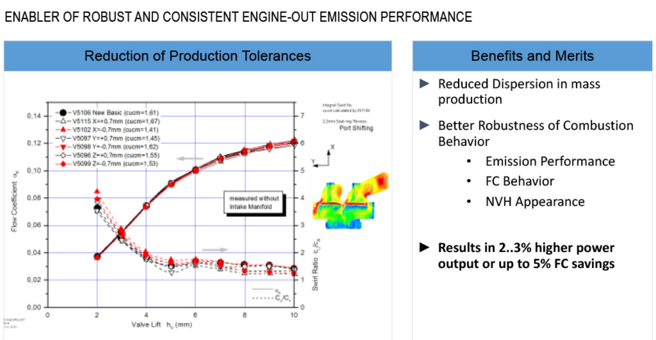


Figure 10. Swirl- Flow Trade-Off for intake ports with seat swirl chamfer at the cylinder head fire deck including superior robustness versus production scattering

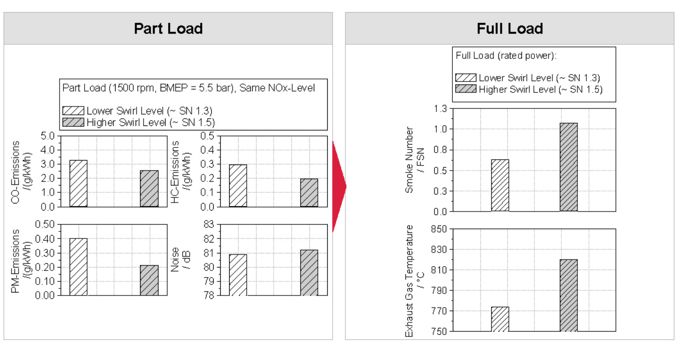


Figure 11. Advantages of highly variable, fully adjustable swirl level on emission performance under light part load and full load conditions

Furthermore, the high uniformity of the generated swirl from the production line supports borderline calibration settings towards extended EGR tolerance of the combustion system. However, as a compression ratio of 16,2:1 was selected as a compromise between demands from cold start with lower Cetane fuels and mechanical demands concerning low friction designs with adequate peak firing pressures for about 75 kW/l, additional measures for proper fuel atomization and mixing under cold and light load conditions are required. Figure 11 provides exemplarily arguments for the implementation of a variable swirl device to trim the effective swirl optimally to the operational demands. The activation of the additional swirl device at lower engine loads and the amplification of the charge motion offers benefits regarding HC, CO and PM, while lowering the swirl at rated power conditions reduces smoke significantly.

Besides the air path, also the fuel system capabilities are of major importance for reaching low engine-out emissions. For definition of the appropriate nozzle specification the best compromise between full load demands and part load requirements had to be evaluated by advanced simulation routines. Driven by emission requirements and supported by enhanced FIE system capabilities, the nozzle orifice dimensions have been reduced substantially, while the number of spray holes tends to grow, as shown in Figure 12.

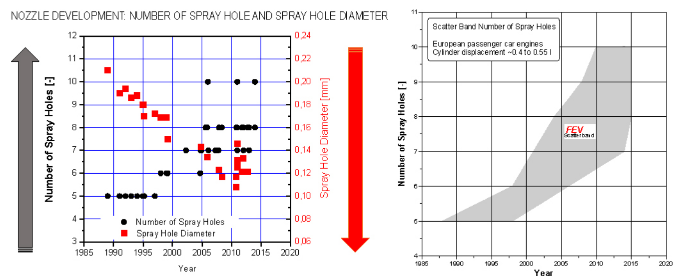


Figure 12. Evolution of FIE system characteristics for improved combustion system performance

Nevertheless, the optimal definition of the injector specification is a key feature of an advanced combustion system, aiming for highest efficiency and lowest engine-out emissions with regard to PM, NOx and HC's. In contrast to EU market, where stringent CO_2 norms drive the trend to smaller engine displacements around 2.0L with power densities up to 90 kW/l, the preference of US customers for large engines as well as the tighter emission standards support larger engine swept volumes, resulting in reduced power densities. Facing GHG reduction requirements, lightweight engine designs with slightly elevated power densities are therefore considered within this study.

As Figure 13 indicates, based on the latest in-production examples, the desired power output of ~73 kW/l requires an injection duration of approx. 35°CA. By utilization of increased injection pressure levels and under balanced consideration of good in-cylinder air utilization but lowered near-wall combustion for reduced heat losses, an 8- to 9-hole injector design offers a favorable condition.

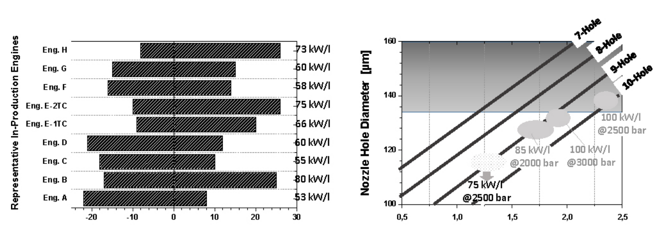


Figure 13. Injection duration under full load conditions and identification of most suitable injector specification.

The trend towards low engine-out emissions regarding NOx and HC emissions is in the conceptual definition additionally supported by micro-sac nozzle designs.

In order to provide additional freedom for the heating strategy calibration to support cold operational conditions, variable valve timing (VVT) functionality was added in conjunction with the DOHC camshaft layout. A driver for this decision is described in Figure 14, identifying substantial merits regarding lowered HC and CO emissions and significantly elevated exhaust gas temperatures with marginal fuel consumption penalty.

