© Strojniški vestnik 50(2004)1,22-30
ISSN 0039-2480
UDK 621.432.4:504.064
Pregledni znanstveni članek (1.02)
© Journal of Mechanical Engineering 50(2004)1,22-30
ISSN 0039-2480
UDC 621.432.4:504.064
Review scientific paper (1.02)

Možne vrste cenenih motorjev s prostornino 50 kubičnih centimetrov z majhno emisijo

Possible Solutions for EURO 2 "Low-Emission Low-Cost" 50cc Engines

Roland Kirchberger - Gernot Koller

Predpis EURO 2, ki je stopil v veljavo junija 2002, postavlja velik izziv proizvajalcem majhnih dvotaktnih motorjev za pogon koles z motorjem. Če primerjamo razpoložljive tehnologije glede na stroške, tehnologijo izdelave in zmogljivost motorja, najdemo možnosti za uspešno rešitev omenjenega izziva.

Prispevek bo pokazal, da uporaba sistema za vbrizgavanje goriva ni nujno potrebna za dosego predpisov EURO 2 o izpušnih emisijah.

Pri proizvodnji dvotaktnih motorjev za pogon koles z motorji so stroški izdelave zelo pomembni. Ta prispevek opisuje metodo za doseganje predpisanih mej izpušnih emisij brez velikih stroškov, ki jih zahteva vrhunska tehnologija.

Opazno zmanjšanje škodljivih emisij in hkratno povečanje moči in navora motorja je mogoče doseči brez uporabe dodatnih delov, zgolj z optimiranjem termodinamike in mehanike motorja, kar kažeta raziskava osnov delovanja motorja in proučevanje prototipa.

Preskusi različnih serijskih agregatov kažejo uporabnost predlagane izboljšave za serijsko izdelavo ob hkratnem izpolnjevanju zahtev po EURO 2.

(Ključne besede: motorji dvotaktni, emisije majhne, stroški majhni)

The EURO 2 emission regulation, which has been in force since June 2002, is a challenge to the industry that produces small two-wheeler two-stroke vehicles. A summary and comparison of the available technologies, concerning costs, production technologies and aspects of performance will give a survey of the state of the art and will show possible ways of coping with this challenge.

It should be classified in advance if the use of an injection system is necessary in order to meet the EURO 2 exhaust-emission regulations.

Production costs are of special interest when dealing with the topic two-wheeler engines. This paper describes a method for achieving the required exhaust-emission limits without having to resort to "high-tech & high-cost" technologies. Without using any additional parts, only by optimising the given engine thermodynamics and mechanics, basic research and studies of prototypes will show how to achieve significant reductions in emissions and increases in the engine power and torque output.

Various vehicle tests will show the suitability for mass production, taking into account the required modifications necessary for fulfilling the EURO 2 exhaust-emission regulations.

(Keywords: two-stroke engines, low emission, low costs)

0 INTRODUCTION

It is a fact that an increase in the economic wealth of a society is matched by a growth in the amount of traffic.

Fig. 1 shows that there is a coherence between the per-capita gross national product and the number of vehicles in use. Therefore, an increase in the number of vehicles worldwide will, in all probability, occur for the foreseeable future. Estimations for the next 10 years show that the global number of vehicles will increase by 45%. A disproportionate growth rate, of approximately 60%, will occur in the sector known as "two-wheeled vehicles".

This above-average growth in the two-wheeler sector is caused by the higher demand of the Asian markets. Legal regulations in most Asian

