Powertrain optimization using a comprehensive systems approach

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Abstract

Over the next few years, the framework conditions for mobility will be redefined. Legislation will significantly reduce the mandatory limits for CO₂ and emissions. Other developments will also play a role. We will see a continuing rise in customers’ expectations relating to driving comfort, as well as an universal trend toward connected and automated vehicles. Each of these developments will significantly affect powertrain design.

A market which is today dominated by combustion engines will likely move toward electrification. From today’s perspective, it cannot be said whether this change will be revolutionary or evolutionary. For this reason, Bosch is continuing to develop both powertrain concepts. In addition, the combination of these two powertrain types opens up new potential, which gives the combustion engine in particular a new chance of fulfilling exacting standards.

The present article highlights the current and future potential arising from the interplay of these different powertrain concepts, and illustrates this potential with concrete examples.

Check against delivery
Global megatrends

The world is changing. Four major megatrends will determine the mobility of the future – and with it, the powertrain.

1. From today’s roughly 7 billion, the global population will grow to some 8 billion by 2025, and by roughly another billion by 2050. By 2030, the average age of the world’s population will have increased by 4 years, to reach roughly 33. In the advanced industrialized countries, it will rise to just under 44. In the OECD, therefore, the significance of the over-60 age group will continue to grow.

2. Urbanization will continue over the next decades. In 2030, some 60 percent of the global population, or just under 5 billion people, will live in cities.

3. Especially because of population growth, energy and climate change will continue to dominate the global agenda. Despite the growing importance of renewable energy and resource-conserving products, it will scarcely be possible to limit global warming to 2 degrees Celsius. In the future, priority will be given to mitigating the consequences of climate change.

4. Everything is going online: connectivity and the internet of things will change our world, and the car with it. By 2020, 50 billion things will be connected.

These developments will change our perception of cars and mobility. The developments we come up with now will determine what the car of the future looks like. It is up to us to choose the right developments.
Efficiency and emissions will continue to dominate the powertrain agenda, and this on two levels. They will do so globally, because a growing number of people will become mobile. And they will do so locally, because there will be more people per square kilometer in the megacities who want to be more mobile. The powertrains of the future will have to emit even less CO₂, particulate matter, and NOₓ – or may even have to run locally with zero emissions.

But mobility will change even more fundamentally, as the following points show:

1. Even in the aging society of the future, people will want to maintain their unrestricted mobility.
2. Multimodal mobility: when deciding how we get from A to B, the actual means of transport will be less important than questions of travel time and convenience.
3. The increase in global energy demand will go hand in hand with stricter emissions standards – for industry as well as for transport. Renewable energy will grow in importance, not only in our power grids but also in our powertrains.
4. The car will become an active part of the internet, not only as a result of apps for the driver, but also as part of a connected ecosystem in which car-to-car, car-to-infrastructure, and car-to-x communication will help enhance efficiency.

In the future, vehicles will be increasingly automated, connected, and electric. As an active part of the internet, cars will offer customers additional value: simple use combined with a high level of
convenience, remote diagnosis all the way to remote management of the maintenance process, and customized assistance functions.

Bringing these things about involves a number of challenges. To help meet them, Bosch is already series-producing a number of connected mobility solutions. The combination of software, hardware, and services in the powertrain makes even more efficient driving possible. As in the past, our development work is guided by the conviction that innovative powertrains should use resources more efficiently, reduce emissions, and enhance driving enjoyment.

### Engine-related innovations

Up to now, the technological development of the powertrain has taken place between two divergent demands. On the one hand, legislators have called for reduced emissions and, on the other, customers for higher performance and more comfort.

Since 2000, it has been possible to reduce the CO₂ emissions of the European passenger-car fleet by some 25 percent. But over the same period, vehicles' average weight has increased by 10 percent, and average engine power by as much as 20 percent. The share of automatic transmissions in newly registered passenger cars has risen 75 percent.
It is these challenges – social-policy goals on the one hand and individual purchase decisions on the other – that form the basis of powertrain innovations such as direct injection in diesel and gasoline engines, combined with downsizing, turbocharging, and many other measures.

In the near future, the divergent demands outlined above will continue to dominate the picture. There are no signs of any change in purchasing behavior, and emissions standards are set to become stricter in all the world’s major automotive markets. Europe leads the way here, with its ambitious 95g CO₂/km target for 2021 and imminent legislation on real driving emissions (RDE).

