Title
Road Vehicle Noise versus fuel consumption and pollutants emissions

Authors
P.J.G. van Beek (pieter.vanbeek@tno.nl)
M.G. Dittrich (michael.dittrich@tno.nl)

Search terms
Engine noise, exhaust emission, CO2 emission

Introduction

In the context of proposed changes to EU regulations for both vehicle noise and exhaust emissions, clear information on current technology trends is required to be able to identify correlation between these parameters. In this memo a comparison is made between noise emission, fuel consumption and CO_2 emissions of road vehicles. The main focus here is on passenger cars and small delivery vans, but the basic principles also apply to trucks, lorries, buses and motorcycles.
In real traffic, vehicle operating conditions vary widely from low to high vehicle speed and/or acceleration accompanied by full (WOT = Wide Open Throttle), partial or idle engine load. All these operating conditions have their own characteristic noise emission, fuel efficiency and exhaust emissions including CO_2.

Noise

The main exterior noise sources of road vehicles are powertrain noise, tyre-road noise and aerodynamic noise. Powertrain noise is produced by the engine (and turbocharger, if present), intake and exhaust, cooling system and the transmission (gearbox and drive axles). For the relation between noise and fuel efficiency, the engine, the intake and the exhaust are the most important components for which a possible conflict between these two parameters may occur. In contrast, the transmission can be optimized to minimize noise emission, without affecting the fuel consumption. However, all these components are interconnected and therefore interact to a certain degree. The challenge for the NVH engineer is to minimize this influence and to configure the whole powertrain, such that vibrations of individual components do not lead to noise radiation by others.

Fuel efficiency

Besides engine design, fuel efficiency by is also affected by the engine settings, control and driver usage. Reduced fuel consumption leads to lower emissions, and lower engine speeds and accelerations can lead to significant noise reduction.
Any reduction of engine internal friction, play or inertia to reduce noise can potentially also reduce energy dissipation and thereby improve fuel efficiency and reduce exhaust emissions.

There are some conflicts between fuel efficiency and pollutants emissions, depending on the engine technology and pollutants concerned. Measures for reducing engine out NOx tend to cause a higher fuel consumption and vice versa. In order to reduce unburned hydrocarbons and CO, higher temperatures are needed, with benefit of fuel economy but drawbacks on NOx production. Engines are therefore calibrated so as to have the lowest fuel consumption whilst complying with legislation limits. This last aspect is limited by the performance of the aftertreatment system.

Engine noise

In terms of sound radiation, noise from internal combustion engines is radiated by the intake and exhaust, and by the engine block and its components. Most of this noise is ultimately generated by the combustion process in the cylinders, but other mechanical forces caused by friction, impacts and inertia/unbalance also contribute. Cooling fans can also contribute significantly. At lower frequencies the noise from the intake and exhaust tends to dominate, with the medium and high frequencies filtered off by the exhaust and intake silencers. At medium and higher frequencies, the mechanical noise from the engine block and its components tends to dominate together with fan noise. Mechanical noise can originate from combustion pressure, piston rattle, valves, camshaft and timing drives.

Combustion pressures

In order to consider the combustion process in more detail, a distinction between different categories of engines should be made, i.e. diesel (Compression Ignition, or CI) engines on the one hand, and Spark Ignition (SI) engines on the other. Both categories can be further subdivided into DI – Directly Injected, and IDI – InDirectly Injected engines. Whereas nowadays all diesel engines sold in passenger cars are DI engines due to their higher efficiency, for SI engines a majority of the passenger car engines sold is still IDI. This is mainly due to the fact that DI SI engines need a high pressure fuel system and more advanced engine management system, making them more expensive.

However, there are countless variations possible within each engine category, since most engine manufacturers apply their own (sometimes unique) techniques for engine development and management in order to obtain a certain desired performance and emission. Inevitably this results in many unique engine characteristics for each type or size of engine under each type of load condition, so in principle the physical principles and noise inducing mechanisms can only be treated in general terms. In actual practice, however, such unique characteristics will only give a certain deviation on a typical average noise emission pattern of a main category of engines. An illustration of this is shown in figure 1, where the noise emission pattern of two different petrol engines is shown, relative to the overall range for this category of engine.