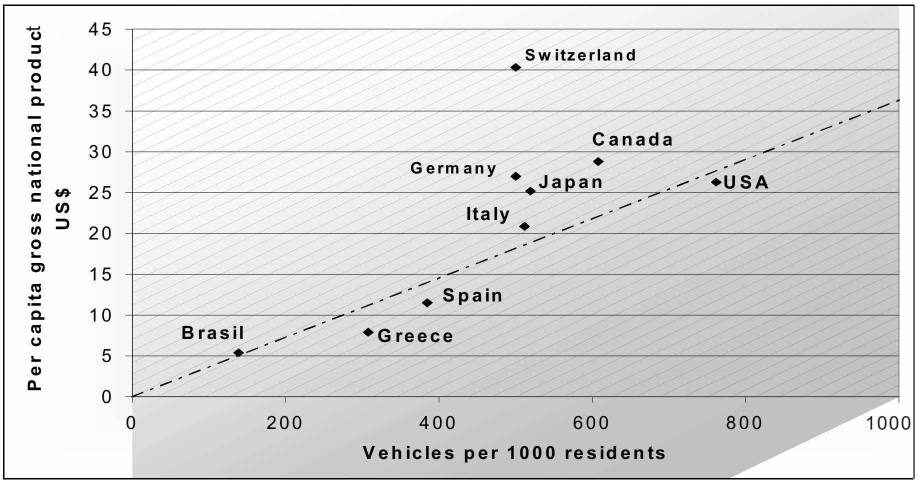

Fig. 1. *Per-capita gross national product versus vehicles per residents [1]*

countries take European regulations as a model. Taiwan, for example, has already established emission limits that are even stricter than those of the European Union. For this reason, two wheelers complying with the EUROMOPED Euro 2 exhaust-emission regulation, which came into force on the 1st of June 2002, are of global interest.

Most of the Euro 2 mopeds on the market today make use of high-tech and high-cost technologies in order to fulfill the legal requirements. This paper will show that Euro 2 can also be achieved with existing Euro 1 technologies, simply by optimizing the engine's thermodynamics.

1 REQUIREMENTS AND DEVELOPMENT TARGETS FOR SMALL TWO-WHEELER ENGINES

The first essential development target for all engine-development projects is to fulfil the corresponding legal regulations concerning maximum power and torque, anti-tampering, as well as exhaust and noise emissions.

An additional requirement, especially for the small engines used in scooters and mopeds, are the production costs. The acceptance of additional costs for technologies necessary to fulfil legal limits is rather low. This means that the additional costs caused by the implementation of new technologies must be kept to the minimum. For this reason, lean production and the use of standard technologies are required for these engines.

Further development targets are weight optimisation, low fuel consumption, low maintenance and service costs as well as good performance characteristics and driveability.

1.1 EUROMOPED EURO 2 exhaust-emission regulation

Fig. 2 shows the large reduction in the exhaust-emission limits from the Euro 1 to the Euro 2

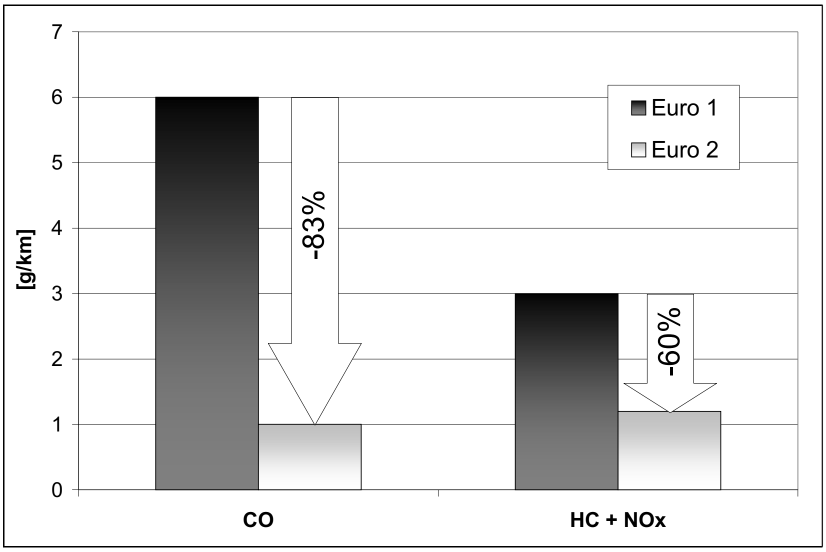

Fig. 2. *Comparison between the Euro 1 and Euro 2 exhaust-emission limits [2]*

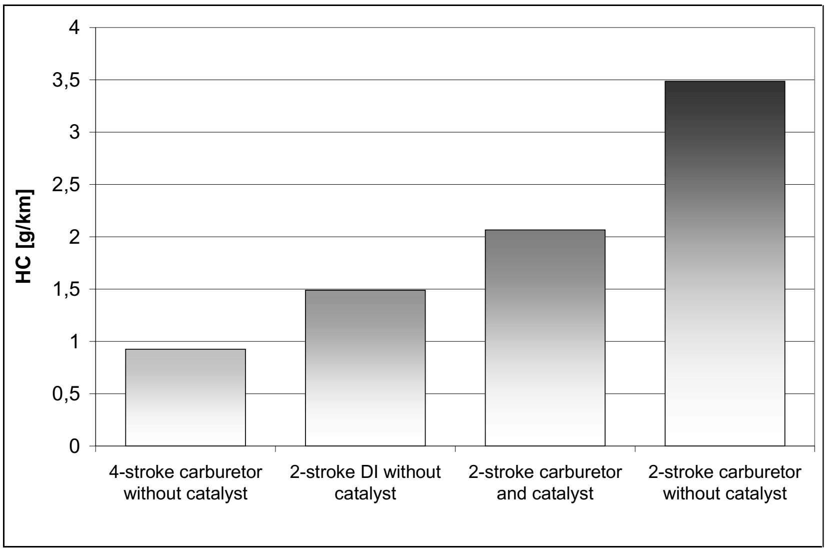

Fig. 3. *Comparison between four-stroke and two-stroke HC exhaust emissions*

regulation. This dramatic decrease in the tolerated level of exhaust emissions is a challenge for the small two-wheeler industry. The following is a short description of the different possible strategies to cope with this challenge.

