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Tomić M., Popović S.:

ACTUAL TRENDS IN PASSENGER CARS SPARK IGNITION ENGINE DESIGN AND DEVELOPMENT

AKTUELNI TRENDOVI U KONSTRUKCIJI I RAZVOJU OTO-MOTORA ZA PUTNIČKA VOZILA

University of Belgrade, Faculty of Mechanical Engineering, Belgrade, YU

IZVOD U radu se diskutuju savremena rešenja u konstrukciji oto motora za pogon putničkih vozila, kao i mogućnosti koje ona pružaju u pogledu poboljšanja performansi, ekonomičnosti i kvaliteta izduvne emisije. Kod oto motora to je ostvarenje smeše putem ubrizgavanja benzina i primena katalizatora, primena natpunjenja, varijabilni usisni sistem, varijabilna šema razvoda i varijabilni stepen sabijanja. Na osnovu statističke analize celokupne svetske produkcije oto motora za pogon putničkih vozila u 1996. godini, u radu se prikazuje osnovni konstruktivni parametri kao i raspostranjenost pojedinih koncepcija i konstruktivnih rešenja kod savremenih motora.

KLJUČNE REČI: oto motor, konstruktivni parametri, statistička analiza.

ABSTRACT In this paper actual trends and solutions in spark ignition (SI) passenger cars engines design has been discussed. Expected benefits and some possible negative features of these solutions, as well as their possibilities in engine performance, fuel economy and exhaust emissions improvement has been pointed. For spark ignition engines these solutions are: fuel injection and 3-way catalyst application, engine turbocharging, variable inlet system, variable valve systems and variable compression ratio. The results of statistical analysis of complete world wide production of SI engines for passenger cars in 1996 has been also presented. They show the basic design parameters and the spread of characteristic conceptions and solutions in actual passenger cars engine production.

KEY WORDS: spark ignition engine, design parameters, statistical analysis.

1. INTRODUCTION

Automobile is by all means one of the modern civilization symbols, and it is related to our civilization by complex interactive connections. On one hand, it relates the fundamental characteristics of our civilization, not only as a very rapid and effective mean of transport, but also as a symbol of primeval human aspirations to the unbound freedom in space and time. On the other hand it impacts significantly nature environment. According to relevant estimations automotive transport contributes with about 50% in the consumption of fossil fuels, and over 50% in global environmental pollution. For these reasons at the beginning of 21st century further automobile development is strongly conditioned by very complex demands. These demands, besides those usual for the products of modern technology such as quality, reliability and durability, give special accents to high performances, good fuel economy and low emissions of pollutants and noise.

Most of mentioned demands depends crucially on the characteristics of automobile power source. Therefore, research efforts are specially focused to the development of automotive engines. Although the application of alternative power sources has been intensively investigated (hybrid and pure electrical drive), all relevant estimations consider that spark ignition (SI) or otto and compression ignition (CI) or diesel internal combustion (IC) engines remain the main passenger cars power sources for at least first half of 21st century. So far, spark ignition engines dominate in global world passenger cars engines production, especially in USA and Asia. This is shown in Fig. 1.

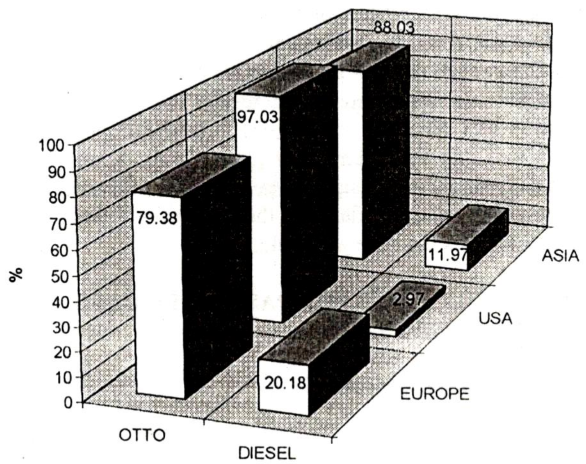

Fig.1-The share of SI and CI passenger cars engines in world wide production.

