# Internal Combustion Engines for the Future

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**ABSTRACT**

Future internal combustion engines for light duty applications will have to cope with a very complex set of customer, legal and business requirements. Customers are expecting further improvements in durability, reliability, drivability, fuel economy, and cost of ownership. Legal requirements are focused on significant emission and fuel consumption reductions. Additional manufacturing cost reductions will be essential to maintain, or better grow the business in a very competitive environment.

The challenge for the diesel engine will be to meet the future emission standards at affordable cost, while maintaining its fuel economy advantages. Regarding the emissions, advanced diesel technologies will have to focus mainly on NOx reduction. New combustion system concepts in combination with advanced airhandling/boosting and control systems offer a promising potential.

The focus for future gasoline engine development will be on fuel economy improvements through improved combustion systems and reduced throttle losses at part load operation. This can be achieved through e.g. direct fuel injection with stratified lean part load operation. Downsizing in combination with boosting offers an additional potential.

Internal combustion engines still have a huge potential to deal with the challenges of the future. In comparison with alternative powertrain concepts, at least for the next 20 years, the internal combustion engine should be able to maintain its advantages regarding high power density, low manufacturing cost, recyclability, long driving distance between two refueling events, well established fuel supply infrastructure, and its capability to use a wide variety of fuels.

**Key-words:** Diesel and Gasoline Engines, Fuel Economy, Emissions, Combustion, Boosting

**INTRODUCTION**

Future powertrains for light duty applications have to fulfil a very complex set of requirements (Figure 1), and there is always the question: "Will the internal combustion engine be able to cope with these challenges also in the future?"

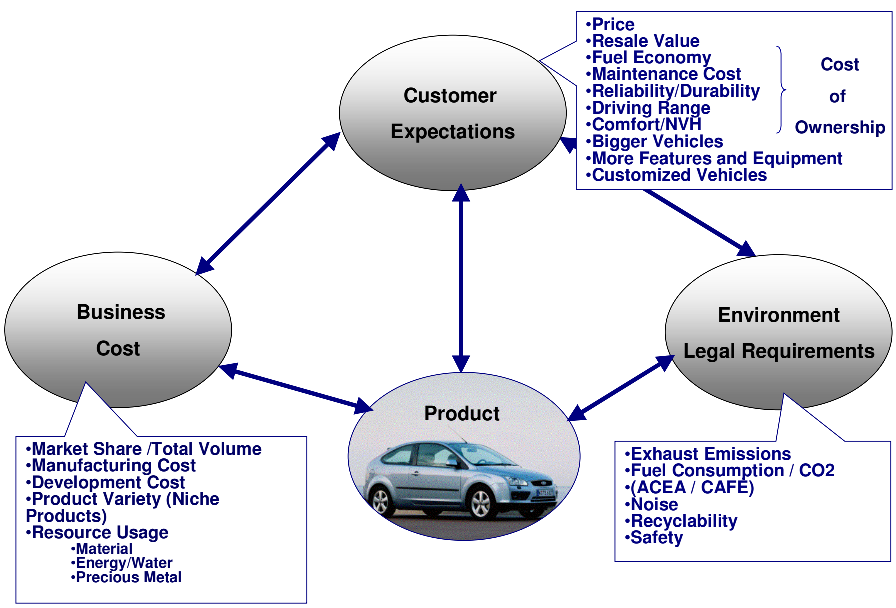


**Figure 1**: Interaction between Customer Expectations, Environmental/Legal Requirements and Business Aspects

Regarding customer expectations, trends are very similar for gasoline and diesel engines, especially in the volume segments and markets. Customers are very focused on total cost of ownership, which is determined by such factors as price, resale value, fuel consumption (and fuel price), maintenance cost, as well as reliability and durability. At the same time, customer expectations regarding "fun to drive" are still increasing. This translates into a continuation of the "power and torque race" to further improve vehicle performance and drivability (Figure 2).