1.1.1 Four-stroke engine

Fig. 3 shows the hydro-carbon exhaust emissions in g/km in the ECE R 47 test-cycle for various 50cc engine configurations.

The comparison between the standard two-stroke and standard four-stroke engines, both with carburetor and without catalyst, shows a big advantage for the four-stroke concept. Not even the two-stroke direct-gasoline-injection technology can completely eliminate the disadvantage of the two-stroke concept with respect to HC emissions. This disadvantage is the result of the short circuiting of the fresh mixture to the exhaust port(s) during the two-stroke scavenging process. Because of the higher development, production and maintenance costs, combined with the lower power output, hardly any four-stroke 50cc vehicles are available on the market at present.

1.1.2 Two-stroke engine

Standard two-stroke engines for two-wheeler applications utilize the loop-scavenging process and a carburetor. By lean engine tuning and the application of an oxidation catalyst it was possible, until the commencement of the Euro 2 exhaust-emission limits, to comply with the exhaust emission limits. However, the upcoming stricter emission regulations are forcing two-wheeler manufacturers to apply new technologies to two-stroke engines in order to fulfill the legal requirements.

Fig. 4 gives a schematic overview of the different injection strategies for two-stroke engines. Figure A shows a possible solution for a high-pressure fuel-injection system. Figure B is a low-pressure injection system, and figure C shows a possible layout for an air-assisted fuel-injection system.

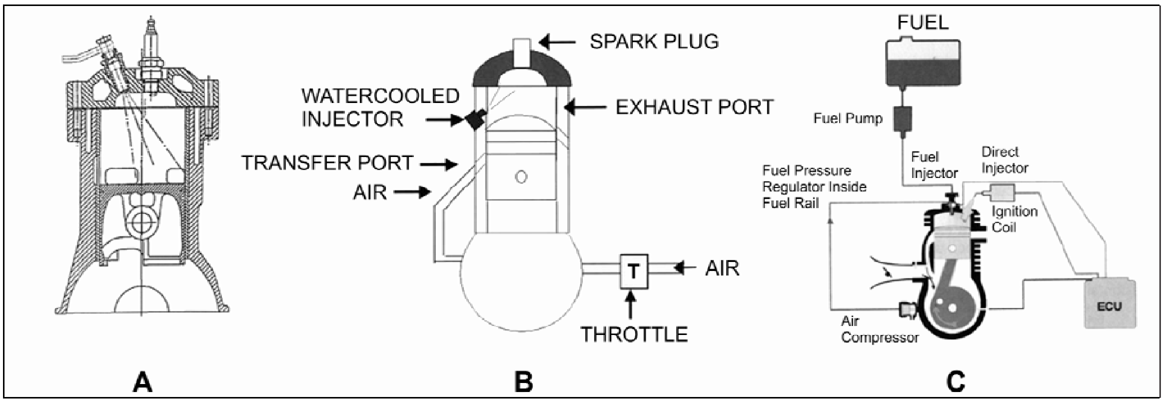

Fig. 4. *Two-stroke injection systems ([3], [14] and [15])*

1.1.2.1 High-pressure direct fuel injection

The biggest advantage of using a high-pressure direct-fuel-injection system in a two-stroke engine is that the fuel injection occurs after the complete or at least partial closing of the exhaust port(s). This leads to the prevention, or at least to the reduction of fresh-mixture short circuiting. For this reason, direct high-pressure fuel injection can dramatically reduce the hydrocarbon concentration in the engine's raw emissions and improves the engine's fuel consumption.

An additional advantage is that the engine can operate with stratified charge, meaning that an area with a rich mixture can be positioned around the spark plug, within a global lean-mixture operation. This, potentiality, is a suitable way to reduce raw emissions of carbon monoxide and hydrocarbons. Furthermore, the engine can operate with a higher compression ratio, which leads to a higher break-mean-effective-pressure potential.