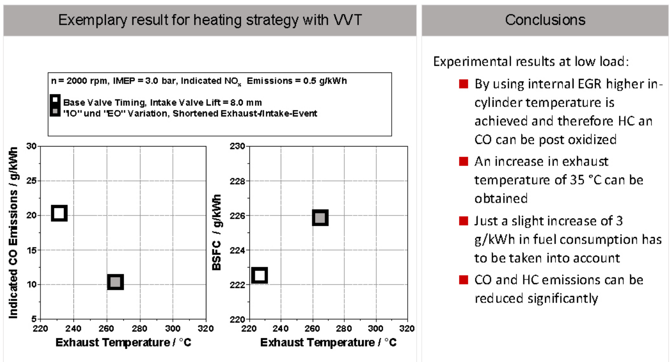


Figure 14. Potential of VVT functionalities for reduction of engine-out gaseous emissions (HC / CO) and gain in exhaust temperature for better catalyst light-off

EATS Design and Functional Description

Besides the above described efforts to reduce the engine-out exhaust emissions significantly for a successful achievement of the ambitious emission norms, the appropriate functionality of the Exhaust Aftertreatment System (EATS) plays another key role in the overall system set-up and optimization process. A favorable EATS layout was selected based on detailed analysis and performance studies, which were executed ahead of this engine system assessment. The defined exhaust aftertreatment configurations out of the full investigation matrix are depicted in Figure 15.

Based on the requirements of the targeted application a combined exhaust aftertreatment system, consisting of a LNT, DPF and active, urea-based SCR, was selected for this study. [1]

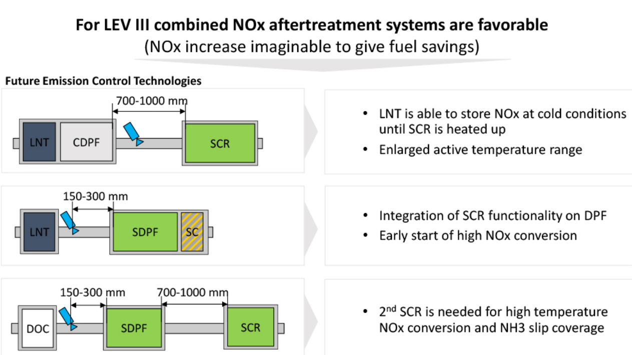


Figure 15. Possible EATS configurations with multiple, combined DeNOx system arrangements (2x LNT + SCR/SDPF, 1 x dual-stage SCR).

According to realistic packaging restrictions and installation conditions, especially for the Vee-type arrangement, an exhaust system configuration containing a closed-coupled LNT/CDPF compound in conjunction with underfloor mounted sufficiently dimensioned SCR catalyst was defined, as shown in Figure 16.

Highly-refined emission performance simulations indicated already with the first catalyst volumes and specifications and based on the optimized engine-out emission levels quite positive and promising results, like exemplarily displayed for the inline 6-cyl. engine in Figure 16.

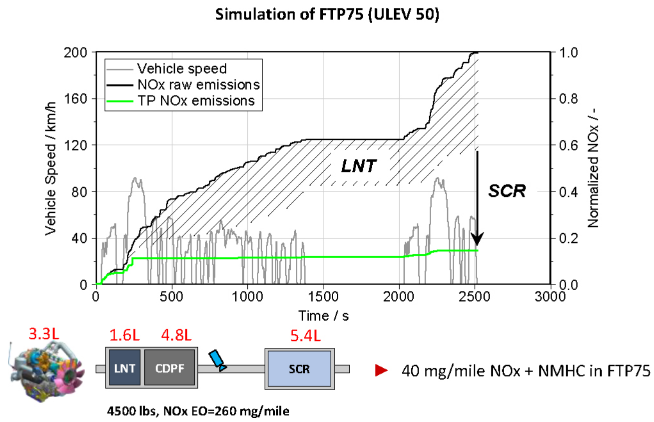


Figure 16. Base emission prediction of a 3.3L I-6 on full-size pick-up truck with optimized base engine-out emission calibration and initial EATS definition.

Figure 17 shows the engine out levels achieved with a state of the art application with cooled high pressure and low pressure EGR. The highly transient nature and high load requests of the US06 result in significantly higher engine out NOx emissions than in the FTP 75 and Highway Fuel Economy Test (HWFET).

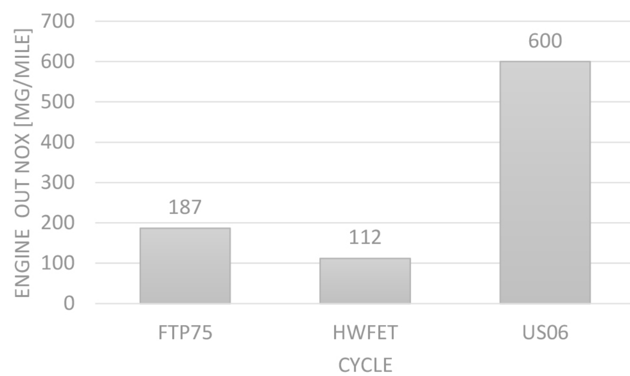


Figure 17. Achieved engine-out emission levels with a State-of-the-Art application with cooled high pressure and low pressure EGR (here 3.3L V6 configuration)

The definition of an appropriately designed combustion system with ultra-low engine-out NOx emission capabilities in conjunction with a powerful high performance exhaust aftertreatment system represents the key aspect in the overall development process. As already mentioned before, the initial part of the FTP-75 cycle directly after the cold engine start exhibits the dominating phase for ensuring a fuel consumption optimized system and robust compliance with the legal limits. In various studies electrically assisted catalysts have been highlighted as a possible opportunity to ensure the fast heat-up of the DeNOx aftertreatment system with the required conversion efficiencies. From a purely technical view, the principle benefits of such a system exist and can be utilized adequately.

