MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Combustion Engine Noise – a Historical Review

Spessert, Bruno M., bruno.spessert@eah-jena.de
Ernst-Abbe-University of Applied Sciences Jena
Faculty Mechanical Engineering, Carl-Zeiss-Promenade 2, D-07745 Jena

Fischer, Martin, martin.fischer1@thyssenkrupp.com
thyssenkrupp Bilstein GmbH
T&I: NVH / Measurement Technology, August-Bilstein-Straße 4, D-58256 Ennepetal

Kühn, Bernhard, bernhard.kuehn@eah-jena.de
Ernst-Abbe-University of Applied Sciences Jena
Faculty Mechanical Engineering, Carl-Zeiss-Promenade 2, D-07745 Jena

ABSTRACT

Noise reduction is a main task in developing combustion engines. Therefore measures like silencers, covers or plastic timing gears were always used since more than a hundred years ago. Measurements of vehicles produced around 1910 emit-ted sound power levels of their industrial engines around 100 dB(A) with an acoustical efficiency[1] of 1 - 2×10^{-6}.

Nevertheless the noise emission increased especially due to higher speed and cylinder pressures and via the introduction of diesel combustion process. In the 1970ies sound power levels of around 115 dB(A) and acoustical efficiencies of up to 10×10^{-6} were measured for industrial engines.

Beginning in the 1980ies the sound emission was mainly reduced by turbocharging and lower speed. In the 1990ies an additional noise reduction was reached by mo-difications of e.g. pistons and timing gears and especially of engine structures like the engine block. In the 2000ies the introduction of common rail injection systems was acoustically advantageous. Thereby the sound power levels and the acoustical efficiency of industrial engines decreased up to 105 dB(A) and 0.3×10^{-6} for modern low noise diesel engines.

Keywords: Engine Noise, Acoustical Efficiency, History of Acoustics
I-INCE Classification of Subject Number: 06

1. INTRODUCTION

Since 100 years ago, engine noise reduction measures like e.g. covers or silencers have been described in technical literature. However, noise mea-surements only became common in the 1960ies. Therefore there was a “knowledge gap” concerning the noise emissions of very old engines.

To close this gap the noise emissions of historical vehicles respective engines were measured. Thereby their sound power levels and acoustical efficiency could be described for engines of around 1910.

Until the 1970ies, rated speeds increased continuously. Additionally the diesel com-bustion was introduced for industrial, lorry and finally car engines. Thereby the noise

[1] The acoustical efficiency is the ratio of sound power to effective power output.

emissions increased more than the power outputs, and thus the acoustical efficiency reached its maximal values.

During the 1970ies and 1980ies turbocharging was introduced. The turbocharging increased the power outputs but decreased rated speeds and combustion noise and thus overall noise emissions and acoustical efficiency. To explore this further, experiments and computation noise reduction methods were developed.

In the 1990ies the noise excitation by pistons, crankshafts, main gearings and injection pumps became more and more interesting and could be lowered remarkably. Additionally the engine structures were optimized acoustically. In the 2000ies the introduction of common rail injection systems decreased the noise level once more.

2. EARLY VIBRATION REDUCTION

Vibrations are always irksome. Additionally they endanger the structures of vehicles and cause deep frequency noise emissions.

In the beginning of the 20th century, vibrations were reduced mainly by an increase of the cylinder number. The influences of the 1st order mass forces and of the firing orders were well known, but the influence of the 2nd order mass forces were still unknown. At first the single cylinder engines were replaced by the V- or the inline-engines with two cylinders. Between 1905 and 1910 the two cylinder engines were replaced by the four cylinder inline engines. Only in rare cases six and eight cylinder inline engines or V-engines with four cylinders were built. [1]

In the 1920ies Frederick William Lancester (1868-1946) developed the well-known vibration balancer, which removes the vibrations by the 2nd order mass forces of four cylinder inline engines, and a torsional vibration damper to reduce the vibration of crankshafts (e.g. [2, 3]).

Until the 1920ies an isolation of the car frame from the vibrating engine was still uncommon; the engine was fixed by bolts. For luxury cars wood was used for the frame instead of the usual steel, because wood dampens the vibrations much more. The use of elastic rubbery elements started just in the 1930ies (e.g. [3, 4]).

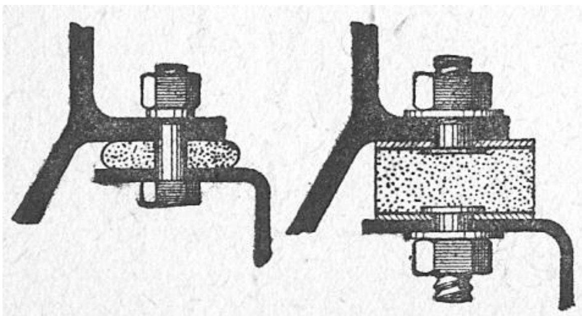

Fig. 1: Ineffective elastic rubbery element (left side) and effective element (right side) for the isolation of the vehicle frame from the engine [3]

3. EARLY ENGINE NOISE REDUCTION MEASURES

Around 1910 the reduction of high frequency noise emissions was reached mainly by the exhaust silencers. These mufflers used reflection and throttling. [1, 5]

The oil consumption of early petrol engines was very high; usually the oil consumption was around 10 % of the fuel consumption. Soot in the muffler was a real problem. *"If the muffler is not designed properly and is too small, or it becomes clogged with soot, then the burned gases cannot be expelled as rapidly as should be. The result is back pressure, or a tendency for the gases to work back against the outcoming exhaust, and also a retention of heat, thus causing overheating of engine and a slight loss of power, due to the back-pressure."* [2]

The "solution" of these problems was the "exhaust cut off": *"The exhaust cut-off is a device which can be placed in the exhaust pipe, between the engine and muffler. It is arranged so that it can be opened by a foot pedal, thus permitting the exhaust gases to pass into the open air instead of the muffler. The cut off is now seldom used ... because of the noise ..."* [2] In Germany the exhaust cut off was interdicted in 1925.

