

Low-CO₂ technologies for road vehicles

The need to continue reducing the CO₂ emissions of road vehicles—passenger cars, utility vehicles, and trucks and buses—will be met using all available means, acting not just on the engine but also on the vehicle itself. Engine displacements should continue to shrink; this downsizing will be accompanied by the optimization and greater complexity of the air loop (turbocharging and exhaust gas recirculation systems). Internal friction in the engine will be reduced and, through changes to components (injection, timing, and after-treatment systems), more efficient combustion modes, at low temperature or highly diluted, may in time be introduced in mass-production vehicles. Better management of electric power on board, associated with the increasing electrification of vehicles, from the powering of auxiliaries to actual electric propulsion (hybridization), is a very important improvement approach. The gradual replacement of a share of gasoline and diesel by natural gas for vehicles (NGV) will be also very beneficial in terms of CO₂ emissions, especially in those cases where the design of the internal combustion engine makes allowance for the characteristics of NGV (engine with a high compression ratio). As for the vehicle, the use of “fuel-saving” tires that reduce rolling resistance can be expected to spread, and a reduction of the weights of passenger cars, a key factor in reducing fuel consumption, is also probable.

Road vehicle CO₂ emissions reduction targets

Internal combustion engines (both spark and compression ignition) powered by hydrocarbon fuels are in very widespread use in the road transport sector, and this situation is likely to persist. This predominant role, which has lasted more than a century, is the result of steady technological progress in many areas, from the match between engine and fuel to the depollution of the exhaust gases, naturally without neglecting the optimization of combustion.

Even so, the efficiency of internal combustion engines averages only 20% in urban use. This is because, in actual use, engines sometimes operate at high load, where they are most efficient—up to 36% for a gasoline engine

and 45% for a diesel truck engine—and sometimes at low load, in zones of low efficiency, not to mention idling, where the efficiency falls to zero (Figure 1).

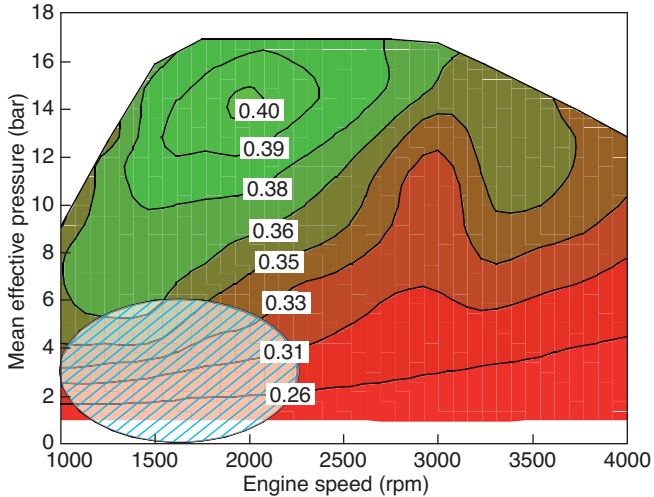
Standards for emissions of regulated pollutants, and in the longer term emissions of CO₂ in response to the commitments made by the European auto makers, make it necessary to find permanent solutions that do not prevent further improvement of vehicle safety, driving pleasure, and comfort.

Quite apart from standards, all users of means of road transport want the fuel consumption of their vehicles to be reduced. This is especially true of carriers, for whom fuel is very often the second largest expense item, after the payroll.

This being the case, all players in transport are motivated by the goal of reducing the fuel consumption of vehicles.

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Fig. 1 - Map of typical passenger-car diesel engine efficiency (Hatch-marked area: engine loading during operation of the vehicle in an urban environment)



Source: IFP

Note that this article deliberately refrains from consideration of the subjects of hydrogen and fuel cells, which are solutions for a much longer term than any of the other technologies mentioned in the paragraphs that follow.

Low-CO₂ technologies for passenger cars

Technologies at the level of the vehicle

The fuel consumption of vehicles is directly related to the power delivered by the engine in response to the speed requested by the driver. This power is used to overcome three resisting forces:

- friction, which combines rolling forces (tire, rolling) and transmission forces—to a first approximation, proportional to the speed of the vehicle,
- an aerodynamic force that depends on the frontal area of the vehicle, on its drag coefficient (Cx), and on the square of the speed,
- when accelerating, the inertia of the vehicle and of its rotating parts (mainly the wheels and the transmission).