When considering all these advantages and potentials of high-pressure direct-fuel-injection systems, the disadvantages cannot be ignored. The injection system must generate a high fuel pressure (30-70 bar). For this reason, additional high-tech and high-cost elements have to be added to the engine. To use the full fresh-mixture short circuiting prevention potential of high-pressure fuel-injection systems, the injection timing has to be, in the ideal case, short before the closing of the exhaust port(s), but the time between the exhaust closing and the ignition is very short. This can be best illustrated by the following example: If the ignition timing is 20° before TDC and the exhaust ports close at 100° before TCD, only 80°CA can be used for the fuel injection and the mixture formation. At an engine speed of 8000 rpm, which is a recommended value for 50cc engines, the time the crankshaft needs to move 80°CA is about 2 milliseconds. These facts limit the possible field of application for high-pressure direct-fuel-injection systems in small two-stroke engines.

1.1.2.2 Low-pressure fuel-injection

The costs for the application of low-pressure fuel-injection systems, which work in a fuel pressure range of 3 to 6 bar are considerably lower than for a high-pressure system. For these (semi-) direct-injection systems, standard automotive fuel injectors can be used. The potential of avoiding fresh-mixture short circuiting is not as high as that of high-pressure fuel-injection systems.

Compared with a standard carburetor engine, the fuel consumption can be decreased by up to 30%, hydrocarbon raw emissions by up to 60%, and carbon monoxide emissions by up to 70%.

These improvements are the result of improved fuel atomization, lower fresh-mixture short circuit losses and the improved possibilities to optimize the air/fuel ratio for the whole engine operating range.

1.1.2.3 Air-assisted fuel injection

An additional possibility of fuel injection is the use of an air-assisted fuel-injection system. These systems inject a compressed air/fuel mixture into the combustion chamber. An air compressor boosts air at a pressure of up to 6 bar into an injection chamber. Into this mixture chamber, fuel is added with a low-pressure injector. This prepared air/fuel mixture, with a good level of atomization, is injected into the combustion chamber, as far as possible after the complete closing of the exhaust port(s). In some systems, this injection is controlled by a pressure-sensitive valve. In this case the injection timing cannot be adjusted during the engine operation. An additional optimization possibility is the use of a solenoid valve; this leads to higher system complexity and costs, but enables improved engine settings, especially under part load conditions.

The advantages of air-assisted fuel-injection systems are similar to those of high-pressure direct-fuel-injection systems. Additional costs are caused by the need for an air-compressor. The fuel injectors are working in a lower pressure range and are therefore cheaper than those that are applied in high-pressure injection systems.

1.2 Costs

Increasing competition due to globalization reduces the benefit margins for two-wheeler manufactures. In the compact two-wheeler sector the pressure on costs is particularly high. *Fig. 5* shows a comparison of the engine-production costs for different engine configurations.

The standard two-stroke engine with a carburetor and an oxidation catalyst, and the two-stroke engine with a low-pressure-in-cylinder injection are the most common ways to fulfill the legal requirements for EUROMOPED EURO1. All the other above-mentioned two-and four-stroke engines are known as having the potential to fulfill the strict Euro 2 emission limits, but with even higher production costs. This is the motivation for a development project with the aim to achieve Euro 2 homologation by only optimizing the components of a standard two-stroke engine.

2 A POSSIBLE "LOW-COST" TWO-STROKE SOLUTION

This section describes the results of a "low-cost" two-stroke scooter-engine development project, which has been carried out at the Institute

