

NVH Challenges and Solutions for Vehicles with Low CO₂ Emission

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ABSTRACT

Driven by worldwide climate change governments are introducing more stringent emission regulations with particular focus on fuel saving for CO₂ emission reduction. Downsizing and weight reduction are two of the main drivers to achieve these demanding regulations. Both aspects however might have a strong negative effect on the overall vehicle NVH behavior.

Weight reduction directly influences NVH due to reduction of absorption and damping material and due to light-weight design affecting the dynamic responses of powertrain and vehicle structures. Engine downsizing however has multiple negative effects on NVH. Beside higher vibrations and speed irregularities due to lower cylinder numbers and displacements also reduction of sound quality is a critical topic that will be handled within this publication.

The first part of this publication will focus on excitation of engines with different number of cylinders, an alternative mounting solution for 3 cylinder engines and an overview on the changes of sound quality for downsized engines.

In the second part two solutions for vehicles with downsized engines will be presented. The first vehicle is equipped with a 4 cylinder engine and electrical cylinder. By applying appropriate NVH measures the same NVH behavior as for the original 4 cylinder without cylinder deactivation can be achieved. Second example is a vehicle powered by a turbo charged two cylinder engine. Using active noise generation the unconventional sound characteristic of that vehicle can be changed to that of a standard 4 cylinder engine in order to increase sound quality and reduce real life fuel consumption by positive effects on driving behavior.

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INTRODUCTION

CO₂ reduction and achieving future emission compliance are forcing OEM's to downsize their powertrains via displacement reduction and reduction of numbers of cylinders. These drivers however have a very high influence on NVH behavior of powertrain and vehicles. Therefore improving NVH by keeping low fuel consumption and improved emissions is one of the major tasks of NVH engineers throughout the world.

In order to give some ideas how this can be handled the first part of this paper focuses on the challenges for NVH engineering with these future trends in more detail. The second part of this paper is dedicated to two solutions developed by AVL that focus especially on the sound character and sound quality of two powertrains.

All presented results are taken from an on-going internal AVL research project dealing with sound engineering for

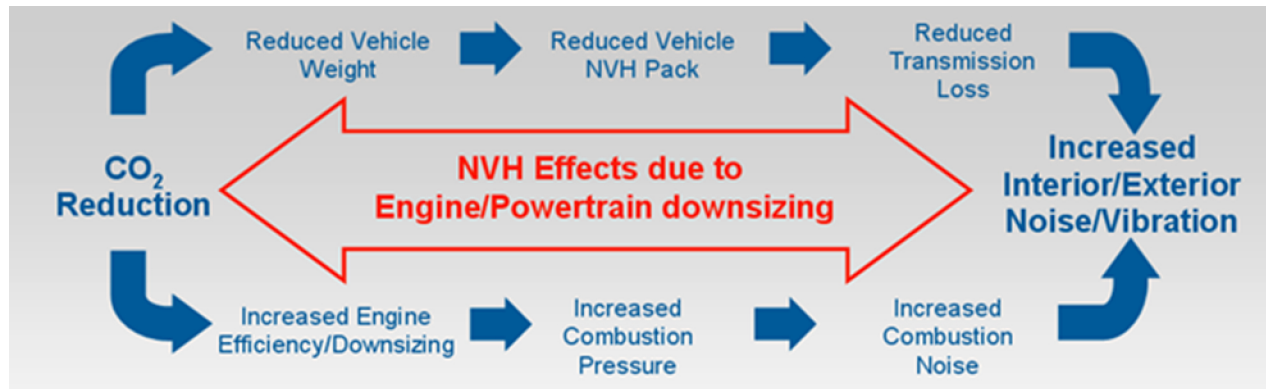
downsized powertrains and powertrains with cylinder deactivation.

CO₂ - REDUCTION AND INFLUENCES ON POWERTRAIN AND VEHICLE NVH

CO₂ reduction is currently one of the most important requirements for internal combustion engines. Other topics for vehicle development, like NVH, have to be adapted to this trend. From an NVH point of view two main roadmaps for CO₂ reduction are important. An overview of those two NVH influencing measures is given in [Figure 1](#).