Without doubt, the challenge here is to set future emissions limits in such a way that, at an early stage, the automotive industry has a reliable basis for the introduction of new technologies, while at the same time keeping the innovations needed to achieve these limits affordable for the end customer.

I will now go into some of the innovations shown in figure 3 in more detail.
Given RDE legislation, and especially the particle number limit (PN) connected with it, attention is focusing especially on an increase in the system pressure of gasoline direct injection for spark ignition engines. Improved fuel atomization, more efficient mixture formation, reduced formation of wall film, and reduced injection times are the most important technical parameters. As figure 4 shows, they can result in a considerable reduction in particulate emissions compared with a 200-bar system.

All in all, a system pressure of 350 bar is a good compromise between a higher-performance injection system and the total cost of the direct injection engine.

The most prominent advantages of the 350-bar system are higher load points and more dynamic engine operation. This is demonstrable in the RTS cycle, which is a widely accepted approximation to the demands of RDE tests. In addition, greater pressure requires a cost-intensive change of technology on the component level, as well as a lot of effort to reinforce camshafts and cylinder heads. Because of the improved mixture formation in systems up to 350 bar, the demand that fuel consumption should remain the same is largely fulfilled.

The third generation of Bosch gasoline direct injection offers shorter intervals during multiple injection, greater metering accuracy, improved metering range, and better acoustic behavior than
its predecessors. The Bosch injector is suitable for lateral and central installation and allows spray patterns to be designed flexibly. The flexibility of the pump’s hydraulic connections and the modular components mean that it is considerably easier to integrate the system into the engines of different customers.

Water injection

Water injection – key features

- Cooling of charge to minimize/avoid fuel enrichment
- Improve knocking behavior
- Increase compression ratio
- WI port injection: low complexity and high effectiveness
- Bosch is developing WI with pilot customer

The compression ratio of a spark ignition engine has always been a compromise between part-load efficiency on the one hand and performance and efficiency at full-load conditions on the other. Current production engines typically retard ignition timing at high loads to avoid knocking. This leads to a loss in fuel efficiency, reduced engine power, and increased exhaust-gas temperatures. Water injection (WI) can mitigate these drawbacks, if not remedy them completely.

The use of water injection leads to an improvement in all knock-limited operation areas:

- Reduction of fuel consumption at high loads and low rpm
- Reduction or avoidance of fuel enrichment and lower exhaust-gas temperatures at high loads and high rpm

Figure 5

Water injection

Reduced consumption and improved performance

Turbocharged engine: 20 bar @ 5000 rpm

NEDC up to 4% improvement (via higher compression ratio)
Both effects result in lower CO_2 emissions in real driving conditions. The first-named effect also reduces CO_2 under the conditions of the future WLTC test cycle.

Moreover, this reduced knock tendency can also be utilized to increase engine compression, which has additional benefits at part load. It also results in lower fuel consumption and reduced CO_2 emissions in the areas relevant for the NEDC and WLTC.

Instead of enhancing efficiency, WI can also be used to increase torque. The additional cooling of air makes a bigger charge possible, and thus greater torque.

Measurements performed on an experimental engine with direct injection at 5000 rpm and a mean effective pressure of 20 bar show that stoichiometric operation is possible once the proportion of water reaches 35 percent. In other words, fuel enrichment during full load can be completely eliminated. At this operating point, fuel consumption can be reduced by 13 percent.

Water injection thus shows significant potential for reducing consumption and CO_2 emissions in test cycle conditions, as well as for closing the gap between test-cycle and real fuel consumption.

In close cooperation with a pilot customer, Bosch is developing a WI system for series production. This port water injection system comprises a water pump, a water rail, and injectors which have been designed to handle the specific challenges arising as a result of operation with water.
In a passenger-car diesel engine, RDE means that not only CO$_2$ emissions but also raw emissions have to be further reduced. In the past, the preferred way of doing this was through the injection system and reduction of stationary emissions. As a result of RDE requirements, the focus has now widened to include optimization of raw engine emissions in transient operation. Here, the engine’s air system plays the main role. This comprises charging, exhaust-gas recirculation, and the ECU functions needed to control air management. As R. Busch et al. show in their lecture “Emission and Fuel Consumption Optimized Turbo Charging of Passenger Car Diesel Engines,” also presented at this year’s Vienna Motor Symposium, Bosch is supporting these optimization efforts with innovative turbocharging technology and new, model-based control strategies.