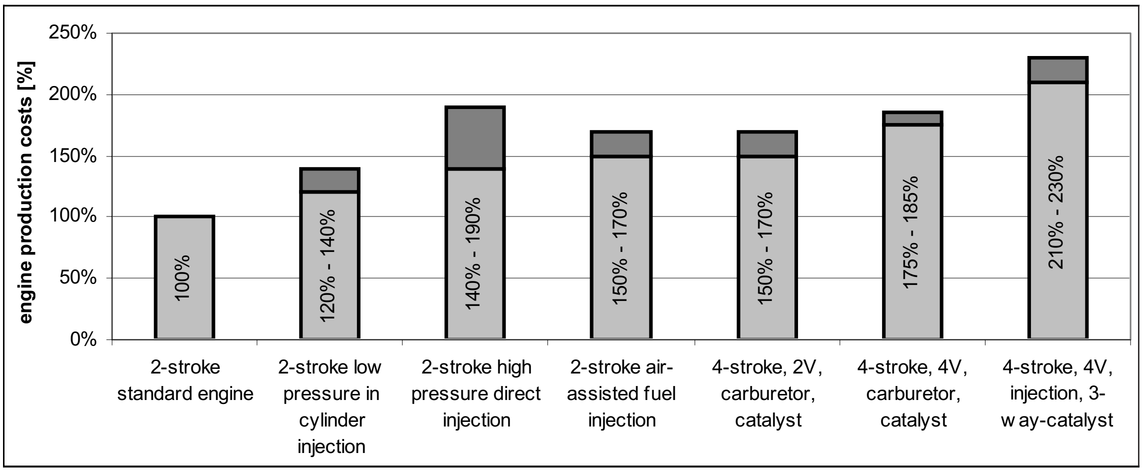

Fig. 5. *Comparison of production costs for different engine configurations [3]*

for Internal Combustion Engines and Thermodynamics at Graz, University of Technology. The starting point for this project was a 50cc fan-cooled scooter engine, which has already been optimized for EUROMOPED Euro 1 homologation. In the following the necessary modifications and optimizations to achieve the EUROMOPED Euro 2 exhaust-emission limits are listed.

2.1 Modified engine components

As the production costs of the new engine had to be kept as low as possible, as few modifications as possible should be made to the already existing engine.

2.1.1 Intake silencer / air-filter box

To ensure that the intake flow and pressure conditions are the same for each engine, the intake cross section of the intake silencer / air-filter box has to be exactly and reproducibly defined. For this reason, the design of the existing part had to be improved to avoid leakage and to guarantee that the only possible air-intake flow is through the calibrated cross section of the intake snorkel.

2.1.2 Carburetor

The aim for the carburetor setting is to achieve a lean air/fuel ($\lambda > 1$) mixture in combination with a good throttle response and vehicle drivability. To reach this goal across the entire required engine-speed range, a balanced setting of the carburetor's setting parts (main jet, idle jet, slider valve, needle jet, needle) had to be worked out and tested on the engine and the vehicle test-bench.

Although the emission measurement in the ECE R-47 test-cycle does not include the cold-start phase, an auto-choke time, that is as short as possible, is required. During the auto-choke time the delivered air/fuel mixture is rich. The fuel evaporation heat leads to a colder combustion and exhaust-gases temperature. For a short light-off time of the catalyst, high exhaust temperatures are essential, even more so for aged catalysts.

2.1.3 Cylinder and cylinder head

For two-stroke engines the design of the cylinder with its scavenging ports has an essential influence on the engine characteristics, achievable exhaust emissions and the leaning potential.

Due to the fact that during the two-stroke scavenging process the intake and exhaust ports are open at the same time, an optimization of the ports' geometry is essential to avoid high hydrocarbon exhaust emissions, caused by fresh-charge short-circuiting scavenging losses. At the same time, improved trapping efficiency is necessary to optimize the engine's fuel consumption. Furthermore, the scavenging must enable the engine to run on the lean side, without hesitation in the throttle response or misfiring. This can be realized by a high cylinder-charge turbulence velocity induced by a high cylinder-entrance velocity. To achieve this high cylinder-entrance velocity the entrance area of the transfer ports must be optimized.

The left-hand side of *Fig. 6* shows a section view through the cylinder and cylinder head of the optimized engine. The right-hand side of *Fig. 6* shows the symmetrical arrangement of the cylinder's scavenging ports. This layout of the ports is optimized for the loop scavenging process and consists of two main and two auxiliary transfer ports and one rear transfer and one exhaust port. Loop scavenging refers to the flow pattern generated by the transfer port's duct shapes and the port entry angles and area. The gases are directed to merge together and travel up the intake side of the bore into the head and loop around towards the exhaust port [10]. This scavenging process was already patented