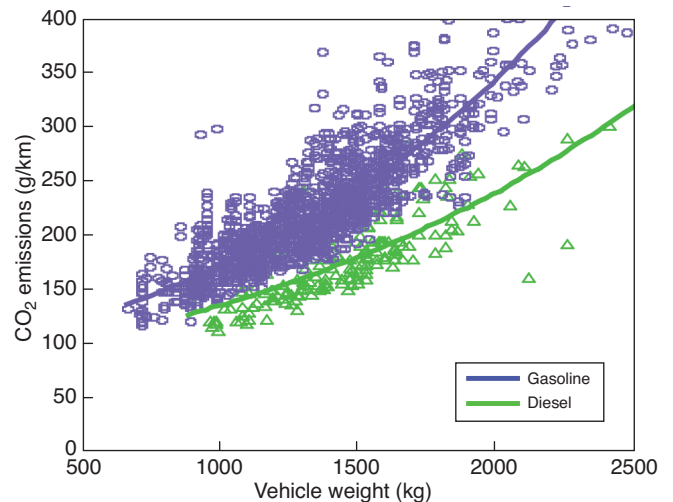
In a context where the safety and comfort of vehicles keep evolving, the technologies planned to reduce power demand are the following.

Reducing tire friction is a major development theme for equipment suppliers. One can mention the marketing of low-friction tires yielding fuel consumption savings of the order of 1 to 3%. Further progress along these lines is expected; the objective is to contribute a 3 to 5% reduction of the CO₂ emissions of vehicles by 2012.

Improving the aerodynamic performance of vehicles seems to be becoming more and more difficult because of vehicle design requirements, in particular those driven by customers' expectations (for example, the larger average frontal area of vehicles due to the demand for minivans). This factor becomes even more significant at high speeds: lower traffic speeds therefore contribute to limiting aerodynamic losses. We can however report that newer vehicles offer SCx coefficients—the product of the frontal area S by the Cx—that are relatively low.

Reducing vehicle weights, for example by making them smaller. The use of materials having lower densities (aluminum, composites) may lead to a significant improvement of CO₂ emissions, or at least offset the increase in average vehicle weight for reasons of comfort (power steering, air-conditioning, electrically operated windows, etc.) or of safety (air bag, reinforced structure, etc.). After several decades of rising vehicle weights related to comfort and safety, the trend seems to have reversed in the last few years (Figure 2).

Fig. 2 - Influence of vehicle weight on CO₂ emissions



Source: IFP

Engine technologies

Conventional engines (gasoline and diesel)

Technologies common to gasoline and diesel

In addition to improvements in combustion, the efficiency of internal combustion engines can be expected to continue improving, thanks in particular to progress in the following areas.

The reduction of internal friction in the engine, with a very positive effect on the urban use of the vehicles. The new technologies in the pipeline include advanced

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lubricant formulations, better control of the engine temperature, new surface treatments on the timing system and on the crankshaft, smaller friction areas on pistons, and the optimization of piston rings.

Changes to transmissions, including a larger number of gear ratios and a longer top gear, so as to reduce engine speeds and operate in the zones of optimum efficiency. This is combined with precise control of the transmission according to the use of the vehicle. Automatic transmissions and robotized manual transmissions are also being generalized for better driving comfort, optimized engine management, and fuel savings thanks to the steady improvement of efficiencies.

Improving the management of auxiliaries, in particular by electrifying them. Electric power-steering pumps are already on the market, and electric water and oil pumps are under study.

Improving thermal management of the engine to make the engine warm-up time shorter or to enable the engine to operate with a higher coolant temperature so as to improve friction and combustion efficiency.

Adding a stop&start function to cut off the engine when the vehicle is stopped (red light, traffic jam, etc.). Its generalization depends on the cost/CO₂ emissions reduction ratio, and it is being introduced for both spark ignition and diesel engines.

Improving the use of electrical energy through the introduction of piloted alternators and battery charging management and the development of batteries delivering improved performance and life.

Technologies specific to the gasoline engine

The gasoline engine, when it operates at stoichiometry, is an excellent energy converter capable of attaining a low local pollution level (emissions standards in the NEDC¹) thanks to controlled exhaust gas after-treatment by three-way catalysis. On the other hand, its CO₂ emissions are significantly greater than those of the diesel engine, by about 20 to 30%. This is due mainly to its operating mode, throttling of the intake to control the charge, entailing pumping losses, and to its higher combustion temperature, entailing thermal losses. The use of a moderate compression ratio to avoid destructive combustion modes (knock, rumble, etc.) also impairs efficiency. Technologies that will become available in the near future to improve the operation of the gasoline engine include:

- a smaller displacement, coupled with turbocharging,
- variable timing,

- the deactivation of cylinders,
- stratified combustion,
- new combustion modes,
- variable displacement and compression ratio.