The first measure to reduce CO₂ is the on-going effort to reduce vehicle weight. On the one hand lightweight construction is used to further decrease weight of the body in white. More critical from an acoustical perspective however is a weight reduction of NVH packages. In this case mass reduction is usually directly proportional to a decrease in



Figure 1. Overview of how CO₂ reduction effects NVH

cylinder configuration	inline 2			inline 3	inline 4
crank layout					
ignition Interval	180° - 540°	270° - 450°	360° - 360°	240° - 240° - 240°	180° - 180° - 180° - 180°
main firing order(s)	0.5, 2	0.5, 1.5	1	1.5	2
firing order	uneven	uneven	even	even	even
1st order mass forces	0	$\sqrt{2} \cdot P_{\parallel}$	$2 \cdot P_{\parallel}$	no	no
2nd order mass forces	$2 \cdot P_{\parallel}$	no	$2 \cdot P_{\parallel}$	no	$4 \cdot P_{\parallel}$
1st order mass moments	$a \cdot P_{\parallel}$	$a \cdot P_{\parallel}$	no	$\sqrt{3} \cdot a \cdot P_{\parallel}$	no
2nd order mass moments	no	$a \cdot P_{\parallel}$	no	$\sqrt{3} \cdot a \cdot P_{\parallel}$	no
torsional speed fluctuaction	high	high	high	medium	medium
$F_r = m_r \cdot r \cdot \omega^2$ $P_{\parallel} = m_o \cdot r \cdot \omega^2$ $F_{\parallel} = P_{\parallel} \cdot \cos 2\varphi$ $a \dots$ cylinder distance $r \dots 0.5 \cdot \text{stroke}$ $m_r \dots$ rotating mass $m_o \dots$ oscillating mass $\lambda \dots$ conrod ratio					

Figure 2. Property overview of inline 2 to 4 cylinder engines

transmission loss and therefore an increased interior sound pressure level.

Increased engine efficiency is the second measure that influences NVH and is a direct result of the downsizing trend. In order to achieve e.g. the same performance using an inline 3 cylinder instead of an inline 4 cylinder engine, the peak torque excitation on the crankshaft has to increase by 33%, what of course leads to an increased combustion pressure and combustion noise.

Assuming that the structural attenuation of the engine stays the same this increase in combustion noise directly effects the engine noise contribution on the vehicle interior and exterior. Additionally vibration and speed irregularity increases considerably for downsized engines. Both NVH relevant topics are discussed in more detail in the following two chapters.

VIBRATION

Due to cylinder reduction during the downsizing process a shift from higher to lower order excitation takes place. A short overview of cylinder reduced engines and corresponding crank shaft layouts is given in Figure 2.

Independent from the number of cylinders usually an even firing order is used, which results in a well-defined excitation containing a single order and its harmonics. If firing order is uneven e.g. in cases of 2 cylinder engines beside 1/2 order also other orders are dominating.

As can be seen in Figure 2, 2 to 3 cylinder engines show a significant higher excitation in respect to mass forces and mass moments than common 4 cylinder inline engines. Additionally the higher combustion pressure that is necessary to reach the same torque as engines with more cylinders is one reason for a significant increase in torsional vibration. In order to control higher vibrations due to higher mass forces and moments, mounting concepts have to be improved.

Due to cylinder reduction main excitation order is reduced from 2nd order for 4 cylinder engines down to 1.5th order for 3 cylinder engines, 1st order for 2 cylinder engines with even firing order or even to 1/2 order for 2 cylinder engines with uneven firing order.

The effect of using a conventional mounting layout for transversal powertrain installation for engines with lower cylinder numbers is shown in Figure 3. The well-known mounting system consists of one engine and one gearbox