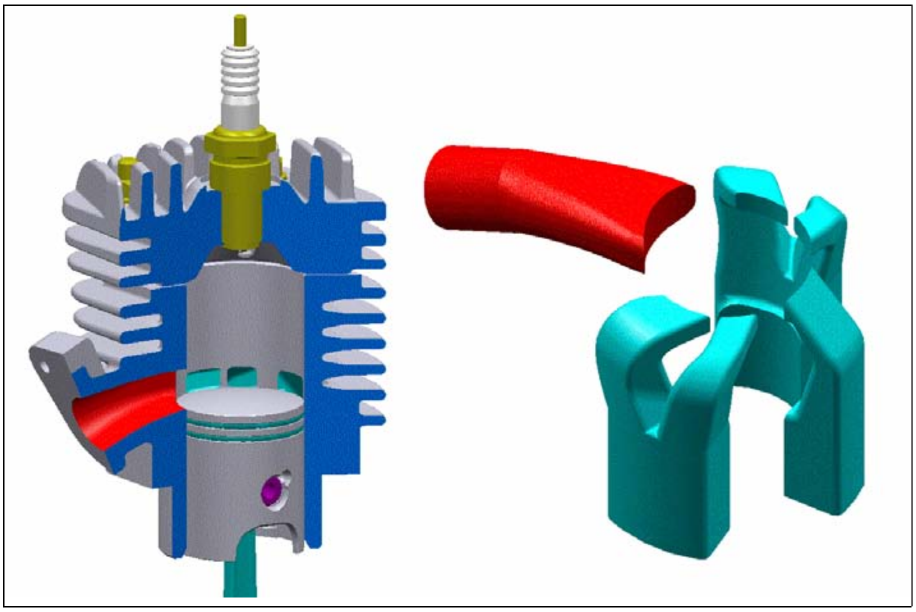

Fig. 6. *Cross-section through cylinder and cylinder head and ports geometry*

in 1908 [13], and is a suitable way to decrease the fresh-mixture short circuiting losses.

Because of the higher temperature of lean combustion the cylinder cooling had to be improved. For this reason, additional cooling fins were added and the fins' length on the opposite side of the fan was increased to compensate for the bad cooling situation on this cylinder side, which was caused by the lower air flow.

A well-adjusted cooling system is essential to avoid asymmetric thermal expansion of the cylinder. The cooling of the cylinder head had to be improved as well. Two additional fins, orthogonal to the cylinder axis, were added to force the air flow directly to the hot areas around the spark plug. This modification causes higher production costs, due to the additionally needed die separating direction.

The combustion-chamber volume is designed for a four-stroke combustion ratio of $\varepsilon_{4\text{-stroke}} = 8.4$, which leads, when combined with the port timing, to a two-stroke compression ration of $\varepsilon_{2\text{-stroke}} = 5.9$.

The material of the cylinder is, due to low-tech production requirements, gray-cast iron, and the cylinder head is made out of cast aluminum alloy.

2.1.4 Piston

Because of the higher combustion temperature of lean combustion, the heat transfer between the piston and the cylinder must be increased. For this reason, a small the clearance between cylinder and the piston is required. To avoid piston seizure an extensive piston-shape development is essential. Additionally, this small clearance helps to avoid noise emission caused by piston slap. Because of the lower thermal expansion coefficient of the gray-cast-iron cylinder a cast aluminum alloy with a high percentage of silicon was chosen as the piston material.

Due to the optimized cylinder cooling, an approximately round cylinder shape can be ensured during engine operation. For this reason, a round-shaped piston can be used. To assist the heat transfer and to reduce the friction, the piston surface should have $R_{3Z} < 3\mu m$.

2.1.5 Exhaust system

The main requirements for two-stroke engines exhaust systems are the support of the scavenging process with its gas dynamics, the conversion of the raw exhaust emissions with the integrated oxidation catalyst and the reduction of noise emissions.

The length of the exhaust manifold and the geometry of the diffuser are important for the engine characteristics. A well-positioned oxidation catalyst in the exhaust system is important for finding a compromise between a short light-off time, due to the small distance to the exhaust port(s), and low impact, due to the engine-boosting exhaust system's gas dynamics.

2.2 Additional costs for the "Low-Cost" Two-Stroke Solution

Table 1 shows an overview of the additional mass-production costs for the required modification to the proposed "Low-Cost" Two-Stroke Solution. The basis for the cost calculation is a fan-cooled engine, already optimized to fulfill Euro 1 homologation regulations.

Table 1. *Additional costs for the "Low-Cost" Two-Stroke Solution*

Part	Additional costs		Part costs [% of engine]	Cost-increasing facts
	part costs	% of engine cost		
Intake Silencer	10%	0,2%	2,0%	calibrated intake snorkel, improved gasket design/material
Carburetor	0%	0,0%	5,0%	no modification
Cylinder	15%	1,0%	6,5%	higher casting quality, port positioning, additional material for improved cooling
Cylinder Head	40%	0,6%	1,5%	additional die separating direction and material
Spark Plug	10%	0,1%	0,5%	long-thread version required
Piston	10%	0,3%	2,5%	material and machining costs
Crank Mechanism	0%	0,0%	9,0%	no modification
Crank Case	0%	0,0%	16,0%	no modification
Exhaust System	20%	2,5%	12,5%	catalyst with higher cell density, heat-resistant material
Transmission	0%	0,0%	29,5%	no modification
Covers	0%	0,0%	6,5%	no modification
Electronic parts	0%	0,0%	8,5%	no modification
Total		**4,6%**	**100,0%**	

A cost-splitting of the engine parts indicates the estimated increase of costs caused by the conversion of the engine from the Euro 1 to the Euro 2 emission level. The cost increase is less than 5% compared to the already optimized Euro 1 serial production engine. This can be said to be the most effective way to achieve the Euro 2 emission level, if only the costs are considered.