Smaller displacement, made possible by the turbocharging of gasoline engines to increase the specific torque and power, has the largest potential for reducing CO₂ emissions, by as much as 25%. Improvements of 10% have been demonstrated on vehicles that are on the market (and therefore comply with standards for emissions of pollutants) equipped with turbocharged indirect-injection gasoline engines. Again, the use of a turbocharged direct-injection engine with camshaft phasers (VVT: Variable Valve Timing) yields improvements of from 20 to 22%. In the longer term, its use in conjunction with technologies to vary the compression ratio could generate improvements by as much as 25 to 30%.

Vehicles equipped with stratified-combustion gasoline engines have been brought to market with cycle fuel savings of the order of 10% and a potential of the order of 15%. Progress is expected in the key areas of direct injection and after-treatment systems, making it possible to lower the cost of these systems and improve consumption for the customer, in particular in more heavily loaded uses of the engine.

New combustion modes, such as CAI², can be expected to yield fuel savings of 10 to 20% at low loads (urban driving), operating with a lean mix, without recourse to complex nitrogen oxide (NOx) after-treatment systems, but at the cost of more complex air loop management incorporating the necessary very high exhaust gas recirculation level.

Disconnecting cylinders, in other words deactivating some of them at partial load, yields savings of the order of 10 to 15%. This technology was introduced a few years ago in large engines (V12 and V8) and has been applied more recently in a V6 engine having a displacement of 3.5 liters. In the future, its application could be extended to 4-cylinder in-line engines, representative of the great majority of European applications, provided that a way can be found to relieve the problems of vibration and roughness resulting from the deactivation (Figure 3).

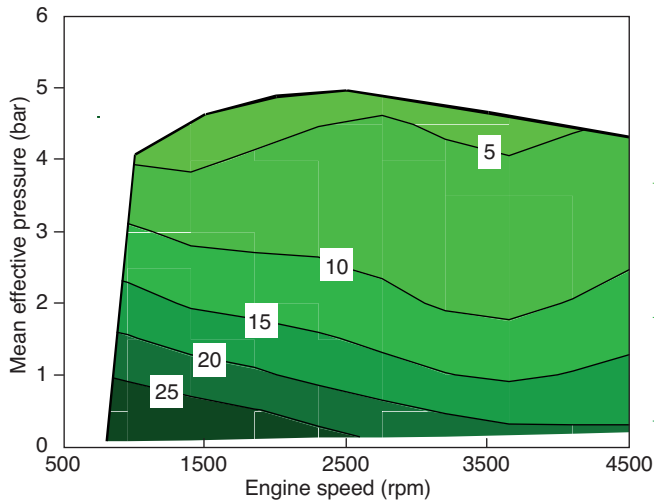
Variable timing exists at different levels of complexity, from a simple camphaser (VVT: Variable Valve Timing) through mechanical systems allowing variable lift (VVL: Variable Valve Lift) to electromagnetic or electrohydraulic systems without camshafts that adjust each lift of the valves according to engine demand. VVT allows savings of the order of 3 to 5%, in particular by favoring internal

[1] New European Driving Cycle.

[2] Controlled Auto Ignition.

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Fig. 3 - Potential fuel saving (in %) from the deactivation at partial load of 2 cylinders of a 4-cylinder engine



Source: IFP (OvaLiD® concept)

gas recirculation. In combination with VWL systems, savings of 5 to 10% are possible. Finally, more complex systems without camshafts could yield savings of 10 to 13%, and up to 18% when combined with the disconnection of cylinders.

Technologies specific to the diesel engine

Compared to the spark ignition engine, the diesel engine is very efficient, especially at partial load, which is frequent in vehicle applications. On the other hand, its operating principle leads to NO_x emissions in an oxidizing medium (lean mixture), making catalytic reduction in the exhaust system difficult. The challenge is therefore to cut emissions of nitrogen oxides without sacrificing efficiency, or even while improving it. The technologies that will make it possible to improve the compromise between fuel economy and emissions of pollutants in the diesel engine are:

- smaller displacement,
- advanced turbocharging,
- cooling of the recirculated exhaust gases,
- new combustion modes (LTC, HCCI, etc.),
- advanced injection system,
- variable timing system,
- advanced exhaust-gas after-treatment systems.