As the illustration of very strong regulations related to automotive air pollution, Fig.2 shows European Economic Community (EC) exhaust emission limits during last decade of this century (I stage 1992 and II stage 1996), as well as the proposition of German Bureau for Environmental Protection for the end of this century (BMU-proposition-1999) /1/. American regulation for exhaust emission are even stronger (so called LEV - Low Emission Vehicle and ULEV - Ultra Low Emission Vehicle).

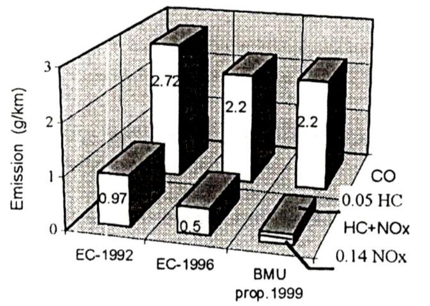

Fig.2-Europian regulations for SI engines exhaust emission.

At the present, passenger cars fuel economy is not under the low regulations, but considering limited resources of fossil fuels and also the problem of carbon dioxide (CO_2) emission, strong restrictions can be expected in near future. Although nontoxic, CO_2 has an important role in global climate deterioration caused by the effect of "greenhouse". Since its emission can not be decreased, as far as the fuel containing carbon is used, remain the only possibility to reduce global fuel consumption and in that way indirectly reduce CO_2 emission. The recent experimental attempts to create super economic vehicle, (such as the project 3 l/100 km fuel consumption), are in fact the preparation for future strong restriction in this field. All such experimental projects use highly economical diesel engines with direct fuel injection and turbocharging and this also involves a new challenges for SI engines further development.

In this work a short review of modern conceptions and solutions in passenger cars SI engines design has been given, as well as the discussion of their potentials concerning above mentioned problems and the possibilities of their commercial application in serial production. Also, the statistical analysis of complete world wide production of SI engines for passenger cars in 1996 /5,6/. has been evaluated and some interesting results are presented. Data base contains 685 types of engines, 358 from Europe, 98 from America (USA) and 229 from Asia (Japan and South Korea). Statistical analysis includes engine types and not sold units, since, unfortunately, the complete data for the production quotes for all types of engines has not been available.

2. MODERN SOLUTIONS FOR PASSENGER CARS SI ENGINES DESIGN

2.1. Mixture formation systems

Fig.3 shows the share of SI engines mixture formation systems. It can be considered that the share of fuel injection systems also gives the spread of 3-way catalyst systems for exhaust gas cleaning out of the cylinder.

The restrictive regulation for exhaust emission can be satisfied only with electronic fuel injection and closed loop mixture strength control (application of λ- sonde or O_2- sensor) together with 3-way catalyst system. Therefore, naturally aspirated SI engine with electronic fuel injection and 3-way catalyst appears as the basic variant for all comparisons. The diagram shows that the use of carburetor has been almost entirely disappeared. In Europe a little remaining percent (~ 5%) mostly results from some east European countries, in Japan there are 1.75% carburetor engines left, while in USA carburetors have disappeared. It can be also noted that in USA and Asia MPi systems dominate in high per cent (97%). MPi systems enable better cylinder to cylinder mixture distribution and higher possibilities of inlet tract geometry optimization what make these systems very potential in engine performances, fuel economy and exhaust emission improvement.

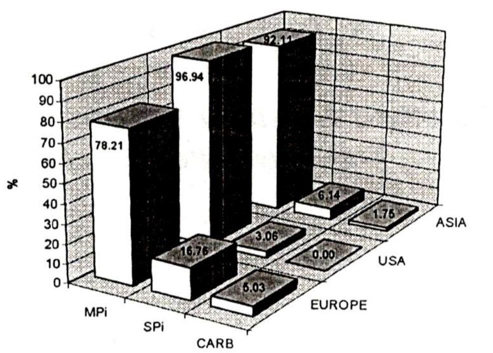

Fig.3-The share of SI engines mixture formation systems (MPi- Multi point injection, SPi- Single point injection; carb- carburetor).