2.3 Achievable results

The reduction of HC and CO emissions during the ECE 47 driving cycle is remarkable (Fig. 7). The light-off of the catalyst in the EURO 2 engine occurs during the first seconds of the second full-load period in the test-cycle, while the EURO 1 engine needs 3 complete cycles to start the conversion of HC emissions. These effects are due to the higher exhaust-gas temperature of lean combustion and a higher oxidation level caused by an oxygen surplus [4]. After the warm-up phase, HC and CO emission levels are significantly lower than in the EURO 1 engines. This is the result of reduced scavenge losses caused by the optimized scavenge-port geometry.

The impact of the new scavenge strategy and the new exhaust geometry can be seen in the

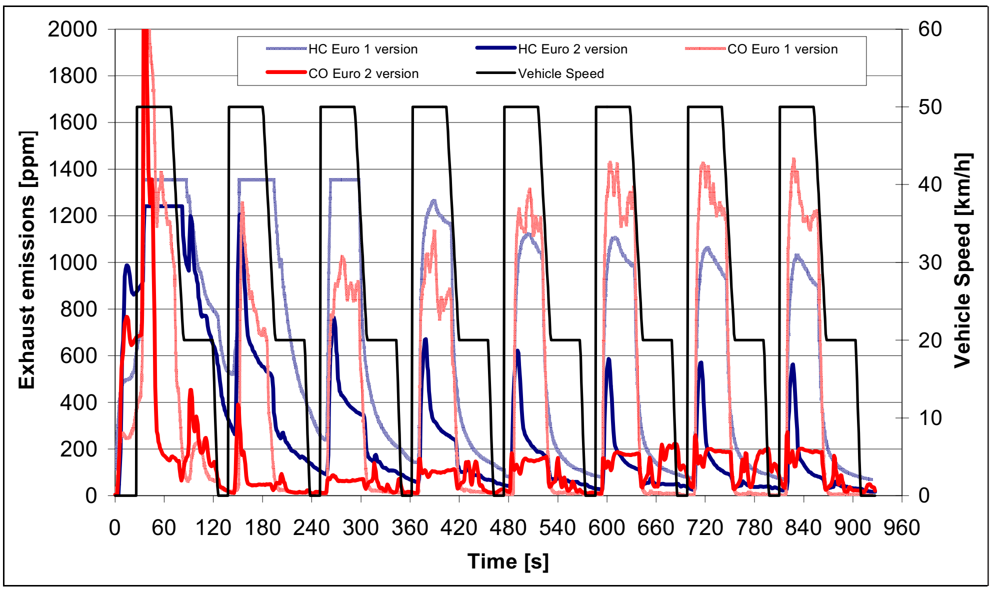

Fig. 7. *Exhaust emissions during the ECE R 47 driving cycle*

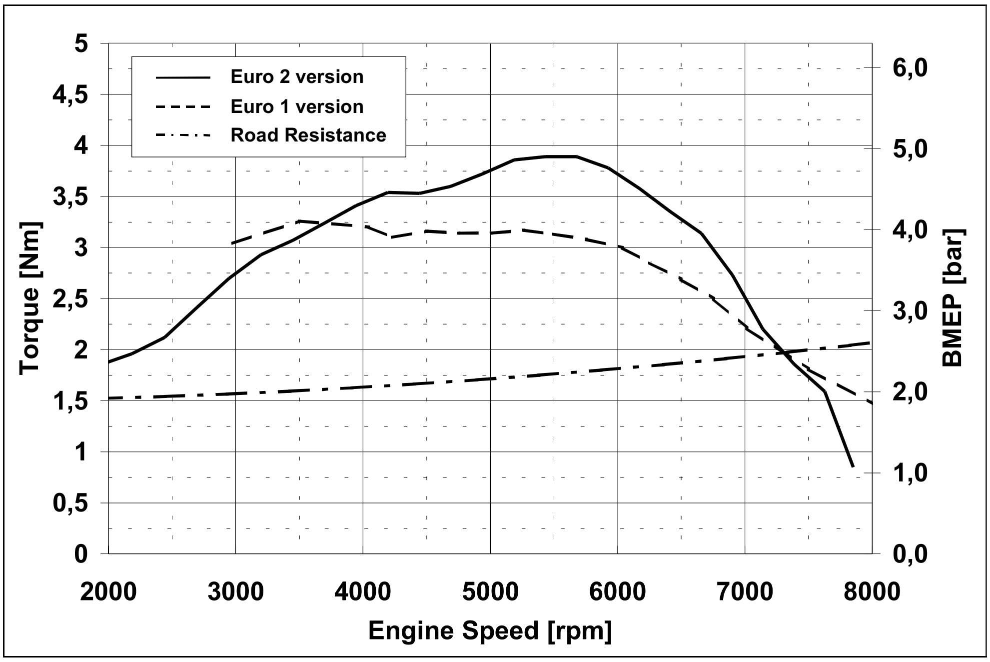

Fig. 8. *BMEP comparison of the Euro 1 and the Euro 2 engine*

achievable performance of the engine (Fig. 8). The rise of BMEP over the complete engine speed range gives a better drivability, especially in terms of acceleration and climbing. With the EURO 2 engine the maximum speed can be adjusted accurately, because the decrease of the BMEP curve at high engine speed gives a well-defined cross-section of engine torque and road resistance. With this defined intersection, different speed versions for different markets can be realized, simply by changing the transmission ratio.