Common-rail injection systems, which now constitute the great majority of the systems in use, have made a very large contribution to improving combustion in diesel engines. Current and future progress in multiple injection and higher injection pressures is improving the compromise between fuel economy, pollutant emissions,

and combustion noise. Future technologies include injectors with direct control of needle lift, allowing staging of the combustion thanks to the high precision of the quantities injected. Combined with higher exhaust gas recirculation levels, this technology can yield fuel savings of the order of 4% by adjusting the combustion profile at constant pollutant emissions.

Mechanical variable timing systems are an interesting approach to reducing HC and CO emissions and thereby making it possible to employ low-temperature combustion at low loads (urban driving), with a positive effect on fuel consumption (3 to 4%) and NO_x emissions. And further savings can be achieved at medium loads using more complex systems.

The new low-NO_x combustion modes, such as low-temperature combustion (LTC), already applied at low loads, can be expected to be applied more broadly; the goal is to cover the whole range of engine use in urban driving. To achieve this, advances are expected in engine control (looped combustion) and air loop control (two-stage turbocharging, for example).

Intake gas temperature management, with in particular the use of high-capacity exchangers to cool the recirculated exhaust gases or the air downstream of the compressor, can improve the NO_x/fuel economy compromise.

Advanced turbocharging systems, such as the two-stage turbocharging recently introduced on up-market vehicles. These systems improve efficiency, thanks to operation with more excess air, which favors the reduction of gross pollutant emissions, and combustion timing that is optimal in terms of efficiency. Their generalization to other cars will depend on the added cost and on future advances in the efficiency of turbochargers for smaller engines.

Based on their effectiveness, the new nitrogen oxide after-treatment systems can shift the NO_x/consumption compromise of engines and so have a beneficial effect on CO₂ emissions. Current developments and the effectiveness of complex after-treatment systems in which NO_x, particulates, CO, and HCs are all treated allow more latitude for optimizing efficiency through combustion adjustments, since the additional pollutants engendered are dealt with by the after-treatment system.

Alternatives to and enhancements of the conventional internal combustion engine

Among the unconventional propulsion systems of which the development is sufficiently advanced that they might be on the market or under consideration for industrial production before 2020 (and come into widespread use in subsequent decades) are those used in electric and hybrid vehicles.

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The necessary diversification of energy sources for the production of alternative fuels (expanding supply) also leads to relevant fuel/technology pairings. Like the first- and second-generation biofuels, gaseous fuels such as natural gas are very promising.

Electric vehicles have always aroused great interest because of their intrinsic advantages: no local emissions of pollutants, very low noise, and high starting torque, which makes urban driving especially enjoyable. Development work on them has been going on for more than a century (Ferdinand Porsche's first automobile was an electric!), and there are large government incentives. Large-scale demonstration operations have been conducted, and yet this type of vehicle has never achieved the expected success: its share of the market is tiny. The main problem is the limited performance and excessively short range of these vehicles, typically 100 to 200 km in actual use. This situation is due essentially to the still inadequate performance of the batteries used to store electrical energy aboard the vehicle. Although the spread of this propulsion system will probably be limited, at least initially, to niche applications, several auto makers have announced electric cars; their success will nevertheless depend on the development of a network allowing the recharging of the vehicles (recharging terminals, suitably equipped stations). For the approach to be of value with respect to CO₂ emissions, electricity not produced by burning fossil fuels will also have to be available.

The hybrid vehicle, on the other hand, partially overcomes this drawback. It uses two energy storage systems—a fuel tank and a battery—and two propulsion systems, an engine and an electric motor. In the most flexible configuration, all types of combinations are theoretically possible: the engine can be used either to recharge the batteries or to power the vehicle, while the electric motor can be used both to move the vehicle and to recover braking energy.

Several levels of hybridization are distinguished according to the power of the electrical part. A "micro hybrid" vehicle has an electric motor delivering approximately 2 to 6 kW. In addition to the stop&start function mentioned earlier, it is possible to recover a small share of the vehicle's kinetic energy during braking. The mild hybrid category concerns vehicles equipped with electric motors in the range of approximately 10 to 15 kW. The braking energy recovery capacity is greater and the electric motor can assist the engine in powering the vehicle. With even higher electric power ratings—20 kW and more—the full hybrid vehicle can be driven using the electric motor alone, without recourse to the engine.