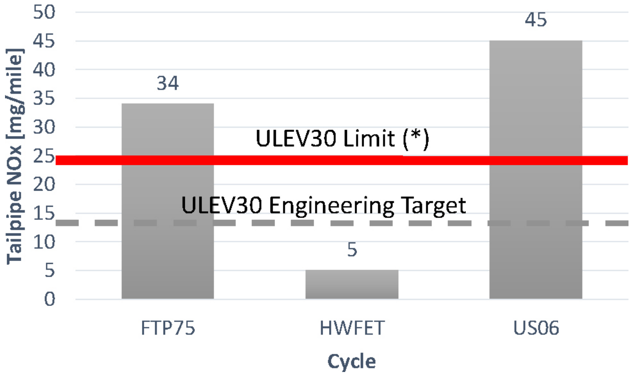


Figure 18. Merits of insulated exhaust piping for catalyst conversion rates under various cycle conditions

Figure 18 shows the corresponding tailpipe levels achieved with this calibration. The graph also shows the ULEV30 legal limit considering an NMHC impact of max. 5 mg/mile. To ensure sufficient robustness against various disturbance factors an engineering target of 15 mg/km NOx has been considered. While tailpipe emissions in the HWFET are very low, emissions in the cold started FTP75 are slightly above the legal limit and approximately a factor of two higher than the established engineering target. For the hot US06 tailpipe NOx are even a factor of three higher than the legal limit.

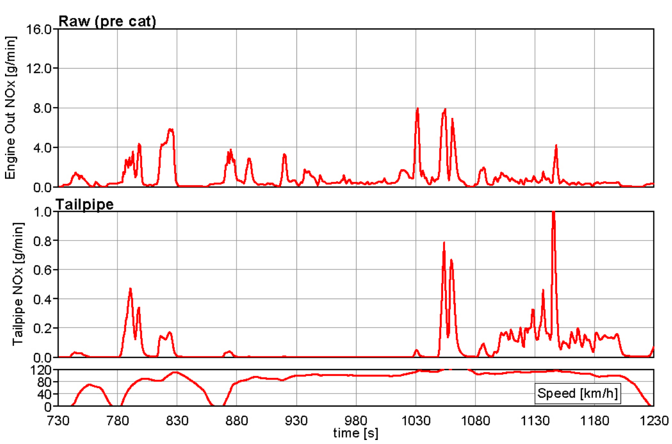


Figure 19. Focused engine-out and tailpipe NOx emission performance for the US06 cycle (here 3.3L V6 configuration)

Figure 19 shows the engine-out NOx and tailpipe NOx for the US06 cycle in detail for the given layout. The engine-out NOx peaks between 780 and 830 seconds also result in tailpipe peaks. After the aftertreatment achieves very high NOx conversion efficiencies and the tailpipe NOx does not continue to increase. The high speed accelerations cause high engine-out NOx peaks which break through the selected SCR system. In the following it shall be discussed how the engine out NOx and tailpipe position can be further improved with the help of additional hardware upgrades and more advanced calibration strategies.

Within the given development constraints, the prioritized path considers a continuous utilization of the traditional 12V vehicle power circuit. With this boundary condition, the established LNT or SCR based aftertreatment solutions have to be enhanced with regard to light-off behavior and conversion efficiency. Furthermore, a variable valvetrain can be applied additionally for tailored adjustment of exhaust temperature increase without substantial fuel drawbacks and with parallel strong HC/CO reduction.

As pointed out in Figure 16 the initial phase of the first cold part of the FTP-75 cycle as well as the time period after the engine re-start, are extremely critical to achieving the tight tailpipe emission limits. In this regard, passive thermal management strategies like material insulation or thermal shielding offer significant potential. Double-walled exhaust manifold and sheet metal turbine housing modules have been used in gasoline engines since 2009. They also offer the potential in modern Diesel engines to reduce both emission of pollutants and fuel consumption. Further advantages in terms of component weight and surface temperatures in comparison to classical cast iron components are possible. BENTELER Automotive and FEV Group have conducted a detailed investigation of these potential advantages for modern ultra-low emission Diesel engines. The optimum solution for the considered integrated exhaust manifold turbine module in this study with maximum exhaust gas temperatures of up to 880 °C, is a double-walled system with an additional fiber material inserted in the air gap between the inner and outer system.

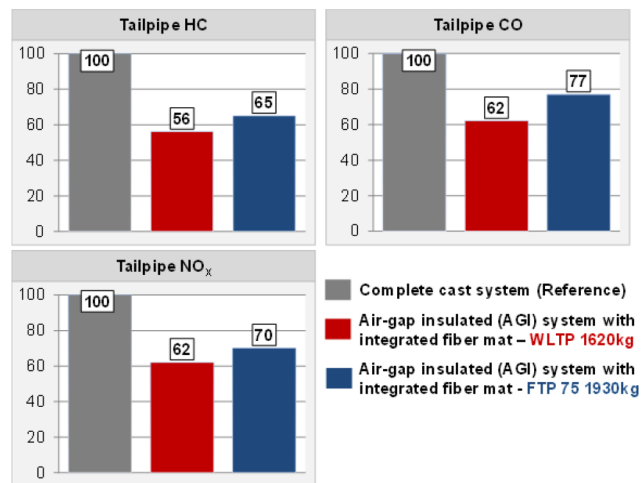


Figure 20. Merits of insulated exhaust piping for catalyst conversion rates under various cycle conditions

As indicated in Figure 20 this upgrade of the hot end of the exhaust system offers substantial benefits with regard to gaseous emissions, like HC and CO, as well as concerning the urea dosing release, resulting in an earlier activity of the underfloor SCR catalyst and therefore overall elevated conversion efficiencies.

