When considering an alternative fuel for light-duty vehicles, Compressed Natural Gas (CNG) offers favorable prerequisites that support increased use. Long-term availability of natural gas resources as well as widespread availability have been forecasted. CNG offers a favorable carbon to hydrogen (C/H) ratio that presents the potential for up to a 20% reduction in CO₂ emissions.

With respect to the availability of CNG in the gas station network, coverage is not comparable to that of gasoline as of yet, but a significant increase in CNG gas stations has been noted in many European states in recent years. From the vehicle manufacturer’s perspective, CNG vehicles can represent one buil-
Dear Readers,

In the transportation sector, there are two primary advantages of natural gas: its availability and its specific CO₂ emissions, which are approximately 20% lower than gasoline or diesel fuel. Worldwide, it is notable that there are concentrated efforts to invest in electric propulsion which requires the mobilization of heavy batteries, while we continue heating our homes with natural gas instead of electricity. There are many technical and political reasons for this. In this special edition of Spectrum, we discuss the technical challenges associated with the use of natural gas as a transportation fuel:

- Light-duty applications rely on high torque at low engine speeds and at the same time component protection at rated speed - technologies such as variable compression ratio open completely new degrees of freedom.
- Heavy-duty applications with lean burn operating systems are being replaced by stoichiometric combustion systems because of the increased stringency of emission standards in Europe and in the U.S.
- Marine as well as stationary applications lend themselves to natural gas operation, which allows a resolution to some of the emissions challenges. Large bore engines employ pre-chamber, lean burn combustion systems and, in selected cases, dual fuel engines are used.

In this issue of Spectrum we discuss the worldwide effort to expand the use of natural gas in the transportation sector. We would also like to support your natural gas application development efforts both today and in the future.

Sincerely

Dr.-Ing. Markus Schwaderlapp
Executive Vice President FEV GmbH

Fig. 1: Fuel cost in Germany

The increase in engine efficiency in combination with the relatively low price of CNG (Figure 1) results in reduced operating costs for the end user and a comparably short amortization time to offset the higher purchase price of a CNG passenger car. In addition to the economical aspects, it is essential for the success of CNG engines that they meet the technical requirements in competition with the gasoline-run variants. Competitive driving performance must be ensured here as well as reliability and durability. To compensate for the lower calorific value of the mixture and to benefit of the knock resistance of CNG, engines with turbocharging systems are especially interesting for operation with CNG. The engines must meet more stringent mechanical and thermomechanical requirements in the process. These are due to the lack of CNG additives as well as the high-efficiency combustion with consequently higher cylinder pressures and combustion temperatures. Furthermore, the enrichment of the combustion air ratio for thermal component protection purposes that is typical at high rotational speeds can only be used to a very limited degree for CNG. Scavenging, which is typically used in direct injection gasoline engines at low rotational speeds to increase the basic torque and/or to de-
crease the basic rotational speed, can be applied to a clearly more limited degree with today’s CNG intake manifold injection. Mechanical systems in combination with turbocharged systems represent an option to compensate for this. To prevent having to employ this corresponding type of comprehensive solution with a reduced potential, we also want to list the optimization at the injection valves and strategies for representing the required gas flow. The conversion to CNG direct injection offers a high potential for representing a high low-end torque. However, it failed in the past because series production injectors that work reliably in all operating conditions and provide a permanent seal were not available. An assessment of the upcoming injector generation is still pending at this point.

Necessary and well-known measures for safely operating engines with CNG in the long-term without fuel additives are selecting suitable materials for valve seat rings, guides, and valves. Adapted seat ring geometries and valve lift curves for reducing the valve contact times must also be listed here. Figure 2 shows the results of a seat ring analysis in a durability test, during which wear was determined at defined time intervals. With the original design for the gasoline engine, the maximum permissible wear rate was already exceeded as early as after the second inspection. With the final design for CNG operation, it was possible to limit wear to a very low rate far below the permissible wear limit after a certain running-in period.

The higher mechanical load of the crank assembly components and the thermal load of additional engine components such as spark plugs, valves, manifold, turbine, and catalytic converter are significant factors behind the current upper limit of the specific output of series production CNG engines at 75 kW/l. Optimized cooling is therefore even more important in CNG variants that have the same output in comparison to gasoline-run engines. DI injectors must also be noted in connection with the combination of PFI injectors for CNG and DI injectors for gasoline operation that are widely used today for the high-performance CNG operating range. These injectors can easily exceed critical injector peak temperatures at high thermal loads without the cooling flow of gasoline.