In these terms, the relation to engine efficiency is mainly that DI diesel engines are more fuel efficient than the current generation of SI engines. This difference in fuel consumption is primarily caused by the higher compression ratio of DI, which brings an overall higher thermal efficiency of these engines than SI engines; furthermore, under conditions of partial load, an SI engine is controlled by limiting the total amount of intake mixture by means of a throttling valve causing throttling losses, whereas a CI engine operates unthrottled even under partial load, since the power is controlled by limiting the amount of injected fuel only. This in turn is caused by the fact that a SI engine needs to operate at stochiometric conditions, whereas a CI engine can handle very large air/fuel ratios, and hence has no need to limit its air intake. Part of the development effort of future SI engines is directed at attempts to allow them to operate under unthrottled (or only mildly throttled) conditions as well.

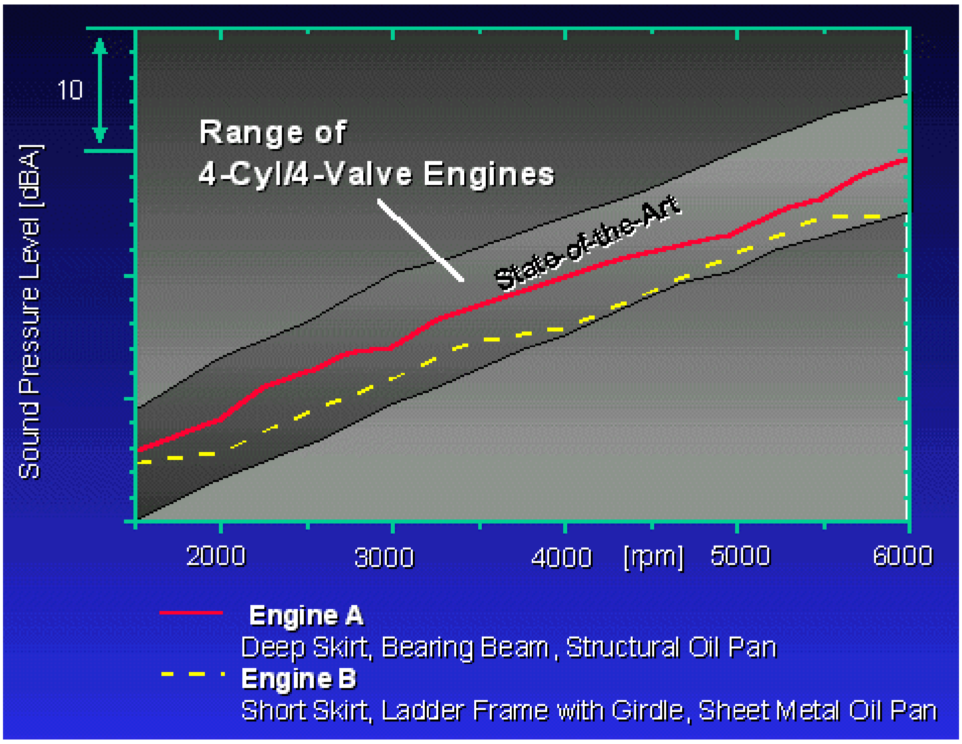

Figure 1: Noise emission for different powertrain designs as function of engine speed (from FEV).

Combustion pressure and pressure gradient
An example of the different noise emission characteristics of different engine technologies is given in figure 2. Diesel engines tend to produce more combustion noise than an SI engine. This is mainly due to the steep pressure rise of the diesel engine, which is higher than in a SI engine. Modern injection technologies, such as the common rail, allows a better control of the injection and combustion process. This means that, with ‘pilot injection’, the cylinder pressure gradient at the start of combustion can be reduced. An example is shown in figure 3, where such a pilot injection is applied: the pilot injection increases the local temperature and the charge turbulence, realizing more favorable conditions for the main fuel injection and reducing the ignition delay. More generally the pressure gradient is affected by the timing and rate shaping of the fuel injection, by the design of the combustion chamber and by the characteristics of the fuel itself. These parameters are used both for the reduction of engine emissions as well as for the noise. Turbulence in the combustion chamber *may* have a negative effect on noise emissions, but is generally regarded as ‘neutral’, if applied in a sensible way.