The combination of base engine measures like incorporation of VVT functionalities with upgrading options on the exhaust system like capable insulation concludes in a combined configuration and in conjunction with an optimized combustion calibration in a significantly improved emission performance, as displayed in Figure 21.

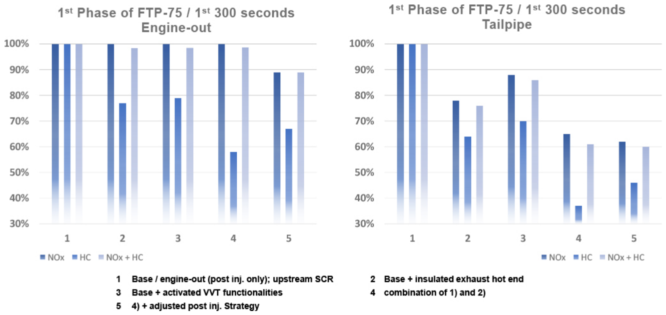


Figure 21. Results of various improvement options for enhancement of 1st (cold) phase of FTP-75 test cycle regarding NOx and HC optimization

With an advanced injection strategy the NOx/PM/combustion noise tradeoff can be further improved. Figure 22 shows how an advanced digital injection rate shaping strategy enables significantly higher rail pressure levels without compromising combustion noise. At 1400 1/min and 7.5 bar IMEP the rail pressure is continuously increased from 450 to 650 bar, engine out NOx are kept constant. A conventional solenoid injector with short dwell times is used. For a traditional double pilot & split main injection strategy the rail pressure increase causes a continuously increasing maximum cylinder pressure gradient which results in a combustion noise level increase of ~6dB(A). With an advanced injection profile with up to seven pulsed injection events the maximum cylinder pressure rise is kept at an almost constant level and the combustion sound level remains low.

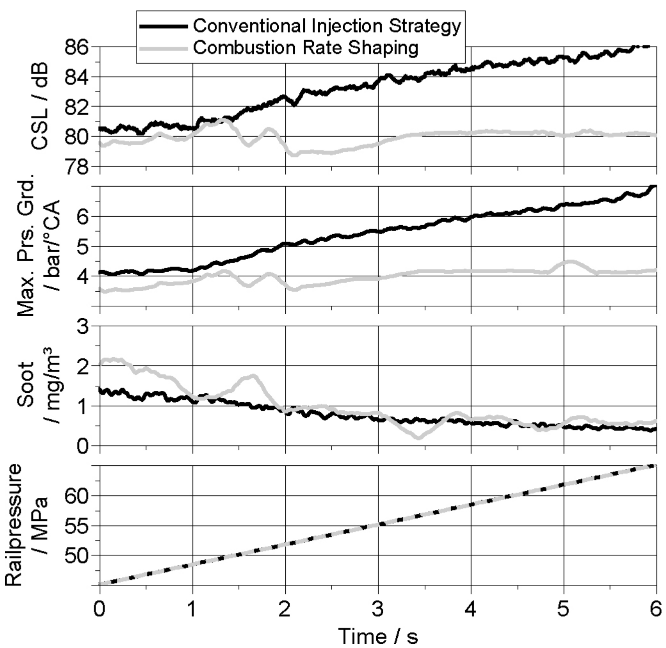


Figure 22. Benefits of an advanced injection strategy regarding NOx/PM / combustion noise trade-off

The improved spray atomization results in a soot reduction of more than 60%. This enables higher EGR rates, thus lower engine out NOx in comparison to the baseline without increasing engine out PM.

For the highly transient accelerations as e.g. in the US06 a NOx reduction potential of ~15-25% is anticipated.

These combined technologies considerably improve the robustness of the system in regards to compliance with the targeted SULEV30 standards. Figure 23 shows the engine-out NOx levels with the baseline application after utilizing an advanced injection rate shaping strategy and FEV's direct NOx control for the air path.

Figure 23. Engine-out NOx emissions in various legislative cycles with advanced fuel and air path control

The US06 cycle engine-out NOx emissions have been reduced by 40%, as especially the transient NOx contribution has been minimized. Also for the FTP75 a substantial reduction of approximately 30% was achieved. In the less transient highway test, the improved fuel and air path control has a lesser impact of approximately 15%. With the baseline aftertreatment system the improved engine-out emissions result in tailpipe NOx emissions below the legal limit for ULEV30 if NMHC emissions are not considered (Figure 24).

With an advanced aftertreatment control which enables higher conversion efficiencies with reduced NH_3 slip risk and an increased SCR catalyst volume the NOx conversion efficiency in US06 can be further improved. Tailpipe emissions below the engineering target are achieved by the combined measures, Figure 24. To reduce NOx emissions in the cold started FTP75 further, the introduction of an LNT enables tailpipe emissions robustly below 15 mg/mile. The impact of the LNT rich purge operation on CO_2 is lower than the CO_2 impact of an aggressive conventional heating strategy, which would be required without an LNT. The assistance of VVT functionalities and insulated exhaust manifolds offers further benefits in fuel efficiency, NMOG compliance and OBD monitoring.