The fuel savings yielded by hybridization depend very much on how the vehicle is used. They are greatest in urban driving, especially when the itinerary is tough

(frequent acceleration/deceleration and many short stops). Some common uses are an ideal match for hybrid vehicles: mail delivery, other deliveries in urban areas, garbage collection, etc.

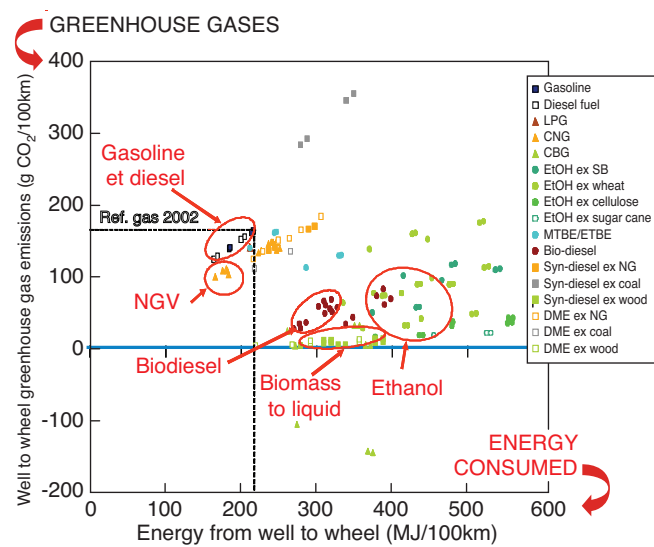
While the micro hybrid and mild hybrid yield on average fuel savings of from 5 to 20% compared to gasoline vehicles delivering comparable performance, the full hybrid vehicle can in some cases considerably reduce both emissions of pollutants (in all-electric operation in town, for example) and fuel consumption: a reduction of 30 to 40% can be anticipated for gasoline vehicles. For diesel vehicles, more efficient to start with, the saving is of the order of 20 to 30%. But note that hybridization adds substantially to the cost, in particular because of the battery. As it happens, a great deal of R&D work is being done on batteries, with a view in particular to making less use of expensive materials, improving their life between charges, and making their operation more reliable.

The dedicated natural gas engine is also regarded as a very strong candidate, notably because of the qualities specific to this fuel. Emissions of pollutants are potentially lower than those of conventional engines, because of the properties of the gas, and their toxicity and their reactivity in the atmosphere are less because of its composition (basically methane). In addition, natural gas has a high octane number (of the order of 130), making it possible to optimize the compression ratio and thereby increase the thermodynamic efficiency of the engine. This characteristic also obviates the necessary degradation of ignition advance encountered in gasoline engines and the richer mixtures it requires for operation at full load: the resulting savings compared to gasoline are large, up to 10% at full load.

Finally, because of the low ratio of carbon to hydrogen, the engine's CO₂ emissions are much lower than with petroleum-based fuels (approximately 23% for the same energy input). Altogether, an engine optimized for natural gas can be expected to emit from 5 to 10% less CO₂ than a diesel engine. On the other hand, as with any gaseous fuel, problems of range may arise. The use of natural gas in a hybrid vehicle is potentially one of the most effective solutions, along with biofuels, in terms of "well to wheel" emissions of CO₂. Technologically, natural gas engines are often adaptations of existing gasoline engines. Two approaches are being considered. The first is based on full downsizing, with performance preserved by turbocharging. The next step, even more effective, is to install the resulting engine in a hybrid vehicle. The mass production of such advanced propulsion systems is surely destined to grow for applications both in passenger cars and in buses and urban vehicles (Figure 4).

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Fig. 4 - "Well to wheel" emissions of alternative fuels



Source: EUCAR/JRC/CONCAWE study, 2005

Low-CO₂ technologies for trucks and buses

Heavy vehicles for the long-distance transport of goods and passengers

In this sector, only the diesel engine is used, because of its performance and the low specific fuel consumptions it can attain. Unlike passenger-car engines, truck engines are used most often under high load conditions, in other words conditions that are optimal in terms of combustion efficiency. Given the limited scope for reducing the weights of these vehicles (they exist precisely to transport heavy goods) and for improving their aerodynamic performance, there is less room to improve their fuel economy, especially since the drivers are professionals, already trained in economical driving.

In a stringent regulatory context, and in view of the Diesel engine for the light vehicles (LV) and the commercial vehicles (CV), current and planned developments for the engine part are globally similar to what is being done for passenger cars, and more particularly:

- higher specific power,
- advanced turbocharging systems,
- variable timing,
- low-NO_x combustion modes,
- powerful cooling of the air loop,
- high-performance injection systems (pressure, fuel mass flow, etc.),
- reduction of internal friction.