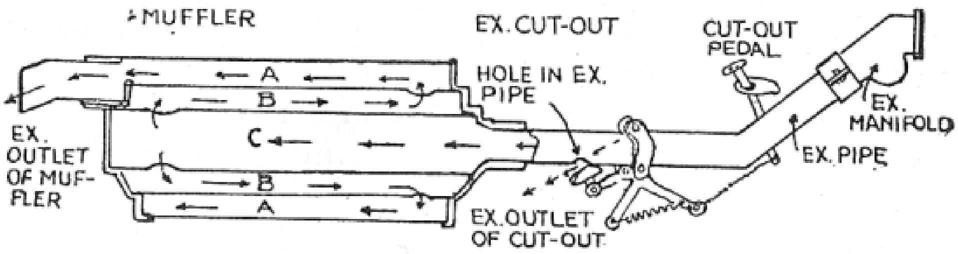

Fig. 2: "Sectional view of a muffler also showing how a "cut-off" is aced on the exhaust pipe" [2]

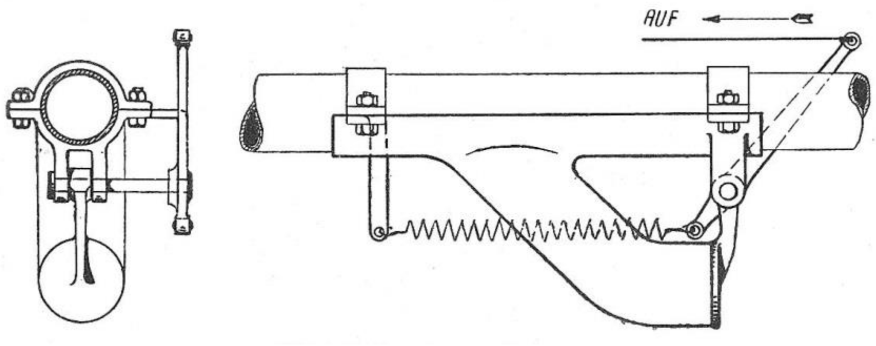

Fig. 3: Exhaust cut-off [6, 7]

Perhaps more than the lack of power or the danger of overheating the "sportive sound" was the main cause to use the exhaust cut off – it was something like a predecessor of the modern "sportive mufflers" with their reckless "sound design". In the opinion of the authors every kind of "sportive mufflers" should be interdicted, too. And the authors are pleased about an initiative regarding this, which was taken by the environment ministry of the German federal state Saarland. [www.saarland.de/242081.htm]

The history of mufflers and intake silencers will not be further considered – the authors will instead concentrate on the noise emissions by the engine surfaces.

In the early times the engine surface noise was remarkably influenced by the valve train. Hereby clearances were important. *"In case of wear of the end of the valve stem or tappet, it is apparent, that as the wear increases, the space or air gap increases, and valves will have less lift, open late and close early, and become more noisy, all of which will affect the power of engine."* [2] A simple noise reduction measure was proposed:

„A noisy valve tappet, resulting from wear, and where no adjustment is provided, can be, in some instances, remedied by placing fibre or steel washers under or over the valve ends." [2]

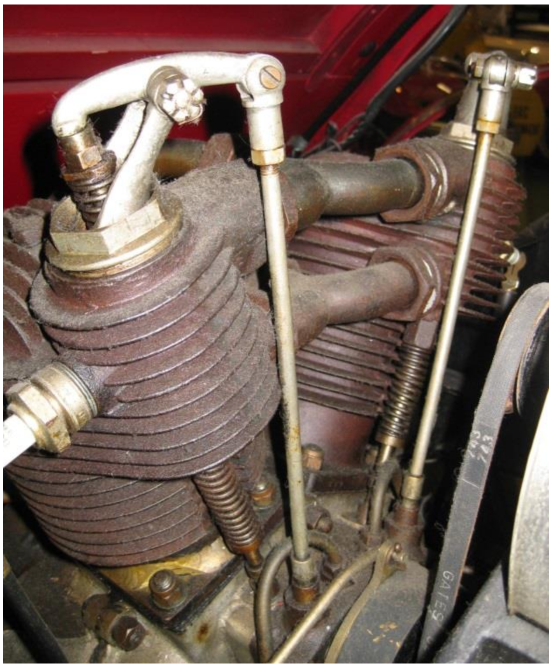

Fig. 4: Totally uncovered valve train of a "piccolo" car engine (production year 1907, producer A. Ruppe & Son, Apolda, Thuringia/Germany) (photo: Spessert)