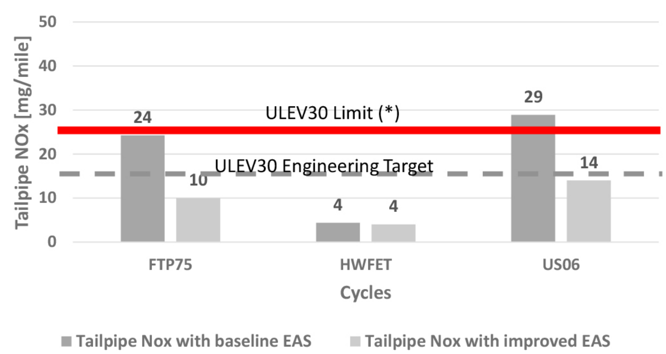


Figure 24. Comparison of tailpipe emission performance with an original and optimized EATS layout and specification (3.3L I-6 configuration).

Engine Management and Diagnostics System Functionalities

As the fulfillment of the extremely tight emission standards requires the installation and application of multiple highly sophisticated technology features, it is absolutely mandatory to realize the maximum potential of all sub-system capabilities. For this purpose, the utilized engine management system has to be upgraded in parallel to the hardware optimization. As the area of requirements is extremely large, covering highly transient operational conditions and also external impacts like ambient conditions, the utilized software functions must be very capable and fully integrated.

For robust compliance with the ultra-tight emission norms of SULEV 30 over an extended mileage range, it is obvious that drift and deterioration tendencies of individual emission control systems have to be compensated very spontaneously and precisely, without violating other engine/vehicle attributes substantially.

In this context a global emission management system has been created to control comprehensively the exhaust emission performance, primary for NOx control, but all other pollutant emissions as well. As a direct function of the DeNOx system status, the global emission management system regulates the engine-out emission performance as well as the LNT purging and SCR dosing strategy under all operating conditions. A general depiction of the controller set-up is provided in Figure 25.

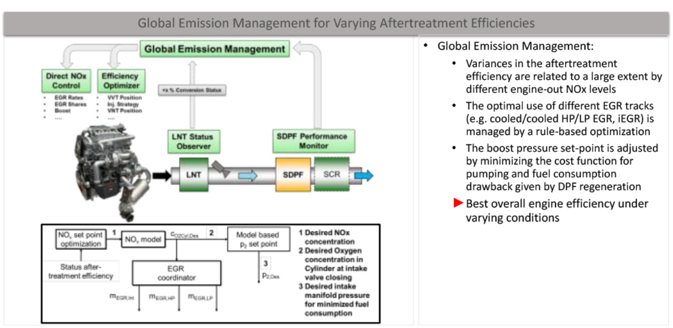


Figure 25. Global emission management concept for multi-stage monitoring and control of all emission related sub-systems.

The EATS status defines the dominating input parameter for the key settings of the engine-out NOx emission performance which requires a fast adjustment of the combustion behavior and characteristics.

According to well-known physical mechanisms, the in-cylinder oxygen concentration is besides the combustion phasing the leading contributor for NOx generation. As a consequence, the "Direct NOx control" algorithm governs the main influencing parameters like EGR rate, boost pressure and intake air temperature spontaneously to optimal settings, based on an inverted NOx model in the corresponding ECU module, Figure 26. For long-term drift compensation, a NOx sensor signal is utilized to adapt the core NOx model. According to steady-state optimized calibration settings and incorporated dynamic correction functions, the "Direct NOx control" algorithms identifies very rapidly the most-optimal settings for EGR rate, source and ratio between all available EGR loops by actuating EGR valves and throttle plates as well as EGR cooler bypass flaps.

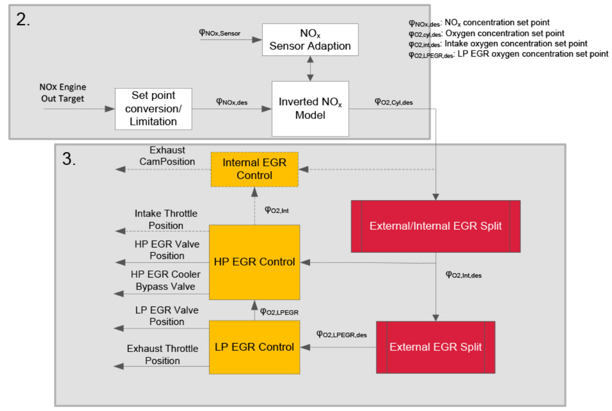


Figure 26. Schematic depiction of advanced, cascaded "Direct NOx" air path control module

However, the interaction between exhaust gas cleaning and overall efficiency is relatively complex, therefore also secondary effects have to be considered. As a direct consequence, advanced and comprehensive models have to be used to clearly identify the overall optimum. Figure 27 below provides a draft impression of the higher level layer, which computes and assesses the interlinked effects between in-cylinder NOx suppression and NOx purification by exhaust aftertreatment elements.