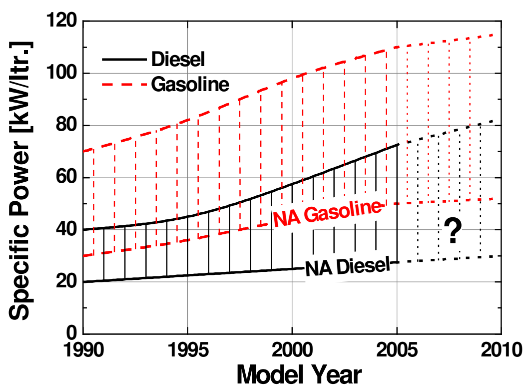


**Figure 2**: Development of Specific Power of Gasoline and Diesel Engines

Advanced boosting technologies will play a major role to further increase specific power and torque. In this context, turbocharging will maintain it's dominant role.

In addition to performance improvements, at steadily rising fuel prices, customers are expecting further improvements in fuel economy and comfort (NVH) in bigger (heavier) vehicles with more features and equipment. Another set of conflicting boundary conditions for the reduction of the fuel consumption, and thus the CO2 emission, is being set by the exhaust gas emission standards (see below).

The maintenance cost for the engine itself has been dramatically reduced during the last years. Oil changes, and oil as well as fuel filter changes, are the only maintenance items left for most modern light duty engines during the first years of operation. And the oil change intervals will be further increased in the coming years.

Regarding the business aspects, for all volume manufacturers ("value brands"), it is essential to maintain or better increase the market share, and thus the production volume to stay competitive. Volume effects can also be achieved through joint ventures with other OEM's, as PSA and Ford have established it for diesel engine manufacturing, development and research, and of course through the reduction of the number of different engine architectures. Most of the globally engaged OEM's are following the latter approach with an increasing degree of rigor. However, while the number of base engine variants will be reduced, the challenge will be to customize these base engines for an increasing multitude of applications, and to cost effectively handle the resulting complexity.

Effective resource usage of all material, energy, water, transportation, needs to be further improved. A major task for the future in this context will be to reduce the dependence on precious metal application in exhaust gas aftertreatment systems /1/.

Considering the legal requirements for exhaust emissions and fuel economy (e.g. CAFÉ), as well as the CO2 emission reduction commitment of the European car industry (ACEA Commitment), there are major differences in the future development priorities between diesel and gasoline engines. While the target for the diesel – the thermal engine with the best efficiency – must be focused on cost effective emission reduction and further refinement (e.g. NVH or cold start improvements), the focus for gasoline engines will be on fuel economy improvement.

A look at the emission trend forecast until 2010 as shown in Figure 3, exhibits the importance of further CO2 emission reduction from road transport.

While diesels will maintain a major fuel consumption advantage for the customer who pays the fuel bill by the litre, the CO2 emission advantages of current diesel engines will be challenged by advanced gasoline engine concepts. The gap will be narrowed.

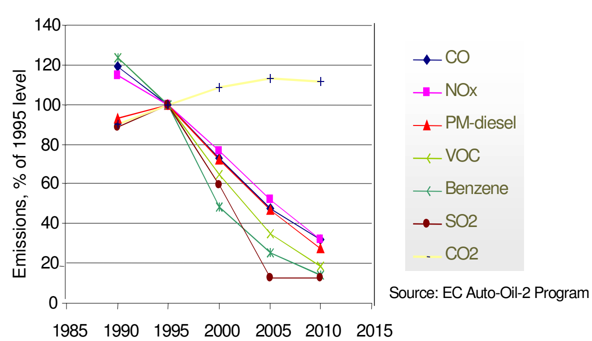


**Figure 3**: Road Transport Emission Trend

Figure 4 depicts the CO2–emission targets of the ACEA commitment, which shall result in an average fleet CO2 emission of 140 g/km in the NEDC cycle by 2008. To achieve this goal, both, gasoline and diesel engines will have to deliver a major contribution from the powertrain side in addition to appropriate vehicle actions. Until 2008, the diesel contribution will mainly stem from an increase in the diesel share. Further contributions will result out of the usage of smaller, lighter and higher specific power diesel engines.