Spot tests of vehicles currently on the market show that the development requirements to achieve the EURO 2 emission standards are comparable for four-stroke and two-stroke standard engines (Fig. 9). Already-existing DI two-stroke engines with much higher production costs (see Fig. 5) have the same backlog demands to achieve the legal limits of EURO 2. The "Low-Emission Low-Cost" concept of Graz, University of Technology, shows excellent emission results as a prototype engine and in pre-serial production. The required modifications for the mass production of this low-cost concept are well accepted and can easily be implemented in mass-production technology.

3 FUTURE PERSPECTIVES

In the years from 2006 to 2010 the Euro moped EURO 3 emission legislation for two wheelers

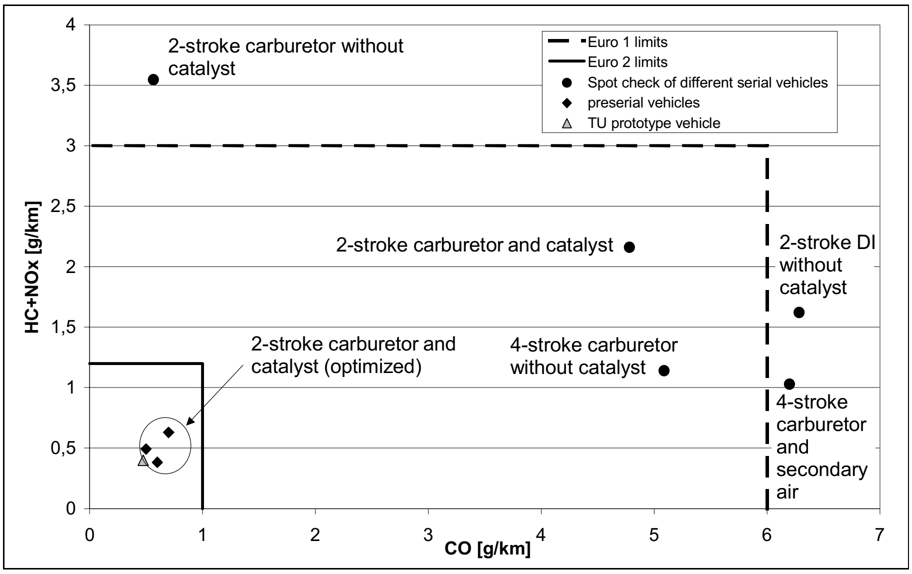

Fig. 9. *Emission results in comparison*

will come into force. The discussions concerning the reduction of HC, CO, and NOx levels and the cold-start behavior are still going on. In any case, the "Low-Emissions Low-Cost" concept has the potential for further optimization. To analyze the further potential of this "Low-Emissions Low-Cost" concept for EURO 3 emission legislation, the following topics need to be investigated:

- reduction of the light-off time for the catalyst by a close position to the exhaust port(s) or an additional pre-catalyst
- reduction of scavenge losses by controlled scavenge parameters
- use of secondary-air and/or improved carburetor technology
- use of new cold-start strategies

In any case, all these further improvements should take note of production costs. Rising competition due to globalization reduces benefit margins, especially in the compact two-wheeler sector. This cost pressure will increase and require lean production and use of low-cost technologies.

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Prejeto: Received: 9.9.2003
Sprejeto: Accepted: 12.2.2004
Odprto za diskusijo: 1 leto
Open for discussion: 1 year