2.2. Multi-valve systems

Cylinder head design with more than 2 valve per cylinder offers some substantial advantages. The most spread multi-valve variant is 4 valve per cylinder (2 inlet and 2 exhaust valves), although there are same solutions with 3V/cyl. (2 inlet and 1 exhaust valve) and a few concepts with 5V/cyl. (3 inlet and 2 exhaust valve). First, multi-valve systems significantly increase gas flow area and accordingly decrease flow losses during gas exchange processes. This gives better volumetric efficiency and less pumping losses enabling higher engine power output and better fuel economy. In addition, this solution offers possibilities of different valve timing for two inlet valve, or even throttling of one of the inlet channels at lower engines speeds, which can improve engine torque, and optimize in-cylinder flow field in wide rage of engine speed. Second, multi-valve design enable optimal central spark plug location what yields short flame front propagation distance and thus rapid combustion. And finally, valve mass and the problems with inertia forces at high engine speed are reduced.

Fig 4. shows general shapes of full load torque curve for standard 2-valve and 4- valve natural aspirated engine, and for turbocharged engine. Curves are plotted relatively so that the potentials of these conceptions can be underlined. As can be seen 4V technique enables engine torque and power improvement of approx. 15-20%.

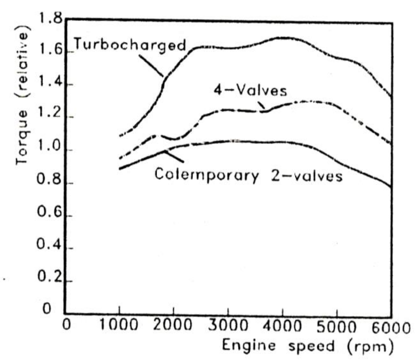

Fig.4-Engine torque curve shape for 2V and 4V naturally aspirated and turbocharged engine /2/.

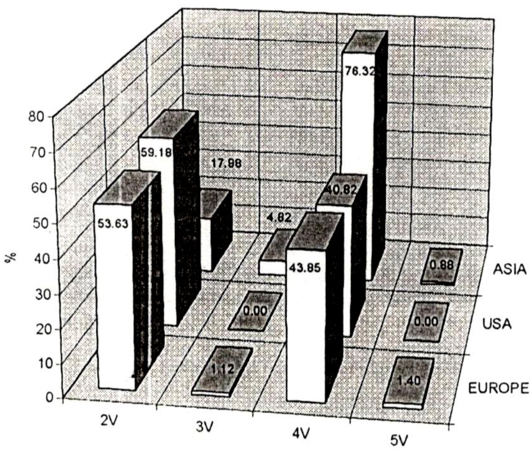

Fig.5-The spread of a multi-valve technique.

Fig. 5 shows the spread of the multi-valve techniques in passenger car SI engines design. It can be also noted that the manufacturers from Asia (Japan and South Korea) lead in this field, using 2 valve cylinder head variant in just a bit under 18 % of all SI engine models produced.

2.3. Variable inlet systems

The shape of torque curve can be strongly influenced by the inlet system design. By use of properly chosen pipe lengths and diameters of an inlet tract, during the last phase of inlet process an extra charging effect through the reflected waves of pressure can be obtained. However, such tuning is extremely sensitive to the engine speed and consequently it is optimal in very narrow RPM range. Fig. 6 shows the Variable Inlet System (VIS) with two different lengths of pipes. The longer one is used for low end torque optimization, while short optimizes pick power at high RPM. Systems featured by continual pipe length tuning over the entire RPM range also exist, by now on an experimental basis only.

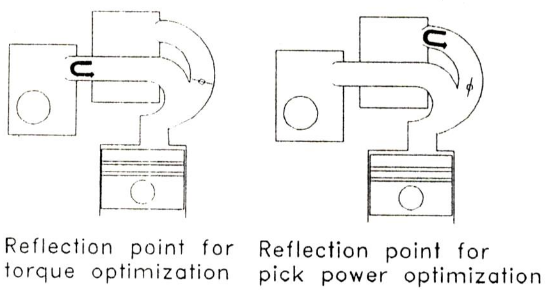

Fig.6-Operating principle of an Variable Inlet System.