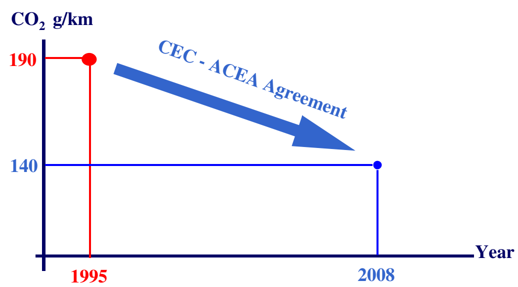


**Figure 4**: ACEA CO2 Commitment

## THE DIESEL EMISSIONS CHALLENGE

The major challenge for the diesel is meeting the very tough future emission targets at affordable cost, while further improving, or at least maintaining the diesel typical fuel economy advantages. Figure 5 provides an impression of the required emission reduction compared to the Euro Stage 4 emission standards, which have to be met as of next year. US Tier 2 Bin 5 represents the most challenging known set of emission standards for diesel powered light duty vehicles. Euro Stage 5 standards have not yet been defined as of now. While there is typically a focus on the NOx and particulate matter (PM) standards, the CO and HC standards may represent an additional major hurdle.

According to today's understanding, there is not just one key technology (such as the three-way catalyst for gasoline engines) that would provide sufficient potential to achieve these future standards. Instead, an integrated systems approach is required, which includes a low NOx combustion process, advanced boosting/

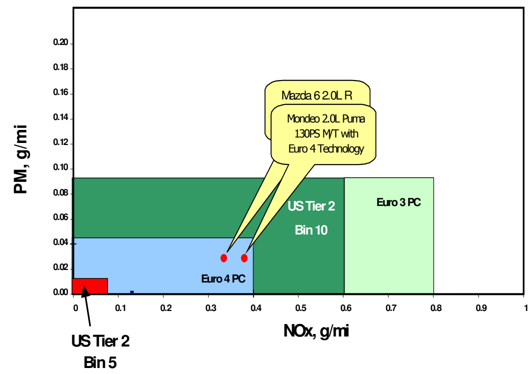


**Figure 5**: NOx / PM Diesel Emission Standards

airhandling/EGR technologies, an exhaust gas aftertreatment system with a diesel oxidation catalyst (DOC), a diesel particulate filter (DPF), and, especially in the US, a NOx reduction catalyst. In addition, advanced control systems will have to integrate the different functions for combustion, airhandling, and aftertreatment system regeneration controls. Moreover the usage of low sulphur, or better, no sulphur fuel will be mandatory.

## LOW NOx DIESEL COMBUSTION

Worldwide, the OEM's, the major internal combustion engine engineering consulting companies, as well as many research institutes are intensively investigating the potential of low NOx diesel combustion processes. Multiple names have been invented for these approaches, such as HCCI, pHCCI, UNIBUS, PREDIC, MK, NADI, ACCP, HCLI, HCDC… An important element for these low temperature combustion (LTC) processes is typically to allow significantly higher EGR rates to limit the bulk temperature of the cylinder charge. Another element is to develop injection strategies that approach a more homogenous mixture formation in the combustion chamber before onset of the combustion. Figure 6 explains schematically two possible approaches (late and early homogenization) which both target to achieve more time for the cylinder charge to mix air and fuel.

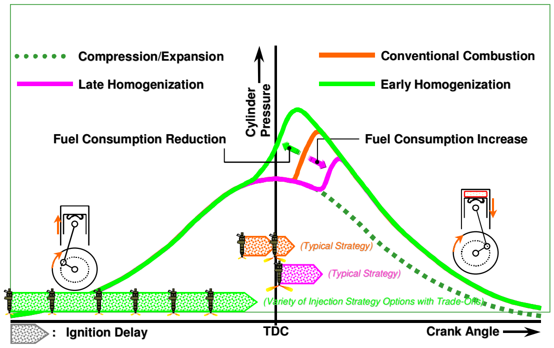


**Figure 6**: Low Temperature Diesel Combustion Alternatives with Late and Early Homogenization

Low NOx combustion processes have already demonstrated a significant potential to reduce both the NOx and PM emissions at part load operation without a major increase in fuel consumption and/or combustion noise excitation. However, an increase in HC and CO emissions has been observed in most cases. At higher loads, and especially at full load, it is very difficult, if not impossible, to achieve low temperature diesel combustion to the same extend as in part load operation. This requires the development of new controls strategies for a transition between the low temperature combustion modes and a more conventional combustion mode at higher loads. The challenge is to make these transitions completely transparent to the vehicle driver.