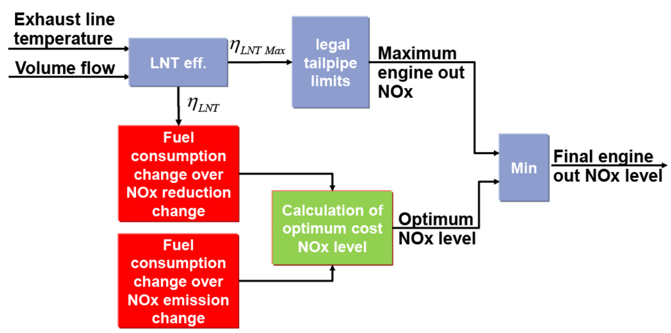


Figure 27. Simplified and schematic illustration of rule-guided, model-based control algorithms to optimize emission performance with highest fuel efficiency

The utilization of a combined DeNOx system, consisting of a closed-coupled LNT and an underfloor SCR catalyst provides additional potential to adjust the aftertreatment optimally to the operational conditions of the engine. The close coupled LNT is capable of reducing NOx already under cold and light-load operation, while also being capable of reducing HC emissions during advanced heating strategies with combined measures, like VVT actuation and according in-cylinder post injection.

As already mentioned above, implementation of necessary heating strategies is key to meet the extremely tight emission norms. Considering also the strict CAFE standards, even heating strategies have to be optimized regarding fuel efficiency. Capable hardware like VVT and insulated exhaust manifolds as well as the optimal calibration of all heating and exhaust temperature control strategies are a major opportunity for fuel savings under real-world driving conditions.

Detailed experimental studies have shown that the optimal combination between best thermal efficiency, for a given torque demand, and achieving exactly the requested enthalpy supply towards the exhaust system, is only possible with the ideal combustion phasing to uniquely shape the heat release. As the operational conditions change, the settings have to be adjusted in order to achieve the best overall performance. An example is provided in the upper half of Figure 28 at 12.0 bar IMEP. In the initial setting, the provision of 0.6 kJ/stroke enthalpy was demanded to meet the targeted temperature level in the exhaust line. For this condition, the center of heat release should be at 44° CA ATDC, whereas after a short time of heat increase, the necessary enthalpy is lowered to 0.4 kJ/stroke. To maintain the identical indicated torque level under these boundary conditions, it is advantageous to advance the combustion phasing with an altered injection profile with the center of heat release at about 29° CA ATDC.

This principle is cascaded to all possible operational modes in the implemented efficiency module of the advanced "Global emission management" architecture of the considered engine management concept, as indicated by the showcase in the lower part of Figure 28. It is obvious, that the freedom in the adjustment of the combustion phasing and shaping is restricted by hard thresholds with regard to temperature upstream turbine (T3), min. rel. A/F ratio and exhaust smoke limits.

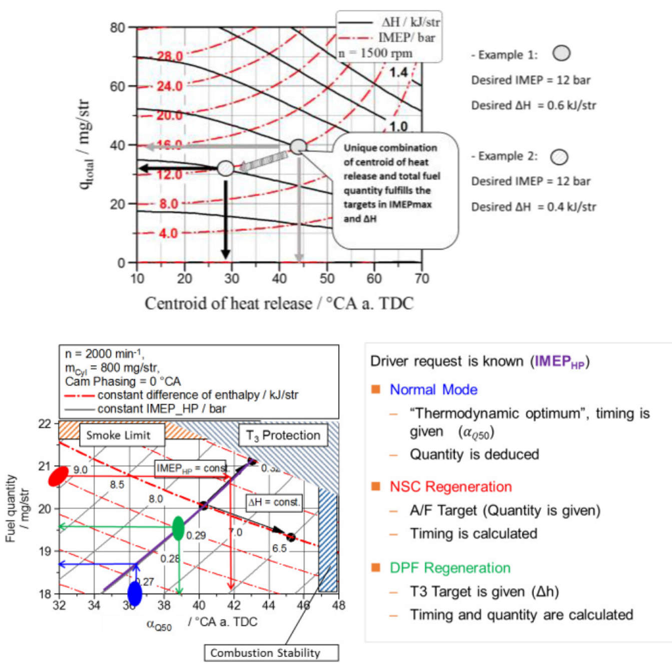


Figure 28. Identification and characterization of optimal combustion phasing and shaping to meet primary combustion mode targets at best fuel efficiency.

A second aspect concerning engine controls and best-balanced management of fuel consumption and tailpipe emissions requires the optimal calibration of the combustion performance for the various operational modes. Besides the normal propulsion mode, where most efficient torque generation under clear emission constraints defines the highest priority, the leading parameters differ under the different heating, regeneration and purging modes. In this regard, it is mandatory to optimize the most beneficial combustion phasing in order to realize the most dominating operational parameter, like T3 temperature, A/F ratio, combustion stability, etc. at the best thermodynamic efficiency, like displayed in Figure 28.

Recent investigations have shown, that the center of combustion characterizes the best leading parameter for ensuring optimal delivery of enthalpy into the exhaust system while keeping combustion efficiency for a given torque at the highest level. This advanced combustion control algorithm ensures with the application of one glow plug sensor, favorably installed in the coldest cylinder of the 6-cylinder arrangement, in conjunction with novel, model-based functionalities, always an ideal multiple injection pattern, that splits the individual injection quantities accordingly, while respecting combustion stability and controllability.

Besides the introduction of extremely tight emission standards, the legal requirements towards on-board diagnostic systems (OBD) of diesel powertrains continue to increase as well. Figure 29 shows significantly reduced margins between emission standards and OBD emission limits. Consequently, robust malfunction detection becomes more challenging, since smaller failures could lead to OBD threshold violation in more sensitive powertrain system. In addition, the increased complexity of new powertrains introduce additional monitoring requirements, which have not been in use before. Under these conditions, current monitoring strategies could not anymore guarantee comprehensive and reliable detection of failed components. The required sensitivity of new and improved monitoring strategies cannot be achieved without tailoring the powertrain to OBD requirements, in addition to emission and drivability standards. This indicates that assessment of OBD strategies and consideration of OBD needs at an early concept phase is highly important. Functional improvements must be achieved by intelligent combination of existing strategies, development of new monitoring approaches and increased interaction between monitoring and control strategies.