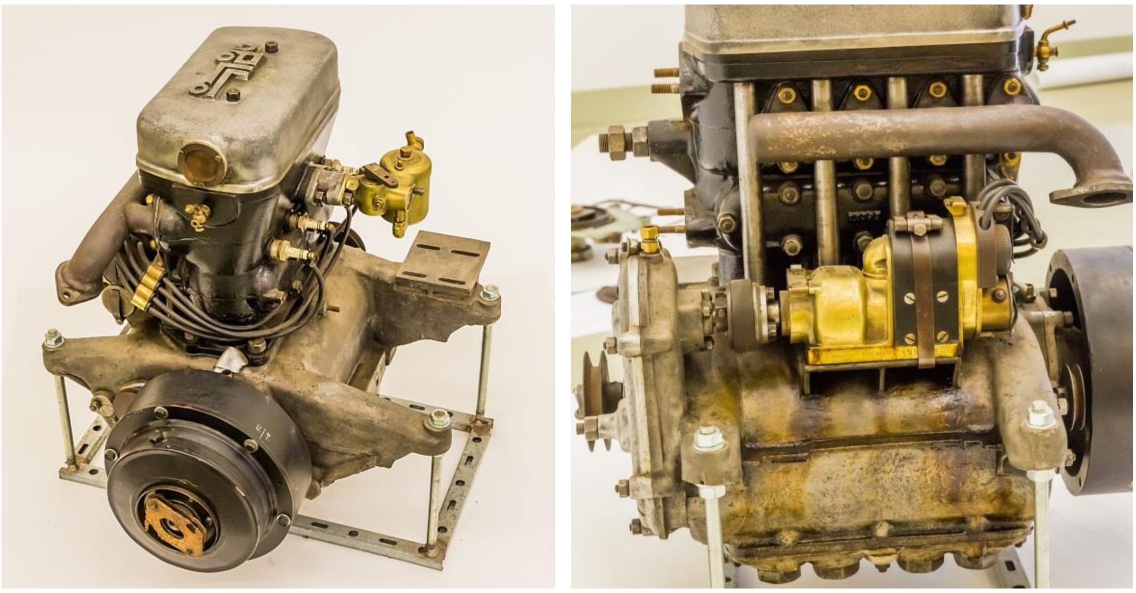

Fig. 5: Totally closed cover of the valve train by a cap and tubes (engine of a Apollo type B, production year around 1923, producer Apollo-Werke A.G., before A. Ruppe & Son, Apolda, Thuringia/Germany) (photos: Beibst)

The connections of power, valve clearances, piston slap, combustion and noise were described: *"Frequently an automobile owner will drive his car in and tell the repairman to "take out the knocks". The repairman immediately proceeds to give the valves less* *clearance, which quiets the valves and at the same time relieves the knocks in the engine at a certain extent. This results from the fact, that the valves are given less clearance than they should have, the valve opens early and closes late, which reduces the compression, thus reducing the combustion and expansion force on the piston. As a consequence the noise is reduced, but power is sacrificed."* [2]

Until around 1910 the total valve trains were uncovered normally. Therefore the driver was able to lubricate the valve train by his own hands before every trip. Later rocker arms were covered by a cap to prevent it from dust, but this cap was often not totally closed. Around 1920 the push rods were covered by tubes and the cap was totally closed. Thereby an automatic lubrication became possible, and additionally noise emission was reduced. Covering of the valve train was well known as a noise reduction measure. [5, 6] *"Enclosed valves are where a cover fits over the valves. This deadens the noise of the lifter when striking the valve stem and keeps out dust."* [2]

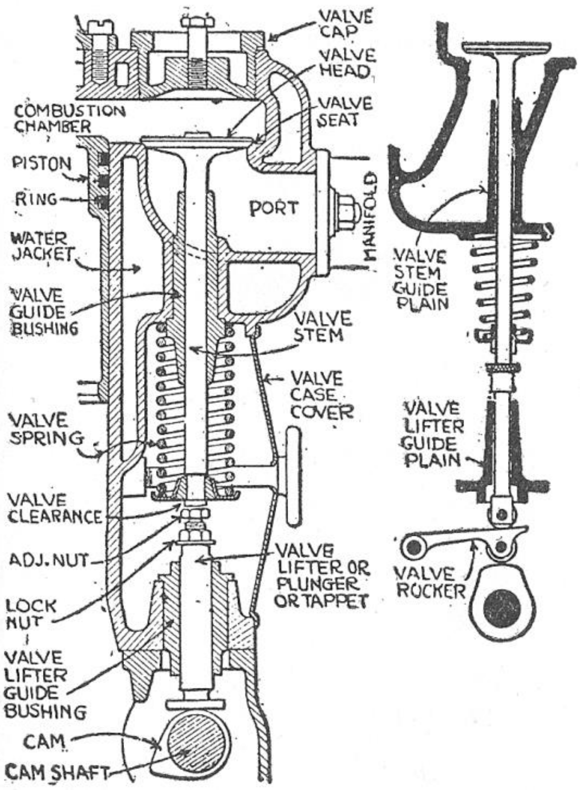

Fig. 6: Valve train with valve case cover [2]

Another important noise source was the timing gear train. To reduce the noise special gearwheels and materials were used. Helical gears were known as relatively less noisy. *"The wide-faced helical gear is the popular type of gear because they make less noise than straight-tooth spur gear. Special materials, such as fabroil, micarta, and other compressed materials, are used by many as material for gears which are silent. Drop-forged gears are also used, so also is steel for the crankshaft gear and cast iron for the cam gear."* [2] A synthetic material called "fiber" was used for gearwheels to lower the noise excitation. [8] The authors really found such a cam gear build from textile fabric soaked with resin between two gear discs from bronze; it was used in a German car engine from around 1910.