An important element for the realization of low temperature combustion is a boosting/airhandling/ EGR system that effectively provides the right mixture out of boost pressure and EGR rate under all load and speed conditions. Figure 7 depicts for different loads (BMEP values) at a constant speed of 2000 rpm that significant NOx reductions can be achieved in the different European and US emission test cycles with advanced boosting technologies that provide more boost at part load than today's turbocharger systems.

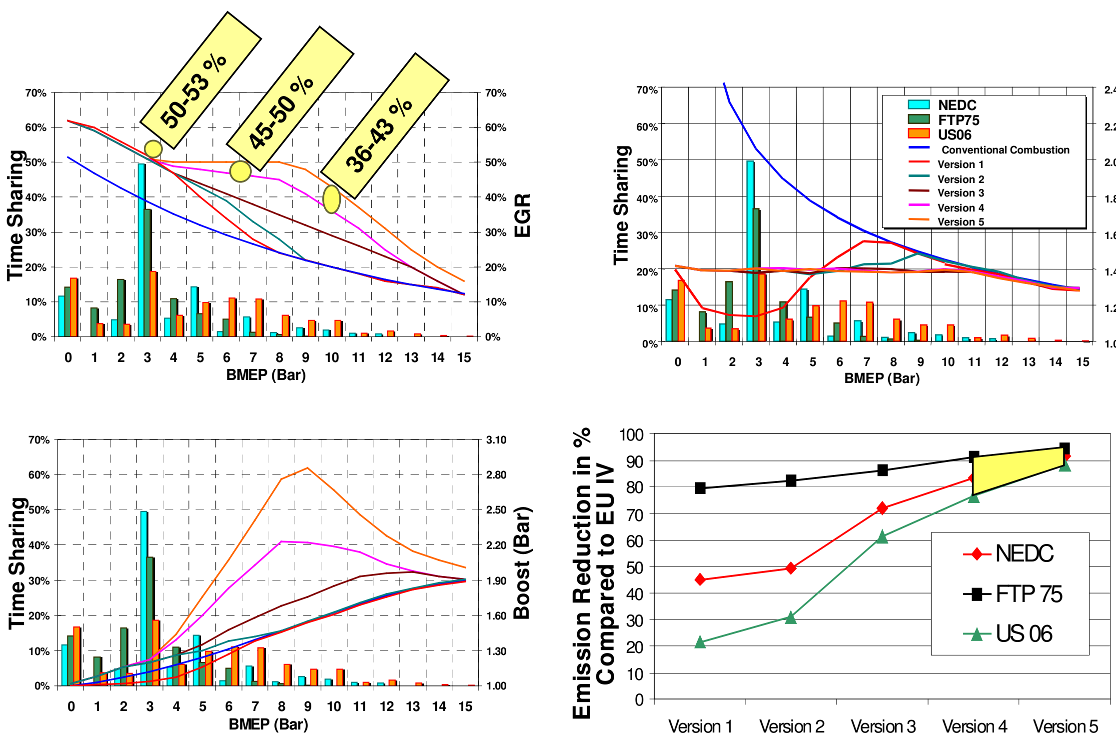


**Figure 7**: The Role of the Boosting System to Improve Engine Raw Emissions /2/

## DIESEL EXHAUST AFTERTREATMENT

While diesel oxidation catalysts and diesel particulate filters can be considered state-of-the-art, this does not apply to the NOx reduction catalysis. The development of Lean NOx Traps (LNT) and Selective Catalytic Reduction (SCR) systems has not yet been successfully completed for light duty diesels. However, it must be stated that the SCR technology is much more mature, has a higher NOx reduction potential because of its wider temperature window with high conversion rates (see Figure 8), and is less dependent on precious metal usage /1/. Moreover, the SCR technology is more tolerant to sulphur in the fuel, and thus offers a better solution for the transition phase from fuels with the current sulphur content to the future low sulphur fuels.

The major SCR disadvantages result out of the need for onboard storage of the aqueous urea solution, and the infrastructure, which is needed for the urea supply.