At the present, variable inlet systems originally developed by some of European and Japanese car manufacturers exclusively for 6 cyl. engines (both in-line and V design), are also widely used on 4 cyl. engines. The application of VIS typically enable engine torque and elasticity improvement between 10 and 15% /2/.

2.4. Variable valve systems

The term Variable Valve Systems (VVS) includes variable valve timing, variable valve lift or their combination. Variable valve timing, which is the simplest solution, most commonly provided by a hydraulic cam phasing actuator has the modest potentials. More complex hydro-mechanical systems enable both variable valve timing and variable valve lift functions. Thus, very good results in gas exchange process and flow field optimization can be reached. Some experimental hydraulic systems, or even camless fully electrically powered VVS, both equipped with electronic control, offer an extensive optimization potential.

In principle, VVS enables convenient shape of engine torque curve and engine torque and elasticity improvement. In addition, an engine equipped with fully adjustable VVS can operate at low and partial loads without any throttle device, and thus improve fuel consumption. Fig. 7 shows in general how this approach can influence engine pumping losses /3/. By now, these fully adjustable systems are available on experimental basis only. Engine torque improvement as well as fuel economy, HC and NOx emissions reduction lie in the range of 15% approx. /1,2/.

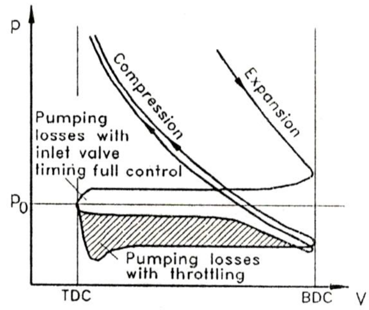

Fig.7-Pumping losses reduction at partial loads provided by inlet valve lift control /3/.

Fig.8 shows the spread of VVS in current serial engine production. It can be noticed that their share is still quite small in spite of their benefits. The reason lies in their complexity and high production costs.

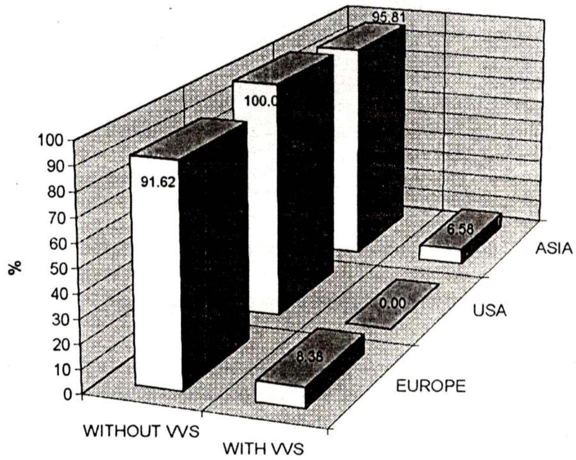

Fig.8-The spread of SI engines equipped with VVS.

2.5. Variable compression ratio

The compression ratio selected for a conventional spark ignition engine is limited by the octane rating of the available fuel. However, these restrictions are related to full load operation, while on light loads knock limited compression ratio can be higher enabling better thermal efficiency. Since an passenger car engine mostly operates at partial loads, variable compression ratio which at light load can be increased (to typically 15:1), can provide fuel consumption improvement of approx. 15% /2,4/.

Variable compression ratio can be obtained through cylinder head movement, additional variable volume chambers and variable piston stroke. So far, these systems are available on experimental basis only.

2.6. Engine charging

The largest engine power and torque increase potential lies in supercharging and turbocharging (see Fig.4). Fig.9 shows the spread of some charging principals (SC-supercharging by mechanically driven compressor and TC-turbocharging). Turbocharging is mostly used by European and Japanese manufacturers (12% and 10% respect.) while those in USA prefer supercharging principle.