Control of the combustion process via optimization of the pressure curve improves the combustion efficiency and has a beneficial effect on fuel consumption. Additionally, controlled turbulence in the combustion chamber is needed to improve the combustion process, especially at high rotational speed. The exact type of turbulence differs for different engine designs, but generally speaking it is not regarded as a significant source of noise. However, the diesel engine injection system can be a very significant source of noise. In order to achieve higher fuel efficiency and exhaust emission reduction, injection pressure in such engines has increased significantly over the last decades, which may lead to an increase of the mechanical noise generated by the injection pumps and other elements of the injection system.

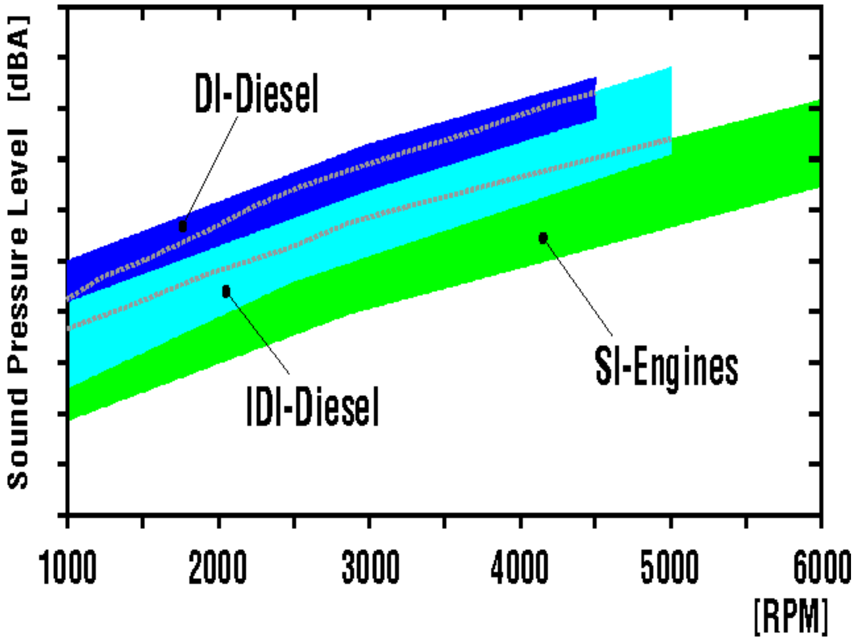

Figure 2. Comparison of the noise emission of different categories of engines as a function of RPM (from FEV).

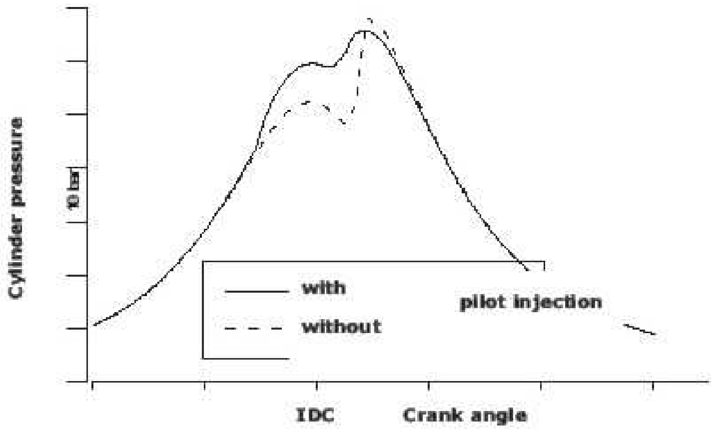

Figure 3. Comparison of the cylinder pressure of a DI Diesel engine with and without pilot injection (from Meier –Daimler Chrysler).