To fully exhaust the further potential of diesel and gasoline engines, both components and the interplay between turbocharger and combustion engine have to be analyzed in detail and optimized.

When it comes to turbocharger development, the focus is on:

- further developing all aerodynamic components and their interaction, so as to improve efficiency,
- reducing friction, and
- reducing the rotor’s polar moment of inertia in order to enhance transience.
In the system as a whole, a significant role is played by the correct dimension and design of the aerodynamic components and their compatibility with the engine used, as well as the engine’s air-charge and combustion concept.

If this approach is applied, further significant potential for reducing diesel engines’ emissions can be opened up. In addition, fuel consumption in the NEDC can be reduced by a further 2 to 3 percent. In other words, an advanced diesel engine can continue to play a valuable part in reducing global CO₂ emissions, even when emissions standards are tighter.

**eClutch**

**eClutch**
Enhanced manual transmission system

Even without electrification, there is a lot of consumption and functional potential that can still be tapped in the powertrain, beyond optimization of the combustion engine. One example is the Bosch electronic clutch system (eCS), developed for manual transmissions. The system is based on the clutch-by-wire principle, and does away with the mechanical connection between clutch pedal and clutch. Still using the clutch mechanism, however, an actuator opens and closes the clutch. The eCS can be integrated into almost any powertrain, without the need to modify the clutch itself. It helps reduce CO₂ emissions and also provides customers with tangible extra functions such as prevention of engine stall or easy engagement of the clutch in difficult situations.
To ease the burden on drivers, the car can run in stop and go mode in traffic jams without using the clutch pedal, provided there is no need to shift gear.

Using eCS, cars with manual transmissions can drive off in start-stop operation in the same way as automatics.

The electronic control of an eCS means that fuel-saving start-stop coasting is also possible. Measurements show that a fuel saving of 10 percent is possible under real driving conditions.

The role of electrification

The above examples are intended to show what potential the combustion engine still has for reaching ambitious emissions targets. From a present perspective, packages can be put together that reduce the technically achievable values for CO$_2$ in subcompacts in the NEDC to less than 85g CO$_2$/km. For diesel engines in the subcompact class, values of 70g CO$_2$/km are feasible. In the compact class, the achievable values for gasoline and diesel engines are less than 95g CO$_2$/km and 85g CO$_2$/km respectively. These values do not take account of additional vehicle-related measures for saving fuel, such as improved aerodynamics or reduced rolling friction.
The 2021 EU limits for CO₂ emissions should thus be reachable for the “best in class” subcompact and compact vehicles. In heavy and large vehicles, however, combustion-engine optimization will not be enough on its own, even if engine-stop phases are made longer. For this part of the fleet, powertrain electrification will be necessary in the future.

At present, the trade-off between the cost of the electrical powertrain and advantages such as reduced emissions, and above all benefits that customers can experience for themselves, has not yet resulted in a resounding market success for electric vehicles or hybrids. Electric vehicles will only achieve a significant market share when there are significant state incentives, especially on the tax side.

Nobody who has ever driven in a powerful hybrid or electric car will dispute that the benefit of an electrical powertrain, such as the way it accelerates from a standstill, is something very tangible.

Bosch is already active in this market, with components and systems for electrification. It has meanwhile received 30 orders for things such as motors, power electronics, batteries, and entire systems.

However, it would be wrong to see electrification as competing with efforts to optimize the combustion engine. Instead, the combination of combustion engine and electric motor in the powertrain gives us more options in our optimization efforts.

Low-voltage electrification is one such option, allowing us to reduce emissions and enhance driving comfort at a good cost-benefit ratio.
With these systems, a 7 percent CO₂ reduction in the NEDC cycle is possible for the compact class. This is achieved above all through brake energy recuperation. And with start-stop coasting, this reduction can be even greater. Here, the internal-combustion engine is stopped not only when the vehicle is stationary, but also temporarily while it is in motion, as soon as drivers take their foot off the gas.

The use of such systems is being encouraged not only by fleet CO₂ targets and ever lower emissions limits, but also by the greater demands made of the onboard power supply and tangible extra functions for customers, such as the boost effect or the comfort start function for the combustion engine. In the latter function, the 48 volt motor on the drive belt supports cars with manual transmissions when driving off.