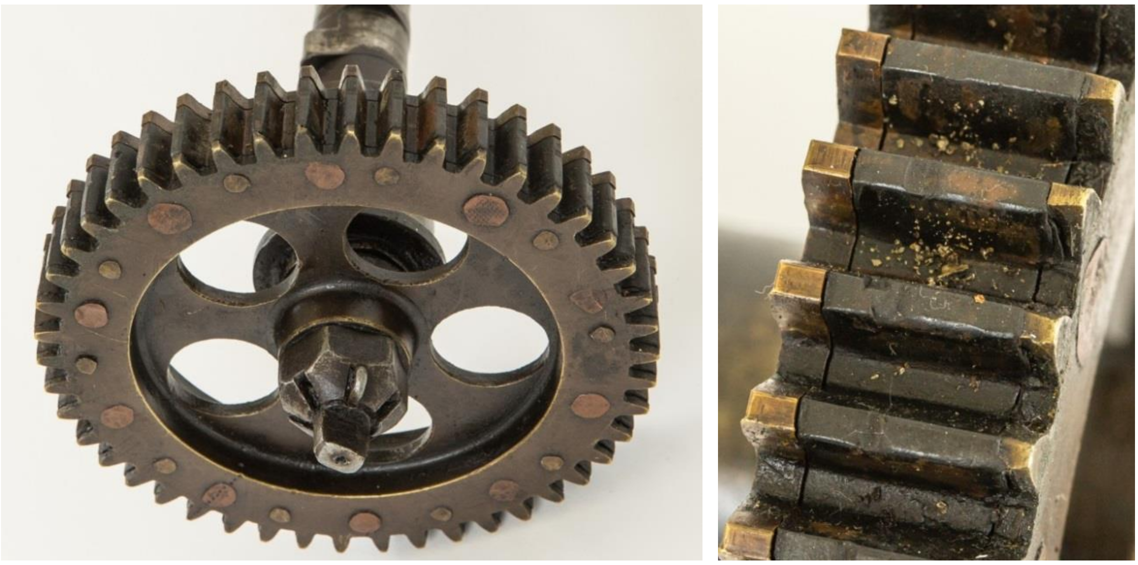

Fig. 7: Cam gear build from textile fabric soaked with resin between two gear discs from bronze (engine of a MAF type D, production year around 1910, producer MAF (Markranstädter Automobilfabrik AG), Markranstädt, Saxonia/Germany)

"The silent chain … is … being used to a great extend for driving the cam shaft. The object is to obtain quieter running." [2] Silent chains were also mentioned in German books. [5, 6, 9] Covering the timing gear train was well known as noise reduction measure, too. [5]

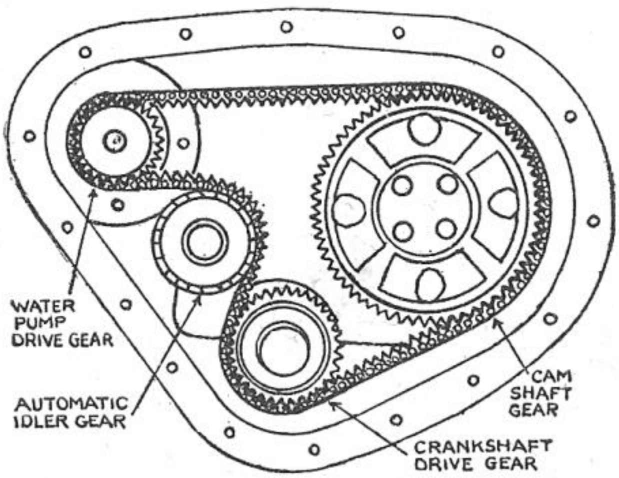

Fig. 8: "A front-end drive system…" [2]

4. ENGINE NOISE EMISSION AROUND 1910

The noise emission of engines around 1910 was investigated by noise measurements of historical cars. [1] Based on car noise measurements for the engines A-weighted sound pressure levels L_{pA} of 90 dB(A) (in 1 m distance and at full power) respective A-weighted sound power levels L_{WA} of 102 dB(A) (at full power) and acoustical efficiencies of 0.9 - 2.3×10^{-6} were computed.

Tab. 1: A-weighted sound pressure level of the engine L_{pA} (in 1 m distance and at full power), A-weighted sound power level L_{WA} of the engine (at full power) and acoustical efficiency; including cooling system noise

type	year of production	full power (kW)	L_{pA} (dB(A))	L_{WA} (dB(A))	*acoustical efficiency*
MAF D	1909	7	90	102	2.3×10^{-6}
MAF F5	1911	9	90	102	1.9×10^{-6}
MAF G8	1914	18	90	102	0.9×10^{-6}

5. ENGINE NOISE EMISSION UNTIL 1970

Comparing industrial petrol engines around 1910 (tab. 1) with industrial diesel engines around 1970 the rated speeds, the combustion pressures, the dimensions like bore and stroke, the cylinder number and thereby the noise emissions were increased. Additionally diesel engines were introduced with their much harsher combustion process and larger noise excitation.