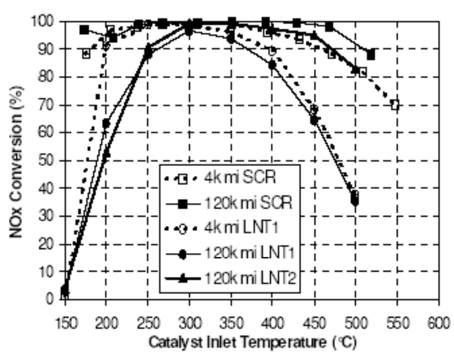


**Figure 8**: NOx Conversation Comparison of Urea SCR and LNT (Steady State Flow Reactor Results) /3/

## GASOLINE FUEL ECONOMY IMPROVEMENT

Figure 9 summarizes the major concepts for the improvement of the fuel economy of gasoline engines. A major focus is on the reduction of the gas exchange (pumping losses) through charge dilution (lean operation), variable valve actuation, and - for larger engines with a higher number of cylinders – through cylinder deactivation. In parallel, improvement of the combustion efficiency shall be achieved through direct fuel injection and/or variable compression ratio.

Controlled Auto Ignition (CAI) could become the ultimate future combustion process for gasoline engines with close similarities to comparable concepts for diesel engines. The CAI operation mode achieves auto ignition of extremely diluted homogenous mixtures and thus enables very low NOx emissions through avoidance of local temperature peaks. In the CAI operation mode, the thermal efficiency is approaching diesel values. Similar to the low temperature diesel combustion concepts, robust CAI operation is heavily dependent on new advanced control strategies that ideally feature a closed loop combustion control with sensors that monitor the combustion process in the individual cylinders.

There is still potential to further reduce the parasitic losses of internal combustion engines through friction reduction of the base engine components and the ancillaries, as well as through improved thermal management.

In the case of diesel engines, we refer to "right sizing" these days. "Right sizing" means that the "right" relation between engine displacement and vehicle test weight should be targeted for the best compromise between vehicle performance, fuel economy and NOx emission in the test cycles. Gasoline Engines are less targeted in this respect, since they usually cover a much broader performance range in a powertrain line-up, and thus offer a bigger fuel improvement potential through downsizing /4/ than diesel engines. Downsizing forces the engine into higher load operation with better mechanical efficiency and reduced pumping losses. Additional fuel consumption reduction potential of downsized engines results out of their typical lower weight.

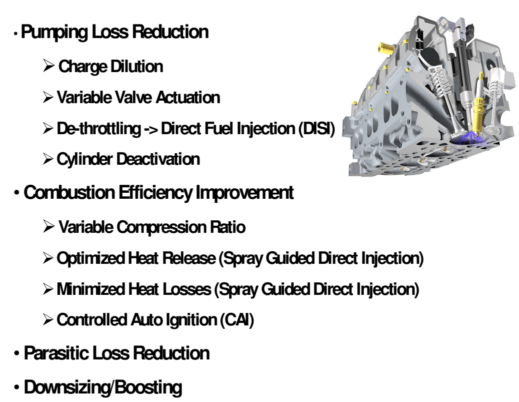


**Figure 9**: Fuel Economy Concepts for Gasoline Engines

Stratified direct fuel injection combustion systems have been developed by different OEM's for several years. First generation systems used side mounted injectors with wall guided or air guided mixture formation (Figure 10). Further improvements, especially in real world fuel economy, can be achieved with spray guided direct injection /5/ (SGDI), which accomplishes a major increase in the stratified operational window, as well as an improved efficiency of the stratified combustion process.

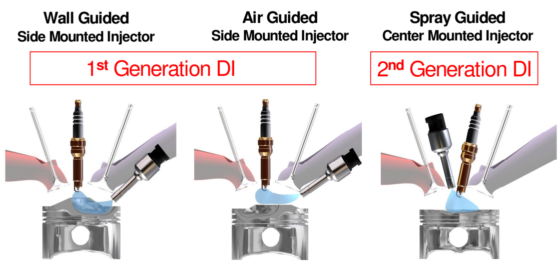


**Figure 10**: DI Combustion Concepts for Stratified Operation

Especially the combination of downsizing, spray guided direct injection and turbocharging (SGDI TC) offers a significant fuel economy improvement potential without any compromises regarding driveability. In this context, Figure 11 compares the NEDC fuel consumption of a 1.6L turbocharged SGDI engine with a turbocharged 1.6L engine with port fuel injection (PFI) and a naturally aspirated 2.3L PFI engine. The turbocharged SGDI engine offers a fuel consumption reduction potential of about 17% based on the downsizing effect. Additional fuel economy potentials can be made available by stratified operation of the downsized engine.