And as a second source of power, the 48 volt motor allows the demand for torque to be distributed between the combustion engine and the electric motor. In the spark ignition engine, this means that aggressive heating strategies for the catalytic converter are possible, without any limits being imposed by the need for the combustion engine to run smoothly. Moreover, transient processes of engine speed, cylinder air charge, ignition angle, etc., which are normally associated with considerable disadvantages for emission values, can be avoided or limited in their effect. All in all, such measures can allow emissions to be reduced – especially of hydrocarbons and particulate matter.
In random trials with a 200-bar gasoline direct injection system, the limitation of the combustion engine torque gradient to 20 Nm/s resulted in a 30 percent reduction in particulate emissions.

The diesel engine also benefits from the freedom to choose how to distribute the burden between the electric motor and the combustion engine.

However, it is NO\textsubscript{x} reduction that is the main target for the following two approaches:

1. Reduction of raw NO\textsubscript{x} emissions during acceleration and under heavy loads by electrically boosting the combustion engine. This effect cuts emissions at source, regardless of the exhaust-gas treatment system used, by between 10 and 20 percent.

2. Shifting the operating point of the engine by boosting or recuperative braking (generator operation), in order to improve the regeneration of NO\textsubscript{x} storage catalyst (NSC) systems: this additional electrical support allows better regeneration of NSC systems by shifting the operating point of the engine into the NSC regeneration range.

As a result of these effects, Bosch believes it is possible to use NSC systems to reduce NO\textsubscript{x} by as much as 80 percent, and in addition to improve efficiency and reduce urea consumption in SCR-based systems.

Linking these systems with other automotive systems paves the way for additional functions which are tangible for customers. To give just two examples, these include electrical remote parking and electrical stop and go. Thanks to eCS, the former is available even for cars with manual transmissions. The latter is a traffic jam assistant for very low speeds.

As Bosch is a supplier of integrated systems, the components it supplies are all compatible with each other. The company’s systems competence means it can combine the combustion engine and the electric motor in the best possible way.
The innovations presented above show how the powertrain can meet future market requirements – first by optimizing the individual domains of combustion engine, transmission, and electrification, but more importantly by optimizing across domain boundaries.

Going beyond this, connectivity and automation offer opportunities for optimizing driving when it comes to safety and resource conservation.
For example, additional potential is opened up if the powertrain is linked with information from additional sources in the Bosch electronic horizon.

In a first phase, this information takes the form of static navigation data. With the help of this topographical information about the route ahead, proactive drive strategies can be developed. The vehicle not only knows the route, but also the gradients along it. And because this topographical information is integrated into route planning, the powertrain can be used efficiently – for proactively controlling speed through start-stop coasting, for example. First studies show that the use of navigation data to optimize operating strategy in start-stop coasting systems can further cut CO₂ emissions by roughly 5 percent in real driving conditions.

In hybrid vehicles, moreover, the “division of labor” between combustion engine and electric drive can be optimized. For example, the electric drive can provide additional support on uphill stretches, and then recuperate energy while coasting downhill. Strong hybrids (sHEV) can save an additional 6 percent CO₂ in this way, while the saving in plug-in hybrids (PHEV) can be as high as 8 percent.
The quality and reliability of the environmental data are crucial here. It is also vital that they take account of the latest information, such as currently valid speed limits.

In the future, Bosch technology will provide real-time information about mobile construction zones, traffic jams, and accidents. In addition to information for drivers, it is also conceivable that driver assistance systems will actively intervene in driving operations in order to brake vehicles in good time before an obstacle (such as the start of a traffic jam). In this way, we are not only keeping vehicles clean and economical, but safe as well.

The final phase will incorporate information from the sensors capturing the vehicle’s environment. 360°logiQ, the Bosch connected horizon, collates information from different sources and offers the basis for pilot functions.
Mobility is changing, and the automobile with it. The vehicles of the future will be electric, automated, and connected. The major drivers behind the development of the vehicles of the future are efficiency, safety, comfort, and driving enjoyment. Electrification will play a key role in the powertrain, giving diesel and gasoline engines a further boost. In short, electrification will take combustion engines to new heights.

One decisive factor for these revolutionary developments will be the connection of cars to the internet. Only connected vehicles can fully exploit the potential offered by electrification and automation. Connecting vehicles to the internet makes them safer, more fun to drive, and reduces fuel consumption. Bits and bytes make cars more efficient. Bosch has laid the foundations for this development: even now, innovative systems link software, hardware, and sensors in the powertrain in order to pave the way for even more efficient mobility solutions.
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