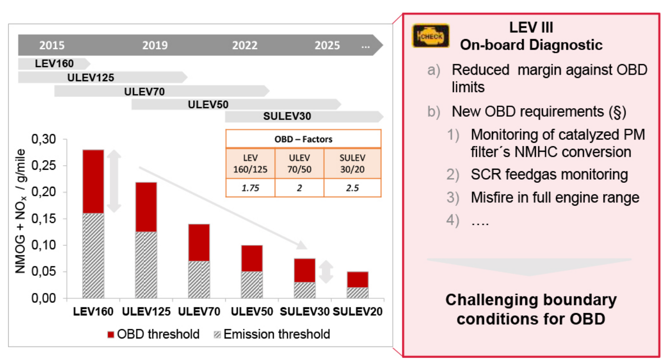


Figure 29. Upcoming OBD regulation with tightened emission thresholds and main additional challenges.

Figure 30 illustrates the approach for a comprehensive OBD function development process including a detailed assessment of regulation, software and hardware requirements definition and early concept validation, supported by simulation tools and rapid control prototyping in order to develop diagnostic solutions for the upcoming challenges. However, not only development of new diagnostic software, but also model improvements and new sensor generations are needed to increase the OBD capability of complex diesel powertrains in the near future. Ultimately, when the efforts for OBD homologation will surpass the effort for meeting emission standards, it is not possible anymore to add compliant OBD strategies to finished powertrains. Therefore, it is mandatory to design emission control systems so that regulation compliant monitoring is possible.

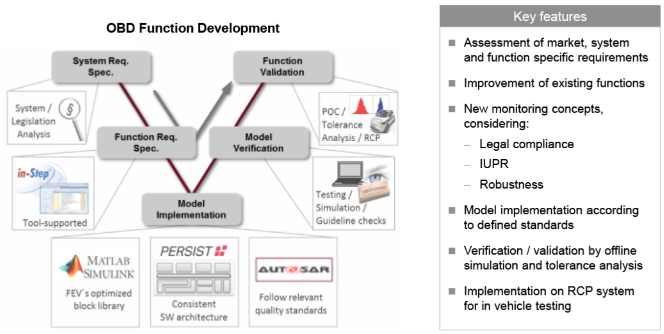


Figure 30. Full chain OBD function development for proper monitoring and diagnosis capabilities.

Further improvements are possible by utilizing innovative, model-based control functions for the SCR system including incorporated algorithms for kinetics and chemical reactions (Figure 31). This approach supports the target to achieve maximum conversion rates under nearly all operating conditions without violating limits for NH3 slip. The typical clean-up catalyst as final device to control NH3 emissions under high dosing conditions can be reduced in volume, which is advantageous for low backpressure designs and reduced component costs.

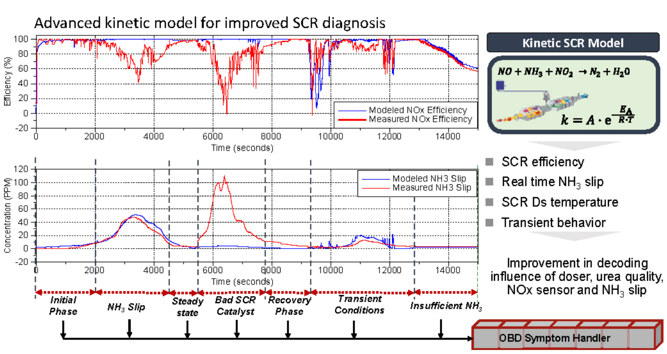


Figure 31. Novel model-based approach for improved SCR monitoring and diagnosis.

The motivation for kinetics based control concepts derives from multiple aspects:

- The monitoring of SCR/SDPF systems under conditions of ammonia slip is increasingly important
- Closed-coupled positions result in higher temperature gradients and tight space constraints, cause potentially less uniform dosing of ammonia and lead to more frequent desorption of ammonia from the SCR/SDPF
- Current in-field SCR monitoring concepts, based on the comparison of measured performance vs. a SCR model, perform partially poorly under ammonia slip conditions, due to the cross-sensitivity of NOx sensors
- Current methods for ammonia slip detection are not robust (and therefore prevent monitoring during such events) because:
    - current ammonia slip models
        - lack regarding necessary accuracy required for consistent prediction of the occurrence of slip
        - feature shortcomings concerning the accurate quantification of slip
    - given ammonia slip measurement methods (using cross-sensitivity of NOx sensors to ammonia)
        - detect slip only after it has become massive (by which time the diagnosis is partly or fully completed)
        - consume a relatively long time to reliably detect slip (by which time the diagnosis is partly or fully completed)
        - are not capable to distinguish between ammonia slip and reduced NOx conversion efficiency

Facing these challenges, new and innovative algorithms are mandatory to optimize the operational behavior and performance of all emission-related sub-systems. The clear benefits of kinetic models in this regard are:

- Kinetic models are global (vehicle independent) and offer better accuracy over empirical models and a wider operating range
- Better prediction of the occurrence of slip, enabling the reset/switch off/pause of monitoring during this phase
- More precise determination of the slip quantity, enabling monitoring even during phases of ammonia slip which is currently not possible

The forecasted NH_3 slip from the kinetic model can be used as valuable input for other control circuits to filter out the cross-sensitivity of NOx sensors to ammonia, thus enabling estimation of actual NOx conversion of the SCR using NOx sensors.