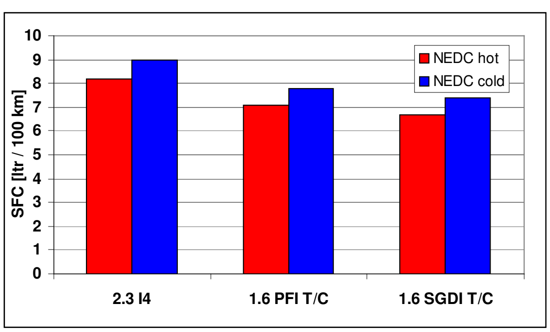


**Figure 11**: SGDI TC Fuel Consumption in the NEDC Cycle

Figure 12 compares the full load performance of the same engines as shown in Figure 11. In the complete speed range, the 1,6L SGDI TC engine offers more torque than the naturally aspirated (NA) 2.3 L engine. It also requires less enrichment ("overfuelling") at higher loads than the 2.3L NA and the 1.6L PFI TC engines due to the outstanding knock resistance enabled by direct injection.

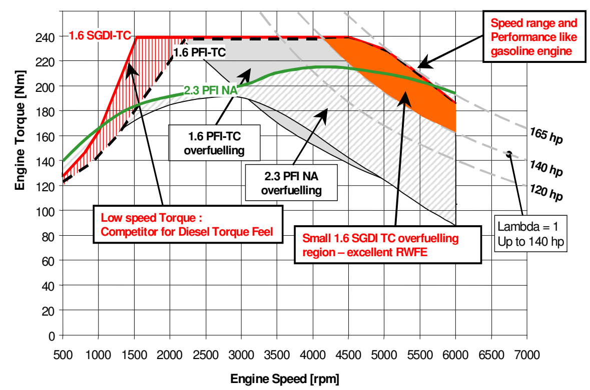


**Figure 12**: Gasoline SGDI and Turbocharging Benefits

## CONCLUSION

The traditional advantages of internal combustion (IC) engines refer to:

- The high power density (power to volume and weight)
- The high energy content and the ease of onboard storage of liquid fuels
- The well established manufacturing processes that has been optimized through many years
- The usage of conventional materials with good recyclability
- The driving distance between two refuelling events (which is typically much longer with IC engines than with many of the discussed future alternatives)
- The well established worldwide fuel supply infrastructure
- The capability to effectively use a variety of alternative gaseous and liquid fuels

IC engines still have a huge potential to effectively deal with most of the sometimes conflicting requirements for future automotive powertrains. In particular they can achieve:

- Further increase of power and torque
- Further size and weight reductions
- Further improved fuel economy
- Further reduced emissions
- Further reduced manufacturing cost

Future diesel engine concepts for higher specific power output, lower engine raw emissions and better NVH will include:

- Advanced boosting / airhandling systems for improved performance and lowest emissions
- Low NOx combustion systems in combination with advanced fuel injection systems (Homogenous Charge Compression Ignition)
- Right sizing (optimized combination of engine displacement and vehicle weight for a given NOx emission standard)
- Parasitic loss reduction
- Weight reduction
- Further increased oil change intervals
- Usage of bio diesel and clean burning synthetic diesel fuels (GTL, BTL)

Future gasoline engine concepts will mainly targeting on further increased specific power output and fuel economy improvements through:

- Downsizing and boosting (in combination direct fuel injection or with variable compression ratio)
- Reduced throttle losses at part load operation through:
  - Direct fuel injection with stratified lean part load operation
  - Fully variable valve timing
  - Cylinder deactivation (especially for engines with larger displacements and cylinder numbers)
- Controlled Auto Ignition (CAI)
- Parasitic loss reduction
- Weight reduction

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