A modified sealing concept of the injector that is used to enlarge the heat dissipating surface can be added by changing the recess depth. Consequences in terms of unwanted secondary effects such as carbonization during gasoline operation must be observed here. Furthermore, the use of cooled integrated exhaust manifolds is an effective solution that is implemented in series production to reduce the thermal load of the components carrying exhaust. Figure 3 shows the wall temperatures at nominal performances within the non-critical range. For significantly higher power densities, additional measures are recommended that take effect as early as during combustion. Cooled exhaust gas recirculation should be considered as a corresponding measure. However, this complex system will probably only be used in applications if at least the powerful gasoline variants from the corresponding engine family are also equipped with this system.

For drivers that place great emphasis on a ve-
The Diesel engine has played a dominant role in the commercial sector because of its inherent advantages related to fuel consumption and durability. For some time, natural gas engines have presented an attractive alternative.

Natural gas engines inherently emit low levels of particulate emissions that are close to the detection limits. Prior to the introduction of EURO VI or US 2010 emission regulations, it was possible to maintain NOx emission levels within the standards by applying lean-burn combustion concepts without the use of exhaust gas aftertreatment systems. The lower fuel cost of natural gas in comparison to diesel or gasoline in combination with the lower CO2 emissions that inherently result due to the favorable H/C ratio of methane represent additional incentives to use these engines in commercial applications. However, the demands on these engines have increased through the introduction of EURO VI. The upcoming NOx and HC standards require adaptation of the combustion system as well as extensive adjustments to the exhaust gas aftertreatment system.

It is generally desirable to combine low NOx emissions with low fuel consumption and this can be accomplished through the application of homogeneous lean-burn gas concepts. However, quenching effects and the resulting unburned hydrocarbon emissions that occur as a consequence of extensive lean operation can only partly be addressed through exhaust gas aftertreatment systems. The hydrocarbon emissions consist primarily of methane and, because of their low reactivity, result in high catalyst light-off temperatures. The resulting low catalyst conversion rates in transient operation need to be addressed through lower engine-out emission levels. Figure 5 illustrates this behavior. The dashed line in Figure 5 highlights the engine-out emissions trade-off between NOx and CH4. Conventional lean-burn concepts employ an oxidation catalyst as an exhaust gas aftertreatment solution, reducing the CH4 levels to meet emission standards up to EURO V/EEV. Any further decrease in NOx emissions to EURO VI levels would result in an increase in CH4 levels, which could no longer be contained through the application of conventional oxidation catalyst technology. The added cold start requirements contained within EURO VI intensify the demand that alternative methods be found to meet regulatory demands.

Two methods are worthy of further exploration: The use of a lean-burn system with reduced lambda

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**Fig. 4: Strategies for bivalent or flex-fuel operation**

VCR connecting rod offers an interesting solution. Figure 4 shows a corresponding design that illustrates the advantages of a variable compression ratio based on a direct injection gasoline engine. While the switchover line of a compression from 8.5 to 13 lies in the medium load range during operation with RON 95 depending on the rotational speed, the engine can be operated with the high compression ratio in the entire operating range during CNG operation. Under the currently valid legal boundary conditions, which are under discussion though, this type of concept can only be implemented as a bivalent concept where the engine timing does not take place as a function of the performance map, but where the driver manually selects the fuel type.
to ensure that methane standards can be safely met. In this case, the increasing NOx emissions are contained with the use of an SCR catalyst. The second method is the transition to stoichiometric combustion, whereby the exhaust gas aftertreatment is performed by a three-way-catalyst. This method has been used for quite some time in commercial applications, but has inherently lower efficiencies and poses additional challenges to Diesel-engine derived hardware as a result of increased exhaust gas temperatures.