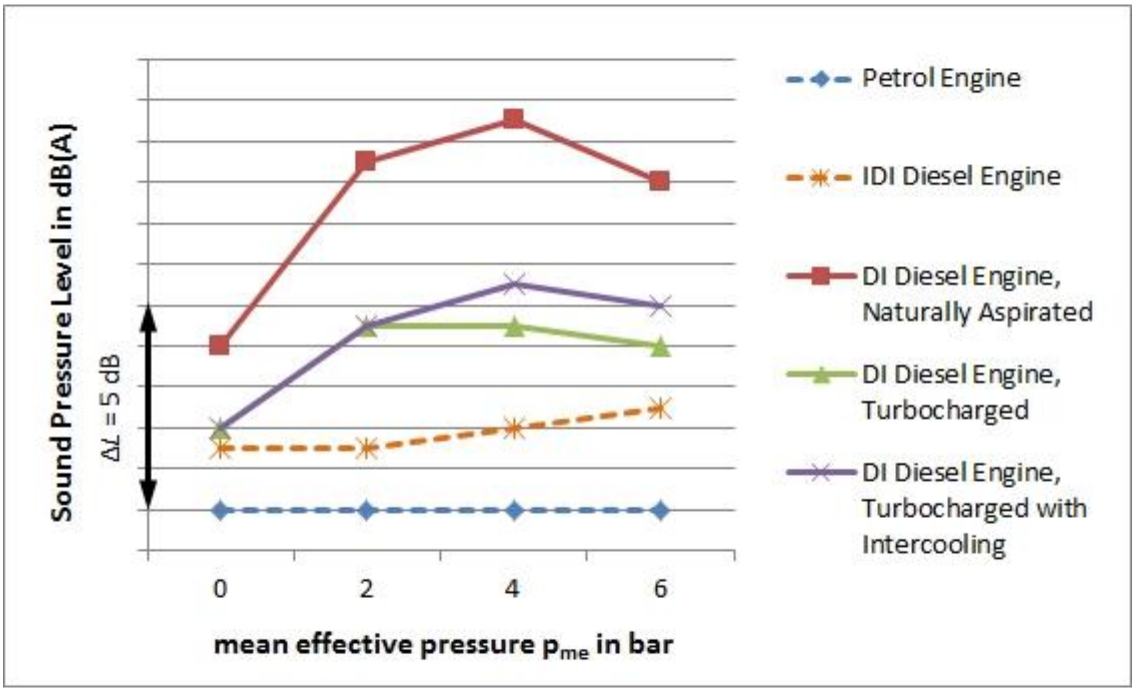

Fig. 9: Relative sound pressure levels of an industrial engine caused by different combustion systems (in 1 m distance at 1.500 rpm)

By increased rated speeds, larger dimensions and harsher combustions a noise level increase of around 20 dB respective to an A-weighted sound pressure level $L_{pA} \approx 110$ dB(A) (in 1 m distance and at full power) can be estimated for a typical industrial diesel engine with a piston volume of 6 dm³. [1]

Simultaneous noise reduction measures were also introduced. Among them, covers were most commonly used. Force transmitting structures were optimized mainly by stiffening. Mechanical noise exciting engine parts like pistons, timing gears, valve trains, crankshafts and so on were acoustically optimized e.g. by smaller clearances and less roughness, lightening and last but not least more favorable shapes. (e.g. [10]) Therefore A-weighted sound pressure levels L_{pA} of 99 - 105 dB(A) ≈ 102 dB(A) (in 1 m distance and at full power) were measured for industrial diesel engines with a piston displacement of 6 dm³ around 1970. [1, 11] The noise level difference of around 8 dB between the estimated value L_{pA} ≈ 110 dB(A) and the measured values L_{pA} ≈ 102 dB(A) can be interpreted as the technical progress caused by the acoustical measures above.