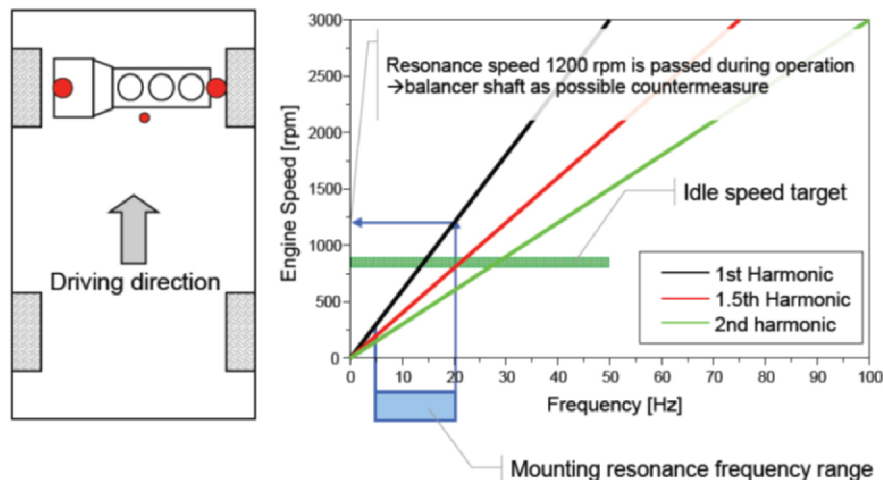


Figure 3. Typical mount concept for transversal installation

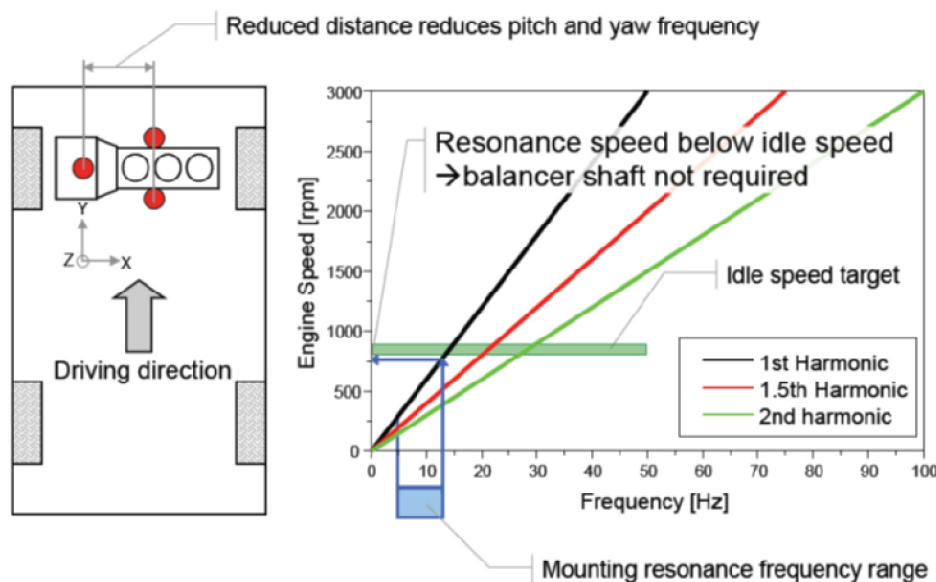


Figure 4. Improved mounting concept for transversal installation

mount as well as one torque support in the rear. As can be seen in the plot of Figure 3 low idle speed for 2 and 3 cylinder engines is not acceptable. Main problem is the mounting resonance frequency range of up to 20 Hz.

As the main firing order should not pass resonance frequencies during operational condition, the 2nd order excitation of a 4 cylinder engine allows low idle speeds above 600 rpm. Using the same setup for a 2 cylinder engine with even firing order leads to low idle speeds above 1200 rpm.

One approach to decrease low idle speed for 2 and 3 cylinder engines is a new engine mounting layout that is shown in Figure 4. Here the gearbox mount location moves slightly towards the COG of the power unit. Engine mount and torque arm are omitted and two mounts are placed in the front and the rear of the power unit. Due to the decreased distance between the gearbox mount and both other mounts

in X direction resonance frequencies could be reduced. Finally the frequency range for mounting resonances could be decreased from 20 to 13 Hz, which leads to a low idle speed of 780 rpm for a 2 cylinder engine with even firing order.

SPEED IRREGULARITY

Beside the increase of vibration mentioned above, also speed irregularity is increased for downsized engines. Assuming the same displacement and torque output for a 3 and a 4 cylinder engine, torque excitation on the crankshaft of the 3 cylinder engine increases by approximately 33% in comparison to a 4 cylinder engine. This fact is demonstrated in Figure 5 where the torque on the crankshaft over 720° crankangle is plotted. While the dark blue line of the 4 cylinder engine just needs a maximum peak torque of approx. 950 Nm, the magenta line of the 3 cylinder engine shows