Intercooler and turbine waste gate are widely used today. This technology also supported by electronic ignition advance control reduces the possibility of knocking, and thus enable higher compression ratios. Waste gate (by-pass valve), which is primarily used to limit the charging pressure, allows also the compressor to rich the nominal pressure at low RPM, and so increases the engine elasticity. The latest models of turbocharged engines use the new technology of variable turbine inlet port geometry improving performances even further.

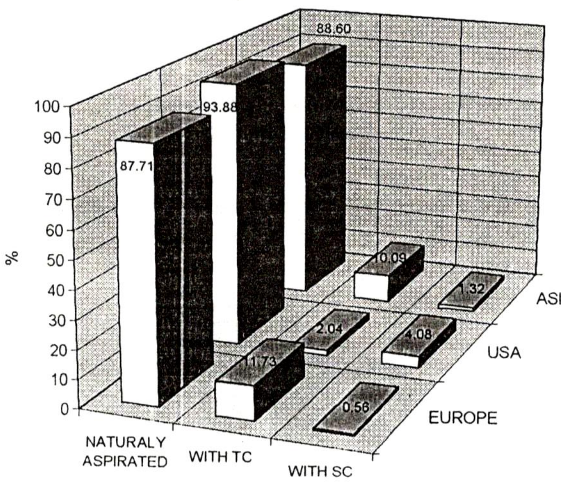

Fig.9-The spread of engine charging systems.

3. DESIGN FEATURES AND PERFORMANCES

Figures 10-13 show the results of statistical analysis for some of the most interesting characteristics related to the design and performances of SI engines for passenger cars. The average and standard deviation (small, partially covered column) have been given. The main goal is to estimate the potential of some technical solutions. Two Valve (2V) and Four Valve (4V) techniques applied on both naturally aspirated and TC engines have been taken into account. Also, the results have been given for three main continental groups of car manufacturers (Europe, USA and Asia), which, we can freely say, represent the specific affinities and schools of design. Having in mind the Fig.9, it should be noted that the results of statistical analysis related to the TC engines have sense only for those made in Europe and Asia, since the number of TC engines produced in USA is quite small.

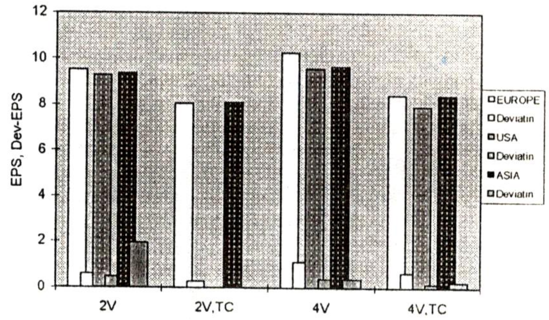

Fig.10-Compression ratio - average and standard deviation.

Fig.10 shows the average values and standard deviation of compression ratio, which for 2V and 4V engines correspond to 9.5 and 10 respectively. In 4V engines centrally positioned spark plug and optimized mixture flow yielding accelerated combustion, increase the knocking resistance, and so enable higher compression ratios. Compression ratios for 2V and 4V turbocharged engines correspond to 8 and 8.5 respectively. Standard deviation for all considered engine categories lie within the range of 5%

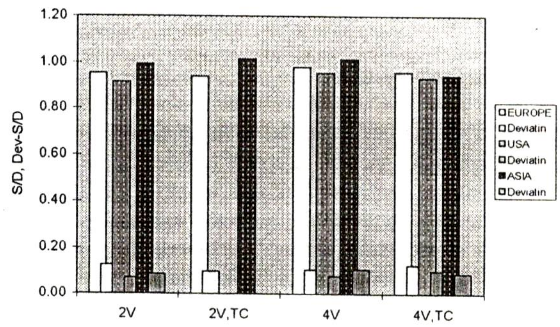

Fig.11-Stroke to bore ratio (S/D) - average and standard deviation.