Recourse to these technologies helps to improve combustion, reduce the weight of the powertrain, and globally improve the emissions/noise/energy efficiency compromise. Even though, for the moment, no standard is planned for the limitation of CO₂ emissions, players in this sector naturally wish to reduce their impact.

Probable evolution of technologies

Higher specific power: for intermediate displacements (11-12 liters), the objective is power outputs of the order of 350 kW. The ability of recent engines to withstand very high cylinder pressures (240 bar) serves to limit the loss of power that results from the higher level of exhaust gas recirculation (EGR) necessary to ensure compliance with the future EURO VI standards. This is because the higher intake pressures necessary to ensure a consumption of air that can maintain suitable richness conditions whatever the level of EGR have the immediate consequence of increasing the cylinder pressure.

Advanced turbocharging systems: in recent years, the variable-geometry turbine technology has been used extensively to increase turbocharging pressures at low load and low engine speed and allow better management of the level of exhaust gas recirculation if necessary. As already indicated, the drastic reduction of NO_x and particulates emissions imposed by the EURO VI standard is going to lead to increasing the level of EGR: engineers are therefore turning to technologies of the two-stage turbocharger type, which allow many possible architectures between the air circuit and the EGR circuit and can substantially reduce the exhaust back pressure (which impacts engine efficiency).

As in the case of passenger-car applications, the potential of variable timing is greatest for the reduction of HC and CO emissions, and for increasing the level of IGR (internal gas recirculation), which is favorable in some conditions to low-NO_x combustion. Recourse to Atkinson or Miller type cycles (advance or retard of intake valve closing) that can under certain conditions also improve efficiencies is planned. But the power consumed to operate these systems remains for the moment an area where progress is necessary.

Common-Rail (CR) injection systems play a preponderant role in efficient, low-pollution combustion systems. They are an alternative to the massively used injector-pump system. Thanks to the various CR injection strategies, the progress of combustion is better controlled, and combustion noise is also better controlled. Large performance improvements are achieved with the higher injection pressures, which in particular favor better atomization of the spray, the shape of which can be

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perfectly matched to the geometry of the combustion chamber. In this field, equipment suppliers are being innovative and proposing systems that provide all the desired adjustment possibilities available with CR with no need to alter head architectures designed for injector-pump systems.

Work in progress on low-NO_x combustion modes and low-temperature combustion (LTC) reveal the full potential of this approach, which can practically eliminate raw NO_x and particulates emissions at low loads. These approaches are still competitive with more conventional solutions based on adjustment of the engine that is near-optimal in terms of efficiency, associated with a DeNO_x after-treatment system such as SCR (Selective Catalytic Reduction) using urea as reducing agent.

Endurance, safety

The systems developed for truck applications are constrained by very high durability requirements in terms of the number of kilometers traveled (the regulation requires a durability of 500,000 km or 7 years). Note that massive EGR and complex air loops can increase the risk of failures, making it necessary to do substantial development work before a product reaches the market. The possibility of higher permissible vehicle weights requires adaptation of the braking system. While putting heavier vehicles (for example 60 metric tons) on the road requires in particular a correct estimate of the impact on road infrastructure, it is justified by the global energy balance: this is because, on a large scale, the extra consumption induced by carrying more weight is offset by the small number of vehicles in circulation for a given tonnage transported. On the scale of the individual carrier, the cost per kilometer per kilogram transported also seems more favorable.

Other vehicles

The engines used for vehicle applications not requiring high power (urban delivery vehicles, for example) have displacements of the order of 4 to 6 liters. The expected developments are similar to those for the larger engines, but with specific features because of more frequent stopping and starting of the engine: the management of transients and of the after-treatment system is in this case closer to that of passenger-car engines.

The engines of city buses and garbage trucks have intermediate displacements, 8 or 9 liters, and deliver from 250 kW to 300 kW of power. The loading mode—alternation between idling and full power conditions—requires special optimization of the air loop.

Forthcoming developments for trucks

The prospects of extensive electrification of both engines and vehicles are the same for trucks. While the pure ICE mode will continue to be used for the road haulage of goods (with electrification of some devices and the fitting of systems allowing the recovery of braking energy), the levels of hybridization and of electrification reached in the long term will be greatest in applications that are urban and require low power. Along these lines, all-electric vehicles can be expected to be proposed for urban delivery missions.

As for the application of NGV to trucks, it is already used in garbage trucks and urban buses.

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