For EURO VI stoichiometric combustion has evolved and is now considered a superior approach because it offers benefits in terms of simpler exhaust gas aftertreatment and the avoidance of an additional reduction medium (urea). Externally cooled EGR offers a possible solution to increase efficiency with a stoichiometric concept while limiting the thermal exposure of the engine. During part-load operation this feature allows the engine to be de-throttled, resulting in a reduction in fuel consumption. Cooled EGR can also significantly decrease the knock-sensitivity during operation at high-loads. As a result, it's possible to increase compression ratio and to advance the center of combustion, reducing temperatures and thermal loading while increasing efficiency. Figure 6 shows the potential as a function of specific CO2 emissions for the various concepts. The 20% CO2 advantage of the lean-burn natural gas engine is diminished through the application of a conventional stoichiometric combustion system, while the EGR concept is nearly able to eliminate this disadvantage.

The main development focus of the otto-cycle concept, using EGR over the entire engine map, is obtaining the highest possible combustion stability, short burning durations and the highest possible knock resistance. FEV has developed Diesel-engine derived commercial natural gas engines, which have application-specific requirements. One example is the patented ATAC (Advanced Turbulence Assisted Combustion) concept shown in Figure 7. This concept features a highly turbulent flow pattern during combustion as well as squish-dependent flow effects that enable stable and rapid conversion of the charge mixture at high EGR rates. FEV continues to work on natural gas engines at all stages, from concept to production, aimed at compliance with various emissions standards.
Natural Gas as a Fuel for Industrial Engines and Ship Propulsion. A Contribution to Reducing Green House Gas Emissions

The use of natural gas as a fuel in industrial engines and in ship propulsion is being driven by a number of factors. Aside from the operating costs, which are primarily driven by the fuel price, regulatory requirements are an important factor in determining the development and deployment of such engines.

Regulatory requirements are apparent in various forms: as general emission standards, as regulations with the aim of reducing greenhouse gas emissions, or in the form of regional requirements or economic development programs. A natural gas distribution infrastructure is also required to ensure broad availability.

A traditional application of a natural gas engine might be a generator set that creates decentralized power, oftentimes as a combined heat and power system. In such applications, the lowest possible NOx emissions without using exhaust gas aftertreatment, are attainable (e.g. 50% Technische Anleitung zur Reinhaltung der Luft, TA Luft – German Clean Air Act). Optimized concepts allow for efficiencies that exceed that of a diesel engine, enabling CO2 based greenhouse gas reductions of over 25%. Typical stationary use includes a connection to area-specific gas supplies such as biogas, landfill gas, water purification system gas, blast furnace gas, mine gas, etc.

The necessity to transport natural gas over long distances with ships established the use of gas engines for ship propulsion. The natural gas is stored on these carriers in cryogenic form (LNG or Liquefied Natural Gas) to reduce the tank volume. The naturally created boil-off gas is used as fuel for the engine. Increased regulatory stringency for ship propulsion systems and the introduction of Emission Control Areas (ECA) has expanded the areas of interest to other vessel types because natural gas technology allows NOx and SOx standards to be met without complex exhaust gas aftertreatment systems. This is resulting in an increased number of vessels with natural gas propulsion as shown in Figure 8. An additional motivation is the “Energy Efficiency Design Index” that has been introduced by the International Maritime Organization (IMO), which regulates the greenhouse gas emissions from ships. Another contributing factor is the forecasted price for LNG in comparison to conventional petroleum-based marine fuels. The main prerequisite for mobile maritime applications is the availability of an LNG infrastructure in ports. Such infrastructural improvements are currently being developed in coastal areas as well as in inland waterways.

Figure 9 shows the efficiencies for current state-of-the-art four-stroke natural gas engines as a function of the bore diameter. Bore diameters up to 260 mm allow an open combustion chamber concept. However, additional aids such as chamber spark-plugs are used above bore diameters of 200 mm to enhance the control of the large flame-paths. Stoichiometric concepts find their spot in applications with the requirement for high robustness and easily controllable emissions. In such cases, the resulting lower efficiencies are accepted. The highest efficiencies can
only be achieved with lean-burn concepts; however, these concepts also pose greater demands on the combustion system. Gas scavenged pre-chamber concepts already demonstrate advantages below a bore diameter of 200 mm. The ignition energy for the main combustion chamber is provided via torch-like jets from the pre-chamber that penetrate the main combustion chamber and ensure ignition of even the leanest mixtures. This results in high efficiency and low NOx emissions. State-of-the-art dual fuel concepts allow operation on nearly pure natural gas where ignition is initiated by a small pilot quantity of diesel fuel. On the other hand, they can operate on diesel only. Such systems always present a compromise between natural gas and diesel combustion and result in reduced efficiencies in comparison to pure natural gas or diesel operation. Each design displayed in the scatter bands requires specific optimization for vital combustion system related parameters, including mixture formation, ignition, charge motion, and the combustion chamber.