As a consequent and clear benefit, the SCR/SDPF monitoring runs more robustly (lower OEM warranty costs) and more frequently (in-use performance ratio higher than legislative requirements).

Increasingly complex OBD requirements demand for generating complex failure pattern during the vehicle homologation process to verify that all diagnosis functions are working correctly. To realize these, electrical manipulation of sensor and actuator signals emulating certain failures represents a very promising and cost efficient technique.

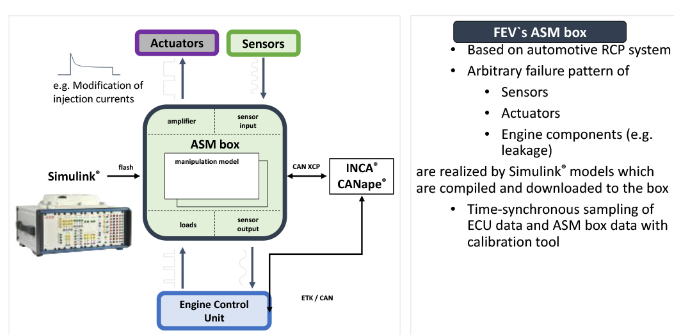


Figure 32. Advanced methodology and calibration tools for accelerated and qualified OBD application

FEV’s TOPexpert ASM box has been specifically designed for this purpose. With its extended set of I/Os, and freely programmable RCP environment, it offers full flexibility to simulate a large set of failure pattern. Its capability to manipulate injection and ignition systems also offers the possibility for realizing complex injection system errors, Figure 32.

Summary and Conclusions

Highly fuel-efficient compliance with upcoming tight US emission standards for very popular LDT applications can be achieved with modern, dedicated Diesel powertrain configurations.

While meeting ambitious emission norms according to Tier 3 respectively LEV 3 regulations, future Pick-Up truck applications, as investigated within this analytical study, offer besides powerful performance for high driving pleasure also highly attractive fuel economy figures of 38 mpg respectively ~262,4 g/mile CO_2 and a beneficial refinement level for superior driving pleasure and mobility comfort.

In the direct comparison regarding engine arrangement - inline layout vs. Vee-type configuration - both counterparts are capable to meet future requirements. The in-line configuration offers benefits regarding thermo-dynamical functionality (trading off between 3..5% in efficiency and up to 10% better emission performance), Figure 33.

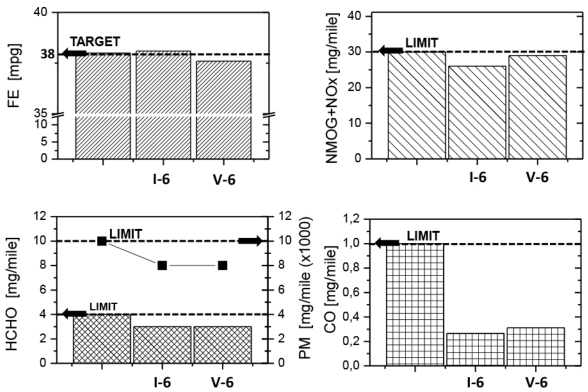


Figure 33. Final FE and Tailpipe Emission results for both types of engine designs with 3.3L capacity in a full-size pick-up truck with the optimized EATS layout.

It is also a lower cost option as it eliminates double hardware components like (2 x cylinder heads incl. camshafts, cam phasers, 2 x TC’s, 2 x rail…).

If vehicle packaging constraints do not restrict the application of an inline engine, it is overall preferable under consideration of the upcoming overall market requirements.

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Definitions/Abbreviations

ASM*(box)* - Actuator / sensor modulation box

CAE - Computer-aided engineering

CAFE - Corporate Average Fuel Economy

CARB - California Air Resources Board

CGI - compacted graphite iron

CO - Carbon Monoxide

CO_2 - Carbon Dioxide

DeNOx - NOx Reduction Systems

DOHC - Double Overhead Camshaft

EGR - Exhaust Gas Recirculation LP: Low Pressure side HP: High Pressure side

EPA - US Environmental Protection Agency

FIE - Fuel Injection Equipment

FTP-(75) - Federal Test Procedure -75 (Legal Driving Cycle)

GHG - Greenhouse Gases

HC - Hydro Carbons

HWFET - Highway Fuel Economy Test

I/O - Input / Output

LDT - Light-Duty Truck

LNT - Lean NOx Trap (synonym for NOx Adsorber Catalyst / NOx Storage Catalyst)

NAC - NOx Adsorber Catalyst (synonym for Lean NOx Trap / NOx Storage Catalyst)

NH_3 - Ammonia

NSC - NOx Storage Catalyst (synonym for NOx Adsorber Catalyst / Lean NOx Trap)

NVH - Noise, Vibration *and* Harshness

OBD - On-board Diagnosis

PM - Particulate Matter

RCP - Rapid Control Prototyping

SUV - Sport's Utility Vehicle

(SU)LEV - (Super Ultra) Low Emission Vehicle

SCR*(Catalyst)* - Selective Catalyst Reduction

TDI - Turbocharged Diesel Direct Injection

ULSD - ultra-low sulfur diesel

US 06 - US Driving Cycle / Pattern

VVT - Variable Valvetrain

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