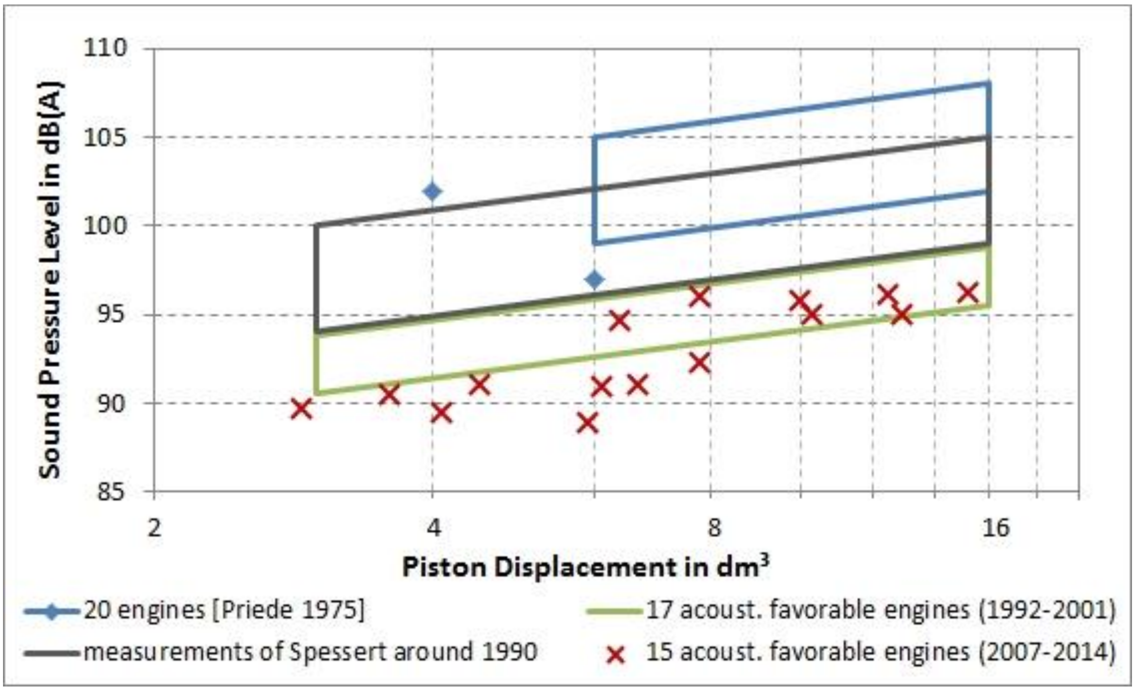

Fig. 10: Development of the sound pressure levels of industrial direct injection diesel inline engines (full load, rated speed, 1 m distance) [12]

6. ENGINE NOISE REDUCTION BETWEEN 1970 AND 1990

During the 1970ies noise and especially road traffic noise was considered as an important environmental problem. Between 1974 and 1995 the noise limits by law were reduced up to 12 dB for cars, transporters and lorries. Therefore the engine noise had to be reduced drastically, too.

For industrial heavy-duty diesel engines typical noise reduction measures were

- acoustical optimization of the combustion process (often by turbocharging),
- decrease of the rated speed and
- optimization of the blower or fan.

As examples of such optimizations some results were shown for DEUTZ production engines. The acoustical efficiency of these engines was reduced from 4 - 10×10^{-6} to 1 - 2×10^{-6}. [1, 13]

The noise reduction by optimization of the combustion process was most important for this period. Especially by turbocharging and by more powerful injection systems the combustion noise and the rated speeds were reduced remarkably. Additionally piston and timing gear noise was decreased. And the improvements of measurement and computation technologies in the 1970ies and 1980ies were the prerequisites for the further noise reduction in the 1990ies.

Tab. 2: Increase of max. power and decrease of sound levels and acoustical efficiency by advancement of heavy duty inline diesel engines (NA – naturally aspirated, TC – turbocharged, TCA – turbocharged with intercooling)

producer	DEUTZ			
type	F4L912	BF4L913	F4L912F	BF4L913C
production year	1971	1985	1988	1990
design	aircooled four cylinder inline diesel engine with direct injection			
combustion system	NA	TC	NA	TCA
max. power (kW)	46	78	53	90
sound pressure level L_{pA} (dB(A)) in 1 m distance at max. power and rated speed	104	97.5	98	99
sound power level L_{WA} (dB(A)) at max. power and rated speed	116.5	110	110.5	111.5
acoustical efficiency	10×10^{-6}	1.3×10^{-6}	2×10^{-6}	1.6×10^{-6}

Tab. 3: Increase of max. power and decrease of sound levels and acoustical efficiency by advancement of heavy duty V diesel engines

producer	DEUTZ			
type	F8L413	F8L413F	F8L513L	BF8L513LC
production year	1972	1979	1992	1992
design	aircooled eight cylinder V diesel engine with direct injection			
combustion system	NA	NA	NA	TCA
max. power (kW)	167	188	174	265
sound pressure level L_{pA} (dB(A)) in 1 m distance at max. power and rated speed	103	101	99.5	99
sound power level L_{WA} (dB(A)) at max. power and rated speed	118	116	114.5	114
acoustical efficiency	4×10^{-6}	2.1×10^{-6}	1.6×10^{-6}	1×10^{-6}

7. ENGINE NOISE REDUCTION SINCE 1990

In the 1990ies the noise excitation by pistons, crankshafts, timing gears and injection pump could be lowered by optimized piston shapes and piston pin offsets, minimized piston clearings, timing gears with high contact ratio and in a position near the flywheel and single element pumps. Additionally the structure borne sound transmission could be reduced by stiffening especially of the engine block and by isolation and by damping of covers. Thereby the noise level was reduced remarkably. A reduction of the sound pressure levels respective to the sound power levels of around 6 dB was realized for newly designed industrial heavy duty diesel engines.