Intake and exhaust noise

Intake and exhaust noise is mainly caused by pressure fluctuations and pressure waves induced by periodical variations of gas flow and equivalent length of the intake and exhaust system. The pressure waves are influenced by:

- The cylinder pressure at the opening of the inlet and exhaust valves (determining the *strength* or *amplitude* of the wave).
- The piping lengths between the valves and any reflecting section along the passage or its end (determining the *frequency* of the waves).

In principle, all these effects can be estimated by computation, although such calculations can be rather complex and the results have different effects on the overall noise level. Flow noise specifically generated in the intake and exhaust systems can also contribute to the overall noise level; this will generally occur at medium or high frequencies.

The efficiency of the noise reduction of the intake and exhaust mufflers can in some cases be increased, but this will only be effective if the noise from the engine block and other sources (cooling system, etc.) is reduced simultaneously. For example, the timing of the exhaust valves determines the pressure drop occurring through the valve itself and heavily affects engine efficiency too. Furthermore, pressure losses along the aftertreatment components need also to be considered as well. Although there might not be a clear conflict, it may be difficult to simultaneously optimize the exhausts valve timing towards both engine efficiency and noise reduction.

Improving the intake or exhaust silencer performance usually will involve the application of geometrical changes (such as larger chamber volumes or additional chambers), increasing muffler absorption, using additional resonators, or using a longer intake manifold equal for all cylinders. But care must be taken not to reduce engine performance due to higher backpressure caused by higher flow resistance. In order to reduce radiation of the exhaust system due to transmitted engine vibrations, a flexible coupling to the exhaust manifold or shape adjustment/improvement can be applied for example. The exhaust manifold itself and the catalytic converter have only a small influence on noise emission.

The influence of engine speed, load and ECU

The instantaneous engine power is proportional to engine torque times engine speed. Together they determine the engine map, which is specific for each engine. These are discussed below.

Engine speed

As shown in figure 1, for a given engine and all other parameters kept constant, the engine speed is a key influence parameter for the noise level. The rate of increase tends to be proportional to about 30 lg (rpm/rpm_0). Any measures that would significantly reduce the engine speed, would therefore also tend to reduce noise. Note that, for a given engine capacity, the same power is delivered at lower speed by a CI engine than by a SI engine (in contrast, DI engines deliver power at higher torque than gasoline).The *use* of lower speeds might reduce both noise and fuel consumption. The *design* of higher speed engines may, in some cases, reduce fuel consumption, but the influence on noise might be negative.

Engine load

The other major parameter for engine noise emission is the momentary load or torque of the engine. As stated above, it is well known that at any given engine speed the torque is proportional to the required power. In theory torque is linked to fuel consumption, since to obtain more torque at a given speed, more fuel is consumed; this tends to affect the maximum pressure, however, rather than the pressure gradient.

Concerning emissions, figure 4 shows that for diesel engines in an ‘undisturbed environment’, an increase in load (front to rear) or speed (left to right) generally leads to an increase in NO_x-emission, but that for a given power required an increase in speed at a simultaneous decrease in load will generally lead to a decrease in NO_x-emission. Such patterns have become completely distorted, however, once emission maps are shaped towards emission legislation (figure 5).