Fig.11 shows the average and standard deviation for stroke/ bore ratio (S/D). No significant difference between categories being observed has been noted. The average S/D ratio of engines produced in Europe and USA is approx. 0.95, while those produced in Asia are featured with an average of 1.00 (though on 4V engines average S/D ratio slightly exceeds the value 1.00). The latest research activities show that optimal engine performances can be obtained with S/D ratio slightly exceeding the value 1.00. As it can be seen, manufacturers from Asia have already accepted and applied these trends.

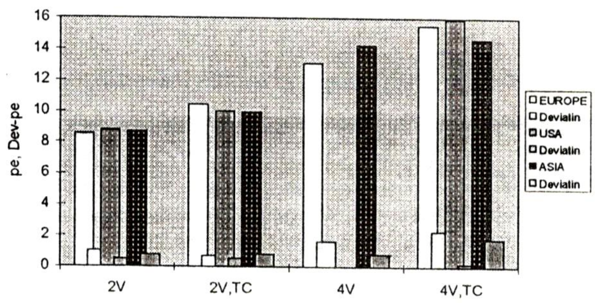

Fig.12-Break mean effective pressure (pe /bar/) - average and standard deviation.

The average value and standard deviation of break mean effective pressure (BMEP) for the categories of engines being observed are shown in Fig.12. The diagram clearly shows the performance potentials of the solutions under consideration. The differences between Europe, USA and Asia are very small which can be also said for the dissipation within the groups (standard deviation less than 10%). Naturally aspirated 2V engines have an average BMEP of approx. 8.5 bars while 4V engines reach 10 bars (increase of over 15%). Turbocharged engines reach a very high average of approx. 15 bars and thus high specific power output of 70-80 kW per liter of swept volume.

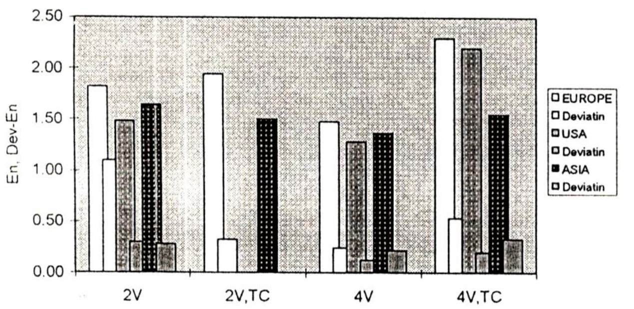

Fig.13-Engine elasticity coefficient with respect to RPM - average and standard deviation.

Fig.13 shows the average and standard deviation of engine elasticity coefficient with respect to engine speed (En) defined as the ratio of engine peak power RPM and maximum torque RPM. Although the dissipation around the average in this case is much higher (what is indicated by high standard deviation of 20-50%), trends can be clearly noticed. 4V naturally aspirated engines have slightly lower elasticity than conventional 2V engines. Nevertheless, turbocharging significantly improves engine elasticity with respect to RPM. This is resulted from modern turbocharging concept which includes turbine waste gate and lately variable turbine inlet port geometry.

CONCLUSIONS

Statistical analysis carried out over the entire current world production of passenger cars SI engines (considering engine types) has yield the following conclusions:

- Electronic fuel injection systems with closed loop λ- sonde control and 3-way catalyst technique absolutely dominate. Carburetors have almost entirely disappeared.
- Multi-valve technique is widely used for all engines categories. As far as the manufacturers from Asia are considered this technique is applied on more than 80% of all engine types.
- Variable inlet systems and variable valve systems are not widely applied in serial production at the present. However, as the solutions enabling the improvement of engine torque curve, fuel economy and exhaust emissions, they are expected to be widely used in the future.
- The application of multi-valve cylinder head and complex electronic engine process management have resulted in substantial compression ratio increase with consequent improvement of engine thermal efficiency.
- The spread of spark ignition engine turbocharging is relatively small. Performances of modern naturally aspirated SI engines equipped with electronic fuel injection and variable inlet and valve tuning systems exceed those of modern turbocharged diesel engines.

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