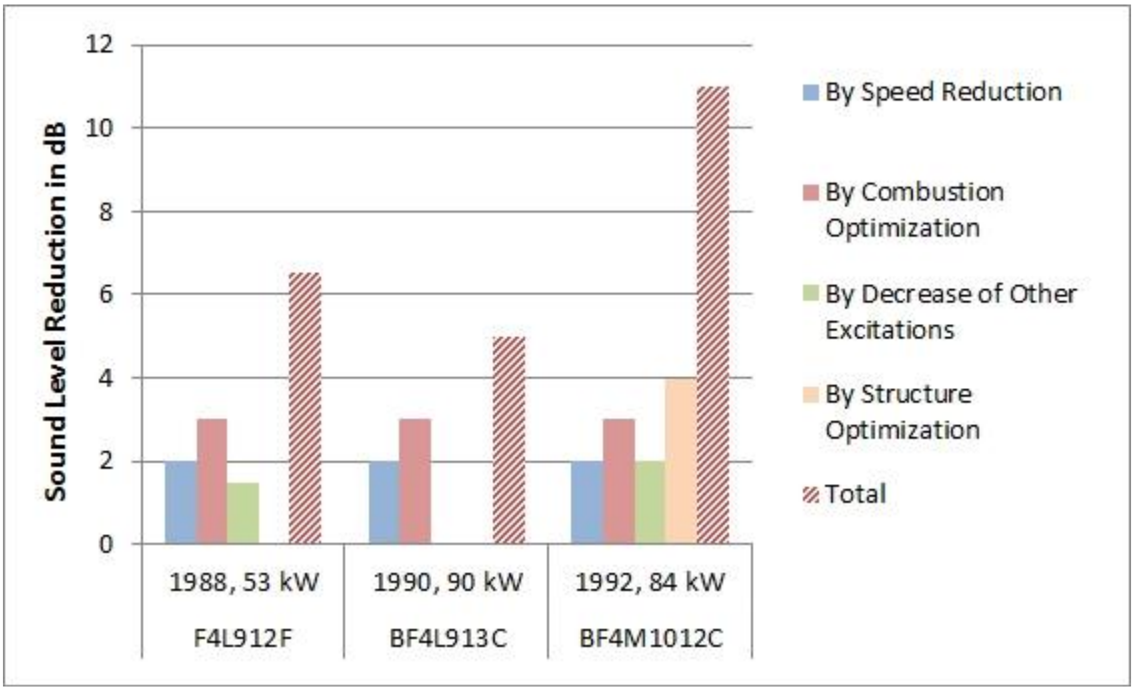

Fig. 11: Noise level reduction by advancement of the heavy duty inline diesel engines DEUTZ FL912 and FL913 and by development of the complete new heavy duty inline diesel engine DEUTZ FM1012 [1, 13]

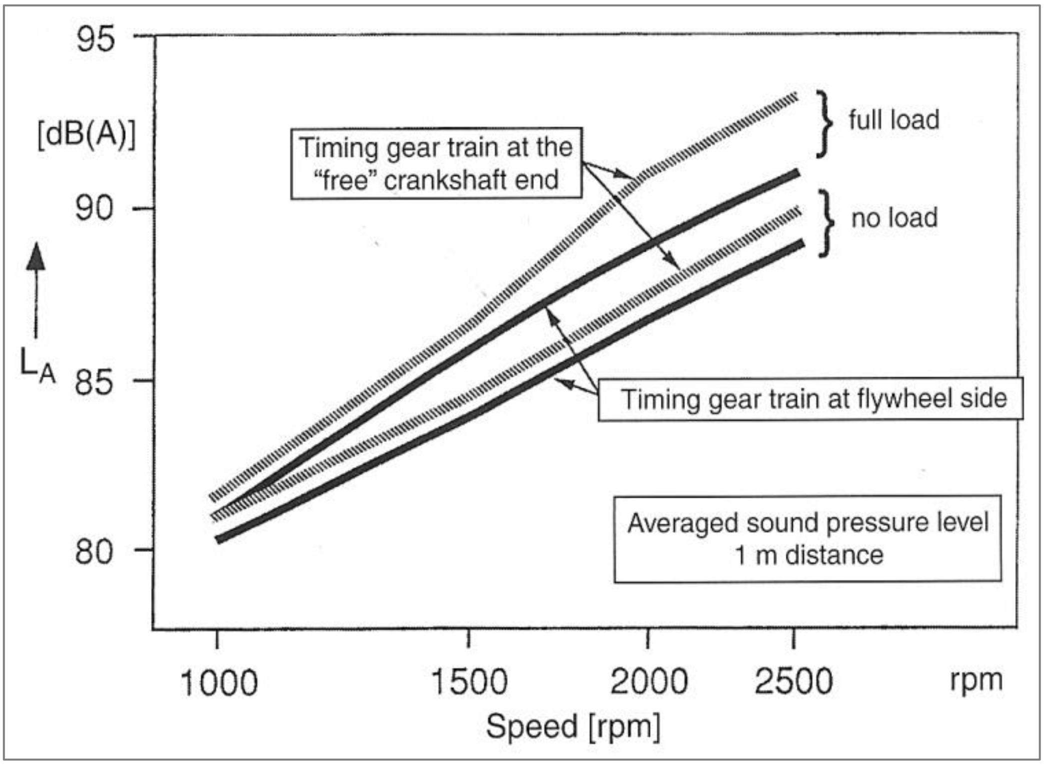

Fig. 12: Influence of the timing gear position [14, 15]

In the 2000ies the introduction of common rail injection systems decreased the noise level once more by lowering the combustion noise as well as the timing gear noise. Sound pressure levels respective to the sound power levels were reduced once more.