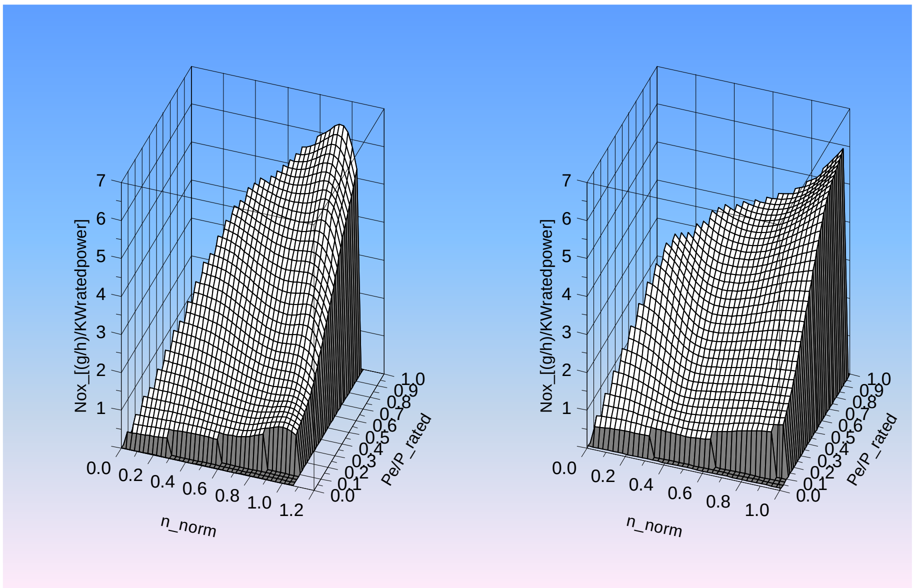

Figure 4: the ‘natural’ shape of a NO_x-emission engine map for two different diesel truck engines

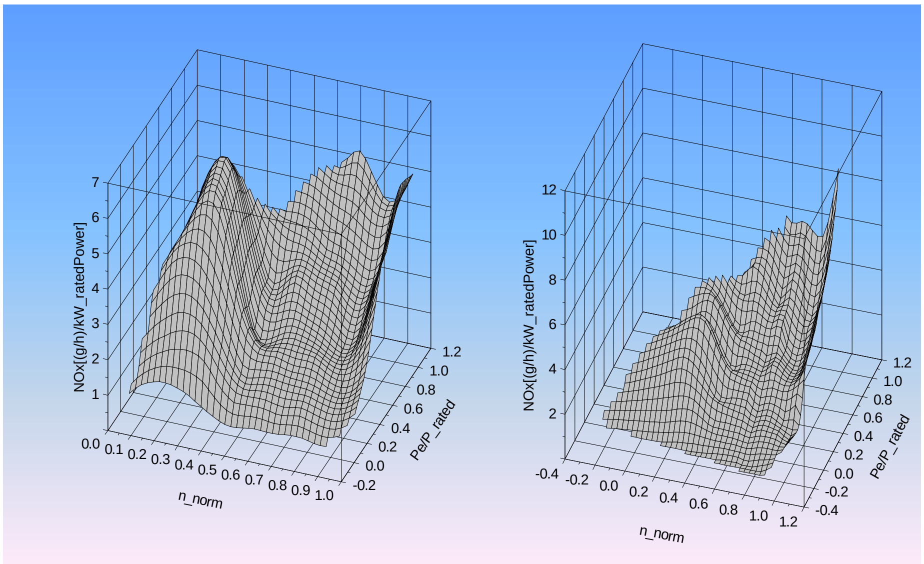

Figure 5: the ‘adapted shape of a NO_x-emission engine map for two different diesel truck engines complying with emission legislation

Engine Control Unit (ECU)
Modern Engine Control Units (ECU) are capable of regulating many control parameters such as fuel supply and mixture, exhaust emissions, etc., etc., and can therefore potentially also be used to optimize among things both noise and fuel efficiency and emissions. Note that, depending on the type of vehicle and engine, in many cases this already occurs.

The influence of engine temperature
For CI engines, there can often be additional noise, due to ignition delay, under cold start conditions. This causes a very high pressure gradient and as a result much noise. Another, perhaps minor, source mechanism, is piston slap. This effect is due to the play present between the piston and the cylinder wall at lower temperatures. Once the engine has reached a normal operating temperature, little variation occurs in noise due to temperature change. The use of a cold engine is also bad for fuel consumption, but is so far unavoidable at the start of a trip. The only remedy might be to advocate less frequent cold starts for short trips, to be replaced by a lower number of combined trips. In countries with very cold climates in winter (such as Scandinavia) engines are often artificially heated during overnight parking. This results in much better fuel consumption and exhaust emissions during the first start in the morning. Noise emission will also be significantly improved during those conditions.