The open combustion chamber design requires that the mixture formation be optimized to enable reliable operation under lean conditions. The ignition must also be optimized for high peak firing pressure and offer a sufficient buffer to compensate for growing electrode distances to maintain acceptable spark-plug change intervals. The combustion process is controlled through the adaptation of the inlet port geometry and the combustion chamber layout. Target is the optimal support of the combustion process by turbulence. The ATAC concept described in the commercial engine section of this Spectrum edition lends itself equally well to operation in lean-burn combustion systems with open combustion chambers. High power densities and efficiencies can be delivered with the described design.

During the development of scavenged pre-chambers, the design of the pre-chamber is the main focus. The volume as well as the size and orientation of the pre-chamber nozzle orifices play an important role in creating robust conditions for ignition and combustion of the lean mixture. The goal is to establish reliable, stable ignition of the lean mixture through the torch jets penetrating the main combustion chamber as well as widespread and knock resistant ignition. Figure 10 illustrates the development process for a pre-chamber design. The first phase focuses on the optimization of combustion stability. The combination of optimized pre-chamber volume and nozzle orifices allows a stable combustion process with the lowest possible cyclical variations. The high knock resistance allows an increased efficiency while maintaining low NOx emissions. Another key step in the optimization process is the shaping of the rate

![Fig. 10: Combustion system optimization of a gaseous fuel engine with direct-injection scavenged pre-combustion chamber](image)

![Fig. 11: FEV Charge Motion Design (Courtesy of MAN Diesel & Turbo SE)](image)
Dual fuel concepts were originally developed to exploit inexpensive, locally available, natural gas sources, but maintain the liquid based fuel as an easy-to-store backup. The dual fuel engine offers the ability to operate mainly on HFO while meeting the IMO 3 ECA limits in gas operation mode without any exhaust gas aftertreatment. Optimized dual fuel designs feature two liquid fuel injection systems. One system serves as pilot system to ignite the lean natural gas mixture, the second serves as primary system to operate on liquid fuel (MDO, HFO). During natural gas operation it is possible to maintain emissions comparable to those of engines with electric ignition applying small pilot injection quantities (approximately 1% of the total energy).

Simple systems that are sometimes offered as retrofit solutions (and are intended to bridge the lack of a gaseous fuel infrastructure that is still not comprehensive), are using predominantly a standard diesel engine fitted with a gas injection system. Figure 5 shows the basic performance of this type of design. Since the injection system is not designed for very small amounts compared with the pilot system, the minimum diesel portion is approximately 15%. Low load operation requires exclusive use of diesel for stable operation. In order to ensure a combustible air/gaseous fuel ratio, the air/fuel ratio must be reduced by means of throttling during part-load operation, the gaseous fuel fraction is limited. At high loads, the occurrence of knocking prevents the option to operate the engine with high gaseous fuel rates.

Methane emissions, which are critical due to their potential to generate greenhouse gas, remain a general problem. The optimization of these concepts in terms of higher gaseous fuel fractions, efficiency, and low exhaust emissions largely depends on the performance of the diesel injection system. Systems that are uniquely geared towards this type of application represent a significant potential for future improvement.

FEV's Charge Motion Design methodology offers considerable support for these efforts. This method, which is routinely used in the development process for conventional gasoline engines, can also be successfully applied to pre-chamber natural gas engines (Figure 12). This process is defined by the integration of charge motion, combustion chamber geometry and pre-chamber characteristics and is based on the CFD simulation of flow patterns and turbulence levels inside the combustion chamber due to the dominance of the in-cylinder flow characteristics. These are defined by the inlet charge flow, piston motion, and the torch jets exiting the pre-chamber. The relevant parameters for designing and optimizing the combustion system are derived from the theory of flame kernel formation as well as a correlation-based prediction of a 5% to 90% fuel conversion. A reasonably close correlation between the measured and calculated combustion duration can be demonstrated, based on variation of an inlet based charge motion (Tumble), combustion chamber design (Piston), and pre-chamber geometry (Pre).

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