Until today the acoustical efficiency of production engines could be reduced to around 0.3×10^{-6}. Experimental engines reached acoustical efficiencies of even less than 0.2×10^{-6}. [1, 13]

Tab. 4: Decrease of sound levels and acoustical efficiency by development of heavy duty production diesel engine types [1, 13, 16]

producer	DEUTZ		DAIMLER	DEUTZ
type	BF4L913C	BF4M1012C	OM904LA	BF6M2013C
production year	1990	1992	1996	2000
design	inline diesel engine with direct injection			
cylinder number	4			6
cooling system	air	water		
combustion system	TCA			
max. power (kW)	90	84	125	190
sound pressure level L_{pA} (dB(A)) in 1 m distance at max. power and rated speed	99	92	92	94
sound power level L_{WA} (dB(A)) at max. power and rated speed	111.5	104.5	105	107
acoustical efficiency	1.6×10^{-6}	0.34×10^{-6}	0.25×10^{-6}	0.26×10^{-6}

Tab. 5: Sound pressure levels and acoustical efficiency by development of heavy duty experimental diesel engine types [1, 13, 16]

producer	PERKINS	DEUTZ		
type	QHV 90	BF4M1012C	BF6M2013C	
year of development	1988	1992	2000	2014
design	watercooled inline diesel engine with direct injection			
sound pressure level L_{pA} (dB(A)) in 1 m distance at max. power and rated speed	90	89	91.5	89
acoustical efficiency	0.28×10^{-6}	0.17×10^{-6}	0.15×10^{-6}	0.13×10^{-6}

8. CONCLUSIONS

From the beginning reducing noise was a main task in developing combustion engines. But although acoustical favorable measures like covers and silent gears or chains were introduced the noise emission increased until the 1970ies by higher speed and cylinder pressures and via the introduction of the diesel combustion process.

At first in the 1980ies the sound emission could be remarkably reduced mainly by turbocharging and lower speed. Additionally measurement and computation technologies were improved in the 1970ies and 1980ies as prerequisites for the further acoustical progress.

In the 1990ies an additional noise reduction could be reached by acoustical optimization of more noise excitation sources like pistons or timing gears and of the engine structures. In the 2000ies the introduction of common rail injection systems was acoustically advantageous.

Thereby the sound power levels respective the acoustical efficiency of industrial engines increased from 100 dB(A) respective $1 - 2\times10^{-6}$ around 1910 to ca. 115 dB(A) respective up to 10×10^{-6} in the 1970ies and after that decreased to 105 dB(A) and 0.3×10^{-6} for modern low noise diesel engines.

9. REFERENCES

[1] B. Spessert, B. Kühn: *Motorgeräuschverminderung – historischer Rückblick und Stand der Technik*; 10. Symposium Motor- und Aggregate-Akustik, Otto-von-Guericke-Universität Magdeburg 2018, ISBN 978-3-944722-72-6

[2] Dyke, A.L.: *Dyke`s Automobile and Gasoline Engine Encyclopedia*; The Goodheart Wilkox Company, Inc. Publishers, Chicago, 14th Edition 1925

[3] Heinze, E.P.A.: *Du und der Motor*; Deutscher Verlag Berlin 1939

[4] O. von Fersen (Herausgeber): *Ein Jahrhundert Automobiltechnik - Personenwagen*, VDI-Verlag Düsseldorf 1986, ISBN 3-18-400620-4

[5] P.M. Heldt, W. Isendahl: *Der Verbrennungsmotor*; 3. Auflage, Richard Carl Schmidt & Co. Berlin 1916

[6] M. Peter: *Das moderne Automobil*; 3. Auflage, Richard Carl Schmidt & Co. Berlin 1916

[7] M. Peter: *Das moderne Automobil*; 8. Auflage, Richard Carl Schmidt & Co. Berlin 1927

[8] O. Winkler: Entwer*fen von leichten Verbrennungsmotoren, insbesondere von Luftfahrzugmotoren*; Richard Carl Schmidt & Co. Berlin 1919

[9] P. Wolfram: *Die Motorfahrzeuge – ihre Konstruktion, ihr Betrieb und ihre Behandlung*; Heinrich Killinger Verlagsges. m.b.H. Nordhausen/Harz ca. 1926

[10] T. Priede: *In Search of Origins of Engine Noise – an Historical Review*; SAE 800534

[11] T. Priede: *The Problem of Noise of Engines in Different Vehicle Groups*; SAE-Paper 750795

[12] H. Tschöke, K. Mollenhauer, R. Maier (Herausgeber): *Handbuch Dieselmotoren*, Springer Verlag, 4. überarbeitete Auflage 2017

[13] B. Spessert: *Noise Emission of Engines in Different Vehicke Groups: Historical Review*, State of the Art and Outlook; FISITA Congress Helsinki 2002

[14] B. Spessert: *Development of Low Noise Diesel Engines Without Encapsulations*; 20th Congress of CIMAC, 17-20 May 1993, London

[15] K. Mollenhauer, H. Tschöke: *Handbook of Diesel Engines*; Springer-Verlag 2010, ISBN 978-3-540-89083-6

[16] B. Spessert: *Auf dem Weg zum leisen Motor*; 2. Symposium Motor- und Aggregateakustik, Haus der Technik e.V./Otto-von-Guericke-Universität Magdeburg 26. Juni 2001