Mechanical noise
Mechanical noise can be reduced by design, without any penalty on fuel consumption. This is the case for internal gears and drives for components such as camshafts and auxiliary equipment.

An important phenomenon of piston engines is a low frequency ‘booming’ noise. This is related to inherent inertia (mass forces) in the crank-connecting rod mechanism, which is not always sufficiently balanced in certain engine configurations. In practice the influence of the inertia of the moving parts such as the pistons is determined by the 1^{st} and 2^{nd} order of the engine speed. The actual inertia generated *forces* are proportional to the squares of those speeds. In theory also higher order inertia forces would be present, but they are not regarded as of importance in the real world. In the case of e.g. a 4 cylinder in-line engine (the most common engine configuration) the 1^{st} order inertia forces are balanced, but the 2^{nd} order inertia forces are not. Minimising the inertia of the moving parts in the engine can reduce these unbalanced forces. Another option is to select a different engine configuration: a boxer engine, a 6 cylinder in-line engine, or a V8 engine are fully balanced regarding both 1^{st} and 2^{nd} order forces.
However, engine configurations are primarily selected for other reasons, such as overall engine shape or volume in relation to the overall vehicle configuration. A more fundamental option is therefore to apply one or two balancing shafts next to the crankshaft. This solution, which adds production costs, is sometimes selected for V4 2-cylinder motorcycle engines. Solutions adopted by manufacturers in order to cope with engine vibrations and noise do ultimately depend on technical choices, costs and marketing strategy.

So there are no obvious reasons why such measures reducing engine noise should have any negative effects on exhaust emissions and fuel efficiency.

Noise shielding

Engine block shielding and enclosure
Radiation from the engine block itself is often strongest from plate-like components such as the oil sump, valve covers and other covers. For DI engines the high pressure fuel system can also contribute significantly to the overall noise radiation. If the engine is not properly mechanically isolated, sound may also be transmitted through the engine mounts and radiated by other parts of

the vehicle such as the support beams, sub-frame or chassis. There is no reason, however, why this would have any influence on fuel efficiency either way.

Shielding or partial shielding of the engine block is applied in practice and can provide additional noise reduction of several dB. Such measures have to be carefully designed to ensure that engine cooling is still sufficient. In some cases alternative or additional cooling may allow implementation of more effective shielding. The influence of such measures on fuel consumption might lie in the power required to drive any necessary extra cooling fans, and possibly in the additional weight of the shields, but this is not considered to be a significant effect, especially as weight may be saved elsewhere on sound absorbing and damping materials. Fuel consumption models of TNO-Automotive suggest that an additional 10 kg results in an additional emission of 0.12 g CO_2 per km for a SI engine and an additional 0.08 g CO_2 per km for a CI engine. This is less than 0.1 % of the value for an average car. So for limited vehicle weight variations, a rule of thumb relation is that additional 10 kg results in an additional CO2 emission of circa 0.10 g/km. Furthermore much research is already on-going for many years on reducing the weight the complete vehicle and also of shielding and enclosures, making them even less pollutant, while maintaining sufficient noise reduction.

Engine downsizing
The latest trend in the automotive industry is so-called ‘downsizing’. In general a smaller engine has lower absolute friction losses, which is beneficial for the noise radiation, and the working point moves to sectors of better thermal efficiency. However, in order to keep the same engine output for a smaller engine capacity, the mean pressure needs to be improved. This is achieved by turbocharging. A turbocharger tends to reduce exhaust noise. Since it also results in higher torque at a lower engine speed, noise radiation will also decrease. Finally, smaller engine tend to radiate less noise, compared to larger engines.

Start-stop system
The main goal of a start-stop system is to reduce fuel consumption and exhaust emissions at idle engine speed: when e.g. the gear is put into neutral, the engine stops. After that, when a gear is selected, the engine starts automatically. Figure 6 shows that in urban area’s a considerable amount of time the engine runs at idle speed. As a results it will also reduce fuel consumption and exhaust emissions considerably and simultaneously has a (minor) positive effect on noise emission.
Currently more advanced start-stop systems, such as micro and mild hybrid systems and e.g. more specific systems such as the i-Stop / i-ELOOP from Mazda, are available and under further developed.

Region	Cycle	Time idling (%)	Max. speed (kph)	Average speed (kph)	Maximum accl. (m/s^2)
Asia-Pacific	10–15 mode	32.4	70	22.7	0.79
Europe	NEDC	27.3	120	32.2	1.04
NA-city	EPA-city	19.2	91.3	34	1.60
NA-highway	EPA-hwy	0.7	96.2	77.6	1.43
NA-US06	EPA	7.5	129	77.2	3.24
Industry	Real world	20.6	128.6	51	2.80

Figure 6: Idling time of passenger cars in different area’s of the world.

Hybrid powertrains
In general hybrid powertrains are very different from conventional powertrains. Sometimes hybrid SI engines even have a different SI principle; whereas most 'normal' SI engines make use of the Otto cycle, hybrid cars can be equipped with other types of CI engines, such as e.g. the Atkinson cycle engines (Toyota Prius).
In general the combustion engine in a hybrid powertrain is optimized to run at limited engine speeds and loads, i.e. within a limited operating envelope (working points), and can therefore efficiently be optimized regarding fuel efficiency and other aspects, such as noise emission. Furthermore the combustion engine is used for a limited time, making them more fuel and noise efficient.

Tyre noise

The tyre of a road vehicle and its interaction with the road is a major contributor to the total noise emission. Depending on the type of vehicle, the tyres already dominate the noise emission at constant speed from about 40 km/h upwards. A widespread myth is that low noise of passenger car tyres a priori conflicts with rolling resistance and wet grip, i.e. safety. Of course, a tyre has to be optimized for several parameters, but this does not mean a priori that safety and low noise cannot be achieved simultaneously. In several international studies only a very weak to negligible relation between them could be found. Although some tyre manufacturers dispute this conclusion, no evidence of any counterexample could be found in literature.

Another question is to what extent a low rolling resistance in the interest of overall fuel consumption might influence safety and/or noise. Such tyres have been developed and proposed. They may improve the overall fuel consumption by a relatively small but still demonstrable percentage. For passenger cars and light trucks a 10% rolling resistance reduction will lead to approximately 1-2 % fuel consumption reduction.

Aerodynamic noise

For passenger cars and (small) delivery vans, aerodynamic or wind turbulence along the vehicle does not contribute much to the total environmental noise emission, although it may do so for the interior noise level. Especially the aerodynamics in the running direction of the vehicle is well controlled for this purpose. Aerodynamic noise may only be relevant at very high (in most EU countries illegal) speeds or in special cases. Furthermore, low interior aerodynamic noise is a selling point and manufacturers endeavour to reduce it anyway. And fuel consumption and noise emission due to aerodynamic resistance go hand in hand: a better aerodynamic design generally benefits both noise as well as fuel efficiency.

Conclusions

In conclusion, there are some clear synergies between noise reduction, fuel efficiency and exhaust emissions, although these can be conditional.

- Lower engine speed reduces noise and also emissions if operating at an efficient working point;
- Reduction of internal mechanical dissipation caused by friction, play and inertia, can reduce noise and fuel consumption and thereby emissions;
- Encapsulation reduces engine noise and can improve engine efficiency and reduce emissions if designed to work at higher temperature and cooling is improved;

- Downsized, encapsulated engines operating at higher temperatures will result in noise reduction, higher efficiency and lower emissions;
- Advanced control systems, such as start-stop and micro/mild hybrid systems are very efficient for fuel consumption and exhaust emission, especially in urban areas, and can also benefit noise emission;
- Hybrid powertrains will clearly reduce both noise and engine emissions due to the reduced operating time and envelope of the combustion engine;
- Active, exterior noise reduction techniques are hardly applied yet and not expected to applied commercially on a wide scale in the foreseeable future.

To answer the question ‘does further noise reduction on road vehicles conflict with reducing CO_2 emissions’, the answer is clearly no, based both on technical considerations and on-going development of engine and noise reduction technology.